Delineation of fault systems on Langeland, Denmark based on AEM data and boreholes

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SUMMARY

In 1998 Denmark initiated a national groundwater mapping campaign in order to obtain knowledge of the aquifers with respect to their location, distribution, extension, interconnection and to acquire maps detailing groundwater vulnerability. The aim was to establish site-specific groundwater protection zones to prevent groundwater contamination from urban development and agricultural sources in agreement with The EU Water Framework Directive. The mapping campaign involved a dense data acquisition typically comprising boreholes, electromagnetic surveys – both airborne and land based and geoelectrical surveys. The data serve as basis for constructing 3D hydrogeological and groundwater models from which site-specific protection zones are establish. At present time dense geophysical mapping covers approximately 45 % of Denmark.

Based on a dense Airborne ElectroMagnetic (AEM) survey in combination with boreholes, three fault systems in the northern part of the island of Langeland, Denmark are mapped. Two of the fault systems were unknown prior to the mapping campaign. The two unknown fault systems are interpreted as a normal fault and graben structures, respectively. The presence of the hanging-wall block in the fault systems can be observed in the AEM data as a low resistivity layer that clearly distinguish from the underlying and surrounding high resistivity fresh water saturated limestone (footwall block) and the overlying glacial clay till. Soil descriptions from a borehole confirm that the low resistivity layer can be correlated to Palaeocene clay deposits. The fault systems were most likely initiated in the early Neogene during the Alpine orogeny. The fault systems are observed to alter the hydrology significantly and are therefore important to map.

Key words: Geophysical mapping, AEM data, Geological modelling, Fault systems.

INTRODUCTION

In Denmark all drinking water originates from groundwater (Thomsen et al., 2004). The aquifers are typically located in the upper 200 mbsl (meters below sea level) and consist of either glacial meltwater deposits, miocene sandy deposits or limestone depending on the location in Denmark. The limestone was deposited in the Danish basin during the Cretaceous when Denmark was covered by oceans, and carbonate sedimentation prevailed. The Danish basin is flanked by the Fennoscandian Shield to the north and by the Ringkøbing- Fyn High to the south (Figure 1). During the Cenozoic the North Sea Basin including the Danish basin was dominated by subsidence, whilst relative uplift and erosion affected the surrounding landmasses giving rise to a general basin-ward progradation of the Cenozoic basin fill and an overall WSW dip of the base Quaternary surface in the eastern North Sea Basin. The Quaternary subcrop of western Denmark and the eastern North Sea has an increasing age towards the ENE. Cretaceous chalk and limestone is observed towards the north, Paleocene to Oligocene clays and sands along a narrow belt from northwest towards southeast, and interbedded sandy and clay-rich sediments from Miocene to Pliocene towards the southwest (e.g. Liboriussen et al., 1987; Japsen et al. 2002; Nielsen et al. 1986; Rasmussen et al., 2010). During the Middle and Late Pleistocene, Denmark and parts of the North Sea were covered by several ice sheets expanding from the Scandinavian highlands (Houmark-Nielsen, 1987). During the glaciations, glaciogenic sediments e.g. sand layers and tills were deposited

In order to protect the groundwater, the Danish government initiated a national groundwater mapping campaign in 1998 (Thomsen et al., 2004). The scope of the mapping campaign was to establish site specific protection zones in order to secure a sustainable groundwater resource in agreement with The EU Water Framework Directive. Due to the often complex geological setting in Denmark, a dense data cover is needed in order to delineate the aquifers and the surrounding layers with respect to their spatial extent, extension, interconnection etc. (Jørgensen and Sandersen. 2009a; Høyer et al., 2015).

In 2010 the Danish government initiated a mapping campaign on the island of Langeland situated in the southern part of Denmark, see Figure 1. The island is located along the Ringkøbing-Fyn High separating the Danish basin from the North German Basin. Langeland is characterized by a complex geological setting with an upper 25-100 m thick sequence of glacial deposits which are overlying limestone in the northern part of the island and Paleogene clays in the southern part of the island. The lithological shift in the pre-quaternary sediments is correlated to a large fault system (e.g. Vejbæk and Bitze, 1994) and to the presence of a buried valley.

