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Large-scale TEM investigation for groundwater

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ABSTRACT

The transient electromagnetic (TEM) method has proven to be a powerful tool for the delineation of water-bearing sand and gravel layers in hydrogeophysical investigations. Advancements in the technique include newly developed TEM systems—the Pulled Array TEM (PATEM) and the High Moment TEM (HiTEM) systems—along with innovations in data interpretation. The advanced methodology is illustrated in two case histories. The first, a large-scale TEM survey northwest of Aarhus, Denmark, includes more than 2700 conventional 40 m × 40 m TEM soundings and approximately 500 km of PATEM data. Thematic maps of interval resistivities and depth to low-resistivity Palaeogene clays provide a detailed view of the hydrogeological conditions in the area. The second is a groundwater investigation at Hedensted, Denmark. Based on the hydrogeophysical survey, a new well field in this area was located and developed. The initial phase of the survey included 500 TEM soundings. Based on the interpretation of the TEM survey, two seismic sections were acquired across formerly unknown aquifers. The seismic data made it possible to select optimal locations for three wells that were drilled subsequently. The new well field yields up to 400 000 m^3 water/year.

INTRODUCTION

The water supply in Denmark is decentralized and based on private, public, and municipal water works. Groundwater provides 99% of the water consumed in Denmark. Approximately 1000 million m^3 per year are extracted, with household requirements amounting to approximately 250 million m^3. The remaining 750 million m^3 are used for agriculture and industry. Generally, extraction levels are situated in the depth interval from 30 to 200 m, and the typical recharge area is 10 to 15 km^2 per million m^3 of extracted groundwater. Historically, the quality of groundwater has been high; therefore, only limited treatment has been necessary to provide good drinking water. Problems with water quality caused by nitrate contamination, pesticides, and other chemicals were recognized in the early 1980s. Numerous water works were subsequently closed as a result of contamination. Because of increasing urban development, industrialization, and intensified agricultural activity, the possibility of moving extraction sites to other locations is limited. The solution to the water supply problem involves restrictive guidelines for land use in the recharge areas, thereby ensuring a sufficient supply of unpolluted groundwater in the future. This solution has broad public and political support.

Comprehensive geophysical investigations are needed for the administration to handle the demand for pure groundwater. To recognize which areas were to be protected, geophysical mapping methodologies evolved during several phases of a project pioneered in the County of Aarhus from 1990 to 2001 (Sørensen et al., 2003). The project initiated the development of several geophysical techniques: the Pulled Array Transient Electromagnetic (PATEM), the High Moment Transient Electromagnetic (HiTEM), the Pulled Array Continuous Electrical Sounding (PACES), and the Ellog auger drilling methods. These instruments were supported through the development of corresponding data processing and inversion techniques, including the Laterally Constrained Inversion (LCI) method of Auken et al. (2000). The project, initiated in 1990, is a joint venture between the County of Aarhus, the Municipal Water Supply of Aarhus, and the Department of Earth Sciences at the University of Aarhus. The University of Aarhus was tasked with investigating new and existing geophysical mapping techniques for hydrogeophysical investigation.

The geological deposits of relevance to the water supply in Denmark are mainly of Quaternary and Tertiary origin. Aquifers are found within glacifluvial sediments, Neogene unconsolidated fluvial and shore deposits, as well as Danian chalk and limestone. The aquifers overlay Neogene and Palaeogene low-resistivity clay deposits or Danian chalk and limestone.

Important features in Danish hydrogeophysical investigations are buried Quaternary valleys. Those filled with coarse-grained sand and gravel deposits are of special interest, because they are often high-yielding aquifers (Sandersen and Jørgensen, 2002, 2003). The buried valleys were formed during the Quaternary glaciations, which covered large parts of northern Europe. The valleys were formed by glacial meltwater eroding at the base of the glaciers (Jørgensen et al., 2003a, 2003b). Potential aquifers of large thickness are formed where coarse-grained glacifluvial sediments have filled the eroded valleys.

NEW TEM METHODS

Over the past decade, approximately 60 000 conventional TEM soundings have been carried out in Denmark using the Geonics PROTEM 47 system transmitting up to 3 A in a 40 m × 40 m transmitter loop, with the receiver coil in the centre of the loop. It has been an acceptable configuration in the inevitable compromise between resolution and field efficiency. Measurements are made

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from 9 μs to 9 ms. Given typical resistivities of the geological environment and the electromagnetic background noise level, an unacceptable signal-to-noise ratio is usually obtained at 1–2 ms, which corresponds to a penetration depth between 100 and 130 m. For satisfactory lateral data coverage, station spacing is 250 m and is usually distributed over an area rather than along profiles. Operated by two persons, 25 soundings can be performed on an average field day.

High Moment TEM – HiTEM

The depth of penetration of the conventional 40 m × 40 m TEM system was found to be insufficient for the deepest part of the buried valleys. To map deep aquifers, the HiTEM system was developed (Sørensen and Auken, 2003). The high-power transmitter puts approximately 75 A into a 30 m × 30 m single-turn transmitter loop. The magnetic moment is 67 500 A.m^2, or more than 14 times the magnetic moment of a conventional 40 m × 40 m TEM.

