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Rapid tunnel-valley formation beneath the receding Late Weichselian ice sheet in Vendsyssel, Denmark

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Interpretation of Transient ElectroMagnetic (TEM) data and wire-line logs has led to the delineation of an intricate pattern of buried tunnel valleys, along with new evidence of glaciotectonically dislocated layers in recessional moraines in the central part of Vendsyssel, Denmark. The TEM data have been compared with recent results of stratigraphical investigations based on lithological and biostratigraphical analyses of borehole samples and dating with Optically Stimulated Luminescence (OSL) and radiocarbon. This has provided an overview of the spatial distribution of the late Quaternary lithostratigraphical formations, and the age of the tunnel valleys has been estimated. The tunnel valleys are typically 5–10 km long, 1 km wide and are locally eroded to depths of more than 180 m b.s.l. The valleys are interpreted to have been formed by subglacial meltwater erosion beneath the outermost part of the ice sheet during temporary standstills and minor re-advances during the overall Late Weichselian recession of the Scandinavian Ice Sheet. The formation of the tunnel valleys occurred after the retreat of the Main ice advance *c.* 20 kyr BP and before the Lateglacial marine inundation *c.* 18 kyr BP. Based on the occurrence of the tunnel valleys and the topography, four ice-marginal positions related to the recession of the northeastern Main advance and seven ice-marginal positions related to the recession from the following eastern re-advance across Vendsyssel are delineated. All the tunnel valleys were formed within a time interval of a few thousand years, giving only a few hundred years or less for the formation of the tunnel valleys at each ice-marginal position.

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Buried tunnel valleys are common Quaternary features in the Danish subsurface, onshore (Lykke-Andersen 1973, 1986; Jørgensen & Sandersen 2006) as well as offshore (Salomonsen 1995; Huuse & Lykke-Andersen 2000; Kristensen *et al.* 2007). Both onshore and offshore tunnel valleys are elongated depressions, often with undulating longitudinal profiles, and they typically begin and end abruptly. The onshore buried valleys are typically up to 300 m deep and between 0.5 and 4 km wide; they are believed to share their origin with the open tunnel valleys, as found in the present-day landscape (Jørgensen & Sandersen 2006). The buried and the open tunnel valleys are formed close to the ice margin, primarily by subglacial meltwater erosion (e.g. Ussing 1903, 1907; Jørgensen & Sandersen 2006). Buried and open tunnel valleys comparable in shape and size are described from several locations in northern Europe (e.g. Woodland 1970; Ehlers *et al.* 1984; Ehlers & Linke 1989; Huuse & Lykke-Andersen 2000) and North America (e.g. Wright 1973; Mullins & Hinchey 1989; Patterson 1994; Clayton *et al.* 1999; Hooke & Jennings 2006).

The presence of buried valleys in Vendsyssel (Fig. 1) was not known until about 10 years ago. Earlier, the subsurface geology was mapped using borehole data in combination with descriptions of sediments in outcrops and to a certain extent seismic surveys originating from onshore hydrocarbon exploration (Fredericia 1988). These seismic lines focused on the deep part of the subsurface, however, and therefore the data from the shallow part of the succession were limited. As a consequence, structural characteristics of the Quaternary sediments were previously derived primarily from outcrops (e.g. Jessen 1899, 1931; Lykke-Andersen 1971; Pedersen 2005).

During the past 10 years, use of the Transient ElectroMagnetic (TEM) method has enabled mapping of spatial resistivity variations of the sediments in the upper 150 to 200 m of the subsurface (Danielsen *et al.* 2003; Sørensen & Auken 2004). Combined geological interpretations of TEM, borehole and shallow seismic data have provided unique possibilities for visualizing spatial sediment distribution and large structural features (Jørgensen *et al.* 2003a, b). Using this concept, a large number of buried valleys have been mapped in the Danish onshore area (Sandersen & Jørgensen 2003; Jørgensen & Sandersen 2006).

As the descriptions of the stratigraphy in Vendsyssel are based primarily on borehole data and outcrops, data on the spatial distribution of the sedimentary units are limited. Buried valleys, in particular, are difficult to map using boreholes alone (Jørgensen & Sandersen

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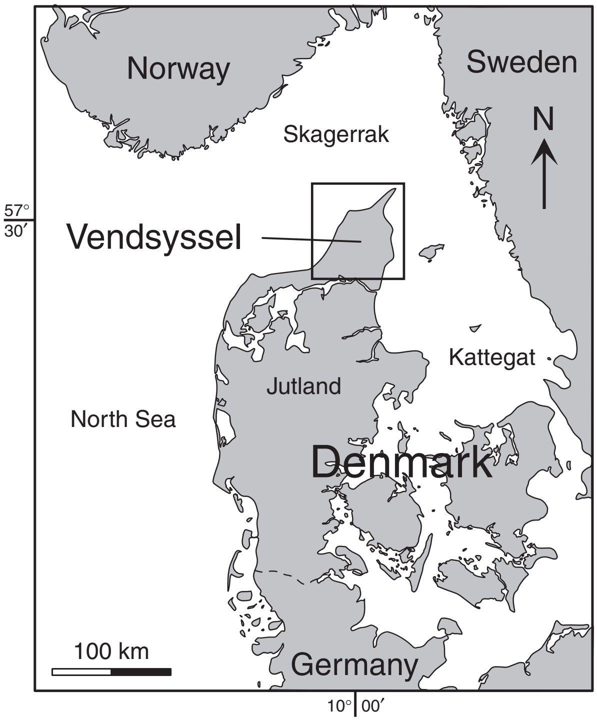

