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Integrated inversion of TEM and seismic data facilitated by high penetration depths of a segmented receiver setup

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ABSTRACT
Research aimed at improving and developing methods for noise reduction in the transient electromagnetic method (TEM) has resulted in an alternative strategy for performing TEM measurements called the segmented receiver coil setup. The measurement strategy involves the simultaneous use of two receiver coils and the resulting TEM data sets have demonstrated signal-to-noise ratio improvements of up to a factor of 25 when compared to the traditional setup. This significant improvement has opened up new opportunities for deeper penetration and hence an enhanced integrated inversion with seismic data sets. A case study is presented in which the segmented receiver coil setup is employed in the western part of Denmark. Previous geophysical investigations performed in the same area include multi-channel reflection seismic measurements and SkyTEM measurements performed with an early version of the SkyTEM instrument having a limited depth of investigation. Deep structures recognized in the seismic data therefore remained unresolved in the SkyTEM data. Notably the elevation of the highly conductive Palaeogene clay, expected to be encountered at approximately 300 m depth in the area, has not been determined by the use of SkyTEM data. With the increased signal-to-noise ratio of the segmented receiver coil setup it is possible to resolve resistivity changes to greater depth and thus to achieve an enhanced integrated inversion together with the seismic data. The geological setting between depths of 200–300 m, which is effectively only mapped two-dimensionally along seismic lines, can be mapped three-dimensionally using the segmented receiver coil setup. In order to obtain the most reliable geological information, from the TEM data individual soundings are inverted in 1D utilizing the seismic data as *a priori* information thereby optimizing every single inversion model setup to the local sedimentary stratification. Ultimately, the larger penetration depth is the key to an improved geological understanding of the study area, because the integrated interpretation of seismic and TEM data sets yields valuable lithological and structural information that cannot be resolved by either data type alone.

INTRODUCTION

A decade of geophysical mapping, carried out within the Danish National Groundwater Mapping Programme, has shown that a successful approach to delineation of aquifers is the combined use of TEM soundings, reflection seismic data and borehole information (Møller *et al*. 2009). TEM measurements are performed in dense grids over large areas in order to obtain spatial information about the lithological properties of the subsurface. This is supplemented by reflection seismic profiles in areas where detailed structural information is deemed most necessary. Finally, the predictions of the geophysical methods are put to test with drilling at key locations (Jørgensen *et al*. 2003).

The resolvable depth of the multi-channel reflection seismic method is highly dependent on data quality, which in turn mainly depends on the material properties of the near-surface sediments (Jørgensen *et al*. 2003). In Danish sedimentary environments the earliest useful reflections are typically found at depths of 20–40 m, while the latest reflections may originate from more than 1 km depth (Nørmark and Lykke-Andersen 2006). Due to the significant cost of seismic surveys, only a few widespread 2D seismic profiles are normally performed within hydrogeophysical survey areas. However, the scarcity of seismic data is alleviated by dense grids of TEM soundings, which will often allow for interpolation and extrapolation of subterranean structures between and away from the seismic lines (Jørgensen *et al*. 2009). Even heterogeneous structures such as buried valleys can often be imaged accurately through advanced pseudo 2D and 3D (local 1D) inversion strategies such as the LCI and SCI techniques. The LCI and SCI inversion techniques introduce distance dependent model parameter constraints between individual 1D

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inversions thereby significantly reducing ambiguity in model parameter estimation for dense data grids (Auken *et al.* 2008; Viezzoli *et al.* 2008).

