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Imaging buried Quaternary valleys using the transient electromagnetic method

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Abstract

Buried Quaternary valleys in Denmark are complex structures filled with various deposits consisting primarily of glacio-lacustrine clay, till and meltwater sand, and gravel. The valleys are important geophysical targets, because they often contain significant volumes of groundwater used for public water supply. About 700 km of buried valley structures have been imaged in the western part of Denmark by the transient electromagnetic (TEM) method. The ability to map the valleys depends primarily on valley geometry, infill architecture and the resistivity of the fill sediments as well as the substratum. One-dimensional (1-D) inversion models of the TEM soundings have been used to construct contour maps of 20 m average resistivities and depth to a good conductor, which provide images for geological interpretation. Images of buried valley morphology, fill properties, infill architecture, such as cut-and-fill structures, valley distribution and valley generations, are characterized for case studies from Hornsyld, Holstebro and the Vonsild/Agtrup areas of Denmark.

Keywords: Transient electromagnetic; TEM; Hydrogeophysics; Imaging; Buried valleys; Quaternary

1. Introduction

Onshore and offshore buried, subglacial valleys are primarily known in areas formerly covered by the Eurasian and the Laurentide ice sheets. 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 latter can be the case if a valley is incised through an impermeable layer between two aquifers. Hence, it becomes important to map the distribution and infill properties of the valleys. The transient electromagnetic method (TEM) has been very effective for a variety of hydrogeophysical investigations (Fitterman and Stewart, 1986; Mills et al., 1988; Hoekstra and Blohm, 1990; Sandberg and Hall, 1990; Meju et al., 1999), and has been increasingly successful in mapping buried valley structures in Denmark (Auken et al., 1994; Sørensen, 1996, 1997; Poulsen and Christensen, 1999; Sørensen et al., 2004).

The existence of buried valleys in Denmark has been known for decades, but until recently it was

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difficult to map their orientations, shapes and lateral extents. Lithological well data are often too sparse for successful correlation. A great advantage of the TEM method is the possibility to collect dense networks of data enabling correlation of well data and three-dimensional (3-D) imaging of the subsurface. Over the last 10 years, large parts of the Danish onshore area have been surveyed with the TEM method. More than 50 000 TEM soundings have been performed with a density of about 16 soundings per km^2, corresponding to a coverage of about 5–10% of the total area of the country.

One-dimensional (1-D) inverse modelling (Menke, 1989; Christensen and Auken, 1992) is found to be an effective means for processing the TEM soundings in the Danish geological environment (Christensen and Sørensen, 1998; Poulsen and Christensen, 1999). The inversion parameters of layer thickness and resistivity are used to construct contour maps of the average resistivity over 20 m intervals at different depths, as well as the depth to a good conductor. 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 resistivities of the sediments in and around the valley structure and on the model presentation. The techniques for mapping and recognizing buried valleys are based on experiences derived from the examinations of extensive TEM data sets supported by drilling data and seismic surveys. About 700 km of buried valleys have been mapped by the use of the TEM method (Sandersen and Jørgensen, 2002, 2003). Sometimes the valleys are difficult to trace because of a low resistivity contrast between the valley fill and the substratum, but they can often be detected indirectly because of resistivity contrasts within the infill sediments. Previous work concentrated on mapping valleys incised into highly conductive Tertiary clay, but examples from areas in Denmark (Fig. 1) illustrate that it is possible to accurately delineate more complicated buried valley structures.

2. Geological overview

Buried valleys in Denmark are primarily of glacial origin. Morphological characteristics can be compared to those of tunnel valleys, because they seem to be overdeepened with irregular floors. Most authors believe that tunnel valleys are the result of erosion by

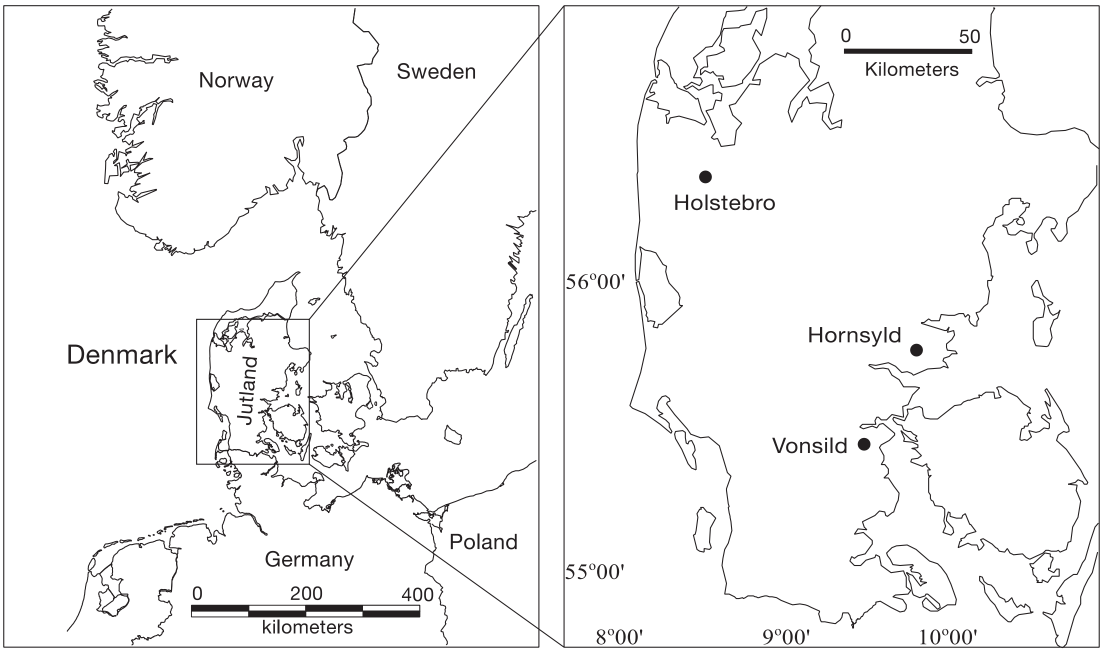


Fig. 1. Maps showing the location of the shown examples: Holstebro, Hornsyld and Agtrup–Vonsild.

subglacial meltwater, either by sudden outbursts of large amounts of subglacially stored water, or by relatively steady-state processes perhaps involving sediment deformation (Ó Cofaigh, 1996). Recently, Huuse and Lykke-Andersen (2000) showed the existence of deeply buried and overdeepened valleys in the eastern part of the North Sea, adjacent to Denmark, that have been ascribed to subglacial meltwater erosion or a combination of glacial and meltwater erosion, because of their overdeepened shapes and abrupt terminations.

