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3D geological modelling of a buried-valley network based on AEM and borehole data

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SUMMARY

In former glaciated areas buried tunnel valleys can often be found. These buried erosional structures can be highly decisive for groundwater recharge and groundwater flow. Delineation of the architecture and infill of the structures are therefore very important in relation to groundwater mapping. The dense data coverage offered by airborne electromagnetic methods makes it possible to map and model the buried valley structures with a high degree of detail. The delineation of the individual valleys and the mapping of the internal cross-cutting relationships are dependent on the geological interpretation, which is founded on the knowledge about geological processes and the regional geology.

In this study, we have investigated a relatively small study area in Denmark with SkyTEM and lithological log data as the main data sources. The area is characterised by a network of cross-cutting buried tunnel valleys, which have been incised into impermeable Paleogene clay deposits. The geological interpretation of the SkyTEM data resulted in modelling of 21 buried valleys belonging to at least 7 different generations. Manual voxel modelling of the infill of these valleys, as well as the surroundings, resulted in a geological 3D model consisting of 43 different units. Most of the valleys show heterogeneous infill, characterized by a predominant lithology (for instance meltwater sand) with local occurrences of secondary lithologies (for instance clay till). In the majority of the valleys, meltwater sand is the main lithology, but clay till and meltwater clay deposits are also commonly found. Due to the heterogeneity of the infill, proper modelling of this type of geology requires voxel modelling instead of layer modelling.

Key words: SkyTEM, Interpreting AEM, geology, buried valleys, groundwater

INTRODUCTION

Buried tunnel valleys are important features for groundwater flow pathways. If filled with coarse-grained deposits, they may act as hydraulic conduits (e.g. Jørgensen et al., 2010), and important groundwater reservoirs are found within buried valley structures in many places (Sandersen and Jørgensen, 2003). However, if filled with clayey deposits, buried valleys might also act as barriers that prevent groundwater flow.

Tunnel valleys are common features in former glaciated regions, where they were created close to the ice sheet margins (Jørgensen & Sandersen 2006; Kehew et al., 2012; van der Vegt et al., 2012). The buried valleys have been identified both on- and offshore in seismic data and in the last two decades EM data have been used extensively to identify these structures (Jørgensen et al., 2003). The dense data coverage is essential when mapping the architecture of the buried valleys and borehole data alone is therefore insufficient (Jørgensen and Sandersen, 2008). This is especially the case, in areas with high complexity as areas where networks of buried valleys cross-cut each other.

The current study is a part of the HyGEM project (Integrating geophysics, geology and hydrology for improved groundwater and environmental management). The main objective of this project is to create tools for the direct and automatic integration of spatially dense geophysical and sparse geological data to construct the hydrostratigraphic basis for hydrological models. The current geological model was therefore created with the objective to compare the results of the groundwater modelling based on the manually created geological model with the results of the automatically generated hydrostratigraphic models.

The study area is placed in an area in Denmark that is characterized by a complex network of cross-cutting buried valleys. The manual, cognitive modelling of such an environment is a time-consuming task and manual modelling of very complex environments can be difficult. However, by setting up and following a manual modelling approach, we have made a model of the surfaces and infill of the network of the

valleys in the area – a total of 21 cross-cutting valleys with heterogeneous infill.

STUDY AREA

The study area is located in the central part of Denmark (Figure 1) and covers 45 km^2. The area is placed just outside *Aarhus* with 300,000 inhabitants. The water supply in the city is completely based on groundwater, and much of the abstraction is situated in the study area.

Impermeable Paleogene clay and marl deposits are generally found close to the surface (20-40 m of depth) and constitute the base of the potential aquifers. The Paleogene deposits are characterized by very low resistivities (5–7 ohmm). In many places, the Paleogene directly underlies the Quaternary deposits. The Quaternary deposits mainly constitute clay till, meltwater sand and meltwater clay deposits. The area has been transgressed by numerous ice sheets during the Pleistocene, and buried valleys are commonly found in the region (Jørgensen and Sandersen, 2006). The valleys were incised into the Paleogene clay, and the Paleogene surface therefore shows a highly varying topography.

