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Compilation of a Resistivity Atlas of Danish lithologies based on direct resistivity measurements and wireline logging data

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SUMMARY

Electrical conductivity, or its inverse, the resistivity, is an important geophysical property within groundwater mapping. It is known to correlate empirically to lithology, primarily through clay minerals and pore water ions. Although, in Denmark, geoelectric and electromagnetic surveys have been carried out for decades, no systematic, nationwide study on the relationship between resistivity and lithology has been carried out.

We present a procedure for generating a resistivity atlas based on resistivity measurements, which can be related directly to specific and well described soil samples. Data are obtained from archives, literature and the Danish national databases. The procedure implies a restricted use of wireline logging data in combination with direct measurements on samples, resulting in resistivity distributions for specific lithologies or geological formations. The use of documented high-quality data ensures reliable results, reflecting actual resistivity of a specific lithology.

This procedure is illustrated on clay till. The resistivity variations obtained for this lithology seems to be related to real compositional variations, which reflect the process of forming the clay till.

Our procedure is likely to provide equally reliable results for other main lithologies. Future detailed studies, in particular on sediments with low clay content, should consider resistivity differences related to the degree of saturation and variations in the formation water resistivity.

Key words: Resistivity, electrical methods, lithology, petrophysical relationship.

INTRODUCTION

Subsurface electrical conductivity or its inverse, the resistivity, is one of the most important petrophysical parameters in groundwater mapping. Resistivities obtained in geoelectric or electromagnetic surveys may be good indicators of the presence of subsurface fresh water. This is due to the fact that formation (or bulk) resistivity is known to correlate empirically to lithology, primarily through clay minerals and pore water ions (Archie 1942 for clay-free materials, e.g., de Lima and Sharma 1990 for clayey materials).

Despite geoelectric and electromagnetic surveys have been carried out for decades in Denmark e.g., groundwater mapping purposes (e.g., Sandersen and Jørgensen 2003, Sørensen et al. 2005, Møller et al. 2009) no systematic, nationwide study on the relationship between resistivity and lithology has been carried out. Only some studies based on borehole lithology and wireline resistivity logging related to specific surveys, covering smaller regions, are found (Jørgensen et al. 2005, Sandersen et al. 2009).

Now, the use of densely sampled large-scale airborne electromagnetic (AEM) surveys in groundwater mapping call for procedures to integrate the geophysical information in the geological and hydrological modelling in an objectively and efficient manner way. This could be automatic or semi-automatic. Descriptions of the relationship between the geophysical data and the lithological data, for instance expressed as resistivity distributions for a specific lithology or geological formation, are essential for the above mentioned methods. The success of such methods may rely on the number of significant lithologies and how distinct their resistivity distributions are defined. This calls for detailed information on the relationship between resistivity and lithology in large regions.

We present first results from a recent and ongoing compilation of an atlas of resistivities of Danish geological formations based on direct measurements on soil samples and wireline logging resistivity data. The aim of the study is to obtain as

exact as possible information on the resistivity of individual geological formations and the variability in resistivity, both laterally and with depth. This study will serve as a benchmark for a similar study using AEM data and other electromagnetic data collected at ground surface (Barfod et al., this volume). Furthermore, we will try to relate the resistivity variations of specific lithologies to the geological depositional processes and environments.

STUDY AREA

Denmark, our study area, is situated in northern Europe at the edge of the Baltic Shield. The main part of Denmark consists of sedimentary basins formed since Carboniferous and Permian. The shallow subsurface consists primarily of soft sediments spanning from Cretaceous chalk, Paleogene limestone, marls and clays, Neogene clay and sand to Quaternary glacial and interglacial deposits. Only at the island of Bornholm, the shallow subsurface consists of crystalline rocks and sediments older than Cretaceous. The Quaternary sediments are dominated by clay till and meltwater sediments deposited during a number of glacial events (Figure 1). Furthermore, interglacial and Holocene lacustrine and marine deposits are found.