A fundamental issue in comparing traditional ground based or airborne TEM soundings with seismic data is the limited depth of investigation achieved by the TEM systems. Traditionally employed ground based TEM systems have maximum depths of investigation in the order of 100–150 m (Danielsen *et al.* 2003). It is well-known that it is possible to increase this depth by scaling up the applied magnetic moment through either an increase in the transmitted current or an increase in the effective transmitter area (McCracken *et al*. 1986). Both options inevitably makes the TEM instrumentation heavier to transport and a larger transmitter side length makes it difficult to find sufficient open spaces in Danish rural areas where it is possible to measure due to proximity to man-made installations. Furthermore, a larger transmitter loop reduces near-surface lateral resolution and very early time data become unusable due to prolonged current turn-off time in the transmitter loop resulting from its increased self-inductance. Attempts have been made at overcoming these issues and a successful ground based instrument, the HiTEM system, was developed achieving a depth of penetration reaching 300 m (Danielsen *et al*. 2003). The HiTEM system avoids increasing the transmitter area by being capable of maintaining a very high current (75A). In order to achieve this high current the weight and bulk of the instrument had to be increased to a degree such that its transportation requires a belt-driven vehicle. Consequently, the field efficiency is relatively low and the probability of damaging farmers' crops during instrument transportation is high, which can make it difficult to get access to private land. Even so, the HiTEM instrument has been used extensively in the Danish Groundwater Mapping Programme when a depth of penetration larger than that of traditional TEM has been imperative.

Following the development of the HiTEM system local research within ground based TEM application has focused on understanding noise and how it may be suppressed. It has been found that instrument noise constitutes a considerable component of the effective noise for a TEM instrument employing a small, wide band induction coil receiver and state-of-the-art low noise electronic components. The relative noise contribution from the instrumentation itself actually dominates the ambient EM noise when performing TEM soundings in typical Danish rural areas. A new TEM measuring strategy, called the segmented receiver coil setup, has therefore been developed. Instead of applying a single high-frequency induction coil for measuring the full earth response two induction coils are used. One coil is optimized for measuring the rapidly decaying, high-frequency, early time earth response while a second shielded and flexible coil is optimized for measuring the slowly decaying, low-frequency, late time response. Using this setup the signal-to-noise ratio (S/N) has increased by a factor of up to 25 for the latest time gates. This markedly increases the maximum depth of investigation for a given magnetic moment, as reducing the effective noise with a given factor is equivalent to increasing the magnetic moment with the same factor when determining the maximum depth of investigation (Spies 1989). Under favourable noise conditions the segmented receiver coil setup makes it possible to obtain a depth of penetration exceeding that of the HiTEM system, while instrument weight, ease of deployment and field accessibility remain comparable to traditional ground based instruments.

In this paper we will present a case study that demonstrates how the significantly enhanced depth of investigation obtainable by a TEM instrument utilizing the segmented receiver coil setup makes it possible to expand the depth interval over which ground based TEM data can complement seismic data in an integrated inversion.

METHODS

The TEM measurements were performed using the WalkTEM system, which has been developed at Aarhus University (Fig. 1c). As a typical setup the WalkTEM system employs a square transmitter loop of 40 m × 40 m. It measures using both a low and a high moment of 1A and 8A, respectively, corresponding to magnetic moments of 1.600 Am^2 and 12.800 Am^2. The transmitted current waveform is an alternating square wave with 10 ms current on-time followed by 10 ms measuring time. The induction coil receiver normally used with the instrument for measuring the transient earth response has an effective area of 5 m^2.

The WalkTEM system has two hardware input channels facilitating the use of the segmented receiver coil setup, which requires a second induction coil receiver of significantly larger effective area measuring simultaneously with the smaller receiver. A 200 m^2 shielded and flexible induction coil receiver has

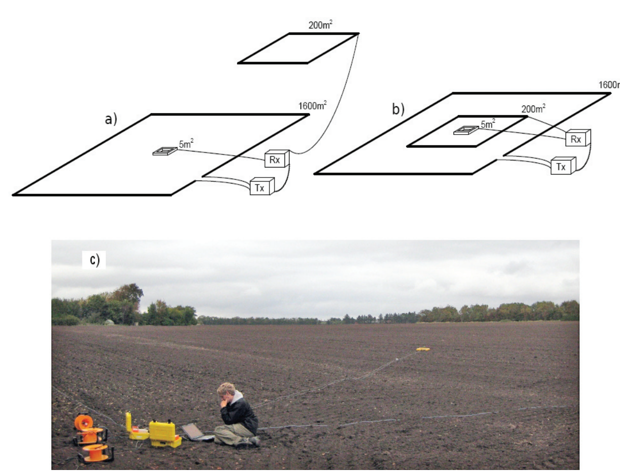

FIGURE 1
Arrangement of receiver coils relative to the transmitter coil. a) The combined central loop and offset loop setup. b) The twin central loop setup, which was the one used for the presented measurements. c) A photograph of the actual WalkTEM field setup used during the measuring campaign.

