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ScienceDirect
Journal of Applied Geophysics 67 (2009) 194–205
JOURNAL OF APPLIED GEOPHYSICS
www.elsevier.com/locate/jappgeo

A comparison of helicopter-borne electromagnetics in frequency- and time-domain at the Cuxhaven valley in Northern Germany

Annika Steuer[a,*], Bernhard Siemon[a], Esben Auken[b]

[a] Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, D-30655 Hanover, Germany
[b] HydroGeophysics Group, Department of Earth Sciences, University of Aarhus, Høegh-Gulbergs Gade 2, 8000 Aarhus C, Denmark

Received 26 February 2007; accepted 9 July 2007

Abstract

Two different airborne electromagnetic methods were applied in the same area: the frequency-domain helicopter-borne electromagnetic (HEM) system operated by the Federal Institute for Geosciences and Natural Resources, Germany, and the time-domain SkyTEM system of the HydroGeophysics Group at the University of Aarhus, Denmark. For verification of and comparison with the airborne methods, ground-based transient electromagnetics and 2-D resistivity surveying were carried out. The target of investigation was the Cuxhaven valley in Northern Germany, which is a significant local groundwater reservoir. The course of this buried valley was revealed by drillings and the shape was determined by reflection seismics at several cross sections.

We applied electrical and electromagnetic methods to investigate the structure of the valley filling consisting of gravel, sand, silt and clay. The HEM survey clearly outlines a shallow conductor at about 20m depth and a deeper conductor below 40m depth inside the valley. This is confirmed by 2-D resistivity surveying and a drilling. The thickness of the deeper conductor, however, is not revealed due to the limited investigation depth of the HEM system. The SkyTEM survey does not resolve the shallow conductor, but it outlines the thickness of the deeper clay layer inside the valley and reveals a conductive layer at about 180m depth outside the valley. The SkyTEM results are very consistent with ground-based transient electromagnetic soundings.

Airborne electromagnetic surveying in general has the advantage of fast resistivity mapping with high lateral resolution. The HEM system is cost-efficient and fast, but the more expensive and slower SkyTEM system provides a higher depth of investigation. Ground-based geophysical surveys are often more accurate, but they are definitively slower than airborne surveys. It depends on targets of interest, time, budget, and manpower available by which a method or combination of methods will be chosen. A combination of different methods is useful to obtain a detailed understanding of the subsurface resistivity distribution.
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Keywords: Airborne electromagnetics, Helicopter-borne electromagnetics; HEM; SkyTEM; Transient electromagnetics; TEM; Continuous vertical electrical sounding; CVES; Hydrogeophysics; Buried valleys; Cuxhaven valley

1. Introduction

Buried valleys in northern Europe were formed by subglacial melt-water erosion during the quaternary glaciations and refilled with gravel, sand, silt and clay. Nowadays they are often completely covered by Holocene sediments and not visible in the surface morphology. Due to their often highly permeable and porous sediments, buried valleys are potential groundwater reservoirs and important for future supply of drinking water. The filling of buried valleys is not uniform (Piotrowski, 1994); especially the hydraulic connections to other groundwater reservoirs and the pathways for contaminants from the surface to deeper reservoirs can vary along their course. Particularly in the North Sea region, saltwater intrusions into groundwater reservoirs of the valleys may occur and this will be of increasing importance as the seawater level is expected to rise in the coming centuries. The natural protection

* Corresponding author. Tel.: +49 511 6432148.
E-mail address: annika.steuer@bgr.de (A. Steuer).

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doi:10.1016/j.jappgeo.2007.07.001

of the aquifers in buried valleys against pollution varies depending on the thickness of covering clay layers. The genesis of buried valleys, or tunnel valleys, are discussed by e.g. Cofaigh (1996), van Dijke and Veldkamp (1996), Piotrowski (1997), Huuse and Lykke-Andersen (2000) and Jørgensen and Sandersen (2006).

Within the interregional Buried Valleys (BurVal) project, co-funded by the European Union, glacial valleys in Northern Europe have been investigated for three years using various geophysical and hydrogeological methods (Kirsch et al., 2006). The aim of the BurVal project has been to deliver substantiated knowledge and understanding of the structural and hydraulic properties, to focus on the vulnerability to surface contamination and other human impacts, and to investigate interactions with other water reservoirs and saltwater intrusions.

Geophysical methods can contribute to map the course, the lateral extent and the internal structure of buried valleys as well as to the determination of the hydrogeological parameters of the sedimentary infill. The most important condition for a successful application of geophysical methods is a sufficient contrast in the physical parameters to be investigated, e.g. electrical conductivity, seismic velocities or density.

Several papers discuss the significance of geophysical methods for groundwater exploration, especially for the investigation of buried valleys. Resistivity mapping is one of the classical geophysical methods used for groundwater surveys. Flathe (1955) investigated the “Possibilities and limitations in applying geoelectrical methods to hydrogeological problems in the coastal areas of North West Germany”. Within the BurVal project, pulled array continuous electrical soundings (PACES; Sørensen, 1996) were successfully used at several buried valleys in Denmark, e.g. Kjærstrup and Erfurt (2006) and Jørgensen et al. (2006). Gabriel et al. (2003) and Wiederhold et al. (2005) summarized the results of different geophysical methods at buried valleys in Northern Germany—including reflection seismic, gravimetric, direct current (DC) resistivity and helicopter-borne electromagnetic (HEM) methods. Jørgensen et al. (2003) presented an integrated application of time-domain electromagnetics (TEM), reflection seismics and exploratory drillings for the investigation of buried valleys in Denmark. Auken et al. (2003) described the investigation of buried valleys using TEM and Danielsen et al. (2003) presented a 2-D model study which showed the limitation of TEM 1-D inversion in the determination of the slopes of valleys. The conclusion of all these studies is that a combination of different methods is essential for a detailed understanding of buried valleys. HEM and TEM were successfully combined for hydrogeological investigations, e.g. by Fittermann and Deszcz-Pan (2001) for saltwater mapping in the Everglades National Park in Florida, USA, and by Stadtler et al. (2004) for groundwater studies in Namibia.

In this paper we focus on the results of helicopter-borne electromagnetic methods, HEM and SkyTEM, which were applied at the Cuxhaven valley in Northern Germany, one of the six pilot project areas of the BurVal project (Rumpel et al., 2006). Eberle and Siemon (2006) showed that buried valleys were successfully delineated using HEM at four case studies in Germany and in Namibia. One of them, the Cuxhaven area, was described in detail by Siemon et al. (2004). SkyTEM was also successfully applied in groundwater surveys and at buried valleys (Jørgensen et al., 2006; Kjærstrup and Erfurt, 2006; Scheer et al., 2006). The airborne results will be compared in detail with proven ground-based geophysical methods such as the continuous vertical electrical sounding (CVES) method and TEM. HEM and conventional DC resistivity results were previously compared along a profile that crosses the northern part of the Cuxhaven valley (Wiederhold et al., 2005). In this study, we discuss the advantages, disadvantages and limits of both helicopter-borne EM methods.