A small transmitter loop with a high current is very mobile and field-efficient, but several issues are associated with configuration design. Measuring with the central-loop configuration with a high magnetic moment results in saturation of the receiver amplifiers, due to high voltages arising from the turn-off of the primary field. Induced polarization (IP) effects can be pronounced in the central loop configuration (Flis et al., 1989). Measurements made in the offset configuration are sensitive to the presence of near-surface resistivity variations (Toft, 2001) and small variations in the offset geometry between the receiver and the transmitter. These issues led to the HiTEM configuration where early time data, acquired from about 10 to 500 ms, are obtained in the central-loop configuration with a 4 A transmitter current. Late-time data, acquired from roughly 200 μs to 9 ms, are measured in the offset configuration with a current of 75 A. Data are not used until half a decade in time after any sign change. At early times, a HiTEM sounding is equivalent to a conventional 40 m × 40 m TEM sounding. Hence, the resolution capabilities are equal in the upper part of the model, while the depth penetration is much larger for the HiTEM sounding.

HiTEM soundings are inverted using the Mutually Constrained Inversion (MCI) approach of Auken et al. (2003). The MCI algorithm inverts the central loop and the offset loop data sets concurrently, and produces two models that are mutually constrained through a constraint matrix. The inconsistencies related to the presence of near-surface resistivity variations and geometry errors in the two configurations are minimized by this inversion approach.

Pulled Array TEM – PATEM

The PATEM system (Sørensen et al., 2003) operates continuously while it is towed across the ground surface. The motivation for the development of the PATEM system was to obtain densely sampled data along profiles enabling a higher resolution of the subsurface resistivity structure and more accurate recognition of coupled data sets. It is important that data sets coupled to man-made conductors are culled before the data interpretation.

Conceptually the system is comparable to an airborne system, but the data quality and earth resolution capabilities approximate those of a stationary ground-based system. The system provides high quality data measured in the time interval from less than 10 μs to about 1–5 ms, depending on the noise level. The PATEM system uses a multi-turn 3 m × 5 m transmitter loop with a 25 m offset between the transmitter and the receiver coil. The system is towed behind a small crawler tractor carrying the electronics. A moment of 750 A.m^2 is achieved by transmitting 16 A in 2 turns. The turn-off time is 3.0 μs. Late times are measured by utilizing a transmitter moment of 4800 to 6000 A.m^2 achieved with 40 to 50 A through 8 turns with a turn-off of 32 μs.

DATA PROCESSING

Data Quality

Data quality control is very important for the hydrogeophysical investigations performed in Denmark, because decisions based on the results of the surveys directly affect the life and economic well-being of many people. For data quality control, a TEM test site was established by the HydroGeophysics Group, University of Aarhus, in 2001. Regular instrument calibration is required by the Danish counties for all consultant companies carrying out TEM measurements. Initial testing of nine different Geonics PROTEM 47 systems showed differences of ± 1 ms in the timing between transmitter and receiver, and errors of up to 10% of the amplitude of the transmitted current were observed. Furthermore, several of the instruments had electronic malfunctions. These problems were solved and a procedure provided where the instruments are calibrated according to a standard test sounding. This calibration resulted in a high degree of data confidence in TEM surveys.

Coupling to man-made conductors

Coupling to man-made conductors is probably the most limiting factor for the TEM method when used in densely inhabited areas. In the rural areas of Denmark the population is relatively dense, which means that the countryside is interconnected by all sorts of infrastructure. Consequently, the understanding of coupling to man-made conductors is crucial, and calculation of precautions, such as safety distances from structures, is necessary.

Coupling to man-made conductors cannot be suppressed by stacking, because the coupled response is induced by the transmitter itself. We have observed two different types of coupling circuits: a galvanic return path, and a capacitive return path (Sørensen et al., 2001). Capacitively coupled responses are easily observed in data as they have an oscillating nature as in an LRC-circuit. This is not the case with the galvanically coupled responses that have a non-oscillatory, exponential nature as in an LC-circuit. Unfortunately, the galvanically coupled responses can be hard to recognise in the data, and they can often be fitted well by a 1D model.

Modelling

Deconvolution of system parameters from the data tends to be an unstable process, and therefore the inversion of TEM data is performed using a 1D, least-squares parameterized algorithm that includes forward modelling of low-pass filters (Effersø et al., 1999) and the turn-on and turn-off ramps. Furthermore, the values at the individual time gates are weighted according to the background noise level measured at the sounding site (Munkholm and Auken, 1996).