Based on a dense AEM survey in combination with boreholes, we have mapped two additional fault systems in the northern part of Langeland. Based on borehole information the fault systems have most likely been active in the early Neogene during the Alpine orogeny. The fault systems are observed to have changed the location, distribution, extension, interconnection of the aquifers.

Consequently, limited knowledge about the presence of fault systems can result in misleading geological models and the attendant groundwater models.

The objectives of this paper are therefore (i) to delineate fault systems based on AEM data and boreholes on Langeland, and (ii) to construct a 3D geological model based on the dense AEM data and boreholes.

STUDY AREA

The study area is located at the northern part of the island of Langeland, Denmark (Figure 1). The area covers 100 km^2 with the towns of Lohals, Snøde, Tranekær and Tullebølle as the largest. Water is abstracted from the limestone in the study area and from glacial meltwater sand aquifers south of the study area. The geological setting in Langeland is complex with large differences in between the southern and northern part of the island with respect to the pre-quaternary sediments (Figure 1). In the north the pre-quaternary sediments comprise Danien limestone, whereas the southern part comprises Paleocene and Eocene clay deposits. The Danien limestone was deposited in early Paleocene between 65 to 62 mill. years ago. Based on borehole samples, the chalk is described as soft bryozoan limestone. In areas where the limestone contains fresh water the resistivity is 80 -100 Ohmm, whereas the resistivity is around 5 Ohmm is areas where the limestone is saturated with saltwater. In the southern part of Langeland the pre-quaternary sediments comprise of Paleocene and Eocene clay deposits which were deposited between 62 to 34 mill. years ago. The Paleocene deposit is Kerteminde Marl, which is described as soft and silty marl with a Chalk content of 50%. The Eocene deposits consist of Røsnæs clay and Lillebælt clay and are described as heavy clay with little or no chalk. The Paleocene and Eocene deposits are characterized by very low resistivities (5–7 Ohmm).

Throughout the island the pre-quaternary sediments are covered by 25-100 m of quaternary deposits. The quaternary sediments vary from meltwater deposits ranging from fine to medium grained meltwater sands to lacustrine silts and clays to clay tills. The clay tills have resistivities ranging from 20 to 60 Ohmm and the meltwater sand from 50 to 100 Ohmm. In the southern part of Langeland Eemian deposits are reported (e.g. Madsen, 1916; Ehlers, 1979; Kristensen et al., 2000; Sjørring et al. 1982). Hence, the lower parts of the quaternary sediments are pre-Saalian of age whereas the upper parts are deposit during the Weichselian glaciation.