2. Survey area

One of the investigation areas of the BurVal project was the Cuxhaven valley in Northern Germany (Fig. 1). The valley was carved into Tertiary sediments by melt-water flow during Pleistocene glacial regression epochs after the Elster glaciation about 350 000 years ago (Kuster and Meyer, 1979; Wiederhold et al., 2005). The valley is filled with coarse sand and gravel, overlain by fine and medium grained sand and silt. In the upper part of the valley, deposits of Lauenburg clay exist. The available geological information and resistivity logs, as the one displayed in Fig. 2, indicate that a large resistivity contrast exists due to thick layers of clayey material embedded in sandy environment.

A part of the Cuxhaven valley, the test area Wanhöden, was selected for detailed geophysical surveying such as reflection seismics, gravity, DC resistivity and HEM (Gabriel et al., 2003; Wiederhold et al., 2005); and ground-based and airborne TEM.

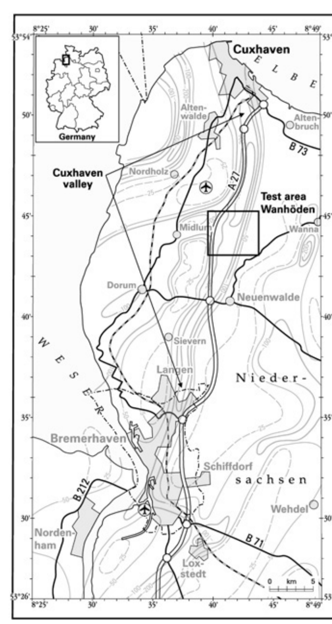

Fig. 1. Area of investigation. The contour lines of the Quaternary base in metres below sea level (Kuster and Meyer, 1995) show that the Cuxhaven valley extends north–south from the city of Cuxhaven to the city of Bremerhaven. The test area Wanhöden (rectangle) is located in the central part of the Cuxhaven valley.

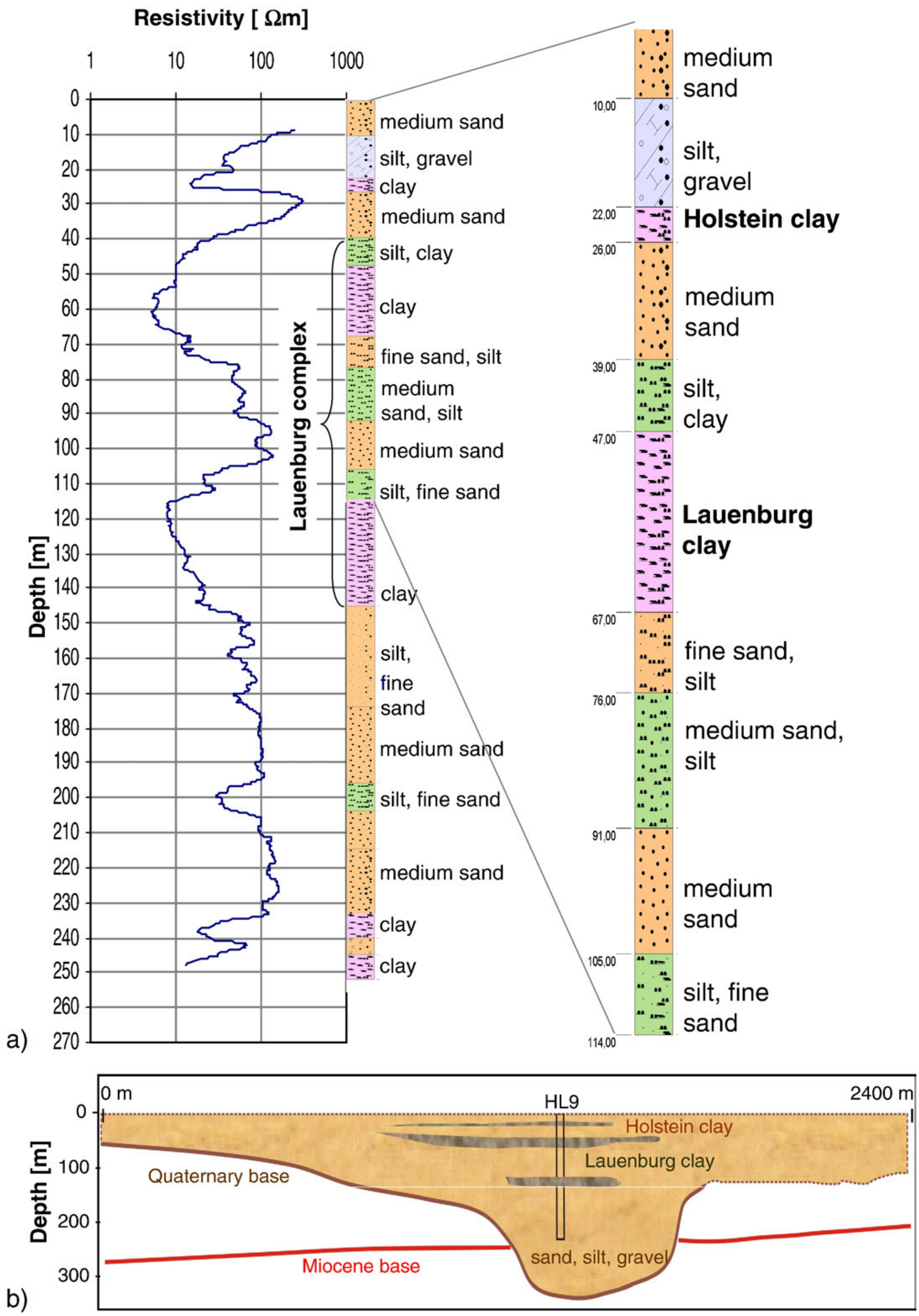

Fig. 2. (a) Resistivity log and lithological log of drilling HL9 (after Besenecker, 1976) located in the test area Wanhöden (cf. Fig. 3). (b) Sketch of the expected valley filling derived from HL9. Quaternary and Miocene base are derived from a seismic section 300 m northwards of HL9 (cf. Fig. 3).

The profiles of the geophysical methods compared in this study are shown in Fig. 3.