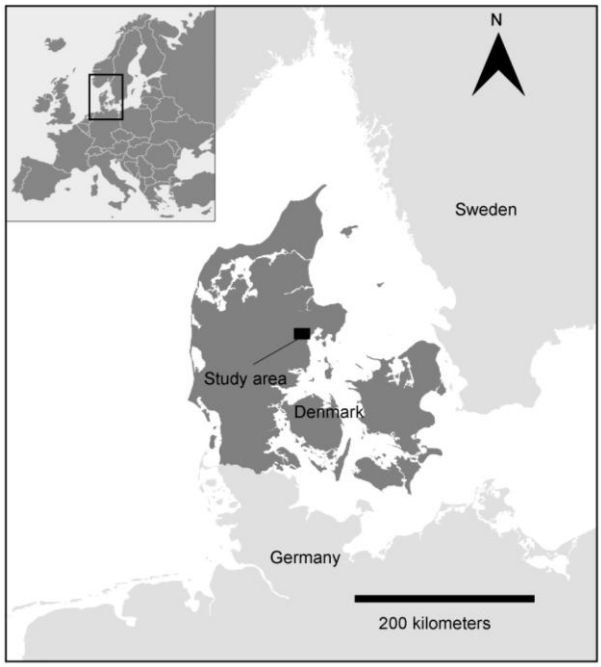

Figure 1. Study area

SKYTEM SURVEY

The airborne dataset was acquired in 2013 with the SkyTEM system (Sørensen and Auken, 2004), which is a time-domain helicopter-borne electromagnetic method, where the system is carried as an external sling load independent of the helicopter. The transmitter loop in this study covers 339 m^2. In order to obtain information about both the near-surface and the deeper part of the geological setting, the system alternates between transmitting a low moment (10 A) with a turn-off time of about 3 µs and a high moment (110 A) with a turn-off time of approximately 44 µs.

The survey covers 333 line km and was acquired with a line spacing of 100 m (Figure 2). The study area is placed in an area characterized by dense infrastructure, and many of the soundings therefore suffered from couplings to man-made conductors and were removed during the processing. The data were inverted as 1-D models, but to obtain quasi 3-D volumes, the model parameters were constrained to neighbouring models, using the spatially constrained inversion (Viezzoli et al., 2008). The soundings were inverted into smooth 25-layer models that were discretised to depths of 300 m. During the inversion also the depth of investigation (DOI) was calculated for the output models. In most of the area, the depth of investigation corresponds to 140-240 m of depth.

BOREHOLES

Information from around 700 boreholes within the area is available in the national Danish borehole database, Jupiter (Møller et al., 2009). Most of these have been drilled for water abstraction. The vast majority of the boreholes is shallow, and only 3 % (21 boreholes) are deeper than 100 m (Figure 2). The boreholes vary considerably in quality and an important part of the cognitive modelling procedure is to estimate the credibility of the borehole information.

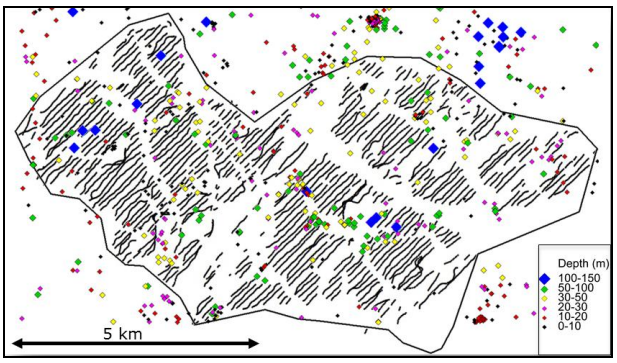

Figure 2. Data in the study area. The SkyTEM data is shown as black dots (that appear as black lines because of the dense data along the flight lines). The borehole data are coloured to show the depths of the boreholes.

