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# The application of the transient electromagnetic method in hydrogeophysical surveys

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#### Abstract

The transient electromagnetic (TEM) method has been used extensively for hydrogeophysical exploration in Denmark for the past decade. Innovative instrumentation combined with multi-dimensional modelling and interpretational insights based on experience gained through numerous case studies have proven to be a successful strategy. In the case study reported here, the combination revealed an unknown and unexpected buried valley complex. Drill hole data were in good agreement with estimates of both the bearings and depths of valleys defined by the TEM surveys. The Pulled Array Transient Electromagnetic (PATEM) system was built to provide high data density for increased lateral resolution. A High moment Transient Electromagnetic (HiTEM) system was developed for delineation of aquifers to depths up to 300 m. Because both of these systems provide high data density, data quality can be assessed as part of the interpretational strategy. When acquiring TEM measurements in areas as densely populated as the Danish countryside, precautions must be taken to minimize coupling between the TEM system and man-made conductors. Modelling the slope of the flanks of buried valleys has challenged the adequacy of the one-dimensional (1-D) assumption for inversion of TEM data. The study shows that for a valley structure in a low-resistive layer, the 1-D assumption is sufficient to track the presence of rather steep slopes. For a valley structure in a highresistive layer, however, the insensitivity of the TEM method to resistors makes it difficult to determine a slope with a 1-D inversion, and only the overall structure is defined.

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# 1. Introduction

In mapping for potential aquifers, buried valleys are features of special interest in the Danish geological setting. The buried valleys are formed by the trans-

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gressions of the ice sheets during Pleistocene glaciations (Huuse and Lykke-Andersen, 2000; Sandersen and Jørgensen, 2003). Subglacial meltwater erosion and glacial erosion formed the valleys in the substratum of Quaternary and Tertiary sediments. Most valleys were subsequently filled and buried by glacial and interglacial sediments. Where coarse-grained Quaternary sediments filled the eroded valleys, potential aquifers of extraordinary thickness were formed (Sandersen and Jørgensen, 2003).

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The water supply in Denmark is decentralized with small private, public and municipal waterworks extracting from local aquifers. Traditionally, the quality of groundwater has been high; therefore only limited treatment is necessary to provide good drinking water. Increasing problems with water quality, such as nitrate and pesticide contamination from intensive farming, were recognized in the early 1980s and caused several waterworks to be shut down. Because of intensive land use, the possibilities of moving extraction sites to other locations are limited. In the 1990s, it became clear that a solution to the water supply problem would involve restrictions on land use in groundwater recharge areas to ensure clean groundwater.

Surface-geophysical investigations, e.g. DC resistivity, electromagnetic, seismic or gravity methods, can provide the necessary knowledge of the size and vulnerability of the aquifers (Jørgensen et al., 2003b). By request from Aarhus County and the Municipal Water Supply of Aarhus, the Department of Earth Sciences at the University of Aarhus is providing the necessary expertise to initiate an extensive subsurface mapping campaign by geophysical methods. After acquiring approximately 60,000 soundings throughout the country, the TEM method has become the most common method for mapping the geology below a depth of approximately 30 m. The TEM method has excellent resolution of conductive layers at depth (Christensen and Sørensen, 1998). The use of the method in a hydrogeophysical context is described by Fitterman and Stewart (1986), Mills et al. (1988), McNeill (1990), Albouy et al. (2001) and Sørensen et al. (accepted for publication).

In large areas of Denmark, highly impermeable Tertiary clays form a conductive layer of  $2-10 \Omega$  m, which often constitutes the lower boundary of aquifers. Other low-resistivity sediments such as meltwater clay or till layers occur higher in the substratum (Jørgensen et al., 2003a). The increased knowledge and understanding of the Danish geological setting suggested the existing TEM systems might be improved with respect to productivity and depth of penetration. Hence, two enhancements of the method were developed at the University of Aarhus: the Pulled Array Transient Electromagnetic (PATEM) system (Sørensen et al., accepted for publication) that measures while moving, and the High Moment TEM (HiTEM), a deep penetration system (Sørensen et al., accepted for publication).