3. Applied geophysical methods

Electrical and electromagnetic (EM) methods both provide information about the subsurface resistivity distribution. As in DC electrical methods current is injected directly into the subsurface they are limited to be applied on the ground. On the contrary EM methods are based on the propagation of EM fields, which induce currents in the subsurface and therefore both ground-based and airborne EM measurements are feasible.

A successful application of DC and EM methods for differentiating subsurface resistivity structures requires a

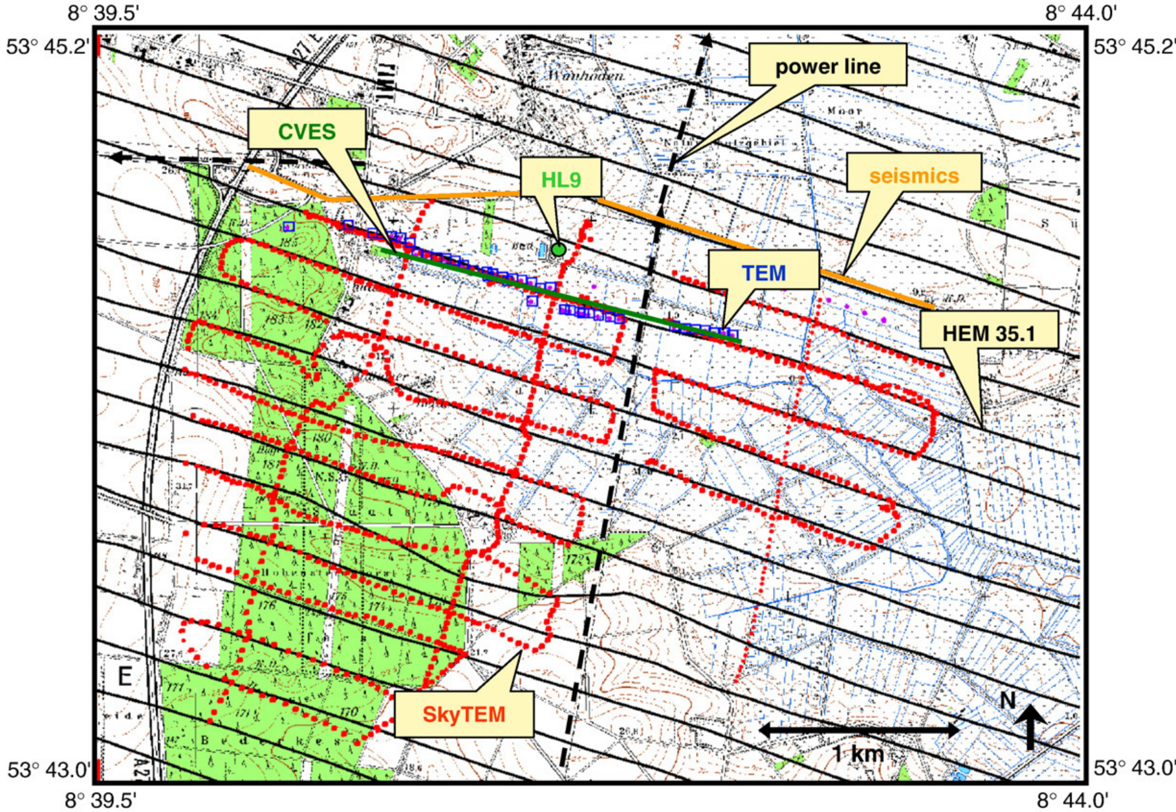

Fig. 3. Location map of the test area Wanhöden. The HEM flight lines are black and the SkyTEM lines are dotted red. The TEM sites (blue squares) and the CVES profile (green line) are located parallel to HEM line 35.1. The location of the borehole HL9 (green point) is about 200 m further north.

sufficiently large resistivity contrast between the target and the surrounding material. The methods are often used in hydrogeological surveys to differentiate conductive formations such as clay-bearing layers, which are aquitards, from more resistive ones such as gravel and sand layers, which often serve as productive aquifers. As the electrical conductivity of groundwater depends on its mineral content, DC and EM methods are useful to distinguish between fresh-, brackish-, and saltwater.

3.1. Frequency-domain helicopter-borne electromagnetics

HEM systems (Fig. 4a) utilise several transmitter and receiver coils simultaneously. The transmitter signals, the primary magnetic fields, are generated by sinusoidal current flow through the transmitter coils at discrete frequencies. The oscillating primary magnetic fields induce eddy currents in the subsurface. These currents generate the secondary magnetic fields, which depend on the conductivity distribution of the subsurface. The secondary magnetic fields measured by the receiver coils are divided by the primary magnetic fields expected at the centre of the receiver coils and the ratio is measured in parts per million. As the secondary fields are very small with respect to the primary fields, the primary fields have to be bucked. The orientation of the transmitter coils is horizontal or vertical and the receiver coils are oriented in a maximum coupled position resulting in horizontal coplanar, vertical coplanar or vertical coaxial coil systems. Typically 4–6 frequencies are used on modern HEM systems. For basics in detail see Frischknecht et al. (1991) and Palacky and West (1991) or more recently Siemon (2006a).

BGR investigated the survey areas Cuxhaven and Bremerhaven in 2000 and 2001 using its helicopter-borne geophysical system (Fig. 4a), which simultaneously records EM, magnetic, and radiometric data. An area of more than 1000km^2 was covered within 19 days. The flight line spacing was 250m and the tie-line spacing was 1000m, totalling about 5000 line-kilometres (Siemon et al., 2004; Eberle and Siemon, 2006).

The HEM system, a DIGHEM$^{\text{V-BGR}}$ bird manufactured by Fugro Airborne Surveys, operates at five frequencies ranging from 380Hz to 192kHz. The transmitters and receivers of the horizontal coplanar coil system are about 6.7m apart. GPS/GLONASS provide the positions of the helicopter and the bird. Laser and radar altimeters record the altitudes of the HEM system and the helicopter, respectively. The nominal ground clearance of the bird is 30–40m. The sampling rate of 10Hz provides sampling distances of about 4m at a flight velocity of 140km/h.

To interpret the HEM data in terms of layered-earth resistivity models the Marquardt-Levenberg 1-D inversion technique (Sengpiel and Siemon, 1998; Sengpiel and Siemon 2000) was used.

