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Application of airborne transient electromagnetic (SkyTEM) technique for buried valley detection in part of Hadsten, Aarhus County, Denmark

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Abstract: Buried valleys of Quaternary age in Denmark are complex structures filled predominantly with glacio-lacustrine clay, silt, meltwater sand and gravel. These valleys are important target for groundwater exploration as they are potentially good aquifers. Most of the Danish aquifer consists of Quaternary sand and gravel deposited in valleys eroded and buried in the Tertiary clay basement. The resistivity of the impermeable Tertiary clay lies between 5 - 20 Ωm, moraines clay are 25 - 60 Ωm and sandy/gravel are from 60 - 200 Ωm. SkyTEM has the ability to effectively differentiate between these lithologies based on their range of resistivity values. In addition, SkyTEM has been proven to have an excellent depth penetration exceeding 200 m. A 1-D inversion was carried out for all the sounding data to obtain resistivity values which were then plotted as contour maps at selected depth intervals. A 3-D image of the subsurface was created by stacking these maps at different depths. The study identified buried valleys located at the southern and northern part of the survey at a depth of 155 and 40 m, and thickness of up to 140 m and 30 m, respectively.

Keywords: buried valley, SkyTEM, airborne electromagnetic method, Denmark

Abstrak - Lembah tertimbus berusia Kuarterner di Denmark adalah struktur kompleks yang diisi oleh lempung glasio-lakustrin, lodak, pasir air lebur dan kelikir. Lembah-lembah tersebut adalah penting sebagai sasaran bagi eksplorasi pencarian sumber air bawah tanah memandangkan ia berpotensi sebagai akuifer yang baik. Kebanyakan akuifer di Denmark adalah terdiri daripada pasir dan kelikir berusia Kuarterner dan kelikir yang terenap di dalam lembah yang terhakis dan tertanam di dalam lempung berusia Tertiar. Nilai kerintangan lempung telap air berjulat 5 -20 Ωm, lempung morain berjulat 25 – 60 Ωm dan pasir serta kerikil berjulat 60 – 200 Ωm. Sistem SkyTEM telah terbukti sesuai dalam penyiasatan sebegini kerana ia mampu mencapai sehingga 200 m kedalaman. Songsangan 1-D dilakukan ke atas kesemua data pemeruman bagi mendapatkan nilai kerintangan yang kemudiannya digunakan untuk memplot peta kontur mengikut kedalaman tertentu. Imej 3-D subpermukaan dibentuk dengan penggabungan kesemua peta kontur pada kedalaman yang berbeza. Kajian ini telah mengesan kedudukan lembah tertimbus di bahagian selatan dan utara kawasan kajian dengan kedalaman maksimum 155 m dan 40 m, dan berketebalan 140 m dan 30 m.

INTRODUCTION

Airborne electromagnetic system (AEM) was first developed more than 50 years ago for base metal exploration and has been in use since then. An airborne transient electromagnetic system (SkyTEM) was recently developed specifically for mapping geological structures (Jørgensen *et al.*, 2003) in the near surface for groundwater and environmental investigations. The SkyTEM system is different from other transient electromagnetic system as it has the capability of measuring very early times that are unbiased (measured voltage at all time gates have less than 1% primary response). All geometry of the system (eg: degree of frame corner) was fixed during assembling of the hexagonal shape frame with cables and other instruments. The entire movement of the system in the air was monitored at all times, including height of the frame from tree top, speed of the production flight and degree of tilting of the frame.

The airborne electromagnetic system techniques are both non-invasive and non-destructive. A great advantage of the TEM method is the possibility to collect dense networks of data enabling correlation of well data and 3-dimensional (3-D) imaging of the subsurface. The system is operated from the air using helicopter and does not require direct contact with the ground. It has the ability to collect a sizeable amount of data in a day's survey. Its excellent penetration depth of greater than 200 m allows it to be effectively used to map deep geological structures (Danielsen *et al.*, 2003). This paper describes the results of a SkyTEM survey conducted to determine buried valleys in part of Hadsten, Aarhus County, Denmark.