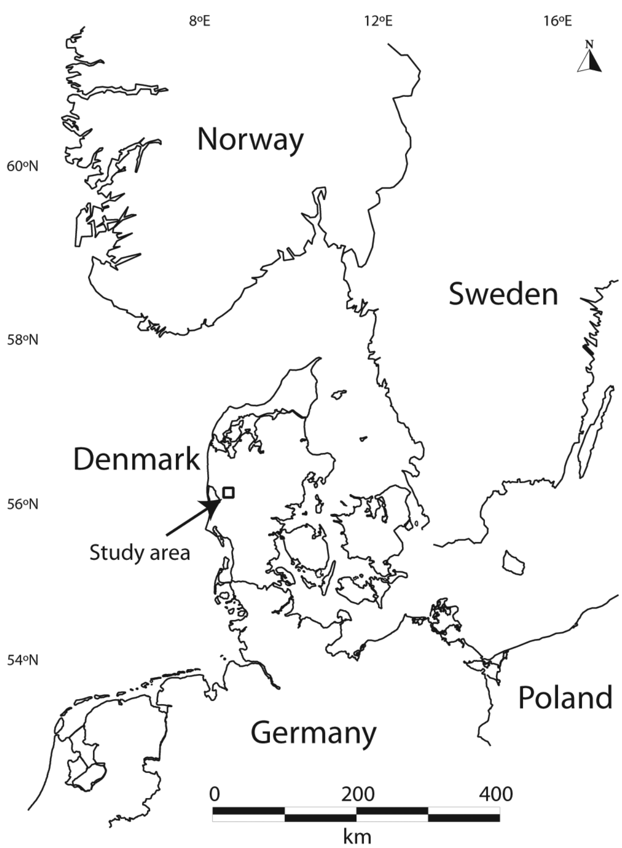

FIGURE 2
Location of the study area (inset box).

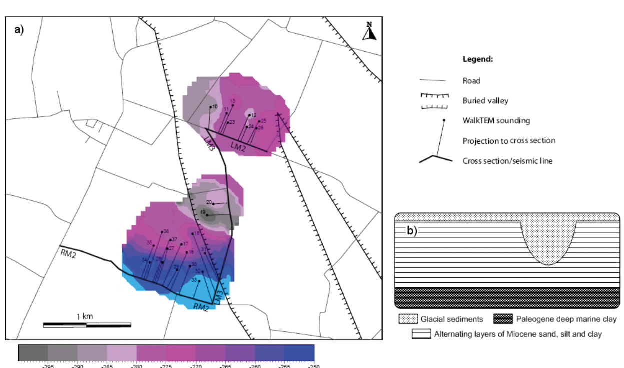

FIGURE 3
a) A map of the study area. The surface of the deep conducting layer is interpolated by using inverse distance and shown on the map using the presented colour scale. b) A schematic cross-section of the local geological setting including a buried tunnel valley.

been developed to be used as a low-frequency, late time receiver. Due to its larger area it produces an induced signal 40 times larger than the induced signal from the 5 m^2 high-frequency receiver for a given ambient magnetic field. In cases where the noise component from ambient EM sources does not completely dominate internal instrument noise sources this increase in induced signal results in an improved S/N. Consequently, the actual improvement in S/N achieved using the segmented receiver coil setup has a non-trivial dependence on the frequency content of the ambient EM noise.

Both receivers are positioned in a central loop arrangement (Fig. 1b). This setup is used because it requires significantly less time to arrange accurately in the field compared to the combined central loop and offset loop arrangement (Fig. 1a). However, the combined central loop and offset loop configuration has the advantage of minimizing the inherent complication of mutual inductance between the receivers.

The multi-channel reflection seismic data used in the case study were acquired by COWI (COWI 2003, 2004). A Minivib II geophysical source vibrator by IVI was employed towing a landstreamer containing 96 geophones with 1.25–2.5 m separation. Data were acquired using the common mid-point (CMP) technique.