3.2. Time-domain electromagnetics

TEM uses a primary field that consists of a series of pulses separated by periods of zero primary fields (Fig. 5). The fast

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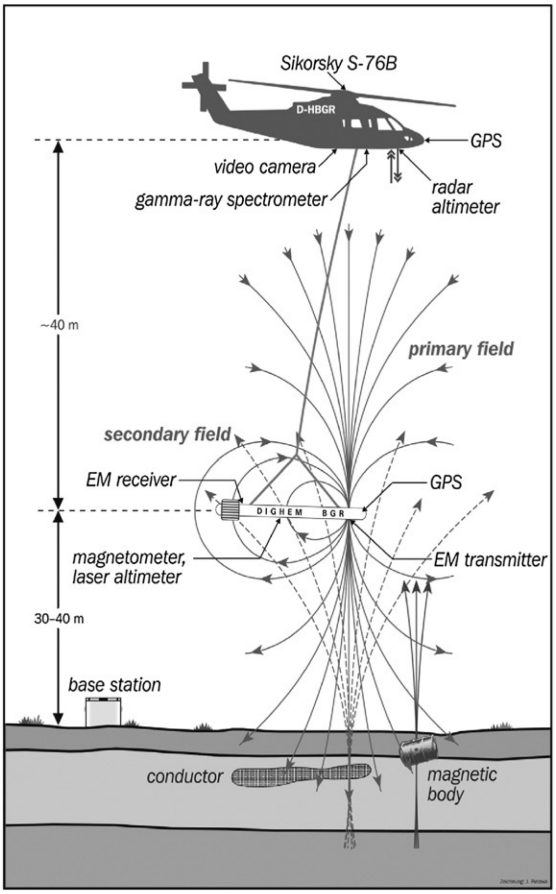

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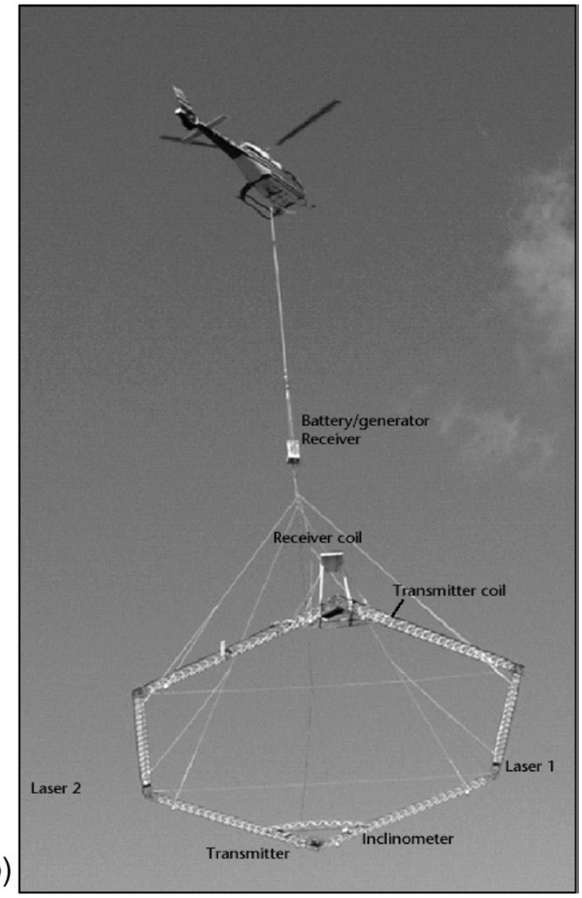

Fig. 4. Helicopter-borne geophysical systems. (a) BGR system: The nominal bird altitude is 30–40 m above the ground. The helicopter is also equipped with differential GPS, video camera and a radar-altimeter; (b) SkyTEM system of the University of Aarhus.

switch-off of a steady current flowing through a transmitter loop as primary field excitation induces a secondary field, which is measured using an induction coil as receiver in the absence of the primary field. A detailed discussion of the TEM method is presented by e.g. Nabighian and Macnae (1991).

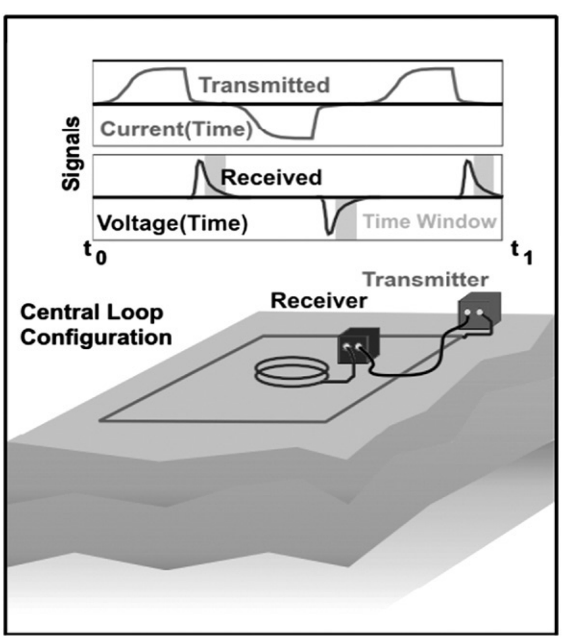

Fig. 5. Shown is a TEM system in central-loop configuration and the transmitted and received TEM waveforms.

A ground-based TEM survey was conducted at the test area Wanhöden in 2005 in order to obtain information about the resistivity distribution at greater depths. The survey line along flight line 35.1 (Fig. 3) was chosen for a direct comparison with the results from the other geophysical surveys. The station spacing on the 2.5km long section was 50m inside the valley and 100m outside. The measuring progress was about 7 sites per day.

The TEM measurements were carried out in a central-loop configuration (Fig. 5) using an analogue Geonics PROTEM 47 system with a transmitter moment of 30 000Am^2 (100 × 100m^2 transmitter loop and 3 A transmitter current). The effective area of the receiver loop was 31.4m^2. Three time segments (6–707µs, 49–2850µs and 101–7040µs) with different gains were measured in order to resolve the signals over the whole voltage range. Each TEM measurement consists of 6 data sets per time segment with 1000 stacks per data set. The data were averaged and combined to one transient decay curve. The standard deviation at times earlier than 3ms is below 1%, at later times it is up to 10% or even higher. Data were inverted using a standard least-squares inversion algorithm (HGG, 2007a).

3.3. Time-domain helicopter-borne electromagnetics

The SkyTEM system is a helicopter-borne TEM system (Sørensen and Auken, 2004). A transmitter loop on a six-sided frame is carried by a helicopter (Fig. 4b). The receiver loop is placed about 2m above the frame. This configuration is chosen in order to efficiently suppress week off-time currents in the transmitter loop. Two laser altimeters placed on the frame measure the ground clearance and an inclinometer measures the tilt of the frame. Car batteries or a generator is placed between the helicopter and the frame supply power to generate the transmitting current.

HGG carried out a SkyTEM survey at the test area Wanhöden in 2005 (Foged et al., 2005). The survey area of about 8km^2 was covered within one day. The flight lines were aligned to those of the HEM survey (Fig. 3).