A large number of aquifers in Denmark are composed of Quaternary sand and gravel deposited in deep valleys eroded in Tertiary clays. The valleys are often covered by inhomogeneous moraine cap. It is generally observed that variations in hydraulic conductivity of these formations are closely related to the variations in electrical formation resistivity. Conductivity is inversely proportional to resistivity values.

The TEM method is an electromagnetic induction technique, of which the response of the earth to an electromagnetic impulse is measured in the time domain. A thorough discussion of the TEM method and interpretation can be found in (Nabighian & Macnae, 1991). This paper will only focussed primarily on the application of the SkyTEM technique in mapping buried valleys.

MATERIALS AND METHOD

Location and geology of survey area

The location of the survey area is shown in Figure 1. The geology of the study area does not differ much from the surrounding areas. It is generally influenced by pre-Quartenary deposition consisting of Upper Cretaceous Danian chalk and limestone covered by unconsolidated ancient Palaeogene clay, Neogene clay, silt and sand (Sorgenfrei & Buch, 1964).

Subcrop studies of the geological setting in Denmark indicates that Aarhus County is predominantly Quaternary clay. Buried valleys in Denmark are known to have eroded into the clay dominated sediments. This type of buried valley (Figure 2) actually can be either (A) partly buried valley eroded deeply into a high lying substratum of Tertiary clay, (B) buried valley eroded into a Tertiary sequence of clay in the lower part and alternating clay and sand in the upper part or (C) a deep valley eroded into the underlying limestone (Sandersen *et al.*, 2003).

Typical resistivity of sediments in buried valleys

Buried Quaternary valleys in Denmark, as well as in other countries, are important geological structures, because they often contain sand and gravel deposits that support good aquifers. They can be the main source of drinking water and they can serve as a conduit from an upper contaminated aquifer to a lower clean aquifer.

The TEM method maps electrical conductors in the Danish sedimentary geology with a formation resistivity up of to 60 - 160 Ωm. Typical resistivities for various freshwater-saturated sediments related to the buried valleys are shown in Table 1. These resistivity values are based on comparisons between TEM data and lithological well logs.

Studies has shown that the formation resistivity of the impermeable tertiary clay lies in the range of 5 - 15 Ωm, the resistivity of the moraines (mixtures of clay and till) are 20 - 50 Ωm and the resistivity of the sandy aquifers are between 50 - 100 Ωm. The resistivities of the aquifers are strongly dependent on the pore water resistivity and the clay content.

The techniques for mapping and recognizing buried valleys are based on derivation of extensive TEM data sets supported by drilling data. Sometimes the valleys are difficult to trace because of low resistivity contrast between the valley fill and the surrounding sediments, however they can still be detected indirectly because of resistivity contrasts between the different layers of sediments filling up the valley.

Theory of TEM method

The TEM induces electrical currents into the earth using electromagnetic induction. A time varying magnetic field in this study is created using a coil or loop of wire attached on hexagonal lattice frame. Faraday's law of induction tells us that a changing magnetic field will produce an electric field, which in turn will create an electric current. Thus, the primary magnetic field from the transmitter loop will create a secondary electric current in the earth.

The secondary magnetic field produced by those secondary electric currents in the earth is then measured. Figure 3 shows the waveform of the primary magnetic field generated by the transmitter and of the primary electric field (electromotive force) accompanying that magnetic field. The primary field impulse (transient) creates eddy currents immediately below the transmitter loop, approximating a mirror image. As the initial near-surface eddy currents decay, they in turn induce eddy currents at greater depths. The third panel in Figure 3 shows the waveform of the