Onshore, in Denmark, buried valleys are found to be between 0.5 and 4 km wide and up to 350 m deep (Sandersen and Jørgensen, 2002, 2003). Seismic surveys across these valleys show that they consist mainly of multiple erosion structures incised into each other (Jørgensen et al., 2003). Although the valleys are filled with glacial and interglacial deposits, it is difficult to ascertain the general distribution of the different types of sediments within a valley or within a single incision within a valley. Most often tills dominate the upper parts of the buried valleys but they are also commonly found in the lower parts (Jørgensen et al., 2003; Sandersen and Jørgensen, 2003). Glacio-lacustrine silts and clays are commonly found as thick and widespread units filling parts or whole valley incisions. Meltwater sand and gravel often occupy the lower parts of the valley sequences (Sandersen and Jørgensen, 2003).

The Quaternary subcrop in Denmark consists of limestone and chalk in the north and east, Paleogene clays in a zone from northwest to southeast, and Neogene sands, silts and clays to the west and southwest. Outside the valleys the sequence of Quaternary sediments is in general up to 100 m thick. In most locations the surface of the pre-Quaternary sediments lies between 50 m below and 50 m above sea level, but it does occasionally include large deviations (Binzer and Stockmarr, 1994). Hence, buried valleys are incised into sediments ranging from consolidated limestone over Paleogene clays and Neogene sands to glacial and interglacial deposits.

Several times during at least four glaciations, Denmark was covered by glaciers from predominantly northerly and easterly directions (Kronborg et al., 1990; Larsen and Kronborg, 1994; Houmark-Nielsen, 1987). It is supposed that the formation of subglacial valleys occurred during these glaciations. In a number of buried valleys, Holsteinian interglacial deposits and Elsterian glacial deposits are found among the infill sediments, which means that at least some of the valleys were probably formed during the extensive Elsterian glaciation (Sandersen and Jørgensen, 2002, 2003).

Table 1
Estimated resistivity values for sediments related to buried valleys in Denmark

Sediments	Resistivity (Ω m)
Meltwater sand and gravel	>60
Clay till	25–50
Glacio-lacustrine clay	10–40
Neogene mica silt/sand: Miocene	>40
Neogene mica clay: Miocene	10–40
Paleogene clay: Eocene–Oligocene	5–12
Paleogene clay: Paleocene–Eocene	1–7
Danian limestone	>80

Typical formation resistivities for various freshwater-saturated sediments related to the buried valleys are listed in Table 1. These resistivity values are based on comparisons between TEM data and lithological well logs. It is important to notice that, according to Archie's law (Archie, 1942), the resistivity of the sediments is inversely proportional to the ion content of the pore water. Hence, the resistivity of coarse sediments varies from region to region resulting in a large variation in resistivity despite small variations in clay content.

3. The TEM method

The TEM method is an electromagnetic induction technique, with which the response of the earth to an electromagnetic impulse is measured in the time domain. A thorough discussion of the TEM method and the interpretation of TEM data can be found in Nabighian and Macnae (1991). Therefore we limit our discussion to issues that are relevant to investigations of buried valleys.

Measurements are commonly carried out using a $40 \times 40\ m^2$ transmitter loop carrying a steady current of 3 A. The response is measured while the transmitted signal is off from times of roughly 10 µs to 5 ms. We refer to this configuration as "conventional" TEM. The penetration depth for conventional TEM is usually not greater than about 130 m dependent on the average resistivity of the subsurface and on the level of the natural background noise (Spies, 1989). Under ideal circumstances the penetration depth can reach up to about 150 m.

Recently, the high moment TEM system (HiTEM), with a larger penetration depth than conventional systems, was developed (Danielsen et al., 2002; Sørensen et al., 2004). A HiTEM sounding can be carried out in about the same time as a conventional sounding, but the magnetic moment is almost 20 times larger resulting in a penetration depth of about 250 m under ideal conditions down to 300 m. The large penetration depth of the HiTEM system makes the system ideal for interpretation with seismic data (Jørgensen et al., 2003).

The resistivity of high-resistivity layers cannot be determined with the TEM method, because of resistivity equivalence (Fitterman et al., 1988). Furthermore, the method cannot be used to accurately estimate the resistivity of layers with resistivity values exceeding 80–120 Ω m that are surrounded by layers with a lower resistivity. The TEM method has, as all electromagnetic diffusion methods, a decreasing resolution capability with depth. Hence only layers that are thick relative to their depth can be detected. Thin layers will combine into an effective single layer with an average resistivity. Near-surface layers will also be averaged into one layer, because the recording does not start until about 10 μs. In environments with resistivities above 30–40 Ω m the upper 20 m is averaged into one layer.

One-dimensional modelling of TEM data in the influence of 2- or 3-D structures has been studied by several authors (Newman et al., 1986; Goldman et al., 1994; Danielsen et al., 2003). Most important for the buried valley problem are effects that prevail close to the valley walls. Slopes less than 30–40° are correctly imaged when the valley floor has a relatively low resistivity compared to overlying layers of relatively high resistivities (Danielsen et al., 2003). For the opposite model—increasing resistivity with depth—the 3-D effect in the 1-D model is more pronounced, and only gentle slopes, less than 20°, can be accurately imaged.

4. Resolution of buried valley features

To illustrate the features of a buried valley structure that can be resolved with the TEM method, simplified models for eight different geological environments, are shown in Fig. 2. The analysis is based upon extensive geological modelling and field experience. Data are assumed errorless. The bold lines denote detectable boundaries: solid lines represent the top of a good conductor, while dashed lines represent the bottom of a good conductor or top of a high-resistivity layer, which is more difficult to resolve. A TEM model is able to estimate the depth to the boundaries marked with bold lines and the mean resistivity of the layers between or below these boundaries.

Fig. 2a shows a simple model of a valley incised into a good conductor of Paleogene clay. The Paleogene clay resistivity is about 5 Ω m. The valley is filled with meltwater gravel of 100 Ω m and covered by clay till of 40 Ω m. TEM soundings can be used to accurately map the surface of the Paleogene clay with respect to depth and resistivity. As noted, however, problems may arise due to great inclination of valley walls, which sometimes are indicated to be more than 30° in both seismic and borehole data. Using conventional TEM the floor of the valley can be mapped if it is less than about 130 m deep. The corresponding depth limitation for the HiTEM method is about 250 m. The boundary between the clay till and the gravel can also be detected if it is more than about 20 m below the surface.

The valley depicted in Fig. 2b is carved into Miocene sand with medium to high resistivity of 80 Ω m, filled entirely with glacio-lacustrine clay (20 Ω m) and, as in Fig. 2a, covered with clay till. The top of the glacio-lacustrine clay is easily detected as a low-resistivity layer under the more resistive till. Once currents have penetrated the clay till, they diffuse relatively slowly through the glacio-lacustrine clay because of the low resistivity, with the result that only the upper part of the valley walls can be mapped.