STUDY AREA AND DATA ACQUISITION

The study area is situated near the town of Rækker Mølle in western Jutland (Fig. 2). The topography of the area is relatively flat with an altitude of approximately 40 m above sea level. The geological setting can be divided into 3 main sequences (Fig. 3b). A lower sequence consisting of Paleogene deep marine clay with very low electric resistivities (1–10 Ωm; Jørgensen *et al*. 2005). Above this sequence are alternating layers of Miocene sand, silt and clay (Rasmussen 2004). These sediments are characterized by resistivities above 20–30 Ωm. The Miocene succession is then unconformably overlain by glacial sediments. The thickness of these is generally less than 40 m but locally, where buried tunnel valleys crosscut the area, the thickness reaches about 225 m (Jørgensen and Sandersen 2009). The tunnel valley infill consists of coarse meltwater sediments with resistivities above 100–200 Ωm.

A series of geophysical surveys were carried out in the area during the period between 2003–2006. TEM data were obtained (Foged and Westergaard 2006) using the recently introduced airborne SkyTEM method (Sørensen and Auken 2004) and reflection seismic data were acquired as part of two separate surveys (COWI 2003, 2004). A distinct reflector visible in the seismic data at a depth of approximately 300 m was interpreted as the interface between the Miocene sediments and Paleogene deep marine clay. The depth of investigation achievable by the airborne TEM system at the time of data acquisition did not allow for the resolution of such a deep layer boundary. This circumstance combined with the lack of sufficiently deep boreholes in the area makes the lithological interpretation of the seismic data highly uncertain at depths greater than 100–200 m.

The significant depth of investigation potentially obtainable with the segmented receiver coil setup made this method an interesting option for supplementing the existing geophysical data. It was expected that the depth to the top of the highly conductive Paleogene clay would be resolvable due to the significant electrical conductivity contrast. Hence, two separate areas on either side of existing seismic profiles were investigated with TEM soundings during September 2009. The two areas represent distinctly different types of subsurface composition encountered in the area, which is highly dominated by the presence of the buried tunnel valleys. Disregarding soundings influenced by cultural conductors, a total of 24 soundings were acquired. Eight of these were acquired north of seismic lines LM2 and LM3 while sixteen were acquired between lines RM2 and LM3 (Fig. 3a). The 10 northernmost soundings were acquired over the buried valley structure.

Man-made conductive installations are always a major issue when performing TEM soundings in Danish rural areas, as the signal distortion due to these installations can be hard to detect and is highly detrimental for data quality. In the study area power lines, farms, animal fences and buried pipelines were abundant and, as a consequence, the spatial distribution of soundings was determined by these cultural features.

The quality of the TEM data was in general high. An example of the data quality obtained by using the segmented receiver coil setup relative to just the traditional receiver is shown in Fig. 4. For this specific measurement the improvement in S/N for the last time gate was determined to be approximately a factor of 21 calculated on the basis of 2000 unstacked noise measurements. In general, the S/N improvement factor for the measurements performed in the study area is in the impressive range of 14–25 for the latest time gate when using the segmented receiver coil setup. As is also shown in Fig. 4, the TEM measurement performed without the segmented receiver coil setup does not achieve a sufficient depth of investigation to resolve the deep layer boundary near 300 m depth.