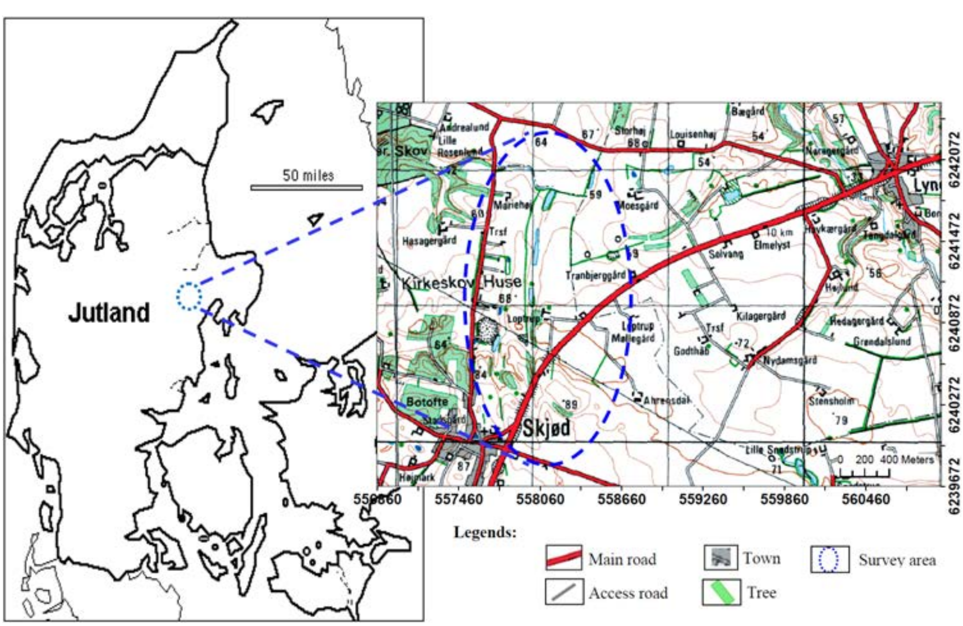

Figure 1: Location of the survey area at Hadsten in Aarhus County, Jutland.

secondary magnetic field, generated by the series of eddy currents induced in the ground.

The magnitude and rate of decay of those secondary currents depend on the conductivity of the medium, (i.e. the electrical conductivity of the soil) and on the geometry of the conductive layers. The TEM receiver measures the magnetic fields created by those secondary currents.

In time-domain electromagnetic techniques the inducing signal is a sharp pulse or transient signal. The induced currents in the earth are initially concentrated immediately below the transmitter loop and with time, those currents will diffuse down and away from the transmitter. This is shown schematically in Figure 4. An analogy with smoke rings is often used to describe the behaviour of the currents in the ground. Initially strong currents form in the ground adjacent to the transmitting loop. The "smoke ring" then expands, weakens, and travels down through the earth. The rate of diffusion depends on the earth conductivity. In resistive media the currents will diffuse very rapidly. In conductive media the currents will diffuse more slowly. A conductive layer at depth may "trap" currents in that layer, while currents elsewhere decay more rapidly.

The expansion of smoke ring is also can be effected by the rate of current used. Low current used for the low moment soundings mode are acquired using a higher frequency and have quicker turn-off times enabling measurements with higher frequency response and provide better information about the near surface while the high moments is used a higher current and lower base frequency provides high quality late time data for deep imaging. The higher current used and longer time off, deeper smoke ring can be move downwards and outwards.

Detail derivation including with noise signal, latest time and penetration depth equation, the only way to increase the penetration of depth is high the moment of transmitter (extend the turn-off time) and decrease the effective of noise level by stacking the transient measurements (Christiansen *et al.*, 2006). TEM method can be set up to be either low moment or high moment mode based on the target being pursued or even dual moment for SkyTEM method explained detail in operation.