The valley section of Fig. 2c is covered by meltwater sand of 80 Ω m, filled with meltwater gravel of 100 Ω m, and cut into Miocene sand lying upon Paleogene clay. In this case, only the surface and resistivity of the Paleogene clay can be mapped. The resistivity contrast between the meltwater sand and meltwater gravel and between the Miocene sand and meltwater gravel is too low for the boundaries to be detected, and the upper part of the valley is invisible in the resulting images of the TEM survey.

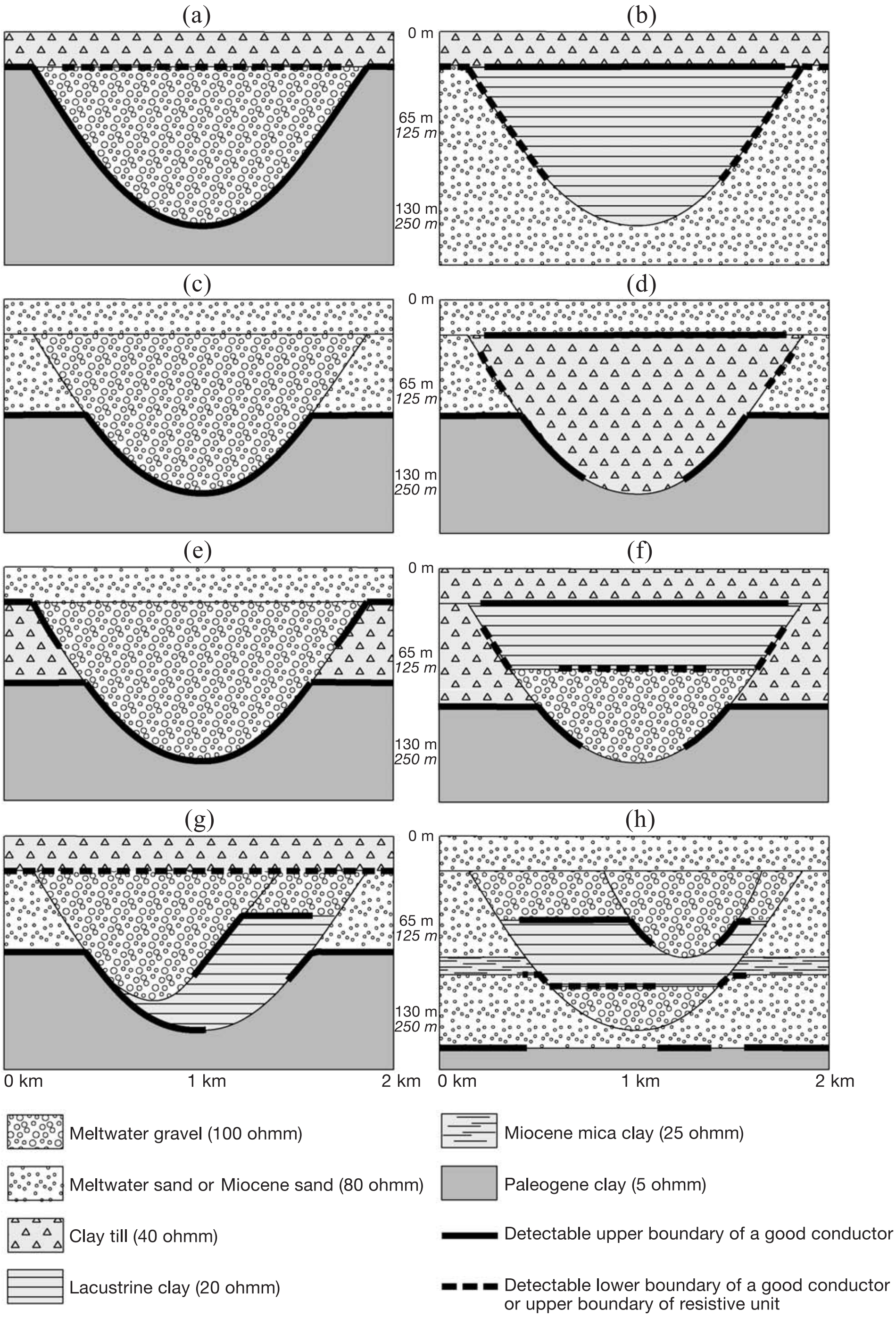


Fig. 2. Simplified cross-sections of buried valleys typical in Denmark. Solid, bold lines represent the top of a detectable good conductor, while the dashed, bold lines represent the bottom of a detectable good conductor or top of a detectable high-resistivity layer. Approximate depth scale is for conventional TEM in normal print and for HiTEM in italic.

In the next cross-section of Fig. 2d, the valley is filled with clay till instead of meltwater gravel. Except for the lateral parts of the valley, where the till fill is thin and its resolution not viable, major portions of the valley can be mapped by imaging of the till fill, which is a good conductor. Because the clay till is underlain by the Paleogene clay, both of which are good conductors, the upper part of the valley is seen as a ridge in the substratum in the TEM imaging. The lower part is seen in the image of the Paleogene clay. The penetration depth through the clay till is somewhat lower than through deposits of higher resistivity. The boundary between the clay till and Miocene sand can be detected in the parts of the valley walls where the layers are thick enough to be resolved.

The valley illustrated in Fig. 2e is incised into a substratum of clay till covering Paleogene clay, filled with meltwater gravel and covered with meltwater sand. In this case, it is possible to delineate the lowest part of the valley in the Paleogene clay and the upper part in clay till, but not the boundary between the valley fill and the sandy cover. In Fig. 2f, the valley is enclosed by clay till on the walls and top and by Paleogene clay on the bottom. The valley fill consists of glacio-lacustrine clay in the uppermost part and meltwater gravel in the bottom. As seen, most of the structure can be mapped. The glacio-lacustrine clay is detected as a good conductor. As in Fig. 2a, the meltwater gravel can also be detected in the central parts of the valley. Near the valley walls, the layer thickness is too thin to be resolved. The valley walls are delineated where the glacio-lacustrine clay layer is sufficiently thick. The lower parts of the valley are imaged in the Paleogene clay, but the penetration depth is low due to the presence of the low-resistivity layers, and the floor of the valley cannot be resolved.