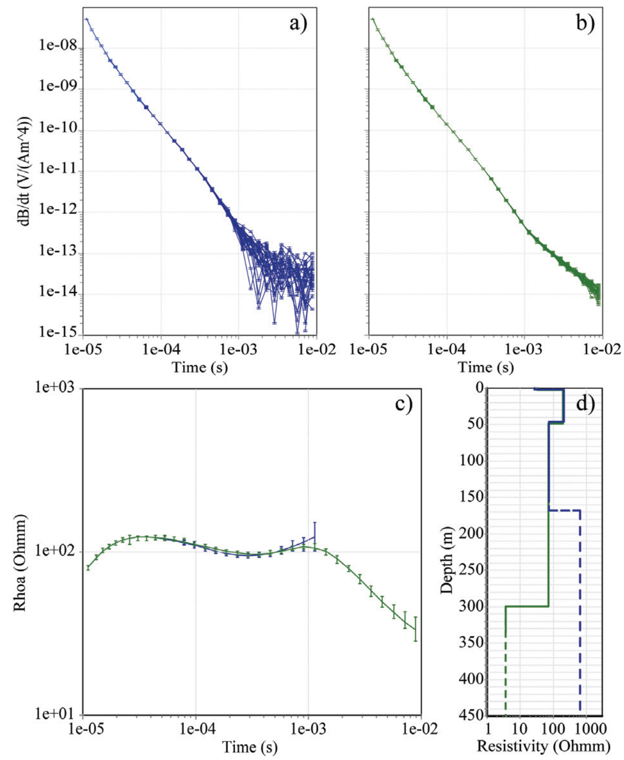

FIGURE 4
Example of the difference in S/N and resulting depth of investigation for a sounding with (green curves) and without (blue curves) the segmented receiver coil setup. a–b) A number of average measurements in ∂B/∂t, each consisting in 1000 single measurements. c) The ρ_a transform of the same measurements averaged together and assigned uncertainty bars. The blue curve is terminated where the uncertainty is estimated as being too large. d) Simple 4 layer 1D inversions of the data in (c). The dashed parts of the line models indicate approximate depths at which no resistivity information is expected to be derivable from the data.

RESULTS

The TEM soundings have been processed and subsequently inverted as 1D models using the in-house software package SiTEM/SEMDI (http://www.geofysiksamarbejdet.au.dk). Initial multi-layer model inversions indicated that seven-layer models would be sufficient to cover the variation in resistivity with depth, so seven-layer inversions were produced without *a priori* information. Using seven-layer unconstrained models, the data were well fitted within the assigned error bars. The error bars (Fig. 4c) represent 5% uniform uncertainty on the measured ∂B/∂t values plus extra uncertainty on every data point based on standard deviation estimates of the actual measured data.

All resulting models exhibit a deep conductive layer, which is situated at a relatively constant elevation throughout the area (Fig. 5). However, the southernmost six models indicate that this deep layer is somewhat elevated (about 25 m) in this part of the area (Fig. 3a). Furthermore, the buried tunnel valley is clearly discernible in the models, as all soundings situated over the valley exhibit high-resistive layers from the surface down to an elevation of around –200 m (Fig. 5). In the surrounding Miocene sediments the models show alternating layering of high-resistive and medium-resistive sediments.

According to tentative interpretations of the seismic data mainly based on reflection characteristics (COWI 2003, 2004), the top of the Paleogene clay is thought to be represented by the strong reflector at about 275 ms TWT below sea level, which is marked with a red dotted line in Fig. 5. If the seismic sections, as shown in Fig. 5, are vertically adjusted, so that the strong reflector correlates to the conducting layer as found in the TEM soundings the resulting seismic velocity amounts to about 2000 m/s. This seems to be a fairly high velocity, since seismic velocities of Miocene sediments are reported to lie within the range of 1750–1800 m/s (Lykke-Andersen and Tychsen 1977; Nielsen and Japsen 1991). It is therefore a possibility that the Paleogene surface should be tied to a much weaker reflector some 30–40 ms below this (marked in Fig. 5 with a blue line).

A basic statistical analysis of the elevation of the deepest layer boundary resolved in the seven-layer unconstrained inversions gives a mean elevation of –274 m and a standard deviation of 16 m, which is a larger variation than expected considering that the seismic profiles (Fig. 5) show that the layering is predominantly horizontal. This fact combined with the somewhat higher resistivities observed in the deepest layer in the five southernmost soundings (sounding 34, 29, 30, 33 and 32) indicates that the deepest layer boundary in these soundings may be located at some intermediate depth of a two-layer downward transition to lower resistivities. This interpretation is supported by most soundings located over the buried valley, as these generally show a two-layer downward transition to lower resistivities starting at an elevation of around –200 m. Several soundings outside the valley show a similar trend, however, the soundings located over the valley are expected to be able to better resolve the resistivity transition compared to the soundings outside the valley. This is because of the higher resistivities of the valley infill, compared to the surrounding Miocene sediments, giving rise to a more pronounced resistivity contrast as well as making the current diffusion happen more rapidly resulting in more of the time gates containing information about the deeper resistivity structure. Removing the aforementioned southernmost soundings from the statistical analysis gives a mean of the elevation at a slightly deeper –281 m and a standard deviation of only 10 m.