SkyTEM Field Operation

SkyTEM is a time-domain, continuous, helicopter pulled TEM method. The system in operation is depicted in Figure 5. The system is carried as an external sling load independent of the helicopter. The equipment is fitted to a hexagonal framework attached to the helicopter via a cable and consists of a transmitter, a transmitter pole and a receiver and two lasers for height determination, an inclinometer to detect deviation from the horizontal and power supply in the form of batteries or generator. The transmitter (in normal configuration) is mounted on a lightweight wooden lattice frame. It is a dual moment system where transmitting a low moment in one turn and a high moment in all four turns. The low moment is about 40 A with a turn-off time of about 7µs; the high moment transmits approximately 95 A

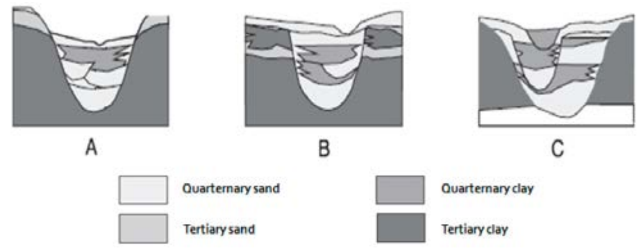

Figure 2: Sketches of possible types of buried valley erode into clay dominated sediments (after Sandersen et al., 2003).

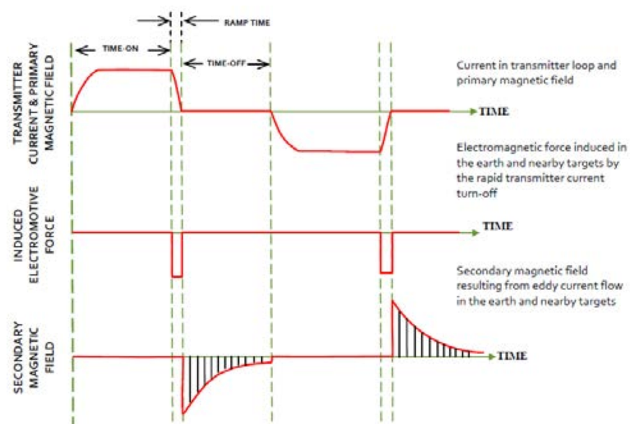

Figure 3: TEM (Transient Electromagnetic) waveforms (after McNeill, 1990).

and has a turn-off time of about 38 µs. The first gate center time on the low moment is in 16 µs while the last gate is 8 ms. These parameters are suitable for a 50 Hz power line frequency operation.

The geographical position is determined by two independent GPS receivers, each receives about 60 positions per minute and a GMT time. The basic physics of TEM method is that it is sensitive to changes in conductivity of the subsurface. In a highly conductive environment (such as in alluvium) the TEM technique has proven to be highly effective in penetrating even into the deeper depths. This is because; materials that are highly conductive produce strong secondary electromagnetic fields.

The depth of a penetration of the SkyTEM system depends primarily on the signal-noise ratio, which in turn, is a function of the selected moment, the geological and noise-related conditions on site, flight altitude and flying speed. In Denmark, typically a depth of 200 m is achieved for hydrogeological investigations. In a standard setting, measuring continuously along flight lines with turn between high and low moment, each raw data set typically contains between 100 and 300 individual transient measurements. These settings include a flight altitude where the ground clearance for the framework is between 20 - 30 m with a speed of approximately 20 km/h (5 m/s) as used in this survey since this study site is just flat area. But, in forested areas, the flight altitude is typically increased to 35 - 45 m above ground level.

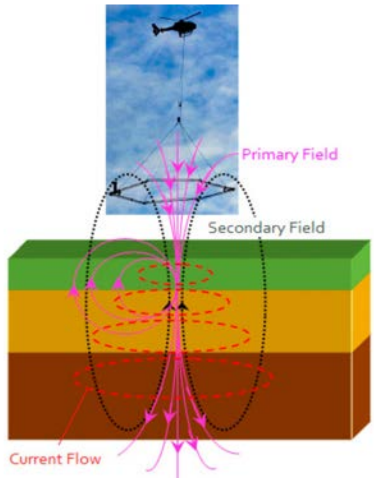

Figure 4: TEM (Transient Electromagnetic) eddy current flow.