A more complex example of a buried valley is shown in Fig. 2g. A younger valley filled with meltwater gravel is cut into an older one, which is filled with glacio-lacustrine clay in the lowest sections and meltwater gravel in the uppermost sections. The old valley is incised into Paleogene clay and Miocene sand, and the entire structure is covered by clay till. As in Fig. 2a, the boundary between the till cover and sandy sequences can be detected if not too close to the surface. The Paleogene clay can be located when the glacio-lacustrine clay is thin or absent and only then can the lower parts of the old valley be imaged. However, the younger valley can be identified because the glacio-lacustrine clay, which is a good conductor, defines the floor of the younger valley. As in the example of Fig. 2c the upper part and the lateral extent of the valley cannot be delineated, but the presence of glacio-lacustrine clay indicates its existence higher in the section.

In Fig. 2h, the Paleogene clay is situated below the valley, but not cut by it. Instead, the valley cuts into layers of Miocene sand of 80 Ω m and Miocene clay of 25 Ω m. The valley is filled with meltwater gravel at the bottom and top, and interbedded with a relatively thick layer of glacio-lacustrine clay. A younger valley is cut into these fill interbeds. The Paleogene clay surface is detectable in the TEM soundings, except where the thick glacio-lacustrine clay deposits mask the response. The layer of Miocene clay is too thin for detection. The valley can be recognized through the presence of the glacio-lacustrine clay, which is imaged as a ridge or as a longitudinal low-resistive body. The high-resistivity sediments delineated below the clay point toward the presence of a valley rather than a ridge, and in addition to this the younger valley shows valley morphology in the surface of the clay.

5. Typical buried valley images in TEM surveys

Buried valleys are particularly easy to image with the TEM method in regions where the substratum of Paleogene clay is located within the uppermost 100 m. The valleys are usually deep enough to incise the clay significantly so that the valley walls and the floor can be detected (e.g. Fig. 2a). Furthermore, the resistivity contrasts between the Paleogene clays and the Quaternary sediments are nearly always significant. Such valleys are typical for large parts of eastern Jutland. In the western part, many buried valleys are cut into sandy Tertiary sediments. When a buried valley cuts into sandy sediments, TEM mapping the valley structure relies on the characteristics of the infill sediments. Many buried valleys of this type are invisible to the TEM method, because they are filled with sand and gravel deposits, which have similar resistivity values to the surrounding sediments. Occasionally, some of the fill material consists of thick clay rich deposits such as clay till and glacio-lacustrine clay that can be detected (e.g. Fig. 2b and h). In contrast to the valleys that are cut into low resistive Paleogene clay, the lateral extent of buried valleys in sandy environments is in many cases not mapped correctly. This problem arises because only the low-resistive parts of the valleys in sandy environments can be imaged, and because many valleys contain cut-and-fill structures filled with varying types of sediments (Jørgensen et al., 2003; Sandersen and Jørgensen, 2002, 2003). Sand-filled internal incisions situated close to the valley margin make the outer valley margin difficult to delineate.

Images of multiple erosion and deposition events are in interval resistivity maps seen as alternating longitudinal structures. These structures indicate sequences that fill single incisions at different depths (e.g. Fig. 2g and h). Sometimes, older remnants of infill sediments can be seen on both sides of a younger incision (Fig. 2h). In other cases they can only be seen along one of the valley margins (Fig. 2g).

At many localities more than one generation of buried valleys are observed. Different generations of valleys can be recognized by the presence of preferred directions of valleys in large areas (Sandersen and Jørgensen, 2002, 2003). Crosscutting relationships of the valleys are basic observations in the determination of relative ages of the incisions. An example is the situation where a valley filled with low-resistivity deposits crosses an older valley filled with high-resistivity deposits; the age relationship is revealed by the presence of the low-resistivity deposits. Another example is when an undetected valley filled with a high-resistivity deposit in a high-resistivity substratum cuts a valley that is detected because of its low-resistivity fill. In this case only the response in the crosscut area marks the existence of the high-resistivity valley. The high-resistivity valley will appear in the low-resistivity structure, or in other words, the presence of one valley indicates the other.

The different types of buried valley images will in the following be shown in examples from the Hornsyld, Holstebro and Agtrup–Vonsild areas. For location of these areas, please refer to the location maps in Fig. 1.

6. Hornsyld

The Hornsyld case provides an example of a valley in clay-rich deposits with good morphological images of valley walls and floors and a valley containing cut-and-fill structures.

The lowest map in Fig. 3 shows the elevation of the Paleogene subsurface that is defined by the deepest conductor with resistivities of less than 7 Ω m determined through 1-D inversion of the TEM data. A total of 734 TEM and HiTEM soundings are used to construct this map. Kriging with 650 m search distance and 150 m between grid lines is used for contouring.

The main valley is mapped for a distance of about 12 km with a width of about 2 km, and a depth between 100 and 150 m. Because the valley extends into the overlying Quaternary sediments, the total valley depth is probably 10–40 m greater than that defined by the incision in the Paleogene clay. There is no explicit surface expression of the Hornsyld valley in the present-day terrain, which in elevation ranges between 20 and 70 m above sea level.

According to the elevation map, the floor of the Hornsyld valley is undulating. This may be a result of an irregular erosional cut, but there are four reasons why this interpretation deserves special attention. (1) Inductive coupling to cultural structures often leads to erroneous resistivity models with fictitious conductors situated high in the section (Sørensen et al., 2004). Inductive coupling is difficult to recognize, and accidental inclusion of the distorted data in the interpretation can result in the formation of "islands" in the contoured elevation map. (2) Drilling data indicate that some of the valley fill consists of clay till. Subglacial activity including glacial erosion and deposition of basal till on the valley floor could lead to local deposition of clay-enriched and low-resistivity tills. Such low-resistivity tills can be difficult to distinguish from Paleogene clay in TEM sounding data. (3) Saltwater intrusion along fault zones into the lower parts of the valley can distort the image by showing a false "floor" located too high in the section. (4) Glaciotectonic thrusting of rafts of Paleogene clay can create 3-D structures. Reflection seismic surveys indicate the existence of glaciotectonic activity (Jørgensen et al., 2003) that can be responsible, at least in part, for the irregularity of the valley floor.