The PATEM system provides high lateral resolution and high data density to ensure data quality. When measurements are performed continuously in time and space, variability in data not caused by changes in geology are clearly visible. The HiTEM system was developed because some of the groundwater resources are situated in deep-seated aquifers of depths up to 300 m. With a penetration depth up to 300 m, the HiTEM system is used in areas where the PATEM and conventional central-loop  $40 \times 40$  TEM systems have insufficient penetration depths.

With enhanced data acquisition systems, interpretation can also be improved. A modelling study tests the validity of one-dimensional (1-D) inversion in the presence of two-dimensional (2-D) buried valley structures. The application of the new TEM systems in conjunction with interpretational advancements forms an efficient strategy for hydrogeophysical investigations. The Skjød case history illustrates the capability of a well-designed and executed TEM survey in resolving a buried valley complex, which was unknown prior to the general subsurface mapping of the area.

#### 2. TEM instrumentation

A single system cannot combine all the potential features of the TEM method. Therefore, we developed the two new HiTEM and PATEM systems and adapted the commercially available Geonics PROTEM system to cover the necessary requirements of resolution at shallow depth, spatial coverage and depth of investigation needed in hydrogeological investigations. The  $40 \times 40$  m<sup>2</sup> central-loop configuration with a PROTEM system allows for coverage of large areas on a 250-m grid. The PATEM system offers high data density through continuously measured profiles. The HiTEM system permits an increased depth of investigation while maintaining high spatial resolution achievable with a small transmitter loop.

#### 2.1. Conventional 40×40 TEM

The Geonics PROTEM 47 system has been used since the initial phase of the Danish hydrogeophysical surveys. The standard configuration was that of a single-turn,  $40 \times 40$  m<sup>2</sup> transmitter loop with the receiver coil in the center of the loop. This configuration was found acceptable in the inevitable compromise between resolution and field efficiency. The transmitter of the PROTEM 47 system has a maximum output of 3 A, resulting in a magnetic moment of 4,800 A m<sup>2</sup>. The measurement time interval is 7  $\mu$ s to 7 ms (related to the end of the turn-off ramp). For typical resistivities of the hydrogeological environment and the electromagnetic background noise level, an unsatisfactory signal-to-noise ratio is usually observed from 1 to 2 ms. This is equivalent to a penetration depth between 100 and 150 m. A general discussion of noise and signal-to-noise ratio in the TEM method is given in Spies (1989) and Macnae et al. (1984). A conventional  $40 \times 40$  TEM sounding is shown in Fig. 1.

Field operation requires two people. On an average day, 20-25 soundings can be completed. To obtain satisfactory spatial coverage and to ensure high data quality, we place the  $40 \times 40$  TEM sounding loops at



Fig. 1. A conventional  $40 \times 40$  TEM sounding with the resulting one-dimensional model. To the left data are marked by error bars, while the model data, calculated by parameterized least squares inversion, are marked by the solid curve. The resulting double-descending model is shown to the right.

250 m intervals distributed over an area rather than along profiles. Hence, in an ordinary field day an area of approximately  $1.5 \text{ km}^2$  can be covered.

#### 2.2. High moment TEM-HiTEM

The high-power transmitter of the HiTEM system transmits approximately 75 A into a  $30 \times 30$  m<sup>2</sup> single-turn transmitter coil for a magnetic moment of 67,500 A m<sup>2</sup>, or more than 14 times the magnetic moment of a  $40 \times 40$  m<sup>2</sup> system, allowing a depth of investigation as great as 300 m. A sketch of the system is shown in Fig. 2. The transmitter and receiver are pulled by a small, belt-driven tractor. The tractor charges the transmitter batteries while it moves from one sounding location to another.

Traditionally, ground-based TEM systems, e.g. the Geonics PROTEM 37 and 57 systems, achieve a high transmitter moment with a moderate current and a large transmitter loop of 100-500 m side length (Nabighian and Macnae, 1991). The advantages of a large loop include the capability of making measurements in the central-loop configuration and obtaining a high magnetic moment with a moderate output current. The disadvantages are low field efficiency and reduced applicability in populated areas due to limited access and a higher degree of coupling with man-made conductors. The combination of a small transmitter loop and a high current of the HiTEM system is very efficient in the field, but during development, several issues addressing the choice between central and offset loop configuration had to be tackled.