The measurements at the Cuxhaven valley were carried out with low and high transmitter moments. A current of 40A in one loop turn generated a low transmitting moment of approximately 9000Am^2. The time span of recording the received voltage was 17–1400µs. A high moment of approximately 47 000Am^2 was obtained with a current of 40–50A in four loop turns. Voltage data of high moment measurements were recorded in the time span of 150–3000µs.

Measurements were gathered in cycles of 4 data sets with low moment (320 stacks per data set) and 4 data sets with high moment (192 stacks per data set). The data from each cycle were averaged to one low and one high moment data set which were interpreted by one geophysical model. One cycle had a time span of about 15s. At an average flight speed of 18km/h we got one model per 60m. The system altitude was 10–25m.

As the SkyTEM transmitter moment (TM) was about 1.5 times higher than the ground-based TEM moment, the investigation depth was 10% higher due to the increase of the investigation depth (d_{inv}) with the transmitter moment ($d_{\mathrm{inv}} \sim \mathrm{TM}^{1/5}$; Spies and Frischknecht, 1991).

SkyTEM data were inverted using the same inversion code as the ground-based TEM soundings (HGG, 2007a).

3.4. Direct current resistivity method

Apparent resistivities are directly derived from DC currents injected into the ground using electrode pairs and electrical potentials measured between other electrode pairs. As the investigation depth generally increases and as electrode separation increases, the vertical resistivity structure is obtained by varying the electrode separation. A detailed description of the resistivity method is given in e.g. Telford et al. (1990).

Multi-electrode or 2-D resistivity surveying (Griffiths and Turnbull, 1985; Dahlin, 1996), also called continuous vertical electrical sounding (CVES), provides much higher productivity and better data quality than conventional 1-D Schlumberger or Wenner surveys. Modern multi-electrode systems having automatically switching electrodes control the measurements using a predefined measurement protocol (Griffiths et al., 1990). A survey produces a high-resolution resistivity section down to a depth limited by the outer electrode distance and the current injected.

The Leibniz Institute for Applied Geosciences (GGA Institute) performed 2-D resistivity measurements along flight line 35.1 in order to provide resistivity data for a comparison with the HEM results. A Geoserve RESECS multi-electrode system was used, which allows the simultaneous setup of 144 electrodes. The total profile length was 1835m with 5m electrode separation. A Wenner-Alpha array with 5m, 10m, …, 235m (max.) electrode spacing was used to create the pseudo-section.

The DC data were inverted using both 2-D inversion with the RES2DINV code (Loke and Barker, 1996) and the laterally constrained inversion (LCI) technique (Auken and Christiansen, 2004; HGG, 2007b). In the following we will only present the LCI results as they give layered models directly comparable to the models from the other systems.

4. Results

The results of the HEM survey, which covered the area between the estuaries of the Elbe and Weser rivers, provide information about the resistivity distribution in the entire survey area. An apparent resistivity map is shown in Fig. 6. Besides saltwater intrusions into the western and north-eastern part of the survey area and the freshwater outlet into the Wadden Sea in the north-west, a linear N–S striking conductive structure stands out. This structure correlates with the Cuxhaven valley (Kuster and Meyer, 1995) and was identified by lithological logs (e.g. Fig. 2) as clay deposits on top of the valley (Siemon et al., 2004). HEM clearly outlines both lateral extent and depth of the Lauenburg clays, but the conductive clay and silt layers limit the depth of investigation and, as will be shown in the following, HEM often fails to penetrate them.

In the following we will compare airborne and ground-based geophysical results at comparable investigation depths, i.e. HEM with CVES and SkyTEM with TEM, along HEM flight line 35.1 (cf. Fig. 3). Then the results of the frequency- and time-domain airborne EM surveys are discussed.

4.1. Comparison of HEM and CVES

Fig. 7a compares the CVES and HEM results along the profile line shown in Fig. 3. Red colours are associated with relatively resistive material of more than 100Ωm, such as sand and gravel layers. Blue colours indicate conductive clay or saltwater. Both methods detect the conductive layers inside the valley of about 30Ωm and 7Ωm at about 20m and 40m depth, respectively. The lithological log (see Fig. 2) confirms that the upper one consists of silt and Holstein clay and the lower one consists of silt and Lauenburg clay. The clay layers fade out to the west of the valley whereas no significant clay deposits occur in the eastern part of the valley. East of the valley the Holstein clay continues in the CVES results up to 2100m profile distance, whereas HEM looses the Holstein clay at 1700m. Both methods exactly agree in outlining the upper boundaries of the conductors inside the valley, but they obtain different thickness