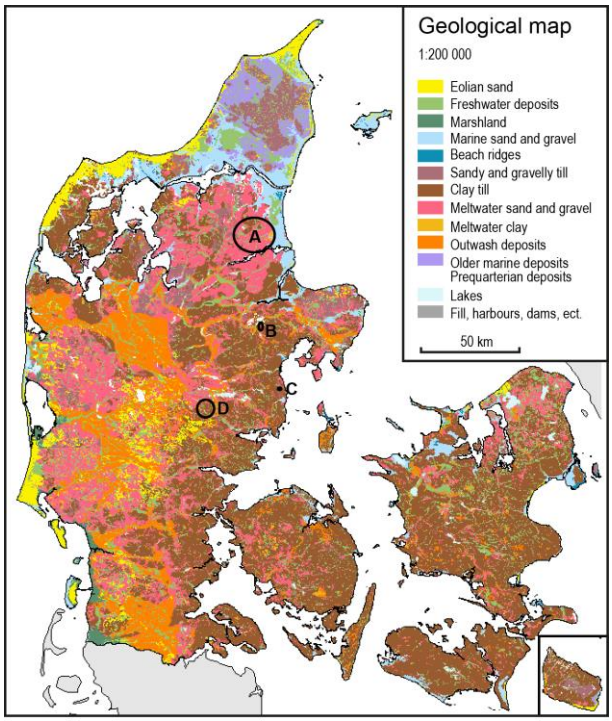

Figure 1. Geological map of Denmark, 1:200 000, for the shallow subsurface (Pedersen et al. 2011). Results from four selected areas (A: Himmerland, B: Hadsten, C: Mårslet and D: Brædstrup) are described and summarized in Figure 2.

MATERIAL AND METHOD

Data sources

Here we focus on resistivity measurements which can be related directly to specific and well described soil samples. Resistivity data acquired over the last four decades in Denmark are obtained from archives, literature and databases. The data sources include (1) direct measurements of resistivity on sediment samples from drill holes or outcrops using a 1 cm Wenner configuration, (2) resistivity measurement obtained by suppressing an electrical field on core sections, (3) electrical resistivity logs acquired *in situ* while auger-drilling combined with a nearby auger drilling for soil samples and (4) electrical resistivity logs acquired using wireline logging tools in boreholes with dense soil sampling and detailed geological descriptions. Many of the resistivity logs belonging to the data source (3) and (4) are drawn from the Danish national geophysical database GERDA (http://gerda.geus.dk) containing more than 2000 geophysical wireline logs (Møller et al. 2009). The borehole lithological information belonging to data source (3) and (4) are primarily drawn from the Danish national well database (http://jupiter.geus.dk) containing geological and hydrological information from more than 240,000 wells (Hansen & Pjetursson 2011, Møller et al. 2009).

Data cleaning and filtering

Resistivity data and lithological data are linked by the borehole number and the sample depth. Before the wireline log resistivity data are connected with the related lithology they are non-spike filtered and reduced to a sampling interval of 0.5 m applying a 1m-running-mean-filter. Within the intervals of combined resistivity and lithology data, a data point is defined for each 0.5 m.

We have chosen only to use wireline logging resistivity data acquired with a normal log with a 64” spacing and long guarded resistivity logs expecting these data to be insignificantly disturbed by the borehole and the borehole mud. Furthermore, we only use resistivity-lithology pairs that are more than three times the electrode spacing (= 5 m for a 64” spacing) away from a layer boundary to ensure that the resistivities can be related to a specific lithology.

For specific lithologies, for instance glacial clay till, or a group of lithologies, e.g., meltwater sand and gravel, resistivity distribution functions are produced and illustrated as e.g., histograms or box plots. The resistivities are presented on a logarithmic scale and the statistics are carried out on logarithmically transformed resistivity data.

RESULTS

We will here focus our results on clay till resistivities derived from the direct measurements on soil samples in four project areas (Figure 1) and from the wireline logging data acquired in boreholes with a soil sampling frequency of one metre. These tills are very common in the Danish subsurface; they typically occur consolidated, and they were mainly formed subglacially as lodgement till.

Survey areas

The resistivities measured directly on soil samples originate from four different field campaigns. In the Himmerland survey, data are obtained from five cored wells approximately 20 m deep situated several kilometres a part. Only three of the boreholes contain clay till samples. In one of the boreholes the

clay till is found in the most shallow 10 m and in the other two boreholes the clay till is found in the interval 10-20 m below ground surface. The Hadsten survey consists of five auger drilled boreholes to c. 30 m depth located along a 4 km line. All of the boreholes have several metres of clay till, often separated by layers of meltwater sand and gravel. The Mårslet survey is carried out on a small field where five auger drillings are located only few hundred metres a part. One borehole is 20 m deep and the others are 5 m deep. All five boreholes mainly consist of clay till interbedded by meltwater clay. In the Brædstrup survey 10 boreholes of 10 m depth are located a few kilometres a part. Here, the majority of the sediments is clay till.