The design of the electronics in the transmitter and receiver was problematic; distortions in the receiver were evident when the receiver and transmitter coils were in close proximity. Therefore, the receiver coil was moved to the offset position. This array configuration also minimizes the Induced Polarization (IP) effect (Flis et al., 1989), which is most significant in the central-loop array. The IP effect appears at later times as the offset between transmitter and receiver increases, and outside the measurement time window. To date no significant IP effects have been observed in more than 2000 HiTEM soundings acquired in different geological settings in Denmark.

Theoretical modelling revealed certain aspects of the offset configuration that are not an issue with the central-loop. Firstly, early-time data measured by the



Fig. 2. On the left is a sketch of the HiTEM system, with the offset- and central-loop configurations. To the right is the data of a HiTEM sounding (marked by the error bars) and the model data (solid curve) obtained by Mutually Constrained Inversion. The resulting models are seen to the right.

offset array is more distorted by near-surface resistivity variations (Toft, 2001). This is most pronounced when the sign reversal occurs as the maximum of the induced current system passes below the offset point of observation (Hoversten and Morrison, 1982). Consequently, as it is problematic to fit a 1-D model to early-times data measured over an inhomogeneous earth, data half a decade after the sign reversal are discarded and near-surface information is lost. Secondly, the response at the sign change is very sensitive to the exact position of the offset. A 1-m error in a 70-m offset can introduce a response error of 30% near the sign reversal. Experience suggests that an accuracy of 1 m is obtainable without compromising field efficiency.

These issues led to the design of a mixed configuration where the early times are measured in the central-loop and late times in a 70-m offset loop configuration. Consequently, a HiTEM sounding has two parts that are measured 70 m apart. A sounding consists of a central-and an offset-loop array using a transmitted current of 2.5 and 75 A, respectively. Because the two configurations have different sensitivities to the near-surface and array geometry, inconsistencies may arise between the two data sets. Therefore, the Mutually Constrained Inversion (MCI) approach (Auken et al., 2001) is used to invert HiTEM soundings. The MCI algorithm simultaneously inverts the inconsistent central-and offset-loop data sets and produces two 1-D models that are constrained through a constraint matrix. The two models are interpretationally similar, but have slightly different physical properties making room for the inevitable discrepancies between two data sets. In the resulting model in Fig. 2, two models obtained by Mutually Constrained Inversion of HiTEM data are shown. Note the small differences in depths to the third and fifth layer, while the remaining model parameters are identical. The deepest resolvable layer boundary at this sounding site is at approximately 200 m depth.

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The HiTEM measurement windows are the same as for  $40 \times 40$  TEM system. However, the higher transmitter moment provides a greater signal-to-noise ratio throughout the entire sounding. Two people can carry out 15 soundings per day. The lower field efficiency compared to a  $40 \times 40$  TEM system is partly due to increased stacking time for improvement of the signal-to-noise ratio at late times.

HiTEM is now used on a routinely basis, and the high penetration depth enables the detection of deepseated valley-fill structures as well as valley floors. It is especially useful in combination with seismic surveys, where HiTEM gives the opportunity to find the depth to certain reflectors (Jørgensen et al., 2003b), and thereby adjust the velocity model for the seismic section.

# 2.3. The pulled array transient electromagnetic method—PATEM

The PATEM system combines a penetration depth similar to a  $40 \times 40$  m<sup>2</sup> PROTEM 47 system with superior lateral resolution. Like the HiTEM system, the PATEM system was developed by the Hydro-Geophysics Group, University of Aarhus. Conceptually comparable to an airborne system, PATEM

measurements are performed while the system moves along a profile line, but the instrumentation and the geometrical accuracy are comparable to a groundbased system. The transmitter coil mounted on a wheeled frame and the receiver coil towed on a sledge with a 25-m offset configuration is sketched in Fig. 3.