GENERAL HYDROGEOPHYSICAL MAPPING METHODOLOGY

The TEM method has proven to be an efficient, accurate, and inexpensive tool in the mapping of subsurface geological structures such as buried valleys (Jørgensen et al., 2003a, 2003b; Sandersen and Jørgensen, 2002, 2003). The relatively inexpensive TEM survey replaces numerous expensive boreholes and/or seismic lines in survey areas. A TEM survey provides a basis for further investigations involving several other methods. The general methodology for large-scale hydrogeophysical investigations includes the following steps:

1. Constructing thematic maps of the bulk resistivities for given depth slices, and the elevation of conducting clays, from one-dimensional (1D) inversion of TEM soundings and other electrical data, such as those from the PACES system (Sørensen, 1996).
2. Defining geological models based primarily on the geophysical thematic maps and existing borehole data. Groundwater reservoirs are delineated, and the natural protection against pollution afforded by clay layers above the reservoirs is determined.
3. Drilling and performing seismic surveys at locations based on the geophysical thematic maps. Lithological and geophysical logs are carried out in the boreholes, and hydraulic and chemical properties of soil and groundwater are evaluated.
4. Building final geological and hydrogeological models and converting them into conceptual geological models for input to numerical groundwater models. The models are used to estimate the recharge areas and rates.

These steps are illustrated schematically in Figure 1.

The use of TEM surveys as part of this general mapping methodology is illustrated in the following two case studies. The first case study is a large-scale TEM survey northwest of Aarhus, Denmark, including more than 2700 conventional 40 m × 40 m TEM soundings and approximately 500 km of PATEM data. The second is a groundwater investigation in Hedensted, Denmark, southwest of Aarhus, where a new well field was located and developed based on 500 TEM soundings and two seismic sections acquired across formerly unknown aquifers. The seismic data made it possible to select optimal locations for three wells that were drilled subsequently. The new field yields more than 400 000 m^3 water per year.

CASE STUDY 1: A LARGE-SCALE TEM SURVEY

Geology of the Aarhus Area

The generalized geology of the area northwest of Aarhus (Figure 2) consists of a Palaeogene heavy clay substratum covered by Quaternary deposits. During several glaciations, deep valley structures were eroded into the substratum, primarily by subglacial meltwater. The valleys can be found in dense networks often crossing each other (Sandersen and Jørgensen, 2002, 2003). Typical structures are 1 to 3 km wide, extend for tens of kilometres, and are filled with Quaternary deposits typically consisting of sand and gravel (Sandersen and Jørgensen, 2002, 2003). These deposits comprise the main aquifers in the area. The depth of the valley floors is between 50 m and 100 m below sea level (mbsl), and occasionally deeper. The elevation of the pre-Quaternary surface outside the valleys ranges from 0 m to 60 m above sea level (masl). The present-day terrain is elevated to 50–100 masl. Outside the buried valleys, the Quaternary sediments are between 10 and 50 m thick.

The Palaeogene formations of the Eocene and Oligocene reach thicknesses of up to 200 m, and are dominated by low-permeability heavy clay and marls. In most of the area, these formations serve as the lower hydraulic boundary of the aquifers. Typical formation resistivities are 2 to 12 ohm.m. In the northeast, the Palaeogene clay was removed by subsequent erosion (Sorgenfrei, 1954), where deep-seated halokinetic movement raised the substratum of chalk and limestone (Madirazza, 1999).

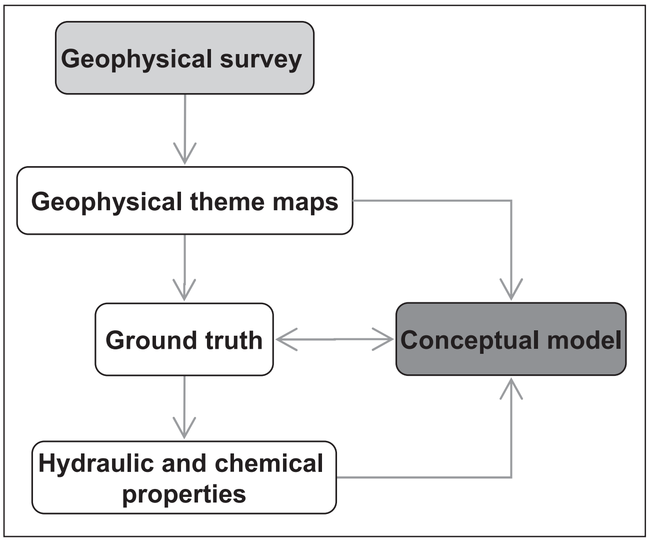

Fig. 1. The workflow for a hydrogeophysical investigation.

The unconsolidated Quaternary sediments are dominated by meltwater deposits of clay, sand, and gravel, and clayey till deposits. The resistivity of the glacifluvial deposits, which contain the main aquifers, is 50 to 100 ohm.m depending on the conductivity of the pore water. Resistivity values of deposits dominated by Quaternary clay typically range between 10 and 50 ohm.m.