More than one valley is seen on the Hornsyld elevation map of the good conductor. In fact, it appears as a system of valleys including some smaller ones located to the south and northwest. The mapped area is probably just a minor part of a larger braided

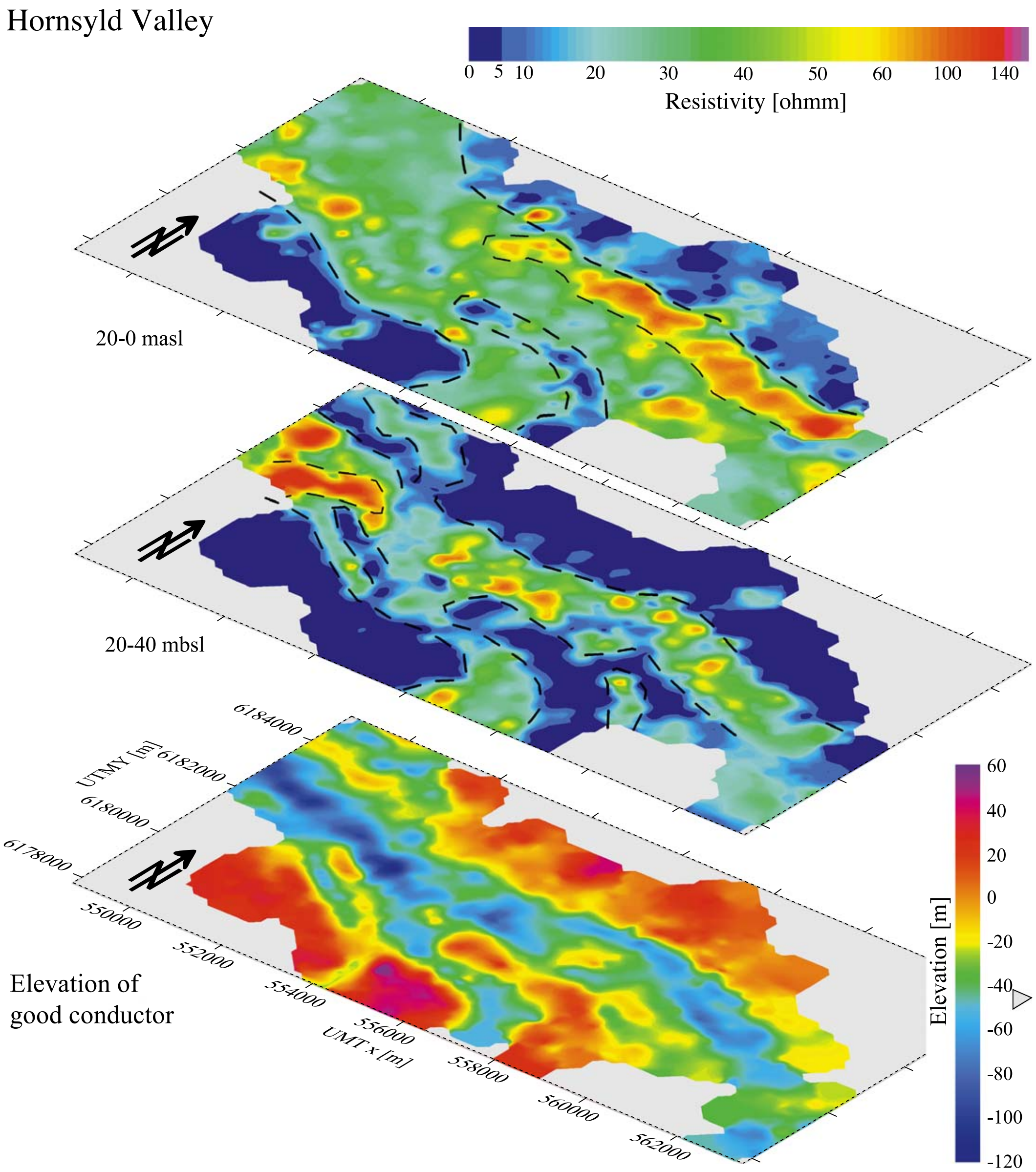


Fig. 3. Contour maps showing the buried Hornsyld valley. The valley is imaged on two depth slices of mean resistivity and on a map showing the elevation of the deepest good conductor as defined by resistivity values less than 7 Ω m. The maps are based on 1-D inversion models of 734 TEM and HiTEM soundings. Thick dashed lines mark valley boundaries. Thin dashed lines mark internal incision boundaries. Field survey: Dansk Geofysik, Rambøll and WaterTech.

system of parallel to subparallel connected valleys, as seen in other parts of Northwest Europe (Wingfield, 1989; 1990; von Schwab and Ludwig, 1996; Huuse and Lykke-Andersen, 2000; Sandersen and Jørgensen, 2002, 2003).

The apparent occurrence of braided systems of buried valleys may be genetically linked to the cut-and-fill structures, which also can be detected in seismic reflection surveys across the area (Jørgensen et al., 2003). Most of the cut-and-fill structures are difficult to determine with confidence in the TEM survey data due to low resistivity contrasts. Two structures, however, occur on the two mean resistivity depth slices of 20 to 0 m (m above see level) and 20 to 40 m (m below see level) shown in Fig. 3. On the slices, it can be seen that the Hornsyld valley is filled predominately with medium-resistivity deposits of 20–45 Ω m, which, according to lithological well logs, consist of glacio-lacustrine clay and clay till. A young valley filled with high-resistivity deposits of