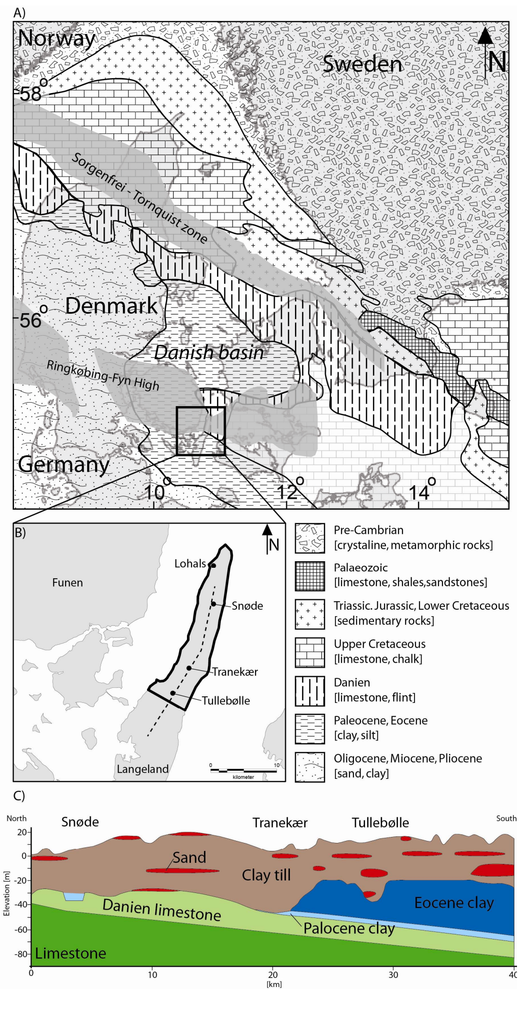

Figure 1: A) Overview map showing the geological setting in the Danish basin. B) The study area (marked with black). C) Conceptual geological profile through the northern part of Langeland. The position of the profile is shown as the dotted line on B.

DATA

AEM

The AEM dataset was collected in 2010 as part of the national Danish groundwater campaign using the SkyTEM system (Sørensen and Auken, 2004). The method is based on time-domain airborne electromagnetic measurements utilizing geophysical equipment fitted to a helicopter travelling with a horizontal speed of 45 km/h. A total of 649 km of profiling data were collected at Langeland of which approximately 300 km were measured in the northern part of the island, see Figure 2. The line spacing was 200 m. In the current study the transmitter loop had an area of 314 m^2 and data were obtained using both high moment and low moment system of app 2.500 AM^2 and 62.800 AM^2, respectively. The maximum Depth of Investigation was app. 300 m.

43 % of the data was removed during the processing due to man-made conductors.

Data was processed and inverted in Workbench as SCI (spatially constrained Inversion) into 5 and 19 layers smooth models The data was presented as 1D soundings as well as quasi 3D maps (Viezzoli et al., 2008). 2D maps of the mean resistivity in every 5 m were also been created. Hence the overall spatial distribution of the resistivity can be achieved within the study area.

Boreholes

A total of 189 boreholes are situated in the northern part of Langeland (1.9 boreholes per km^2, Figure 2). The majority of the boreholes penetrate the interval 5 to 70 m depth. The deepest borehole is drilled to a depth of 209 m. During the groundwater mapping campaign an investigation borehole (DGU no 165.517) was drilled near the town of Snøde (Figure 1). The upper 48 m of the borehole comprises glacial till with minor lenses of sand. Under the clay till, 9 m of Paleocene clay deposits are observed (Kerteminde marl and the Æbelø Formation). Underlying the Paleocene clay, 1 m of Lellinge Greensand and 2 m of Danien limestone are observed. This is the only borehole in the northern part of Langeland in which Paleocene deposits have been reported.