3D GEOLOGICAL MODELLING METHODOLOGY

The manual geological modelling methodology is based on the geological background knowledge and a thorough investigation of the available data. The borehole information is utilised to provide information regarding the groundwater chemistry and the lithological information. The area is not influenced by sline groundwater, and the formation resistivities are therefore in the range of the expected for Danish sedimentary environments (Jørgensen et al., 2005). The lithology is generally interpreted from the resistivity data by relating the lithological information from the boreholes to the resistivity information in the SkyTEM data.

The modelling approach that is used in this study consists of a number of steps, which is summarised in Figure 3: The first step in the modelling (1) is to examine the SkyTEM resistivity data. At this point, the data are visualised as a 3D resistivity cube, which is used as background for the initial interpretation of the data. Also the depth to the good conductor (the top Paleogene) is gridded and studied. The main objective of this

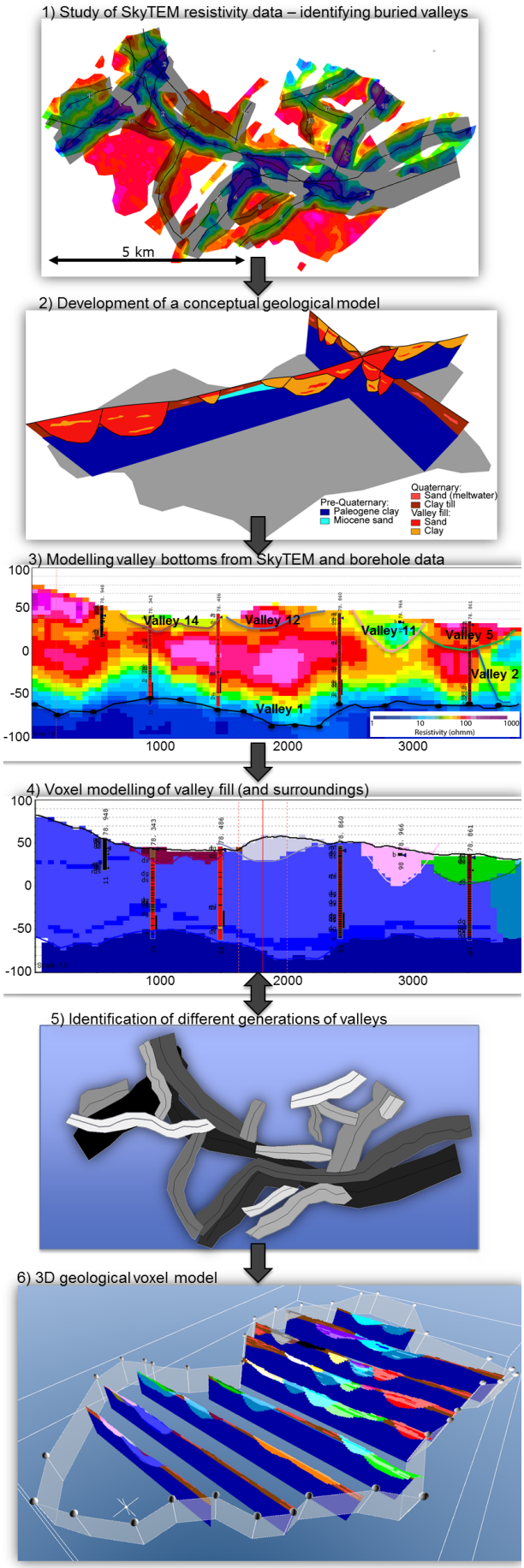

Figure 3. Sketch of the steps used in the manual cognitive 3D geological modelling approach of the buried valleys. 1) Initial study of the SkyTEM resistivity data and identification of the buried valleys in the area. This figure shows the depth to the good conductor – purple colours show low elevation (~ 100 m b. s. l.) and red colours show high elevations (~ 40 m a. s. l). Superposed on the map is gray shade showing the extent of the buried valleys in the area. 2) Creation of a conceptual geological model showing the main structures and lithologies. 3) Detailed modelling of the valley bottoms. (This profile cuts through the 3D resistivity cube and along the deepest part of one of the buried valleys (valley 1). The lithological log information is interpolated onto the profile from a maximum of 100 m: Red colours in the boreholes represent Quaternary sand. Brown colours represent Quaternary clay. Blue colours represent Pre-Quaternary deposits. Vertical exaggeration of the profile = 7x.) 4) Manual population of the voxels with geological units, defined by lithological and/or stratigraphical parameters. The profile is the same as in (3). 5) Concurrent with (4), the age relationships between the valleys are identified. The oldest valleys are shown with the darkest colours. 6) The final result is a 3D geological voxel model – here visualized by nine N-S slices through the voxel model with the 43 different geological units. Vertical exaggeration = 3x.

initial study is to identify the buried valleys in the area. The outcome of this is combined with geological information and utilised to build a conceptual geological model of the area (2). This model identifies the main structures and lithologies expected in the study area. The conceptual model is used during the subsequent detailed mapping (3). The first step in the detailed mapping is to interpret and model the erosional surfaces that constitute the valley bottoms. Here, interpretation points are placed along the valley bottoms and used as basis for the subsequent interpolation of the surfaces. This