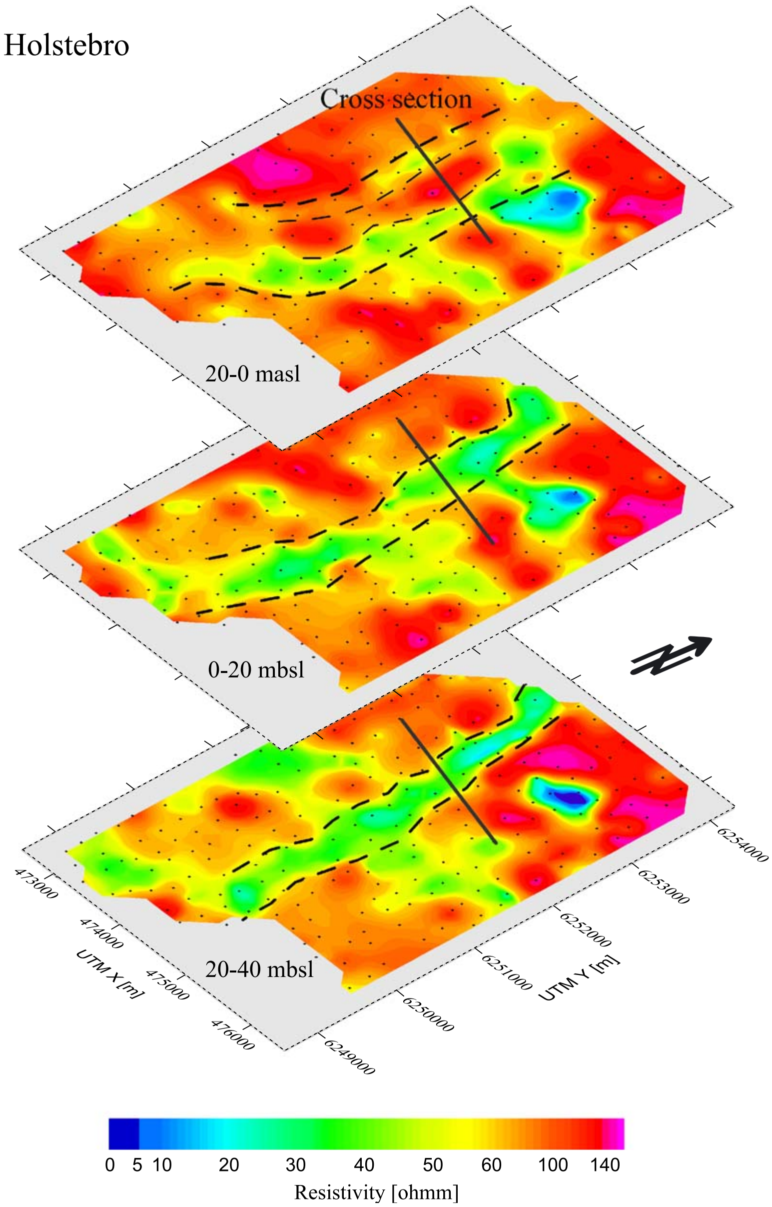


Fig. 4. The Holstebro buried valley depicted in contoured depth slices of 20 m mean resistivity intervals constructed from 1-D inverse models of 224 TEM soundings. Thick dashed lines mark valley boundaries. Thin dashed lines mark internal incision boundaries. The solid, black line marks the location of the cross-section model shown in Fig. 5. Field survey: Dansk Geofysik.

meltwater sand and gravel is imaged in the upper slice inside the northern part of the overall valley structure. As seen in the elevation of the good conductor, the location of this young valley corresponds to the deeply eroded zones in the northeastern part of the surveyed area. This may point to the fact that the young valley is deeper than the older parts of the valley system. Another young incision filled with high-resistivity deposits is seen in the western part of the lowest slice of 20–40 mbsl.

7. Holstebro

In the Holstebro example a valley in sandy environments is presented along with signatures of multiple erosion and deposition events (cut-and-fill structures).

The maps in Fig. 4 show a buried valley situated in northwestern Denmark near the town of Holstebro. The survey consists of 224 TEM soundings from which the 1-D inversion results are presented as slices of mean resistivity for three intervals: 20 to 0 masl, 0 to 20 mbsl and 20 to 40 mbsl. The level of the present-day terrain ranges between 30 and 60 m above sea level. Kriging with 650 m search distance and 150 m between grid lines is used for contouring.

A north–south trending buried valley partly filled with low-resistivity sediments, late Elsterian and Holsteinian clay (Karen Luise Knudsen, personal communication, 2001) is imaged as the longitudinal low-resistivity zones in the map slices. According to a recent deep drilling, the depth of the valley is about 140 m (Jørgensen and Sandersen, 2000). The width is about 1.5 km, and the minimum length is 4.5 km. A less significant low-resistivity structure is seen between UTM Y 6 251 000 and 6 252 000 m striking east–west through the area. Because supplementary data sets (e.g. well control) are lacking, it is at present unknown whether this structure also represents a buried valley.

The signature of multiple erosion events is observed in Fig. 5 as alternating longitudinal structures of high- and low-resistivity sediments at different levels within the valley. In the lowest depth slice of 20–40 mbsl, a low-resistivity structure of about 30 Ω m is outlined. This structure is also seen in the 0 to 20 mbsl slice, although it is generally a bit wider. In the uppermost slice of 20 to 0 masl the pattern is quite different: the region of low resistivity is replaced by a high-resistivity structure, while another low-resistivity

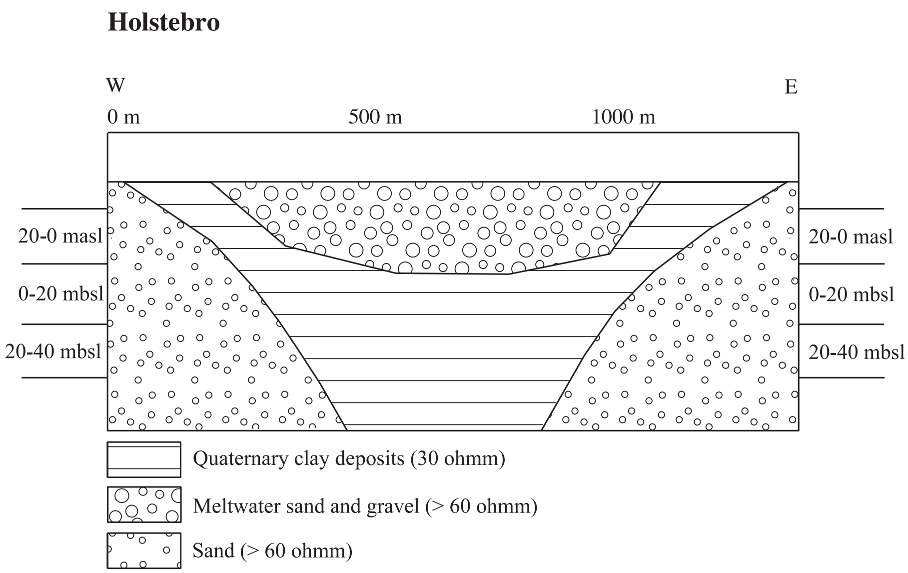


Fig. 5. Cross-section model of the Holstebro valley constructed from the depth slices (in Fig. 4), noted on the cross-section. The model is not to scale.

structure appears in the eastern marginal part and to some extent to the west. These alternating structures are interpreted as multiple erosion and deposition features as shown in the cross-section of the valley in Fig. 5 or in the simplified cross-section model in Fig. 2h. A shallow valley is incised into a deeper one. In the 0–20 and 20–40 mbsl slices of Fig. 4, the older, deeper valley is detected by its low-resistivity Quaternary clay fill. In the 20 to 0 masl slice, the younger, shallower valley filled with high-resistivity sand and gravel appears to be incised into the Quaternary clay fill.

8. Vonsild–Agtrup

The next example shows how to interpret multiple erosion and deposition events (cut-and-fill structures), crosscutting and multiple generations.

The area of Vonsild–Agtrup is situated south and southeast of Kolding in the southeastern part of Jutland. Here, the upper parts of two different valleys with depths of about 300 m are investigated. The valleys are mapped primarily with conventional TEM soundings; however, some of the soundings are acquired with the HiTEM system to map the deep parts of the valleys.