TEM survey in the area northwest of Aarhus

The TEM method is well suited for hydrogeological investigations in this geological environment because the depth to the low-resistivity unit—the Palaeogene clay—is situated within the depth of penetration of a TEM sounding for most of the area. More than 2700 conventional 40 m × 40 m TEM soundings and about 500 km of PATEM data were acquired in the survey area, which covered about 350 km^2. The density of the conventional method is about 16 soundings per km^2; the spacing between the PATEM transects is about 250 m, and the sounding distance on the transects is 25 m. Current processing, modelling, and inversion techniques were used to ensure uniformity. Data distorted with coupling to man-made structures, and low-quality soundings, are culled from the data set, and the remaining high-quality data are used to make the maps shown in Figure 3. Kriging with 650 m search distance and 150 m between grid lines is used for gridding the contour maps.

The map in Figure 3 shows, in plan view, the elevation of the low-resistivity unit defined as the bottom layer in a 1D model with a resistivity less than 12 ohm.m. The elevation of the low-resistivity unit defines the Palaeogene clay surface that constitutes the lower boundary of the Quaternary aquifers everywhere except for the northeastern part of the survey area. The valleys appear in green and blue colours, while the intermediate plateaus of Palaeogene clay are recognized by yellow and red colours. The most significant and deepest valley structures strike southeast–northwest. Other valleys strike northeast–southwest and north-south through the area. Further descriptions and discussions of the buried valleys within this area can be found in Sandersen and Jørgensen (2002, 2003) and Danielsen et al. (2003).

In the northeast of the survey area, the surface of the low-resistivity layer falls abruptly from an elevation of 0–50 masl to more than 100 mbsl. There is a clear and abrupt transition zone between the high plateaus in southwest and the low area to the northeast that defines the outer limit of the Palaeogene clay. Northeast of this zone the Palaeogene clay is absent, and the Quaternary succession rests directly upon the Danian chalk and limestone. Here, the image of the deep, low-resistivity layer reflects a front of saltwater in the chalk and limestone aquifer and not the Palaeogene clay. Because the layers of Palaeogene clay gradually thin towards the northeast, the distinct transition zone does not define the outer limit of the clay correctly. The saltwater front is imaged when the Palaeogene clay layer is too thin to be resolved in the 1D models. Hence, the limit of the Palaeogene clay is somewhat further towards northeast than estimated in Figure 3.

Fig. 2. Map showing the location of Aarhus and the two case study areas.

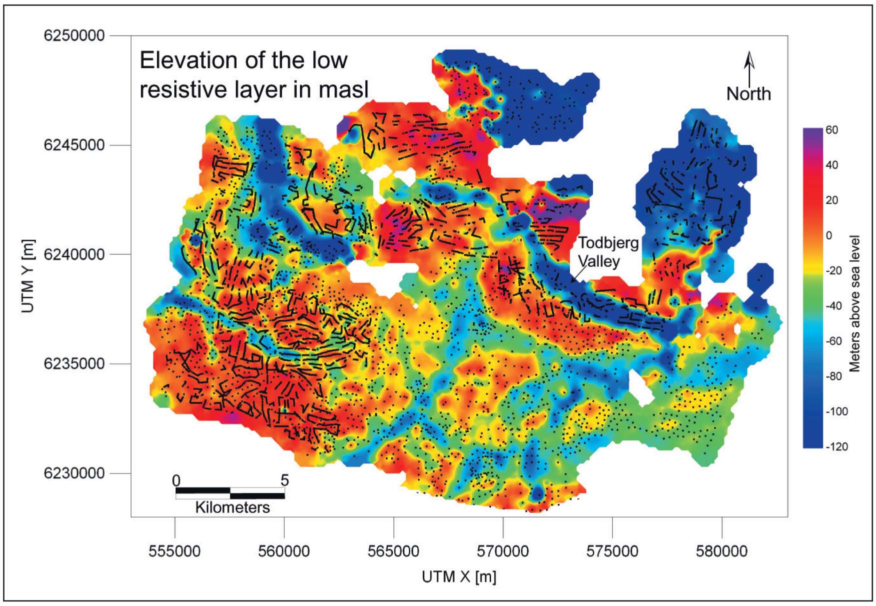

Fig. 3. Contour map of the survey area northeast of Aarhus showing the elevation, in metres above sea level (masl), of the deep low resistive layer as defined by resistivity values less than 12 ohm.m. Conventional TEM sites and PATEM transects are denoted on the elevation map of the low resistive layer by black dots and lines, respectively. The map is based on 1D inversion models of conventional TEM and PATEM data.

The deep structure striking southeast–northwest through the middle, eastern part of the survey area is known as the Todbjerg Valley. It dissects the Palaeogene clay layers and incises the underlying chalk and limestone (Sandersen and Jørgensen, 2003). The valley flanks are defined by Palaeogene clay, whereas the base is defined by freshwater-saturated chalk. The low resistivity at the bottom of the valley (Figure 3) reflects the saltwater front in the substratum of chalk; therefore the depth of the valley is less than the depth to the low-resistivity layer imaged in Figure 3.