Resistivity distributions

The resistivity distributions for clay till at the four sites are illustrated in Figure 2. The geometrical mean of the resitivities at the Hadsten site (57 Ωm) is the highest among the four sites. The geometrical mean in the Himmerland survey (38 Ωm) and the Brædstrup (36 Ωm) site are very similar, however the two distributions are quite different. The Himmerland resistivity distribution is rather wide while that at Brædstrup is skewed with the median close to the lower quartile. The clay till at Mårslet has the lowest resistivity with a geometrical mean of 26 Ωm and a rather narrow resistivity distribution.

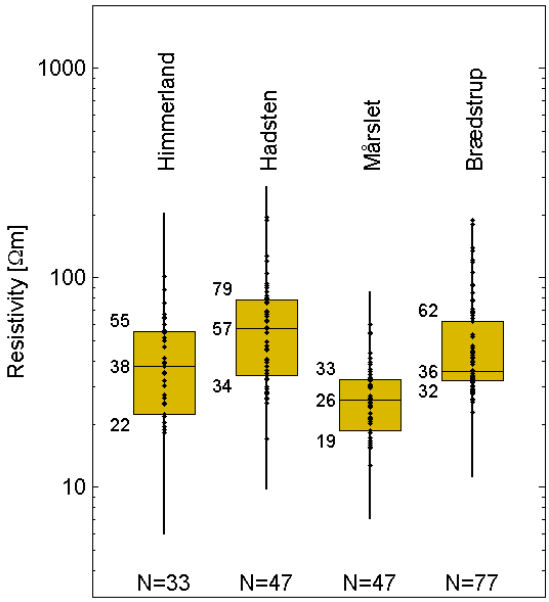

Figure 2. Boxplot of resistivity measurements on clay till samples from four localities in Eastern Jutland (cf. Figure 1). The lower edge of the box mark the lower quartile (25 %), the horizontal line in the middle is the median, and the upper edge mark the upper quartile (75 %). The vertical lines, the whiskers, are indicators of outliers, so data outside the whiskers are potential outliers.

The clay till resistivity distribution obtained from wireline logging resistivity data found in boreholes covering the central and eastern part of Jutland and Funen has an average resistivity of 38 Ωm and 50 % of the data lies within 31 Ωm and 48 Ωm (Figure 3). The average resistivity of the Himmerland and Brædstrup sites (Figure 2) is very similar to the average resistivity of all clay tills from the wireline logged boreholes (Figure 3).

The map in Figure 4 shows that the resistivity distribution obtained from the wireline logging (Figure 3) contains a rather large variation both laterally and with depth. There is a good consistence between the few resistivity measurements directly on soil samples and the wireline logged data.

The rather large resistivity variation both lateral and with depth can be related to the formation of clay tills. A lodgement till is formed at the ice-bed interface, where sediments from the regional substratum can end up as a part of the resulting till further down-ice. Thereby the resistivity of the clay till is likely to reflect the type of sediment in the up-ice, but near-by underlying layer. This seems to be the case at the Hadsten site, where the clay till with inclusions of meltwater sand beds show rather high average clay till resistivity, whereas the clay till at Mårslet, which is interbedded by meltwater clay show relatively low average resistivity.

Further studies focusing more closely on the layers beneath the till may reveal the impact of lithological differences in these layers upon the resistivity of the clay till.

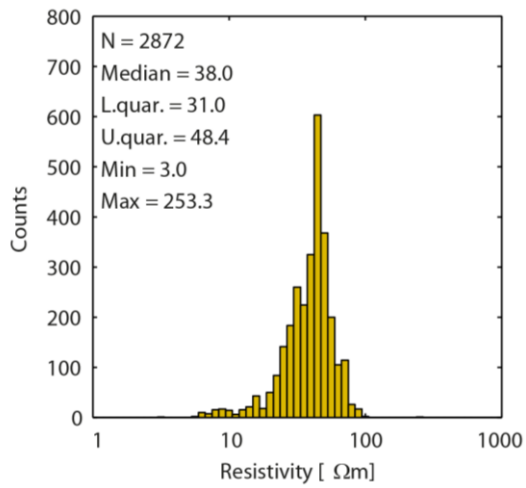

Figure 3. Histogram of clay till resistivities acquired by wire line logging from Jutland and Funen (area displayed in Figure 4).