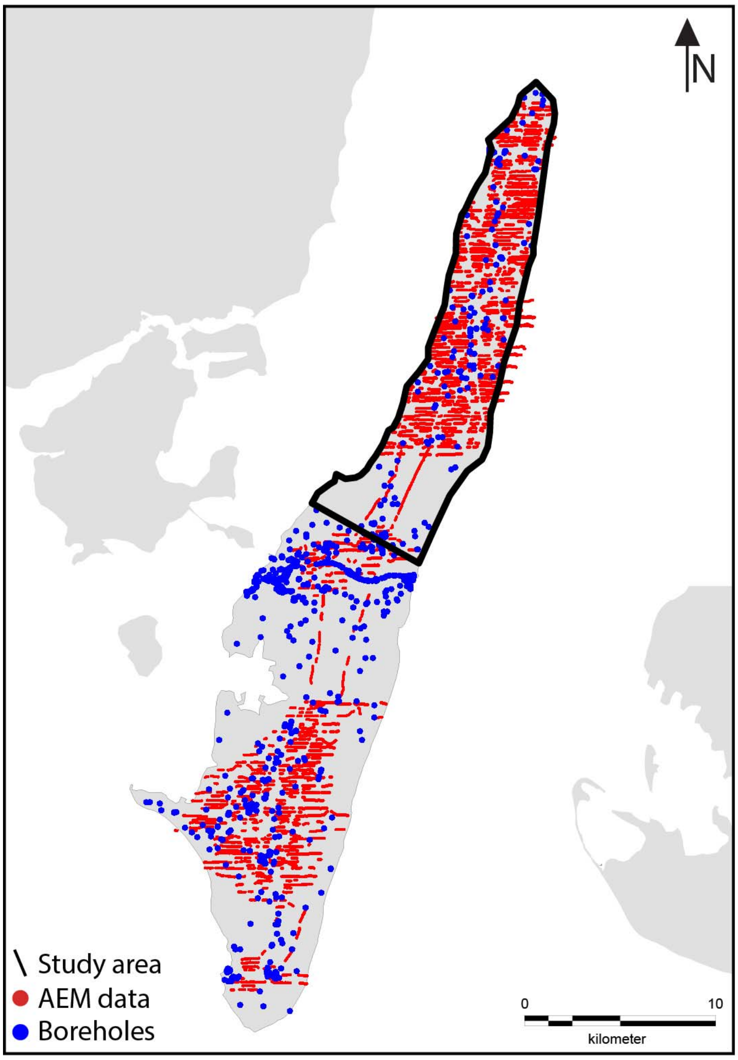

Figure 2: Map showing the data within the study area.

RESULTS

Based on the SkyTEM data and boreholes a 3D geological model is constructed. The SkyTEM data provides the overall spatial distribution of the resistivity. By combining the resistivity with the lithological soil descriptions from boreholes as well as the overall known resistivity of Danish sediments (Jørgensen et al., 2003) we were able to delineate the geology of northern Langeland in detail, see Figure 3. The upper 25 to 100 m of the subsurface comprises glacial clay till with minor sand and clay lenses. The till layer is observed with resistivities of 20 to 60 Ohmm. Underneath the till layer, a 20-100 m zone of freshwater saturated chalk is clearly distinguished from the clayish till above with an increase in resistivity from approximately 40 Ohmm to 100 Ohmm. The underlying transition to saltwater saturated limestone is also clearly observed in the data with resistivities around 5 Ohmm, see Figure 3. With an exception of three areas, this resistivity pattern is observed throughout northern Langeland. The three areas were investigated in detail and interpreted as fault systems. The fault systems number 1 and 2 were unknown before this investigation (Figure 3). Number 3 was known before this study (Vejbæk and Bitze, 1994).

The location of area 1 is illustrated on Figure 3. The areal extent of the fault is clearly delineated by the presence of a low resistivity sequence ranging from 5 to 20 Ohmm at 20 to 50 mbsl with an east –westerly orientation (Figure 3). The layer is located between the freshwater saturated limestone and the clay till. The width of the layer is 2400 m. From borehole DGU no. 165.517, the low resistivity sequence is correlated to the Paleocene clays. Underneath the Paleocene clays the freshwater saturated limestone zone is observed 120 mbsl while in the surroundings, the transition is located around 60 mbsl The area is interpreted as a graben structure where the hanging-wall block has subsided between two, inward-dipping normal faults. Due to erosion of the surrounding footwall block the length of the drop is unknown. However, based on the thickness of the Paleocene clays found in borehole DGU no. 165.517 a subsidence of minimum 9 m can be assumed. The observed deep lying, freshwater saturated chalk is most likely due to increased fresh groundwater infiltration along the slips and cracks of the faults. Hence the fault system has changed the hydrology significantly in the area.

Area 2 is located in the north-western part of Langeland (Figure 3). The fault system in area 2 is observed as a staircase structure with blocks of low resistivity layers stacked on top of one another. Each block is 800 m wide and 15 to 30 m thick. This area is interpreted as a normal fault system with a least 2 hanging-wall blocks. There is no direct lithological information of the low resistivity layer in this area but based on the similarities with area 1 it is assumed that this area likewise comprises of Palaeocene clays. The fault system has an overall north-south orientation and connects with the fault system 3, see figure 3.