Another round of inversions were performed in order to extract further information from the TEM soundings with focus on obtaining better indications of the lithology of the seismic strata. Model inversions were divided into two groups discriminating by whether soundings were located over or beside the buried valley. Tight *a priori* information was imparted on the models, so that layer boundary depths were fixed completely to match average elevations of prominent seismic reflectors using the constant velocity model of 2000 m/s (Fig. 6). These reflectors may represent significant lithological boundaries within the setting, which seems likely as most of the reflectors to some degree match layers recognized in the seven-layer models inverted without constraints. Inversions using seven-layer models were produced for the soundings over the buried valley with the deepest two layers having their upper boundary fixed at elevations of –281 m and –200 m respectively. Inversions using nine-layer models were produced for the soundings beside the buried valley with the deepest five layers having their upper boundary fixed at elevations of –281 m, –200 m, –150 m, –110 m and –70 m, respectively.

As expected, the data fit was in general slightly poorer than in the seven-layer unconstrained case, however, data were still fitted within the assigned error bars. The layer between –281 m and –200 m shows fairly low resistivities with a gradual transition from low resistivities towards the south and east to higher resistivities towards the west and north (Fig. 7). The two layers above show high resistivities while the layer between –110 m and –70 m also shows relatively low resistivities with a transition from low to high resistivity towards the north-west (outside the buried valley). The lithological interpretation of the inversion results is difficult because only a few deep boreholes are present in the vicinity of the study area. Two boreholes (GEUS Jupiter archive no. 93.539 and 93.701) situated about 1 km towards the north-west reach depths of between –120 m and –110 m and provide some useful information for the interpretation. A series of silty and sandy Miocene clay layers are found between around –95 m and –50 m, with sandy layers below and on top. The layer

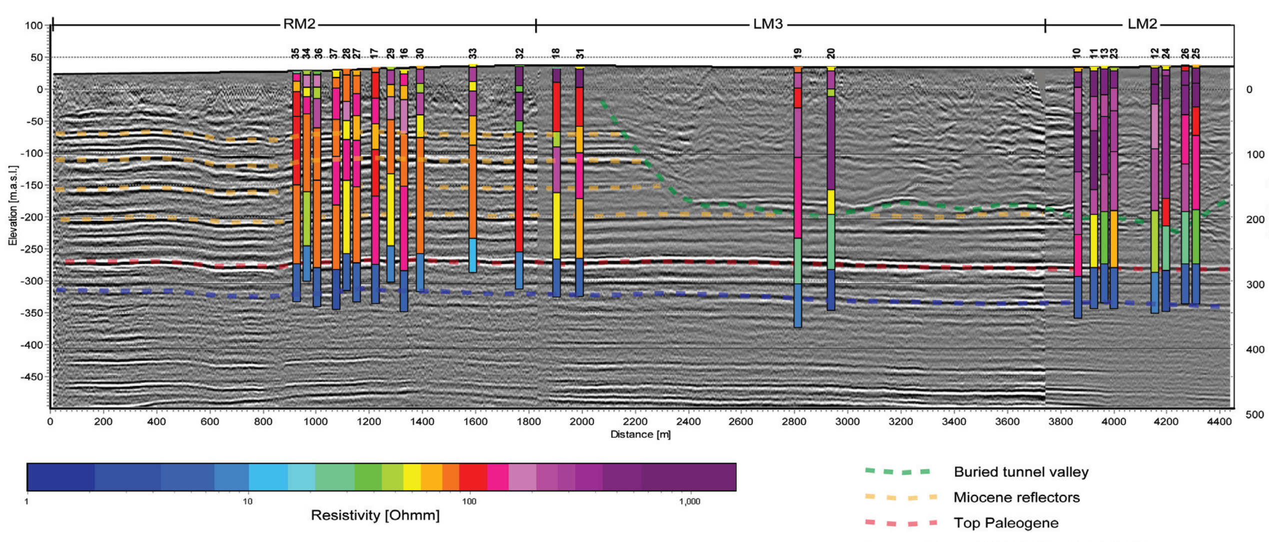

FIGURE 5
Cross-section along segments of three different seismic lines through the case study area (see Fig. 3 for location). Unconstrained seven-layer TEM models are projected onto the cross-section. Projection is done perpendicular to the nearest cross-section. Soundings 18, 31 and 32, however, are projected parallel to the outline of the buried valley. The proposed surface of the Palaeogene is marked by a red dashed line, the bottom of the buried valley with a green dashed line and four strong Miocene reflectors by orange dashed lines. The dashed blue line marks another possible interpretation of the Palaeogene surface.