Figure 5: SkyTEM in operation (courtesy of SkyTEM Aps).

Data Processing

One-dimensional (1-D) inverse modelling (Menke, 1989; Christensen & Auken, 1992) is found to be an effective means for processing the TEM soundings in the Danish geological environment (Christensen & Sørensen, 1998; Poulsen & Christensen, 1999). The inversion parameters of layer thickness and resistivity are used to construct contour maps of the average resistivity at different depths, as well as the depth to good conductors. These maps are combined to create 3-D images of the subsurface. Geological features such as a buried valley can produce different images that are dependent on the resistivity of the sediments in and around the valley structure and on the model presentation.

All the SkyTEM data was processed and inverted using a 1-D inversion package, EM1DINV which is supported in the Aarhus Workbench software. With supported extension, the Workbench software is capable of doing filtering /removing of bad data, inversion, plotting of 1-D contour maps (with different intervals resistivity) and extract profile for selected lines (Aarhus Geophysics, 2009). For this study, data have been processed from 1099 sounding points (ranging from 64 - 117 points for each line). The interval between each sounding point is 10 m. No priori information from borehole logs and other geological information have been used during the inversion process. The geological modelling presented here is mainly based on interval resistivity maps representing intervals of 20 m. Detail information and explanation on SkyTEM processing and data handling can be found in Auken *et al.* (2009).

Table 1: Resistivity range of Danish sediments (after Jorgensen et al., 2003).

Sediment	Resistivity (Ωm)
Saturated sand/gravel	160
Meltwater gravel	100
Meltwater sand/miocene sand	80
Clay till	40
Lacustrine clay	20
Miocene mica clay	25
Palaeogene clay	5

RESULTS AND DISCUSSIONS

Figure 6 shows the location of the SkyTEM survey lines. The length of each line is approximately 1500 m. There are 11 lines in total with 30 m line separation. The average interval between each sounding points is 10 m. The survey was planned taking into account the road network and cabling in order to minimize the amount of data to be culled. It is a well known fact that there are two major challenges when conducting ground electromagnetic surveys in build-up areas. Man-made structures cause a major hindrance in data acquisition as it pose as obstructions to the field set-up. This drastically reduces the speed of data acquisition in build-up areas. However, SkyTEM does not see this as a major obstacle as it is airborne and will still be able to acquire data rapidly. The main concern for SkyTEM (and any other ground EM techniques) is the effect of coupling caused by the presence of man-made conductors such as pipes, fences, cables and electrical power lines (which can be more invasive). Electrical power lines are known to mask ground response and at the same time they can also create magnetic fields that can corrupt geophysical data. A few lines (marked by red dashed lines in Figure 6 from the survey area were removed due to these reasons. These lines were removed as they coincide with known alignment of underground cables.

Figure 7 shows the average resistivity contour maps at 20 m interval for two different depths (40 m and 120 m). Both the maps show high resistivity values (HR) more than 60 Ωm at the southern portion of the survey area. On the 40 m depth, high resistivity (HR) values are observed at the northern portion of the survey area. However, this is no longer observed on the 120 m depth, indicating that the high