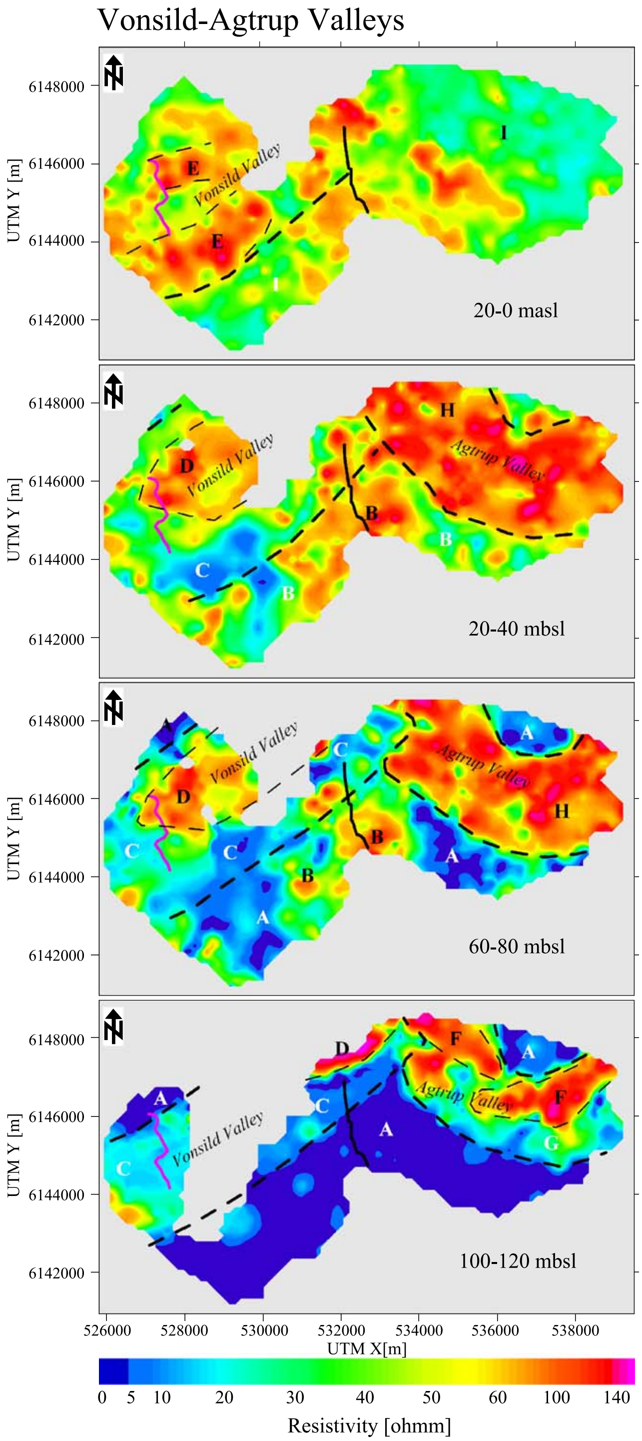
Fig. 6 shows four mean resistivity depth slices of 100–120 mbsl, 60–80 mbsl, 20–40 mbsl and 0–20 masl from the Vonsild–Agtrup area, where the present-day terrain has an elevation between 40 and 75 m above sea level. These maps are based on 820 TEM soundings in an area of 55 km^2. Kriging with 650 m search distance and 150 m between gridlines is used for contouring. Valley boundaries are marked with thick dashed lines on each slice, and internal incision boundaries are marked with thin dashed lines. Interpreted sedimentary units are marked with capitals. The location of a seismic section is marked with a solid pink line. Together with a deep exploratory drilling, this seismic section is described and investigated in Jørgensen et al. (2003). The Vonsild valley strikes through the survey area from southwest to northeast in the western part of the survey area, while the Agtrup valley strikes from southeast to northwest in the eastern part. Both valleys are completely filled with Quaternary deposits and in most places covered by a relatively thin layer of clay till. The lowest resistivities of $< 5–10\,\Omega$ m represent the Paleogene clay on the 100–120 and the 60–80 mbsl slices (Fig. 6, unit A).

Considering the southwest–northeast trending Vonsild buried valley on the 100–120 mbsl slice, the main part of the valley is filled with low-resistivity deposits (Fig. 6, unit C). According to the seismic survey and the exploratory drilling described by Jørgensen et al. (2003), these deposits consist of glacio-lacustrine clays. In the middle of the northeastern part of the valley, a high-resistivity zone borders the clay deposits (Fig. 6, unit D). These high-resistivity deposits can be interpreted as an internal incision or younger valley in the clay filled with sand or gravel.

A more complicated picture is seen in the slices above (60–80 and 20–40 mbsl). Although the highest elevated parts of the Paleogene clay can be seen in the 60–80 mbsl slice, the valley borders become less distinct because the surrounding Tertiary deposits merely consist of alternating Miocene sands, silts, and silty clays (Fig. 6, unit B). The borders are only seen locally, but are in some places verified by reflection seismic sections crossing the borders. One of these sections is presented in Fig. 7, and the location of the section is marked with a solid black line on the slices in Fig. 6.

The glacio-lacustrine unit (Fig. 6, unit C) does not appear as homogeneous in the 60–80 mbls slice as it did in the lowest slice. The reason for this is unclear, but may be explained by local enrichment of silt and sand in the glacio-lacustrine environment. Insufficiently resolved structures, as for example small cut-and-fill structures may also be an explanation for the variable resistivity values.

A high-resistivity unit appears in the central part of the Vonsild valley (Fig. 6, unit D). This unit is in Jørgensen et al. (2003) interpreted as a large incision mainly filled with sand and gravel. The overall composition is comparable with the model of Fig. 2g. The incision seems to have the same trend as the main valley, but apparently it terminates towards southeast. It is possible that this incision correlates to the incision indicated in the slice of 120–100 mbsl, implying that the elevation of the incision rises towards southwest and that it continues into the higher elevated strata. This is however not clearly indicated in the mean resistivity slice of 20 to 0 masl. Here, a high-resistivity zone is located above the low-resistivity deposits of glacio-lacustrine clay along the


Vonsild-Agtrup Valleys
UTM Y [m]
6148000
6146000
6144000
6142000
Vonsild Valley
Agtrup Valley
20-0 masl
20-40 mbsl
60-80 mbsl
100-120 mbsl
526000
528000
530000
532000
534000
536000
538000
UTM X[m]
0 5 10 20 30 40 50 60 100 140
Resistivity [ohmm]