Fault system 3 is located near the town of Tranekær. The fault system is well-known in the literature (e.g. Vejbæk and Bitze, 1994) and marks the change in the pre-quaternary sub-surface going from the Eocene and the Paleocene clays towards the south to the Danien limestone in the north (Figure 1). The fault system is blurred in the AEM data by the presence of a buried valley formed by Pleistocene glaciations. Buried valleys typically occur along fault systems, where the subsurface is easily eroded (Jørgensen and Sandersen, 2009b). This fault system also has a significant influence on the hydrology of the area. North of the fault system the vast majority of drinking water is abstracted from the Danien limestone, whereas in the south the Danien limestone is saturated with saltwater. Hence, all abstracted drinking water south of the fault system is from glacial meltwater aquifers, which are limited in extent and volume compared to the Danien aquifers.

The age of the fault systems cannot be accurately determined from data. The most likely time for the formation of the fault systems is in the early Neogene during the Alpine orogeny where many fault systems along the Ringkøbing – Fyn High have been active (Rasmussen, 2009). This is also in accordance with the observed Paleocene clays in borehole DGU no. 165.517.

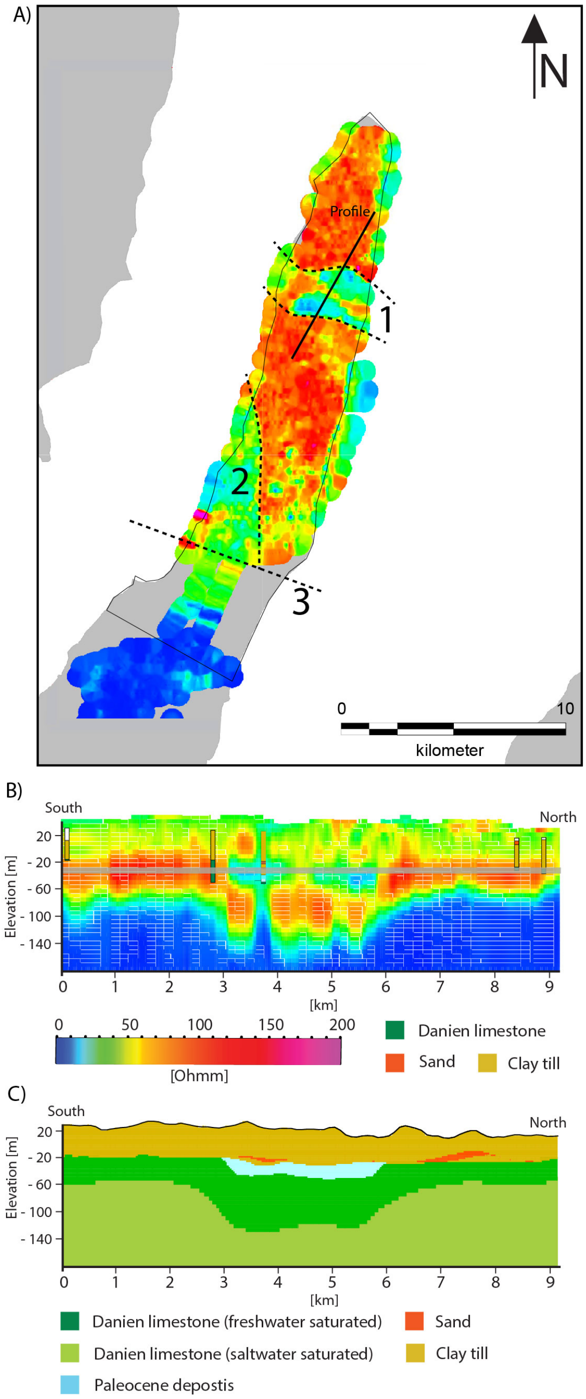

Figure 3: A) Mean resistivity map at the elevation -25 m. B) Cross section through the northern fault system with the presence of AEM data and boreholes. The elevation of the mean resistivity map is shown with the grey line. C) Interpreted geological model

CONCLUSIONS

A dense SkyTEM data in combination with boreholes has revealed three fault systems on the northern part of Langeland in which two were unknown prior to the present investigations. The two newly discovered fault systems are interpreted as a graben structure and a normal fault system, respectively. The fault systems are clearly visible in the AEM data due to the presence of a low resistivity layer of Palaeocene sediments within the hanging-wall block as well as a relatively deep transition from fresh to salt water saturated limestone. The presence of the fault systems modify the distribution, extension and interconnection of the aquifers considerably which has drastic implications for the location of the salt-fresh water interface. In this study the salt-freshwater interface is displaced 60 meter downwards in the central part of the graben structure. This is due to increased freshwater infiltration through highly conductive fault cracks in the limestone.