The transmitter coil is a  $3 \times 5 \text{ m}^2$  heavy-duty loop with a total number of eight turns. Current can be transmitted into either two or eight turns so the system operates with both a low and a high magnetic moment. The former provides near-surface resolution, and the latter significant penetration depth. The low moment of 480 A m<sup>2</sup> is achieved by transmitting 16 A into two turns. Late times are measured with the high transmitter moment of 4800–6000 A m<sup>2</sup>, from 40 to 50 A transmitted through all eight turns. Measurements are made from 10 µs to 5 ms. With respect to both transmitter moment and measurement time window, the PATEM system is comparable to the 40 × 40 TEM system. Hence, the penetration depth is normally 100–120 m and rarely exceeds 150 m.

The receiver system measures the incoming signal on parallel channels. The early-time channels have low gain settings, moderate bandwidth and narrow gates (Sørensen et al., accepted for publication), whereas the late-time channels have higher gains, narrower band-





Fig. 3. A sketch of the PATEM system is shown to the left. To the right is a profile of filtered data from selected gates measured on the high moment. Each curve represents a gate, and the gate center times are stated to the right on the data plot. The distance between each station number is approximately 1.5 m. Processed and inverted PATEM sounding curves are shown in Fig. 14.

width and wider gates. Most of the recording time is spent measuring with the high moment transmitter to obtain the late time response, where the signal-to-noise ratio is smallest.

Continuously measuring, the PATEM system acquires a vast amount of data along a profile line. The data are subjected to various processing routines including stacking, non-spike filters and running mean filters. After processing, the final spatial sampling distance is approximately 25 m. A profile of filtered data is shown in Fig. 3. As the development in data is easily monitored, it is easy for the interpreter to detect corrupt measurements, e.g. the peaks between station number 5600 and 5650. Note the resistivity decrease which starts at 5875, where the gates show an increase in dB/dt.

#### 3. Acquisition and interpretational considerations

The use of three TEM systems generates a rich and complex data set. Problems arising when acquiring TEM data in cultural areas need to be considered and a strategy for minimizing the problems adopted. Complications encountered when interpreting twoand three-dimensional (3-D) structures with 1-D inversion tools can adversely affect the accuracy of the interpretation, as the underlying 1-D model assumption is essentially inadequate. In the worst case this inadequacy leads to inability to fit the measured data and/or an erroneous picture of the subsurface. Modelling of this potential pitfall may increase understanding of the responses and hence the interpretation of field data.

#### 3.1. Transmitter coupling

Even the rural areas of Denmark are rather densely populated, and many kinds of man-made conductors intersect the countryside. This situation is common in many environmental and hydrogeophysical investigations. Consequently, the understanding of transmitter coupling to these conductors is crucial. It is the most limiting factor of the TEM method in a densely inhabited area.

Man-made conductors include overhead power lines, buried pipes and cables and fences. Sørensen et al. (2000) differentiates between two types of coupling: galvanic and capacitive. The names refer to the return path of the current after being induced in a man-made conductor by the TEM transmitter.

In galvanic coupling, the transmitter induces currents in a man-made conductor that is in galvanic contact with the earth. The illustration in Fig. 4 depicts a wire grounded at a pole of an overhead power line, and the corresponding sounding curve. This circuit is a LR circuit that has an exponential decay. The response of the LR-circuit distorts the received signal leading to



Galvanic Coupling

Fig. 4. Illustration of galvanic coupling and a field example of the corresponding TEM response compared to an unaffected neighbouring sounding.

incorrectly low resistivities in the interpreted model. The galvanic coupling response is difficult to identify in the data, and is only recognized by comparing with neighbouring soundings.

Capacitive coupling is due to transmitter-induced currents leaking capacitively from the conducting core through the insulation of a buried cable to the earth as illustrated in Fig. 5, along with the corresponding sounding curve. This current path forms a LCR-circuit that has an oscillating decay, which is easily recognized in the data.

The amplitude of both types of coupling responses is strongly dependent on the size and shape of the man-made conductor, and the distance, a, between the transmitter and the conductor (Sørensen et al., 2000). In general, man-made conductors can be of 3-D, 2-D, or elongated shape with ends, which we refer to as 2.5-D. The response of a confined 3-D manmade conductor decays proportional to  $a^6$ , the response of a 2.5-D man-made conductor proportional to  $a^4$  and the pure 2-D shape proportional to  $a^2$ . Hence, one can measure rather close to a confined man-made conductor without distortion, while a long power line or pipeline (a 2-D man-made conductor) can have a large zone of influence.