Two maps of the bulk resistivity in slices from 40–60 masl and 0–20 mbsl are presented in Figure 4a and Figure 4b, respectively. These maps are calculated from 1D inversion models. From 0–20 mbsl (Figure 4b) the Palaeogene clay dominates the substratum, but the deepest buried valley structures are clearly seen as elongate high-resistivity features, denoted in red and green. Borehole data confirm that the high resistivities come from coarse valley fill sediments. These valley aquifers constitute large, deep-seated, and well-protected aquifers for future water supply. Although water is already being extracted from several of these aquifers, the extraction in most cases takes place at shallower levels. In the northeastern part of the area, where the Palaeogene clay is absent, freshwater aquifers in the upper parts of the elevated chalk are characterised by high resistivities.

A much more complicated picture is seen in the mean resistivity slice from 40–60 masl of Figure 4a. Some elevated parts of the Palaeogene clay are evident in this slice; however, the predominant resistivity values are characteristic of Quaternary deposits. Clay till and other clayey glacial deposits with resistivities in the 20 to 50 ohm.m range are imaged in green, whereas red defines the high-resistivity, coarse, water-bearing sediments. Most of the buried valleys are visible, although less distinct due to the lower resistivity contrasts with the surrounding sediments. The distribution of Quaternary sediments is complex including numerous patches of high-resistivity deposits, in which the valleys cannot be detected. Nevertheless some shallow valleys, which could not be seen in the Palaeogene substratum of the slice beneath, also appear. The patches noticeable in the northeastern part of the survey area represent pre-Quaternary chalk covered with Quaternary deposits of various resistivities. Thus, a complete view of the buried valleys is achieved only when the resistivity distribution of all levels is examined.

The distribution of resistivity values within the survey area provides an excellent overview of the large-scale geology of the area. Structural information about buried Quaternary valleys, the surface and extent of the Palaeogene clay, and the behaviour of the underlying chalk is obtained. Furthermore, resistivity levels give indirect information about lithology and ion content of the pore water. The buried valley deposits, which are clearly imaged as high resistivity values, contain large deep-seated and often well-protected aquifers. The Palaeogene clay, imaged as the deep low-resistivity layer in the main survey area, defines the lower boundary of the freshwater-bearing sediments. Chalk containing large amounts of freshwater is also detected as high resistivities above a low-resistivity unit constituting the saltwater front. At the highest elevations, close to the ground surface, the geology appears to be more complex and is difficult to resolve in geological terms.

CASE STUDY 2: INTEGRATED INVESTIGATIONS BASED ON A TEM SURVEY

The village of Hedensted is situated in Vejle County approximately 50 km southwest of Aarhus (Figure 2). Hedensted is supplied with drinking water from a water-well field located in the village. The water supply system produces about 400 000 m^3 per year, but pesticide pollution in recent years has necessitated the search for a new well field outside the village. However, it is difficult to find deep-seated and well-protected groundwater reservoirs in this area. Palaeogene clays are found 80–100 m below the surface, and Neogene silty sediments are found to constitute large parts of the cover layer. Groundwater reservoirs found in the uppermost 30 m, which consists of Quaternary sediments of varying lithology, are contaminated or vulnerable because of their close proximity to the ground surface. Hence, large, deep-seated, and well-protected ground water reservoirs must be found in the buried valleys, which commonly occur in this region too.

In the area west of the village of Hedensted, 500 conventional TEM soundings were acquired. The low-resistivity Palaeogene clay was well detected with resistivities below 5 ohm.m. The silty Neogene sediments were mapped by resistivities between 40 and 80 ohm.m. The cover of Quaternary sediments showed varying resistivities, mainly between 20 and 100 ohm.m. The TEM data indicated the presence of a buried valley just outside the village, defined as a shallow channel in the surface of the low resistive layer interpreted as the Palaeogene clay. Resistive layers were observed above the channel. Maps similar to those produced for the first case study at Aarhus specified a buried valley filled with coarse water-bearing sediments. Based on the TEM surveys, reflection seismic data were acquired along two profiles across the structure to support the TEM interpretation and provide more information about the internal structures of the valley to optimise the location of drill sites. The seismic data were collected and processed by Rambøll (Jensen et al., 2002).

A compilation of TEM, seismic and borehole log data is presented in Figure 5. The 1D TEM models are superimposed, and lithological borehole logs are projected from distances of up to 300 m onto the seismic section. The location of the seismic profile lines, TEM soundings, and boreholes are shown on the inserted map. Average seismic velocities of 1600 m/s and 1650 m/s are assumed for seismic lines 1 and 2, respectively. Using these velocities the low-resistivity layer in the TEM models correlates with the high-amplitude reflector at about 100 ms two-way travel time. The Palaeogene clay is found in Borehole no. 116.1555 at the same depth as indicated by the 1D TEM model. Consequently, we are confident that the low-resistivity layer defined by TEM soundings in this area corresponds to the surface of the Palaeogene clay with a high degree of precision.