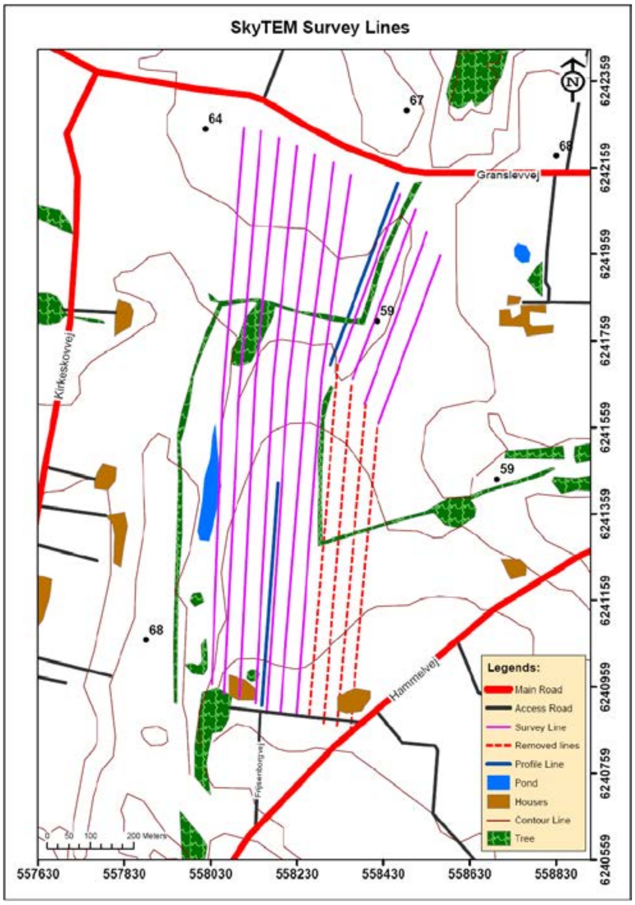

Figure 6: SkyTEM survey lines.

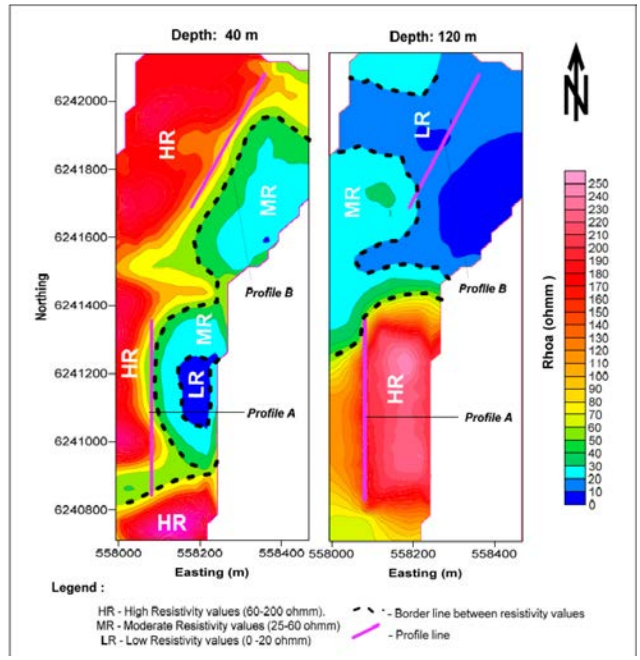

Figure 7: Average resistivities in selected intervals. It shows two different interval resistivity maps which is for 40 m and 120 m depth. Purple lines are the line of selected sounding point that used to plot the vertical profile (Figure 9). Coordinate system: Euref 89 zone 32N.

resistivity sediments are only deposited at depth limited to above120 m. These high resistivity values are attributed to sandy and gravelly sediments. Low resistivity (LR) values caused basically by clayey sediments are observed to be more extensive at the northern portion.

By overlaying and stacking all the 1-D interval resistivity maps starting from 0 m until 140 m depth, a 3-D contour map was created (Figure 8). From the 3-D contour map high resistivity values (on the southern part) is still observed until 140 m depth. It is highly probable that this high resistivity values will still be observed at depths. At the northern portion of the survey area, high resistivity values are only observed from 40 m to 100 m.

The high resistivity (>60 Ωm) values observed in the 3-D contour map probably is a quaternary/tertiary sands that has been eroded into clay sediments (represented by low resistivity values in range 5 to 20 Ωm that surrounding high resistivity values).