For earth resistivities of  $40-80 \Omega$  m, experience suggests a safety distance of 125-150 m from roads with underground cables, pipelines and other conductors. For higher resistivities, the safety distance must be increased. Safety distances are necessary precautions against couplings, but they should not be exaggerated, because acceptable areas would be disqualified resulting in unnecessary low data density. By collecting high-density data (e.g. PATEM), distortions can be identified and contaminated data culled.

#### 3.2. Multi-dimensional modelling

Presently, it is not practical to interpret TEM data with more than 1-D or pseudo 2-D models. Many researchers have questioned the adequacy of a 1-D interpretation of 2-D or 3-D structures, such as a buried valley (Newman et al., 1987; Goldman et al., 1994; Toft, 2001). To investigate whether a 1-D model assumption is sufficient to accurately recover the slope of a buried valley, an intensive modelling study was performed. Two-dimensional, synthetic data were calculated with the finite-difference code of Árnason (1995). A 1-D inversion algorithm (Effersø et al., 1999) was applied to the data with five percent Gaussian noise added. The results of the 1-D inversion were then compared to the true 2-D model.

The generalized model consists of a basement and an overburden simulating half of a buried valley structure. The thickness of the overburden varies from 10 to 70 m. Variations in the slope delineating the transition in the overburden thickness is investigated for different resistivity contrasts. The profile is 600 m



#### Capacitive Coupling

Fig. 5. Illustration of capacitive coupling and a field example of the corresponding TEM response compared to an unaffected neighbouring sounding.



Fig. 6. Four slopes, (a)  $90^{\circ}$ , (b)  $45^{\circ}$ , (c)  $22.5^{\circ}$ , and (d)  $11.25^{\circ}$ , are modelled for a structure with a conductive basement and a resistive overburden. The (1) true structure, (2) stitched-together 1-D inverse model and (3) relative difference are shown for each model. Modified after Toft (2001).

long, and responses are calculated every 20 m. The TEM configuration is that of the conventional centralloop  $40 \times 40$  m<sup>2</sup> TEM. A minimum structure inversion, in which equality constraints are applied to adjacent layer resistivities, is used to avoid the introduction of an interpreter's subjectivity concerning the number of layers in a parameterized inversion.

The response for models with slopes of 90°, 45°, 22.5° and 11.25°, and overburden and basement resistivities of 80 and 10  $\Omega$  m, respectively, were computed. For the four cases, (1) the true 2-D model, (2) stitched-together, minimum structure 1-D inverse model, and (3) the difference between the two are presented in Fig. 6. The following discussion of the model with a 90° slope, Fig. 6a, is general and may be applied to the other three models with the same resistivity contrast, although the magnitudes of the deviations are most pronounced in the model with the 90° slope.

Distortions resulting from 1-D inversion of data acquired over the sloping structure are divided into three zones. Most easily recognized in the difference plot and labelled I, II and III in Fig. 6a-1, the zones are associated with either deficient or excessive 1-D responses compared to the true 2-D model. Zone I is defined by the significant pant leg pattern to the immediate left of the vertical edge. The relative difference is positive, meaning the 1-D inverse model overshoots the true layer resistivities. It is narrow and focused close to the slope, and becomes larger and more diffuse to the left and down. At profile coordinate 100 where the model is essentially 1-D there are small disturbances at depth, because the diffusion currents are small compared to those in an equivalent 1-D model at the observation point resulting in a resistivity overshoot. The reduced diffusion currents are due to the field partly being induced in the highresistivity overburden to the right of the vertical edge.



Fig. 7. The 1-D inversions of the generated 2-D data at selected stations on the profile shown in Fig. 6a. To the left the station 80 m left of the edge, in the middle the station at the edge and to the right is the station 120 m right of the edge. The error bars mark the 5% uncertainty on the generated data, while the solid curves mark the model data obtained by 1-D inversion. The model plots in the top right corners show the true 1-D model in grey and the inverted model in black. At the edge (profile coordinate = 280) the true 1-D model is undefined. The residuals are stated in the lower left corners. The vertical residual is a measure of the degree of fulfillment of the equality constraints in the 1-D models. The total residual is a weighted average of the data and vertical residuals.