The buried valley is indicated on the seismic sections by blue lines. It truncates the generally horizontal reflections, including the surface of the Palaeogene, denoted with red lines. The valley floor is difficult to detect based solely on the seismic sections, but the TEM soundings improve the interpretation by determining the level of the low resistivities at slightly deeper positions. High-resistivity values indicated that the lithology of the valley fill sediments is sand and gravel. Subsequent drilling showing large amounts of glacifluvial sand and gravel verified this interpretation. Depth estimates of the valley floor are verified by the three drill holes at the western end of seismic profile line, Hedensted 2. The cover of Quaternary sediments indicated by low resistivities was found to be clay till in all four boreholes. A new well field is being planned over the buried valley delineated by the hydrogeophysical investigation for a protected and uncontaminated water source for the village of Hedensted.

NEW DEVELOPMENTS

In the future TEM surveys in Denmark might be carried out using the newly developed SkyTEM system (Sørensen and Auken, 2003). The SkyTEM system is a helicopter TEM system. The system is designed to provide the same data quality as obtained from a ground based system. Data are measured continuously which ensures that coupled data sets can be identified and culled before inversion. The system operates at an altitude of 15–20 m and with a flight speed of about 20 km per hour.

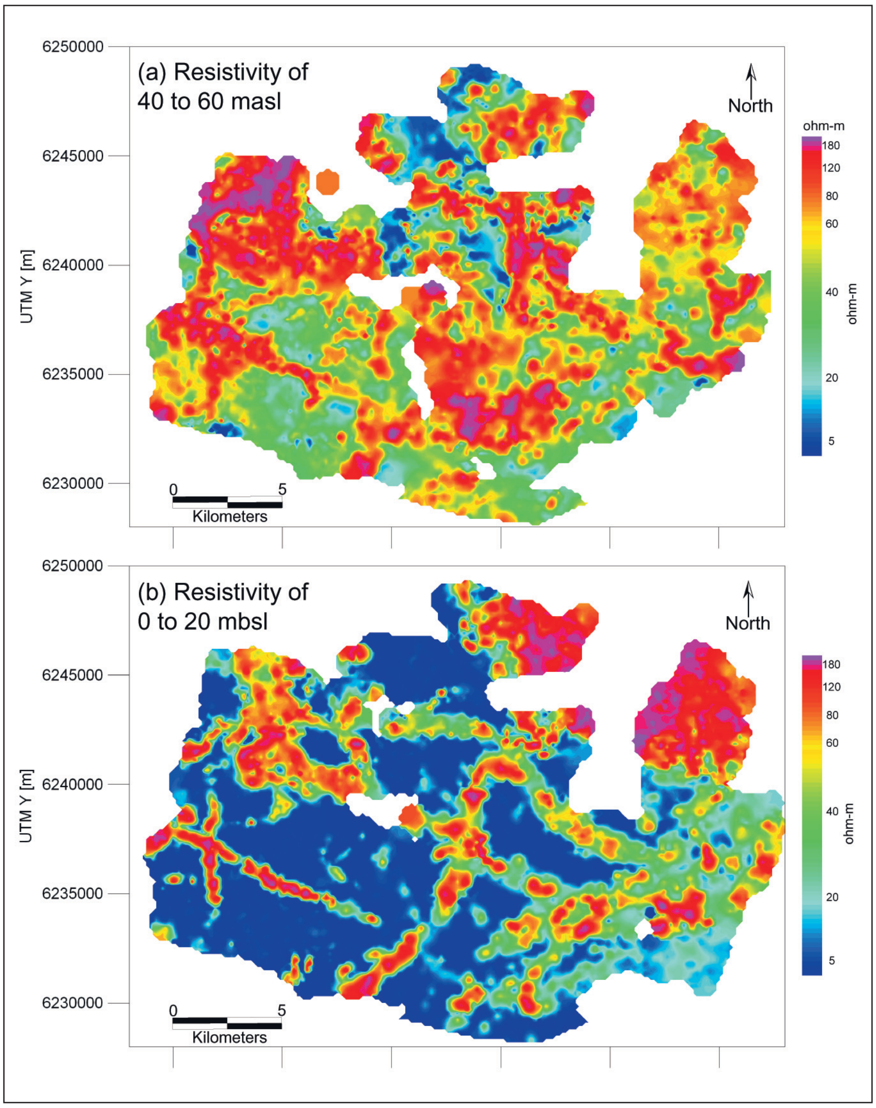

Fig. 4. Contour maps of the survey area northeast of Aarhus showing the mean resistivity in two elevation slices from (a) 40 to 60 m above sea level (masl) and (b) 20 to 0 m below sea level (mbsl). The maps are based on 1D inversion models of conventional TEM and PATEM data at sites denoted in Figure 3.