As described above, high resistivity values observed on the southern and northern portion of the survey area is attributed to the Quaternary/tertiary sands filling up the buried valleys. The low resistivity sediments which are observed to encompass the high resistivity sediments suggest that the buried valley is formed within the clay deposit layer. This characteristic closely resemble to buried valley of type A in Figure 2 which is partly and deeply eroded into a high lying substratum of Tertiary clay.

To confirm the findings, a correlation between the TEM data with lithological information from boreholes obtained from the national well database (GEUS, 2009) and electrical log data from Geo-log Aps was carried out. The lithological descriptions from most of the boreholes and El-log are rather poor. Correlation with both the boreholes and El-log is only possible up to 30 m as that is the maximum depth recorded by some of the boreholes and electrical logging.

Two profiles (Figure 9) are extracted from the average resistivity contour maps (Figure 7) to have a better understanding of the structure of the buried valleys, especially with regards to the width extent and the thickness of the sediments filling up the valleys. In addition, lithological logs from two boreholes (78.979 and 78.976) and two electrical log data (B39 and B42) were also used for correlation (Figure 9).

Generally, the two profiles show a three layer subsurface. A low-moderate resistivity (LR) layer with values ranging from 15 to 30 Ωm is observed as the uppermost layer. The range of resistivity values is indicative of clay till. Boreholes located on Profile A confirmed the presence of Quaternary clay with a thickness reaching to about 20 m. A high resistivity layer (60 - 200 Ωm) is observed to underlie the low resistivity layer. The borehole logs described this layer as meltwater and a mixture of moraine sand and gravels. The ranges of resistivity values observed for this layer suggest the same. The third low resistivity layer (with values ranging from 5 to 20 Ωm) is attributed to Palaeogene clay sediments. No correlation with the borehole logs was carried out as the maximum depth of the boreholes is only about 30 m.

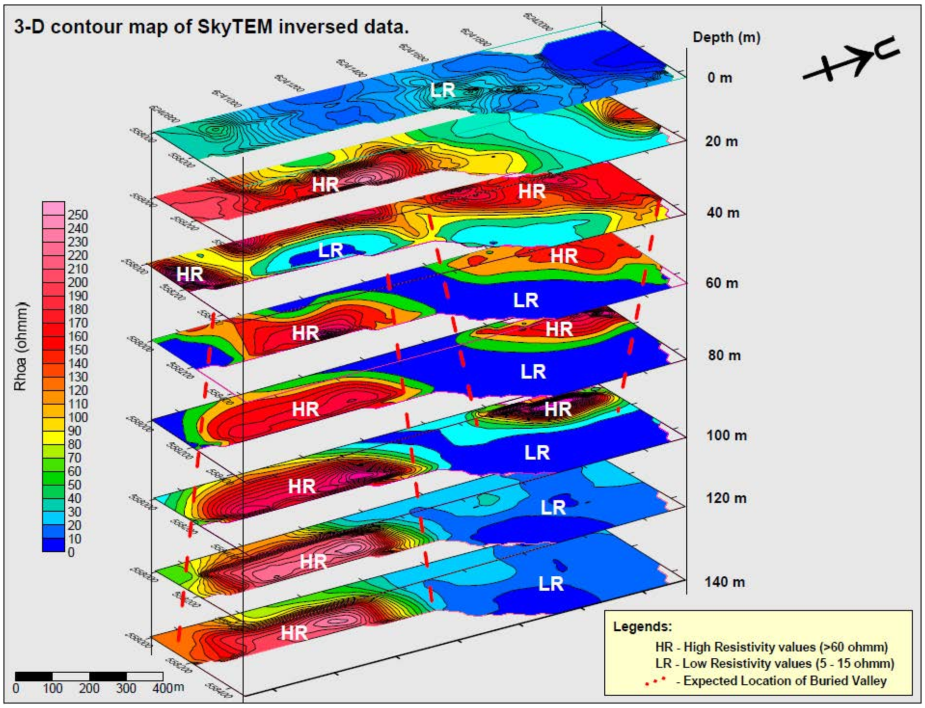

Figure 8: 3-D contour map of resistivity values for different depth. Coordinate system: Euref 89 zone 32N.