Fig. 8. Four slopes, (a)  $90^{\circ}$ , (b)  $45^{\circ}$ , (c)  $22.5^{\circ}$ , and (d)  $11.25^{\circ}$ , are modelled for a structure with a resistive basement and a conductive overburden. The (1) true structure, (2) stitched-together 1-D inverse model and (3) relative difference are shown for each model. Modified after Toft (2001).

Zone II, to the right of the slope at profile coordinate 380, occupies a triangle extending from the vertical edge to the horizontal layer boundary. Zone II is the opposite of Zone I; the resistivity is lower than the true model rather than higher. Physically, the diffusion currents are stronger than for an equivalent 1-D earth, because of the influence of the shallow, conductive basement at profile coordinates less than 280. Zone III extends below the horizontal layer boundary of Zone II. Zone III also shows resistivities too low compared to the equivalent 1-D model, even though the zone is in the conductive basement. This is probably due to generally excessive diffusion currents in the vicinity of the slope compared to the equivalent 1-D earth. Inversion results at three selected stations are seen in Fig. 7.

There is no difficulty in fitting a 1-D model to the 2-D data set. Note the residual is lowest, where the true model is the most 2-D, at profile coordinate 280.

The diffusion currents enter the resistive overburden to the right and the shallow conductive base to the left and produce an intermediate response. The 1-D inversion produces a model with a smoother transition from high to low resistivity, without challenging the equality constraints. Hence, the presence of a strongly 2-D structure is not disclosed by inadequacy of the 1-D model assumption.

The three-zone categorization used above can be applied to the remaining structures in the Fig. 6a-2, a-3 and a-4. The zones occupy a larger part of the profiles, and become smeared when the inclination of the slope is decreased. For the model with minimum slope of  $11.25^{\circ}$  in Fig. 6d-2, the main discrepancy between the true and inverted models is due to the 1-D minimum structure constraint.

It is obvious that 1-D inversion is unable to resolve the  $90^{\circ}$  slope of Fig. 6a-1. At approximately 100 m to each side of the vertical contact, there is a triangular



Fig. 9. The 1-D inversions of 2-D data at selected stations on the profile shown in Fig. 8a. The error bars mark the 5% uncertainty on the generated data, while the solid curves mark the model data obtained by 1-D inversion. The model plots in the top right corners show the true 1-D model in grey and the inverted model in black. At the edge (profile coordinate 280) the true 1-D model is undefined. The residuals are stated in the lower left corners.

zone of average resistivity in the inverse model of Fig. 6a-2, resulting in an apparent inclination of approximately  $30^{\circ}$ . The true model with a slope of  $45^{\circ}$  in Fig. 6b-1 also seems too steep to be accurately recovered by the 1-D inversion in Fig. 6b-2 yielding an inclination of about  $30^{\circ}$ . Even though the exact structures of these two models are unresolved, the stitchedtogether 1-D model sections clearly show the presence of a valley structure. For a valley of this dimension, the midpoint and the depth are accurately obtained with 1-D inversion. Furthermore, the 1-D inversion correctly tracks the valley flanks sloping at 22.5° and 11.25°.

The same models with the opposite resistivity contrast are shown in Fig. 8. The pant leg structures also occur because of greater and lesser amounts of induced currents compared to the equivalent 1-D models. However, examination of the models with a resistive basement shows that these are far more problematic. One-dimensional inversion is unable to estimate the correct resistivity almost anywhere along the profile, and the three zones cover a considerably larger part of the profile. Zone I is an area of low resistivity extending to the left end of the profile. Above this area, the resistivity appears too high, probably in an attempt to compensate for the low resistivity of Zone I. Over- and undershoot of resistivities in the three zones are more dramatic for the structures with steep slopes. The zones associated with the lower slopes tend to be more smeared out, compared to those in Fig. 6. Turning the attention to the data fit of the 1-D inversions, the result at three stations on the profile in Fig. 8a are seen in Fig. 9.