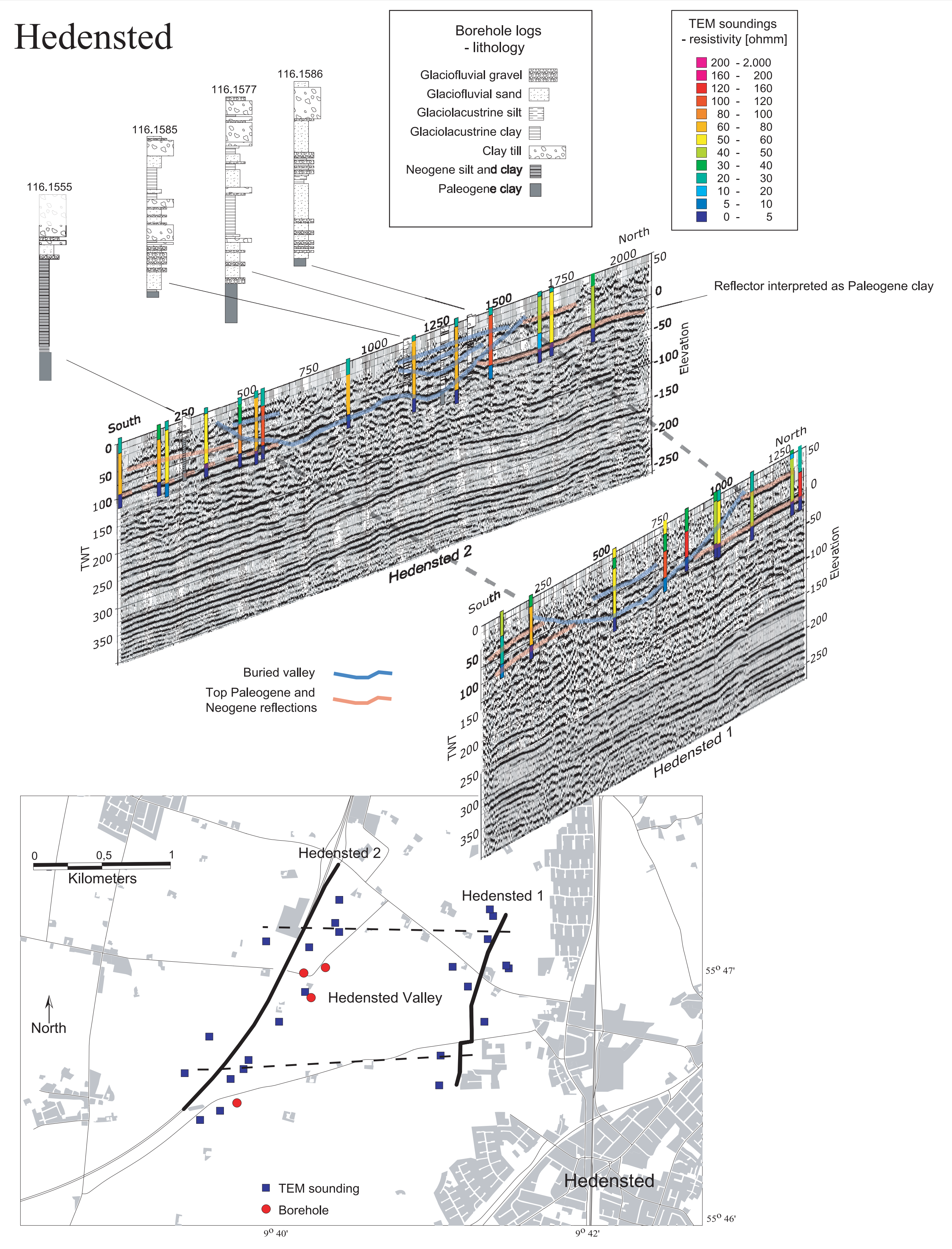

Fig. 5. A compilation of 1D TEM resistivity models superimposed on two seismic sections from the Hedensted survey, and projected lithological information from borehole logs. Seismic velocities of 1600 and 1650 m/s are assumed. Major boundaries are highlighted: blue lines denote the buried valley and internal structures, red lines the top of the Paleogene and some Neogene reflections. The plan map of the survey area shows the location of the TEM sounding sites and the seismic profile lines. The buried valley is outlined as dashed lines on the plan map and between the seismic profiles.

The transmitter is a multi-turn 10 m × 10 m loop with a magnetic moment of 3500 A.m^2 (low moment, early times) and 20000 A.m^2 (high moment, late times).

SkyTEM data are averaged into soundings with a lateral spacing of 30–40 m. A sounding consists of a low-moment segment and a high-moment segment inverted using the MCI approach (Auken et al., 2003).

CONCLUSION

A comprehensive hydrogeophysical investigation can achieve the following objectives: (a) an interpretation of large-scale geological structures, (b) a delineation of the aquifer geometry, (c) an estimation of the distribution of hydraulic properties within the aquifer, and (d) an estimation of the vulnerability of aquifers. A drilling program can be designed based on thematic maps, and the borehole data subsequently used to construct final geological models.