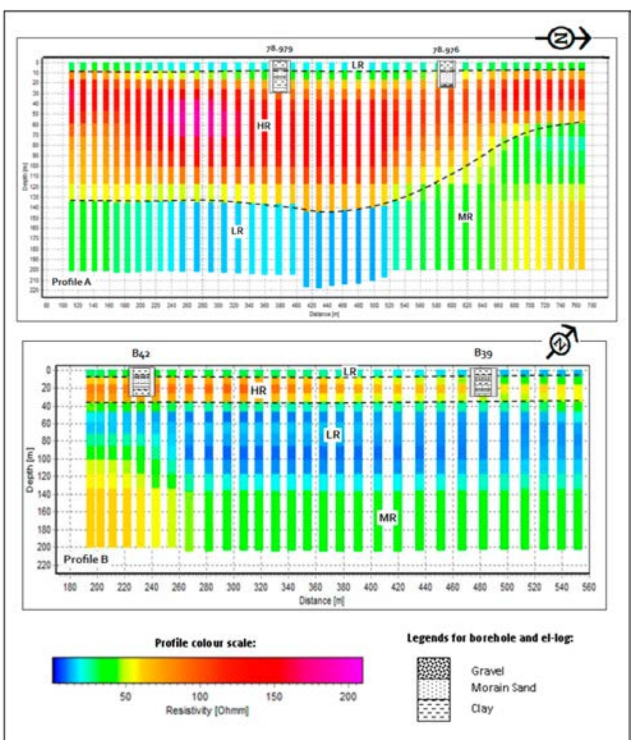

Figure 9: Vertical profile shows the layer that possibly contains the buried valley. Profile A and B are profiles on the southern and northern portion of the survey area respectively. HR, MR and LR stand for high, moderate and low-moderate resistivity.

The high resistivity (HR) values of the second layer on Profile A are attributed to the presence of meltwater and a mixture of moraine sand and gravels. These are the commonly filled sediments found in buried valleys in Denmark. This layer is observed to be thick (140 m) to the south of the profile but thins out towards the north, forming a synclinal shaped structure, closely resembling a buried valley. The thickness of the infilled sediments within the valley is estimated to extend up to more than 210 m with a width extend that could reached more than 660 m. The buried valley is sandwiched between two low resistivity layers attributed to clays.

Similar features are observed on Profile B. However, the second layer of high resistivity values is observed to be much thinner, only about 20 m. Although this layer does not exhibit a synclinal structure, it is still believed to be part of the buried valley; based primarily on the range of high resistivity values observed which are similar to that observed in Profile A. The buried valley identified on Profile A is therefore, interpreted to continue and extend further north of the survey area.

Based on all the contour maps and profiles, the depth of the buried valleys varies from less 25 m to 150 m and probably width is about not less than 600 m. This is common size for valley that has been found in Denmark or even smaller than others (Thomsen *et al.*, 2004; Jørgensen *et al.*, 2003). However, the actual depths and of buried valleys remain undetermined, because the valley floor is not really resolves accurately by TEM soundings. This could either be due to the low resistivity contrast or the valley is deeper than the maximum penetration depth achieved by TEM survey.

CONCLUSION

The SkyTEM technique has proven to be a very rapid and effective geophysical tool in mapping buried valleys, which are potential groundwater aquifers in the study area. Correlation with existing borehole and electrical log information, although limited to about 30 m, further strengthen the existence of a buried river valley. But to be more precise in the correlations, deeper borehole and logging information needed here. SkyTEM has excellent depth penetration exceeding 200 m making it a viable tool in mapping deep seated aquifers. The data acquired can be presented in a number of ways (contour maps, profiles and 3D images) which greatly assisted in the interpretation of the SkyTEM data to further enhance the understanding of the subsurface geology.

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