has been done for all the valleys in the study area – resulting in 21 surfaces, one for each valley bottom. In a few cases the valleys do not reach the surface, and in these cases, also the top level of the valleys has been interpreted. After the modelling of the layers, the model has been transferred into a 3D voxel model by manually populating the voxels with units, defined by lithological and/or stratigraphical parameters (4). Concurrent with this work, the internal age relationships between the valleys are identified and the valley generations are inferred (5). The final result is a 3D geological voxel model (6) which can be shown both with the different units – but also strictly as a lithofacies model.

RESULTS

The study resulted in the modelling of a network of 21 buried valleys. The valleys form a complex network, where younger valleys have been eroded into older buried valleys (Fig. 3,5). Based on the internal age-relationships, the orientation of the valleys, and the valley fill deposits, at least 7 generations of buried valleys have been mapped within the relatively small study area. The dimensions of the valleys vary considerably – some of them are very shallow (20 m of depth), whereas others show depths up to 130 m. The lengths are difficult to

determine, since many of the valleys extend beyond the SkyTEM mapped area in this study.

The final voxel model encompasses 43 different geological units. The base of the model is characterized by Paleogene clays. Above this, Miocene sand is found locally, but in most of the area, the Quaternary sediments are found directly above the Paleogene. The Quaternary deposits are grouped into deposits occurring outside the valleys (sand till, meltwater sand and clay till) and deposits occurring within the buried valleys (meltwater sand, clay till and meltwater clay). The occurring type of sediments in each valley varies according to shifting depositional environments. The units in the model are therefore defined both on the basis of lithology and on the valley stratigraphy. The majority of the 21 buried valleys show heterogeneous infill, and the valley fill deposits are consequently described in 38 geological units. When transformed into a lithofacies model, the model consists of only 8 units: The Paleogene clay (1) and the Miocene sand (2) in the Pre-Quaternary, and in the Quaternary: Sand till (3), meltwater sand (4) and clay till (5) outside the valleys, and meltwater sand (6), clay till (7) and meltwater clay (8) deposited as valley fill.

CONCLUSIONS

Thorough investigation of the SkyTEM resistivity data revealed a spectacular geological setting including at least seven generations of buried tunnel valleys within a very small study area. This type of environment is difficult and time-consuming to model, but by using the modelling methodology suggested in the current study, we have succeeded to produce a reliable model of both the surfaces and the infill structures. In order to incorporate the huge amount of details observed in the SkyTEM and the borehole data and predicted by the geological conceptual understanding, the model was built as a voxel model.

ACKNOWLEDGMENTS

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