Ten years of research, development, and field studies have provided a suite of new TEM instruments and interpretation techniques that have been used successfully for hydrogeophysical investigations in Denmark. The HiTEM system, which provides a high penetration depth, and the PATEM system, which has a high production rate, were both developed. Improvements in instrumentation and field methodology are closely related to the development of procedures for data quality control, high-precision processing, and inverse modelling algorithms. In hydrogeophysical investigations, the anomalies are often only a few percent of the measured background field, and hence the data quality and the accuracy of the forward modelling scheme are crucial.

The TEM method has proven to be an effective tool in mapping large-scale geological structures of hydrogeological importance. As shown in two case studies, the depth to deep-seated, conductive clays is accurately mapped. Resistive water-yielding deposits can, to some extent, be resolved along with units of covering clay, indicating the vulnerability of the aquifer. The efficiency of the method is supported by the precise correlation with seismic data and lithological borehole logs as shown in the case of Hedensted.

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REFERENCES

Auken, E., Thomsen, P., and Sørensen, K.I., 2000, Lateral constrained inversion (LCI) of profile oriented data—the resistivity case: *Proceedings of the 6th Meeting of the Environmental & Engineering Geophysical Society - European Section*, EL06-EL06.

Auken, E., Christiansen, A.V., Foged, N., and Sørensen, K.I., 2003, 1D laterally constrained inversion of resistivity data, Part A: *Journal of Applied Geophysics* (submitted).

Danielsen, J.E., Auken, E., Jørgensen, F., Søndergaard, V., and Sørensen, K.I., 2003, The application of the Transient Electromagnetic method in hydrogeophysical surveys: *Journal of Applied Geophysics*, **53**, 181–198.

Effersø, F., Auken, E., and Sørensen, K.I., 1999, Inversion of band-limited TEM responses: *Geophysical Prospecting*, **47**, 551–564.

Flis, M.F., Newman, G.A., and Hohmann, G.W., 1989, Induced-polarization effects in time-domain electromagnetic measurements: *Geophysics*, **54**, 514–523.

Jensen, J.F., Ringgaard, J., Skjellerup, P., and Vangkilde-Pedersen, T., 2002, Pulled Array Seismic (PAS)—a new method for shallow, high-resolution reflection seismic data acquisition: *Proceedings of the 8th meeting of the Environmental and Engineering Geophysics Society – European Section*, 237–240.

Jørgensen, F., Sandersen, P.B.E., and Auken, E., 2003, Buried valley images in TEM surveys: *Journal of Applied Geophysics*, **53**, 199–213.

Jørgensen, F., Lykke-Andersen, H., Sandersen, P.B.E., Auken, E., and Nørmark., E., 2003, Geophysical investigations of buried Quaternary valleys in Denmark: An integrated application of transient electromagnetic soundings, reflection seismic surveys and exploratory drillings: *Journal of Applied Geophysics*, **53**, 215–228.

Madirazza, I., 1999, The formation of the Voldum salt pillow in the Danish Zechstein basin, Jutland (Denmark): *Bull. Geol. Soc. Denmark*, **46**, 31–46.

Munkholm, M.S. and Auken, E., 1996, Electromagnetic noise contamination on transient electromagnetic soundings in culturally disturbed environments: *Journal of Environmental and Engineering Geophysics*, **1**, 119–127.

Sandersen, P. and Jørgensen, F., 2002, *Kortlægning af begravede dale i Jylland—opdatering 2000–2001*: De Jysk-fynske Amters Grundvandssamarbejde, Vejle Amt: WaterTech a/s, 62 p (in Danish).

Sandersen, P. and Jørgensen, F., 2003, Buried Quaternary valleys in the western part of Denmark - occurence and inferred implications for groundwater resources and vulnerability: *Journal of Applied Geophysics* (in press).

Sorgenfrei, Th., 1954, Geologisk kort over Danmark. Formationerne ved basis af kvartæret: in Sorgenfrei, Th., Berthelsen, O. (eds.), *Geologi og vandboring*. Geological Survey of Denmark, III row, **31**, 106 p (in Danish).

Sørensen, K.I., 1996, Pulled Array Continuous Electrical Profiling: *First Break*, **14**, 85-90.

Sørensen, K.I., Thomsen, P., Auken, E., and Pellerin, L., 2001, The effect of coupling in electromagnetic data: *Proceedings for the 7th meeting of the Environmental and Engineering Geophysics Society – European Section*, 108–109.

Sørensen, K.I., Auken, E., Christensen, N.B., and Pellerin, L., 2004, An Integrated Approach for Hydrogeophysical Investigations: New Technologies and a Case History: *Near Surface Geophysics Vol II: Applications and Case Histories*, S.E.G. (in press).

Sørensen, K.I. and Auken, E., 2003, New developments in high resolution airborne TEM instrumentation: *16th Geophysical Conference and Exhibition, Australian Society of Exploration Geophysicits, Expanded Abstracts*.

Toft, M.W., 2001, *Three-dimensional TEM modelling of near-surface resistivity variations*: M.Sc. thesis, University of Aarhus. [Web document]: Accessed 1 November, 2001. Available at `<http://www.hgg.au.dk/showpage.asp?ID=312>`