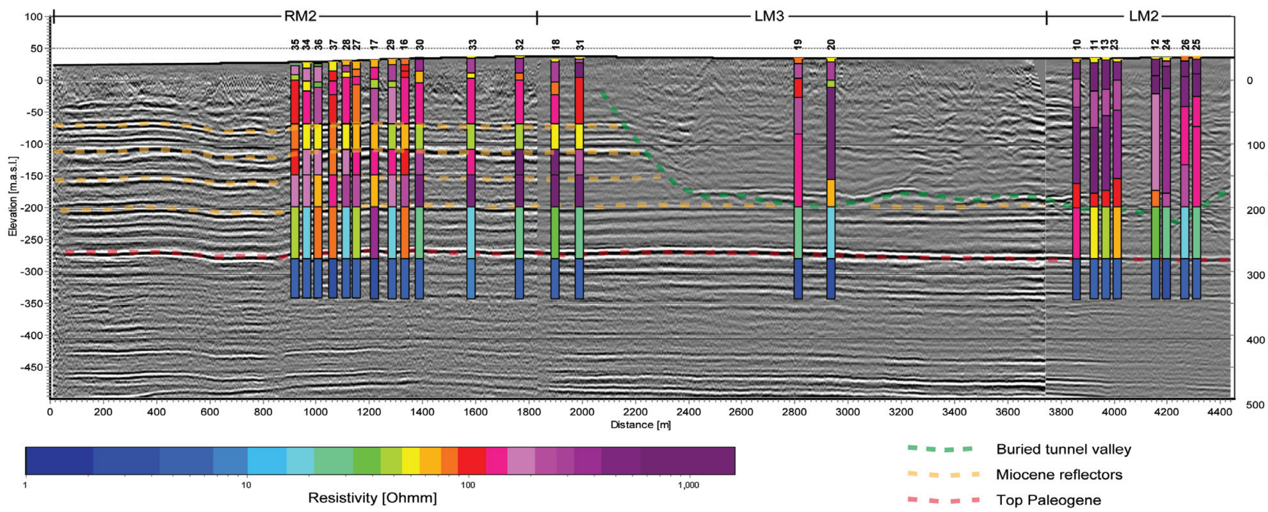

FIGURE 6
The same cross-section as shown in Fig. 5. TEM models with layer boundaries constrained approximately to the highlighted horizons in red and orange. Projection is done perpendicular to the nearest cross-section. Soundings 18, 31 and 32, however, are projected parallel to the outline of the buried valley. The assumed surface of the Palaeogene is marked by a red dashed line, the bottom of the buried valley with a green dashed line and four strong Miocene reflectors by orange dashed lines.