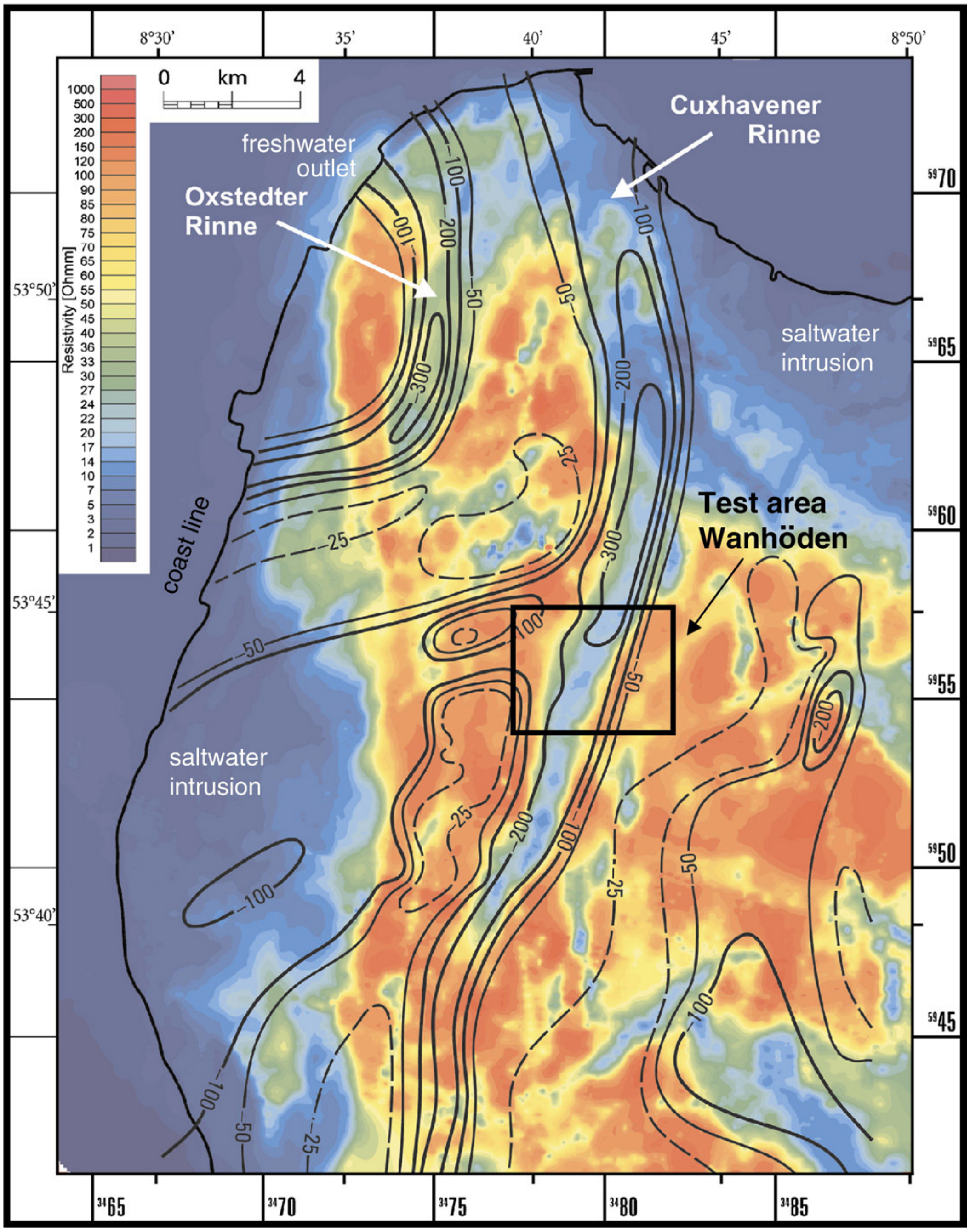

Fig. 6. Apparent resistivity map derived from HEM data at a frequency of 1.8 kHz (after Siemon, 2006b) including contour lines of the Quaternary base in metres (after Kuster and Meyer, 1995). The black box shows the location of the test area Wanhöden.

and resistivity of the upper conductor which is explained by the low resistivity equivalence, in other words the thickness/resistivity ratio is approximately the same for both methods. The base of the lower conductor is revealed by CVES only (and, as seen in the following, by TEM). This is caused by a limited penetration depth of the HEM system to about 60 m here.

The CVES and the HEM results are quite different in the interval from 1750m to 2200m. The reason is that the HEM system had to be elevated to cross the power line resulting in low HEM amplitudes and the data are distorted due to the power line.

4.2. Comparison of SkyTEM and TEM

The TEM and SkyTEM inversion results are very similar (Fig. 7b). The first layer is less resistive above the valley (about 50Ωm) compared to outside the valley (about 100Ωm). The lower resistivity of the layer is caused by the upper conductive layer seen in Fig. 7a which is not resolved but averaged into the first layer in the TEM models. Both methods detect a conductive layer of approximately 7Ωm between 40–60m depth—the Lauenburg clay layer—in the centre of the valley. The layer fades out to the west of the valley with resistivities of

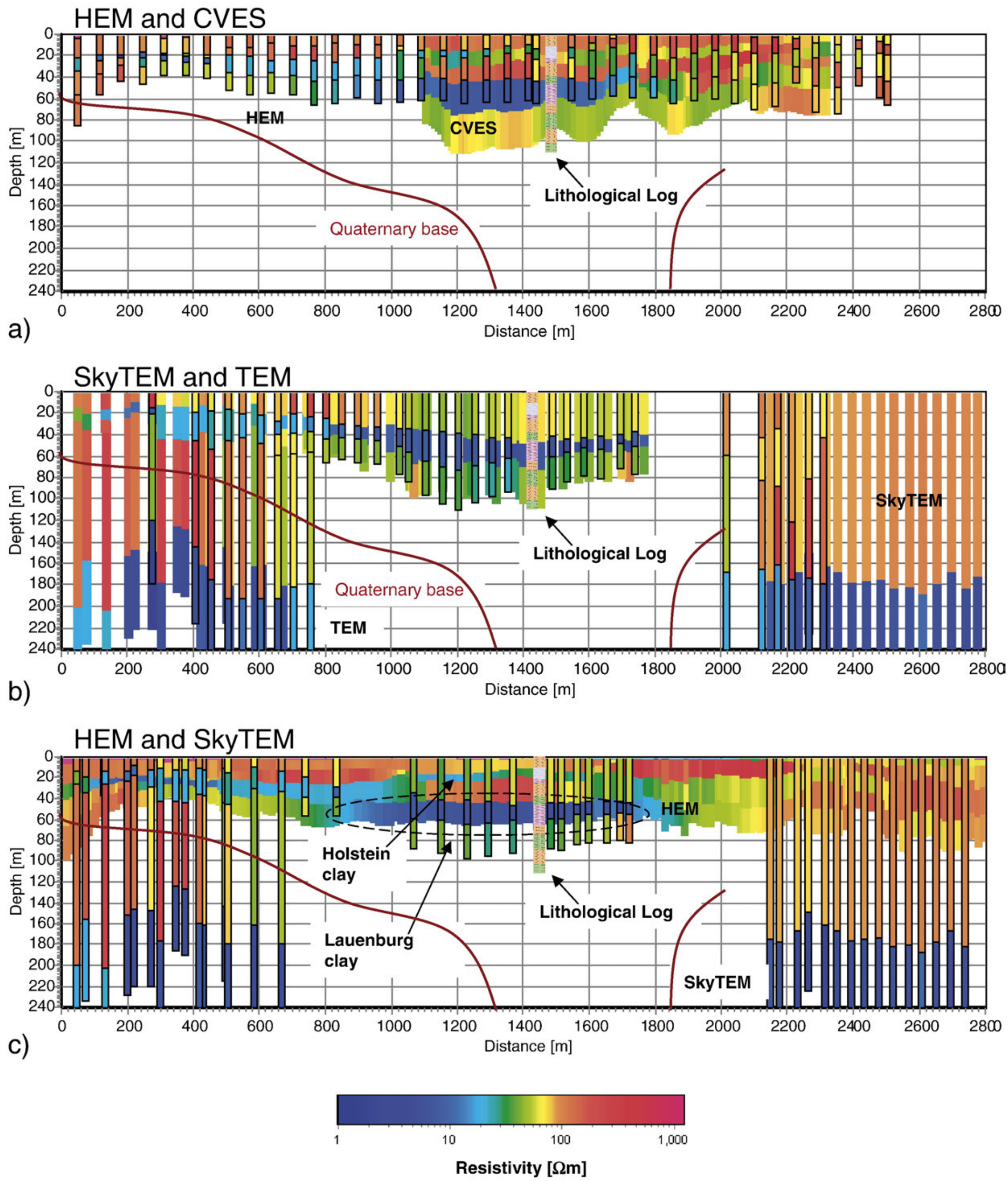

Fig. 7. 1-D inversion results of (a) HEM (framed columns, every 8th station of flight line 35.1) and LCI results of CVES, (b) TEM (framed columns) and SkyTEM (broad columns), (c) SkyTEM (framed columns) and HEM (broad columns). The Quaternary base is derived from reflection seismics (Wiederhold et al., 2005).

about 20Ωm. Outside the buried valley the TEM methods detect another conductive layer at about 180m depth, which is interrupted by the valley. This layer could be identified as a Tertiary clay layer.