CONCLUSIONS

The applied procedure of compiling resistivity distributions by combining direct measurements on samples, with a restricted use of wireline logging data, as illustrated here on clay till, ensures reliable results reflecting actual resistivity of a specific lithology. The resistivity variations obtained for the clay till seems to be related to real lithological variations, which reflect the till forming processes.

This procedure is likely to provide equally reliable results for other main lithologies. Future studies, in particular on sediments with low clay content, should consider resistivity differences related to the degree of saturation and variations in the formation water resistivity.

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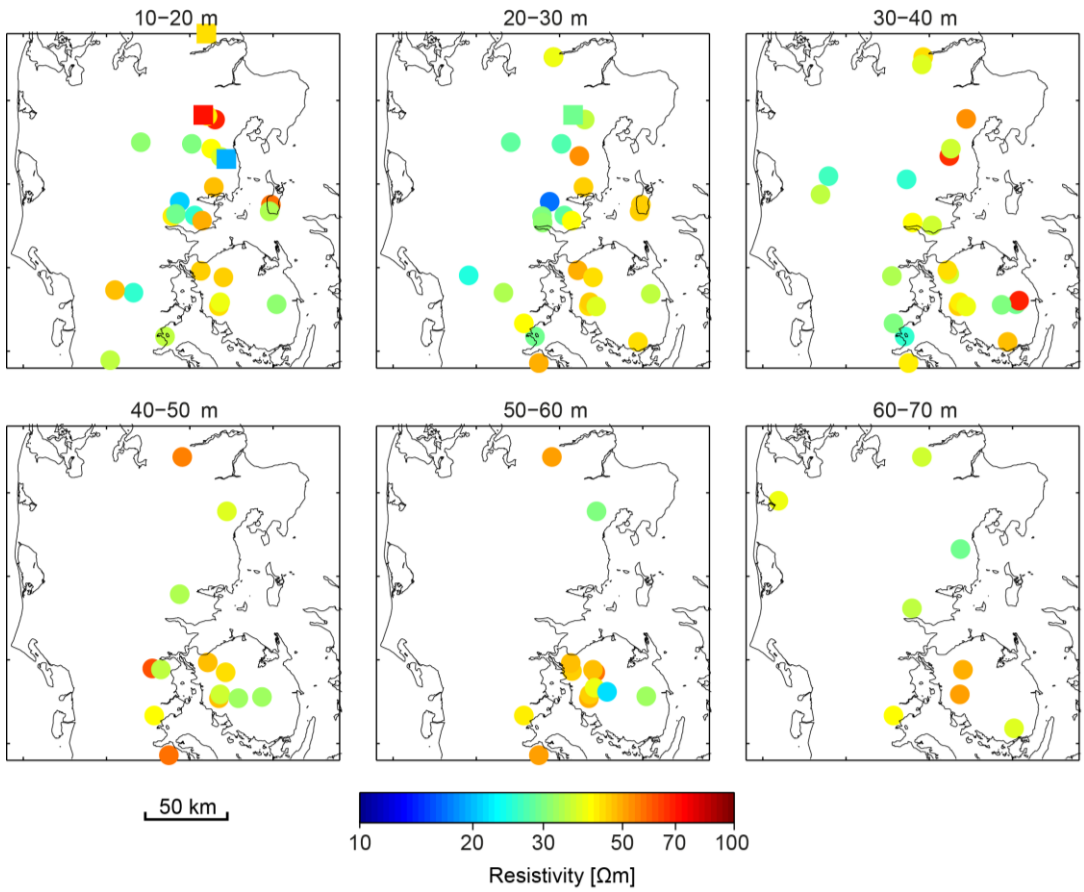

Figure 4. Clay till resistivities acquired using wireline logging (circles) and direct measurements on samples (squares). Individual log resistivities are averages over 10 m intervals from 10 m to 70 m depth for each individual log. Boreholes with a dense soil sample frequency of about one metre are used.