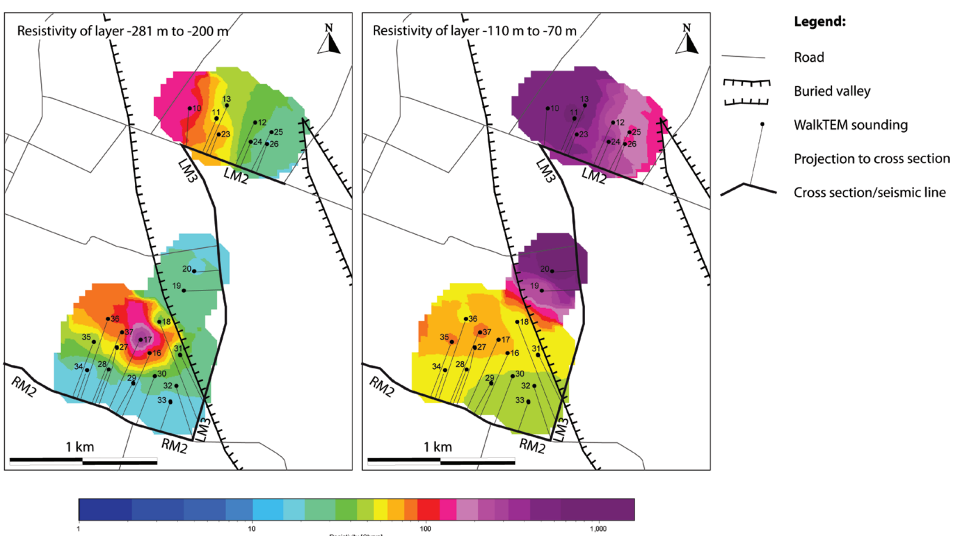

FIGURE 7
Resistivity variations of the two layers with relatively low resistivities: –281 m to –200 m and –110 m to –70 m in the constrained inversion models (Fig. 6). Note that the upper layer is only constrained outside the buried valley. Lateral transitions from low to high resistivities towards the north-west are seen for both layers.

with relatively low resistivities between –110 m and –70 m in the fixed TEM inversion may be linked to these clay layers, despite a minor misfit in the elevation. The gradual lateral shift in resistivity could be a signature of variation in sedimentary facies from being clayey in the southeastern part of the survey area to more sandy/silty in the northwestern part. The sequence below, composed of the two high-resistive model layers is interpreted as being mainly sand and/or silt layers and the model layer between –281 m and –200 m would again be more clayey. The gradual lateral resistivity transition may also be caused by facies variations but at this deep level another likely explanation could be variations in pore water salinity due to occurrences of residual saltwater.

CONCLUSION AND PERSPECTIVES

The depth of the conducting Paleogene clay was determined accurately and consistently by use of the TEM technique without applying lateral constraints or *a priori* information. The reason for this is the inherent sensitivity of the transient electromagnetic method to conducting bodies combined with the superior S/N of the newly developed segmented receiver coil setup. Integrating this depth information into the existing seismic interpretation made it possible to determine a seismic velocity for depth conversion of the seismic section. The depth converted seismic section used in combination with the unconstrained TEM models gave indications of the presence of a number of lithological layers with varying resistivity characteristics separated by prominent reflectors. These reflectors could be followed further along adjacent seismic profiles, displaying an overall horizontal appearance. This gave confidence to the approach of simply defining the position of several of the deep layers in the subsequent inversion. Removing these free parameters in the inversion problem resulted in more reliable information on the resistivity of the individual layers, making it possible to infer lithological properties with greater confidence. Finally, we appear to have resolved a spatial development in the resistivity properties of two of the layers, which shows how improved three-dimensional information can be obtained through integrated inversion of TEM and seismic data.

Experiences in the field with the WalkTEM instrument show that applying the segmented receiver coil setup has many merits. The segmented receiver coil setup is able to record both very early parts as well as very late parts of the transient signal, resulting in useful resistivity information being available from the surface to depths often exceeding 300 m. Furthermore, the entire instrument can be transported by a couple of fieldworkers on foot, which allows for a rapid measuring routine and easy access to otherwise impractical measuring locations. The main disadvantage comes from the fact that the depth of investigation obtainable is highly dependent on the properties of the ambient EM noise, such that the depth of investigation might at times not significantly exceed that of the basic WalkTEM setup. Even so, the segmented receiver coil setup performed very well at the study site resulting in a depth of investigation generally exceeding that of the HiTEM system.

Future large-scale application of the segmented receiver coil setup within the Danish National Groundwater Mapping Programme seems unlikely. Airborne methods have largely supplanted ground based methods with their much higher production rates and lower costs for large-scale surveys. The SkyTEM system, used extensively in Denmark, presently has a maximum depth of investigation reaching 250–300 m, which means that there is only little extra information gained by using measurements with the segmented receiver coil setup as a supplement. The presented case study, however, illustrates how small-scale application of the segmented receiver coil setup can still be highly useful. There are undoubtedly many similar situations, where significant uncertainty exists in the lithological interpretation at large depth in seismic data. While airborne measurements or drillings will often be considered as too expensive options, a small-scale measuring campaign using the ground based segmented receiver coil setup, followed by an integrated inversion of the TEM and seismic data, will be a solution.

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