Due to the reduced penetration of the EM field caused by highly conductive clay layers the deep conducting clay layer at 115–145m depth inside the valley (as seen in the resistivity log in Fig. 2) is not detectable with the transmitter moments used in this survey.

4.3. Comparison of SkyTEM and HEM

SkyTEM and HEM inversion results (Fig. 7c) exactly match the top of the Lauenburg clay inside the valley. SkyTEM, however, is not able to resolve the conductor at 20m depth. Here, HEM has a better resolution and detects additionally the Holstein clay. On the other hand, SkyTEM reveals the bottom of the Lauenburg clay and a Tertiary clay layer at about 180m depth outside the valley. As discussed earlier the HEM resistivities at

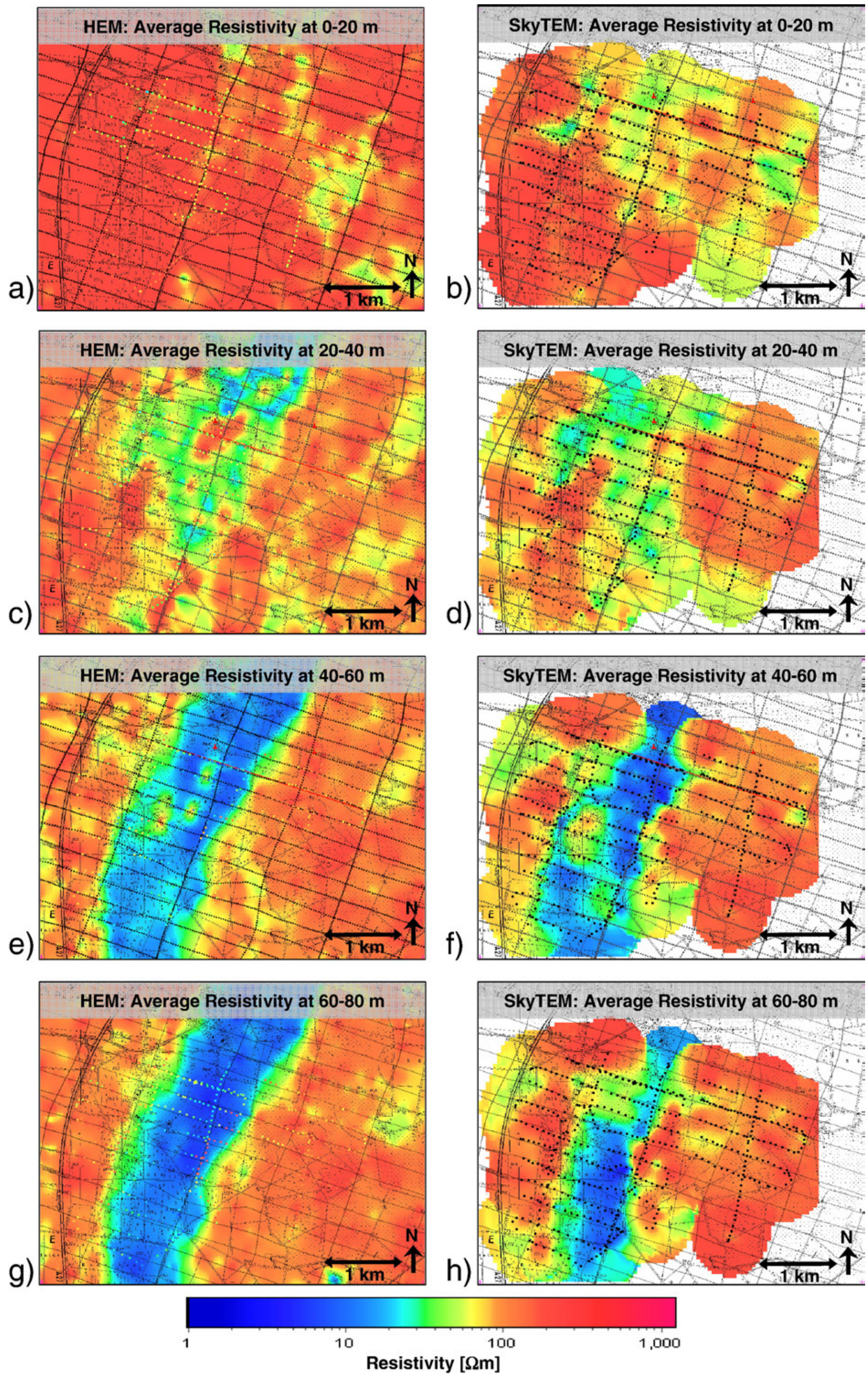

Fig. 8. Resistivity maps for different depth ranges derived from 1-D inversion results. On the left hand side the maps of the HEM models and on the right hand side the maps of the SkyTEM models are shown. On the HEM maps additionally the results of the SkyTEM data are shown as coloured dots to emphasise differences of both methods.

profile distance 1750m–2200m are affected by couplings with the power line. As the coupling is relatively weak in the higher frequencies the data have not been removed. The SkyTEM system would have been equally affected by the power lines, so it was decided from the beginning to avoid survey lines crossing the power line; hence the gap in the SkyTEM data (cf. Fig. 3).

Fig. 8 shows the average resistivity maps at different depth ranges derived from the 1-D inversion models of the HEM and SkyTEM models. HEM and SkyTEM models are shown at the left and right sides, respectively. Furthermore the SkyTEM results are shown on the HEM maps as coloured dots to emphasise the differences of both methods.