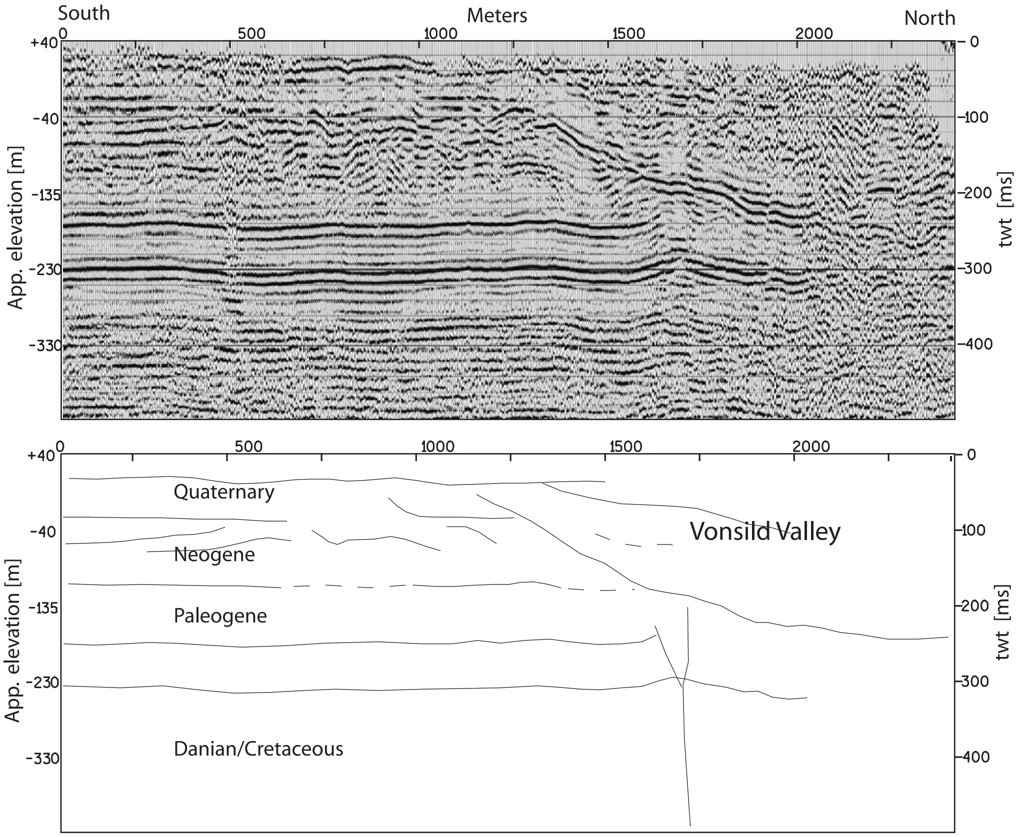


Fig. 7. The southern flank of the Vonsild valley shown on a reflection seismic section (unmigrated 32-fold stack). Interpretations sketched below the seismic section. Location of the seismic section is shown in Fig. 6 as a solid black line. Data collection and processing by Rambøll (Jensen et al., 2002).

southern margin of the valley, while another high-resistivity zone is located approximately above the large incision on the lower slices (Fig. 6, unit E). These zones of high-resistivity are interpreted as younger sand- and gravel-filled incisions. The boundaries of the deeper valley sequences are not clearly present in the uppermost slice. The surrounding sediments consist of Quaternary deposits of mainly clay till (Fig. 6, unit I).

Drilling data and the reflection seismic survey presented in Jørgensen et al. (2003) indicate that the geology of the Vonsild buried valley is complicated containing sedimentary units that are undetectable by the TEM method. However, the model based on the TEM survey given here provides a good overall impression of the valley structure and is significantly less expensive than a seismic and drilling program. The Vonsild buried valley was unknown before the TEM survey was carried out.

Images of cut-and-fill structures can also be seen in the Agtrup valley. In the lowest slice of Fig. 6 (100–120 mbsl), alternating structures with different resistivity values appear within the valley outline in the Paleogene clay. Incisions filled with high-resistivity

Fig. 6. The Agtrup and Vonsild buried valleys shown as contoured depth slices of mean resistivity intervals based on 1-D inversion models of 820 TEM soundings. Thick dashed lines mark valley boundaries. Thin dashed lines mark internal incision boundaries. Location of a seismic section described in Jørgensen et al. (2003) is marked by solid pink line. A solid black line marks location of the seismic section shown in Fig. 7. Capital letters denote sedimentary units mentioned in the text. Field survey: Rambøll and WaterTech.

sediments (Fig. 6, unit F) cut medium-resistivity sediments (Fig. 6, unit G) as well as the low-resistive Paleogene clay (Fig. 6, unit A).

The Vonsild and Agtrup valleys are thought to represent different generations crosscutting each other, as seen in Fig. 6. Because the Agtrup valley seems to erode the Vonsild valley in the slice of 20–40 mbsl, it is believed that the Agtrup valley is the youngest. However, in the two lowest slices the glacio-lacustrine clay fill contained by the Vonsild valley extends halfway into the Agtrup valley, and this can, on the other hand, be interpreted as if the Vonsild valley erodes the Agtrup valley. However, where a deep incision appears in the deepest slice of 100–120 mbsl, the northeastern part of the glacio-lacustrine clay seems still to be eroded by the Agtrup valley, thus again supporting the proposed age relationship. The clay from the older Vonsild valley extending halfway into the Agtrup valley could be an erosional remnant that is part of the undulating floor of the Agtrup valley. Otherwise, the different incisions belonging to each valley would be independently related, meaning that the valleys were formed parallel to each other in time, but in shifting stages through a long period.

9. Conclusion

Buried valleys are found in Denmark in large numbers by use of the TEM method. Despite the resolution limitations of electromagnetic induction methods, the costs relative to seismic surveys and drillings make TEM surveys an attractive and effective technique that provides an overview of large areas and enables an interpretation of the overall geological structures. Buried valleys are large structures that are often easily mapped in TEM surveys. Due to distinct resistivity contrasts, a variety of large-scale valley features are reflected in the resistivity images. Smaller valley features or features with less distinct resistivity contrasts are however difficult to recognize and will require supplementary data sets and experienced interpreters.

Buried valleys that are cut into clay-dominated sediments and filled with sandy Quaternary sediments are more straightforward to map than valleys incised into sandy environments. Hence, valley morphology is imaged when buried valleys are cut into clay, while valleys in sandy deposits are detected based on their fill properties. Valleys with low resistivity contrasts between fill sediments and the environments may not be resolved by TEM at all. Some valleys can only be partially mapped, and the total lateral extension is therefore not delineated.

The images produced from a TEM survey are not always of simple valley structures. Images of ridges can be generated by low-resistivity, nonpenetrating clay fill and sometimes more complicated parallel systems of high- and low-resistivity structures reveal the existence of cut-and-fill structures within valleys. The existence of multiple erosion, deposition, and crosscutting structures as part of a valley sequence is evident in several TEM surveys, and is best imaged and interpreted on the basis of 20-m mean resistivity depth slices.

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