Compared to the 1-D inversion results for the conductive-base structures shown in Fig. 7, the fit is poorer for 1-D inversion of the 2-D structures in a resistive base. However, the residuals are not of alarming size, and would pass unnoticed by the eye of the interpreter.



Fig. 10. Map of the Skjød survey area and the location of the TEM soundings. Single diamonds denote conventional  $40 \times 40$  TEM soundings, while the lines are the PATEM profiles. The UTM coordinates refer to UTM zone 32, datum ED50.

Regarding the ability of the 1-D inverse model to resolve the slope of the valley flank, it is evident that the slopes of 90°,  $45^{\circ}$  and  $22.5^{\circ}$  are not recovered. However, the structure with a slope of  $11.25^{\circ}$  is recognized in the 1-D inverted section but it is questionable whether an interpreter would conclude that the feature in Fig. 8d-2 is the flank of a buried valley, rather than a discontinuity in the high-resistivity base.

#### 4. Case history: Skjød buried valley complex

Skjød is a village located 30 km northwest of the city of Aarhus. The Skjød survey area is shown in Fig. 10. In the autumn 1999 and spring 2000 a major mapping campaign of the area north and northwest of Aarhus was launched by the County. The aim of the campaign was to gain a general knowledge of the subsurface of the area, with special focus on potential

groundwater resources and hydraulic properties (Sørensen et al., accepted for publication). The Skjød survey area of approximately 40 km<sup>2</sup> was covered by conventional  $40 \times 40$  TEM soundings and PATEM profiles. Sounding data were inverted using the parameterized 1-D approach of Effersø et al. (1999).

There were no topographic or geomorphologic features nor geological data to indicate the presence of a buried valley system as previous boreholes were either too shallow or did not coincide with the valley structures. A buried valley system was none the less revealed by the TEM survey. Fig. 11 is an elevation map of the conductive Tertiary clay that is defined as the basal layer with resistivity below 15  $\Omega$  m in the 1-D inverse models. Three main features are apparent: one striking north–south, the second striking south-east–northwest and the third strikes northeast–southwest in the upper right corner of the map. Note the valley flanks descending from approximately 35 m



Fig. 11. The elevation of the deep conductive layer constructed from 1-D inverse models whose bottom layers have resistivities below 15  $\Omega$  m. In the Skjød area, this surface is interpreted as the top of the Tertiary clay. The UTM coordinates refer to UTM zone 32, datum ED50.



a) Mean resistivity in elevation interval 10 to 30 m

Fig. 12. The mean resistivity in the elevation interval of (a) 10 to 30 m and (b) -30 to -10 m. The UTM coordinates refer to UTM zone 32, datum ED50.

above sea level (yellow colours) to approximately 50 m below sea level (green-blue colours), over a few hundred metres.

To get a measure of the resistivity of the sediments filling the valley, two maps of the mean resistivity for elevation intervals (a) 10-30 m above sea level and (b) -30 to -10 m above sea level are shown in Fig. 12a and b, respectively. Outside the buried valleys, both elevation interval maps show the Tertiary clay with a resistivity of  $2-7 \Omega$  m. In the upper interval of Fig. 12a, the resistivity is greater than  $100 \Omega$  m, indicating the presence of the valley filled with coarse-grained, water saturated sediments. In the lower interval of Fig. 12b the valley is narrower, but the mean resistivity is still high.

Based on the map in Fig. 11, the slope of the valley flank is estimated at approximately  $10^{\circ}$ . Assuming a simple valley structure, this slope corresponds to the theoretical model in Fig. 6d-1. As 1-D inverse models were able to recover a slope this steep with a similar resistivity contrast, we expect the images in Figs. 11 and 12 to be realistic depictions of features of the buried valley complex at Skjød. Since the depth to the Tertiary clay lies within the reach of conventional  $40 \times 40$  TEM and PATEM, no HiTEM was engaged as a secondary TEM phase in this survey.

During the summer of 2002, 10 deep holes were drilled in the areas of the Aarhus County TEM surveys. The purpose of the drilling program was: (1) to obtain ground truth evaluating the TEM results inside the valley, and (2) to verify that the conductive layer at the valley floor as well as on the valley flanks can be interpreted as clay layers in accordance with the Tertiary stratigraphic succession of the area. The latter would ensure the presence of a buried valley eroded into the Tertiary surface. The drill hole data confirmed the results of the TEM surveys, as the Tertiary clay was encountered approximately at the predicted depths.