The valley appears on the SkyTEM maps at shallower depths (0–20m) than on the HEM maps (Fig. 8a and b). That is caused by the Holstein clay layer, which is not clearly resolved by TEM, but it reduces the resistivity values in the upper part of the

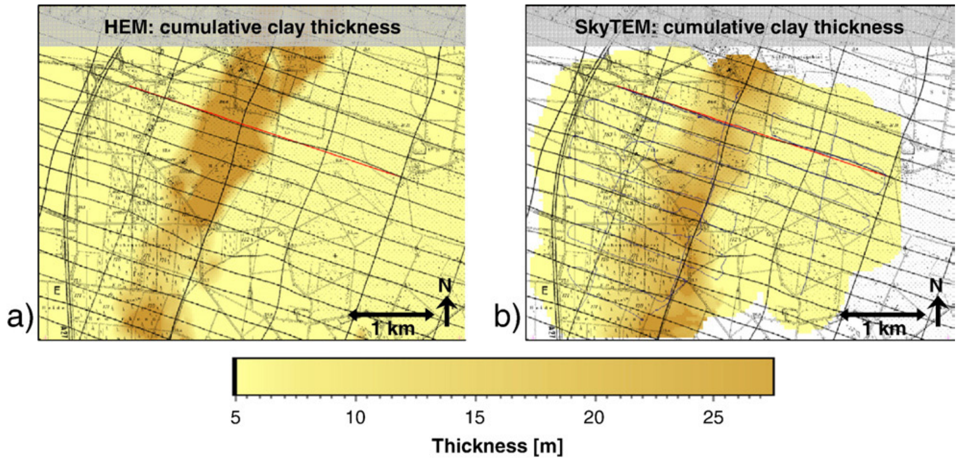

Fig. 9. Thickness of the clay layers with resistivities of 5–30 Ωm in the upper 100 m of the buried valley derived from HEM (a) and SkyTEM (b) data.

valley as seen in Fig. 7b. The resistivity maps are quite similar at 20–40m depth (Fig. 8c and d). The Lauenburg clay is clearly revealed by both methods at 40–60m depth (Fig. 8e and f). As the penetration depth of HEM is lower than that of SkyTEM (and ground-based TEM), HEM is not able to resolve the bottom of the Lauenburg clay layer and therefore the clay layer appears to be too broad at 60–80m (Fig. 8g and h) whereas it actually narrows as seen on the SkyTEM maps. The greenish areas seen in e.g. Fig. 8d in the south-eastern part is due to extrapolation as there is no data coverage.

4.4. Clay thickness maps

Clay layers have a low permeability and often serve as protector for the underlying aquifers against pollution from the surface. Therefore, the clay thickness is an important parameter for the protection of groundwater reservoirs, and can be helpful in delimiting groundwater protection areas (Kirsch and Hinsby, 2006).

The maps of Fig. 9 show the cumulative thickness of clay layers with resistivities of 5–30Ωm in the upper 100m depth. Both methods reveal that the clay inside the valley is thicker than 15m. SkyTEM suggests a smaller clay thickness than HEM, because near-surface clays could not be resolved by SkyTEM. The clay thickness derived from the HEM data must also be handled with care because the bottom of the deeper clay layer is not well resolved.

5. Discussion and conclusion

Resistivity models derived from the two different helicopter-borne electromagnetic methods were compared with each other and with ground-based resistivity models in a part of the Cuxhaven valley. Frequency-domain helicopter-borne EM data were inverted into layered-earth resistivity models applying the Marquardt-Levenberg inversion procedure routinely used at BGR. A similar single-site inversion technique developed at HGG was used to invert ground-based and helicopter-borne TEM data. The CVES data were inverted using the LCI method.

Despite different geophysical data sets acquired and inversion techniques applied, the inversion results of all methods are consistent in locating the top of a strong conductor, the Lauenburg clay, at 40m depth having resistivities between 5Ωm and 10Ωm. The thick Lauenburg clay layer, however, reduces the EM investigation depths within the Cuxhaven valley. Where a thick clay layer exists, HEM often fails to penetrate it completely. The TEM methods are able to determine the base of the Lauenburg clay at 60m depth and to detect additionally a Tertiary clay layer outside the valley at about 180m depth, but they also fail to reveal the clay layer indicated in the lithological log at 115–145m depth inside the valley. Neither the frequency-domain method nor the time-domain methods were able to reach the base of the valley at about 300m depth.

HEM and CVES provide detailed information about the resistivity distribution in the near-surface area and both detect a shallow conductor at 20m depth, the Holstein clay. The existence of the clay layer is confirmed by a drilling and a resistivity log. SkyTEM and TEM, however, are not able to resolve the shallow area of the valley.

The technical potential of the SkyTEM system was not utilised in the Cuxhaven survey. The state of the art in January 2007 is a transmitter moment of 100 000–150 000Am^2, i.e. a 15% increase in investigation depth can be achieved. Also the standard flight speed is 45–75km/h decreasing the costs significantly. Furthermore the system has now by standard measures the first time gate at 10μs and both horizontal and vertical components are measured and inverted. With this system the Holstein clay would have been resolved.

The investigation depth of the HEM method is limited by the lowest frequency, but with lower frequencies the signal to noise ratio decreases and the weight of the system increases. The lowest HEM frequency used is of the order of 100Hz (Won et al., 2003), i.e. an increase in investigation depth of about 45% compared to that of the BGR system is possible but technically challenging.

Recent software developments such as the laterally constrained inversion of SkyTEM and HEM data (Auken et al., 2004; Siemon et al., 2009-this issue) increase the inversion capabilities particularly that of noisy field data and layers with little information in the data. They furthermore enable a simultaneous inversion of both data sets and the inclusion of borehole data. This will combine the high-resolution capabilities provided by HEM with the high investigation depth provided by TEM or SkyTEM.

As SkyTEM is a time-domain method the measurements are slower than frequency-domain HEM measurements. Therefore, HEM is more adequate for fast surveying large areas than SkyTEM. The advantage of SkyTEM clearly is the higher depth of investigation. Ground-based geophysical surveys are often more accurate, but they are definitively slower than airborne surveys and they are limited to areas accessible for measurements on ground. It depends on targets of interest, time, money and manpower available by which a method or combination of methods will be chosen.

Acknowledgements

The CVES, TEM and SkyTEM surveys were part of the BURVAL project, which was co-financed by the Interreg IIIB North Sea Programme of the European Regional Development Fund (ERDF).

The HEM survey was funded by BGR and carried out by the BGR helicopter group, thanks to them all. We also thank our BGR colleagues Gert Sandmann, Robert Bosch and Hanno Schmidt for their assistance in the TEM survey.

The HydroGeophysics Group of the University of Aarhus provided the SkyTEM data. One author (A.S.) thanks especially Esben Auken, Nikolai Foged and Joakim Westergaard for the instruction in SkyTEM processing and interpretation.

We thank Michael Grinat, of the Leibniz Institute for Applied Geosciences (GGA Institute), for providing the CVES data and Franz Binot, of the GGA Institute, for his assistance in the geological interpretation.

Thanks to C.G. Farquharson, an anonymous reviewer and the guest editor N.B. Christensen for their helpful suggestions for improving the paper.

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