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REFERENCES

Ehlers, J., 1979, Fine gravel Analyses after the Dutch Method as Tested out on Ristinge Klint. Denmark. Bulletin Geological Society of Denmark, 27.

Houmark-Nielsen, M., 1987, Pleistocene stratigraphy and glacial history of the central part of Denmark. Bulletin of the Geological Society of Denmark 36, 1–189.

Høyer, A., Jørgensen, F., Sandersen, P. and Møller, I., 2015, 3D geological modelling of a buried-valley network based on AEM and borehole data. ASEG-PESA 2015.

Japsen, P., Bidstrup, T. and Lidmar-Bergström, K., 2002, Neogene uplift and erosion of southern Scandinavia induced by the rise of the South Swedish Dome. Im: Doré, A.G., Cartwright, J., Stoker, M.S., Turner, J.P. and White, N. (eds.): Exhumation of the North Atlantic Margin: Timing Mechanisms and Implications for Petroleum Exploration. Geological Society, London, Special Publication 196, 183-207

Jørgensen, F., Sandersen, P.B.E., and Auken, E., 2003, Imaging buried Quaternary valleys using the transient electromagnetic method. Journal of Applied Geophysics, 53, 199-213.

Jørgensen, F. and Sandersen P.B.E., 2009a, Buried valley mapping in Denmark: evaluating mapping method constraints and the importance of data density. Zeitschrift der Deutschen gesellschaft für geowissenschaften 160, 211-223

Jørgensen, F., and Sandersen, P.B.E., 2009b, Kortlægning af begravede dale i Danmark. (www.begravede-dale.dk).

Kristensen, P., Gibbard, P., Knudsen, K.L. and Ehlers, J., 2000, Last Interglacial stratigraphy at Ristinge Klint, South Denmark. Boreas 29, 103-116

Liboriussen, J., Ashton, P. and Tygesen, T., 1987, The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21-29

Madsen, V., 1916, Ristinge Klint. Danmarks Geologiske Undersøgelse, 4. række, nr. 2.

Nielsen, O.B., Sørensen, S., Thiede, J. and Skarbø, O. 1986, Cenozoic differential subsidence of North Sea. American Association of Petroleum Geologists Bulletin 70, 276-298.

Rasmussen, E.S., 2009, Neogene inversion of the central Graben and Ringkøbing-Fyn High, Denmark. Tectonophysics 465, 84-97

Rasmussen, E.S., Dybkjær, K., Piasecki, S., 2010, Lithostratigraphy of the Upper Oligocene – Miocene succession of Denmark. GEUS, 2010.

Sjørring, A., Nielsen, P.E., Frederiksen, J., Hegner, J., Hyde, G., Jensen, J.B., Mogensen, A. og Vortish, W., 1982, Observationer fra Ristinge Klint, felt- og laboratorieundersøgelser. Dansk Geologisk Forening, årskrift for 1981. In Danish.

Sørensen, K. I., and Auken, E., 2004, SkyTEM - a new highresolution helicopter transient electromagnetic system: Exploration Geophysics, 35, 191-199.

Thomsen, R., Søndergaard, V.H. and Sørensen, K.I. 2004, Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark. Hydrogeology Journal 12, 550–562.

Vejbæk, O. V. & Britze, P., 1994, Top pre-Zechstein (twoway traveltime and depth). Geological map of Denmark 1:750000. Danmarks geologiske Undersøgelse, Kort serie, 45, 9 pp.

Viezzoli, A., Christiansen, A. V., Auken, E., and Sørensen, K., 2008, Quasi-3D modeling of airborne TEM data by spatially constrained inversion: Geophysics, 73, 105-113.