Two holes were drilled in the Skjød Area. Hole D2 was drilled in the southeast-northwest striking valley, while hole D1 was drilled at a distance of 550 m from D2 in the valley shoulder. The locations of D1

Fig. 13. The lithological logs of the two drill holes in the Skjød survey area. Hole D1 is located on the valley shoulder, while D2 is in the middle of the southeast–northwest striking buried valley structure, as noted on Figs. 11 and 12.



and D2 are depicted in Figs. 10, 11 and 12. The lithological logs are shown in Fig. 13.

At D1 on the valley shoulder about 20 m of clay tills cover the Tertiary clay, which is found at 65 m above sea level. Fig. 14 shows data, model data and inverted 1-D models at PATEM soundings near the boreholes. According to the PATEM sounding at D1, the depth to the Tertiary clay (resistivity below 15  $\Omega$ m) is about 30 m. This is a representative value for the TEM soundings around the borehole as seen in Fig. 11. The difference between the sounding and the borehole information is ascribed to either local variations around the drilling site D1 or to a gradual transition from clay till to Tertiary clay. Inside the valley at site D2 alternating sequences of primarily clay-rich glacial sediments are present in the upper 25-30 m. The middle and lower parts of the valley are filled with sandy sediments. The valley floor consists of Tertiary clay, found at a depth of approximately 113 m below the surface. This is predicted by the PATEM sounding shown in Fig. 14. The depth to the 3.5  $\Omega$  m layer is 115 m and these parameters match perfectly with the Tertiary clay observed at drilling site D2. Also the thickness of the sand layer is indicated by the TEM sounding, and the upper alternating sequence is averaged to a single 40  $\Omega$  m layer by the PATEM sounding. All in all, the TEM survey was backed up by the drilling campaign.

As described by Sandersen and Jørgensen (2003), two or three different generations of buried valleys are expected to cross each other at different levels within the Skjød Area. The southeast–northwest striking valley is thought to be a member of the oldest generation since it erodes deeper than the north–south striking valley. The latter is a subtle feature in the deeper resistivity interval of Fig. 12b. Hence, the north–south striking valley is a part of a younger generation of valleys. The third valley is less pronounced and shallower. It cuts through the area from the northeast corner towards the southwest, as seen in Fig. 11. It probably belongs to a third generation with an unknown relative age. Water sampling from an Ellog drilling (not shown) (Sørensen et al., 2002)



Fig. 14. PATEM soundings close to the drill holes D1 (left) and D2 (right). Data are marked by error bars, model data by the solid curve and their corresponding models are shown to the right of the data plots.

placed in the deepest part of the main valley showed high quality groundwater.

#### 5. Conclusion

Geophysical investigations have played an important role in an extraordinary mapping effort to ensure high quality and quantity of the Danish groundwater reserves, which are under pressure by agricultural and industrial activities. The TEM method has proved successful for mapping a low-resistivity, Tertiary clay layer found in large parts of Denmark, and often limiting the downward extension of aquifers. TEM investigations have provided a high degree of understanding of the TEM method and the Danish subsurface, and consequently a need arose to customize the method to suit the specific demands.

The PATEM system, which provides rapid and dense lateral coverage, has made an important contribution to the understanding of transmitter coupling to artificial conductors in populated areas. The deep penetrating HiTEM system has twice the penetration depth of conventional TEM and PATEM systems, and has proven highly applicable when the importance of buried valleys in groundwater perspective was realized.

Modelling showed that 1-D inversion of TEM could accurately recover slopes up to  $22.5^{\circ}$  for a valley in a conductive basement. For steeper slopes, the angle is underestimated, but clearly located. Resolving the slope of a valley in a high-resistivity basement is problematic, even for gentle slopes.

The Skjød case story illustrates the capabilities of the TEM method. A distinct buried valley complex was delineated, and a valuable picture of the overall structures including the depths and bearings of the valleys was provided. A subsequent drilling program, which was sited according to the TEM results, supplied ground truth in good agreement with the TEM interpretations.

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