Fig. 1. The study area of Vendsyssel in the northern part of Jutland (Denmark).

2009), and in order to obtain both detailed point observations and densely covering data grids, a number of exploratory boreholes and a SkyTEM survey have been performed as part of a joint groundwater project in Vendsyssel (Knudsen & Larsen 2009). These new data give an unprecedented insight into the nature of the buried valleys in the area.

The aim of this study is to present the results of integrated geological interpretations of the TEM data and geophysical borehole data and to outline the distribution of the buried valleys in Vendsyssel. With reference to a revised lithostratigraphy for Vendsyssel (Krohn *et al.* 2009; Larsen *et al.* 2009b) and interpretation of topographical features, the buried valleys are attributed to a series of specific Late Weichselian ice-marginal positions, and the timing and duration of their formation is suggested.

Geological setting

The pre-Quaternary surface in Vendsyssel has a northerly dip and is predominantly composed of Upper Cretaceous chalk. The Cretaceous sediments are found close to sea level towards the south, and towards the north the pre-Quaternary surface reaches depths of around 250 m b.s.l. The thickness of the overlying Quaternary sediments exceeds 250 m in the central parts of Vendsyssel, whereas it wedges out towards the south (Larsen *et al.* 2009a).

The Quaternary sediments in Vendsyssel have been studied for more than a century both in exposures and in a large number of exploration and hydrogeological boreholes (e.g. Jessen *et al.* 1910; Jessen 1918, 1936; Andersen 1961; Bahnson *et al.* 1974; Knudsen 1985; Fredericia 1988; Lykke-Andersen & Knudsen 1991; Pedersen 2005). Many of these studies have been concentrated on the lower, mainly fine-grained succession, which was perceived as a continuous Late Saalian to Middle Weichselian marine record (e.g. Jessen *et al.* 1910; Bahnson *et al.* 1974; Knudsen 1985). The upper Late Weichselian glacial, glaciolacustrine and marine deposits have also been subjected to many studies to constrain the stratigraphy and depositional environment (Jessen 1936; Andersen 1961; Knudsen 1978; Richardt 1996; Sadolin *et al.* 1997; Houmark-Nielsen 2003; Pedersen 2005). A preliminary subdivision of the sedimentary succession into lithostratigraphical units was established by Sadolin *et al.* (1997), Houmark-Nielsen (2003) and Pedersen (2005).

On the basis of interpretations of lithological and biostratigraphical data as well as radiocarbon and Optically Stimulated Luminescence (OSL) dating from new boreholes, combined with a reinterpretation of previously published stratigraphical evidence, the previously defined lithostratigraphical units have been revised by Knudsen *et al.* (2009), Krohn *et al.* (2009) and Larsen *et al.* (2009b). The revised stratigraphy of Vendsyssel subdivides the late Quaternary sediments into 13 formations (Fig. 2). Among the most significant findings is that the lower marine succession is incomplete and separated by two intervals of glacial deposits, and that the upper succession is more complex than previously thought, being dominated by several generations of glaciolacustrine sediments. The Quaternary stratigraphy identifies five glacial events, represented by glacial deposits interbedded with marine and glaciolacustrine sediments (Larsen *et al.* 2009a). The revised stratigraphy thus reflects changes between glacial, marine and glaciolacustrine sedimentary environments several times during the *c.* 160 kyr represented by the sediments. In particular, the biostratigraphical data and the established chronology have enabled the results to be put into a wider regional context (Larsen *et al.* 2009a).

The Cretaceous substrate in Vendsyssel is overlain by the 2 to 15 m thick clayey Skærumhede Till deposited by the Late Saalian Warthe ice *c.* 160–140 kyr BP (Larsen *et al.* 2009b). The Skærumhede Till is followed by a thick succession of marine clay, which has been subdivided into the Lower, the Middle and the Upper Skærumhede Clay Formation (Knudsen *et al.* 2009; Larsen *et al.* 2009b). The Lower Skærumhede Clay Formation is up to 80 m thick and comprises Late Saalian to Early Weichselian marine deposits (*c.* 140–65 kyr BP) dominated by silty clay (Larsen *et al.* 2009b).

The marine clays are interlayered by the Brønderslev Formation, which is subdivided into the Brønderslev

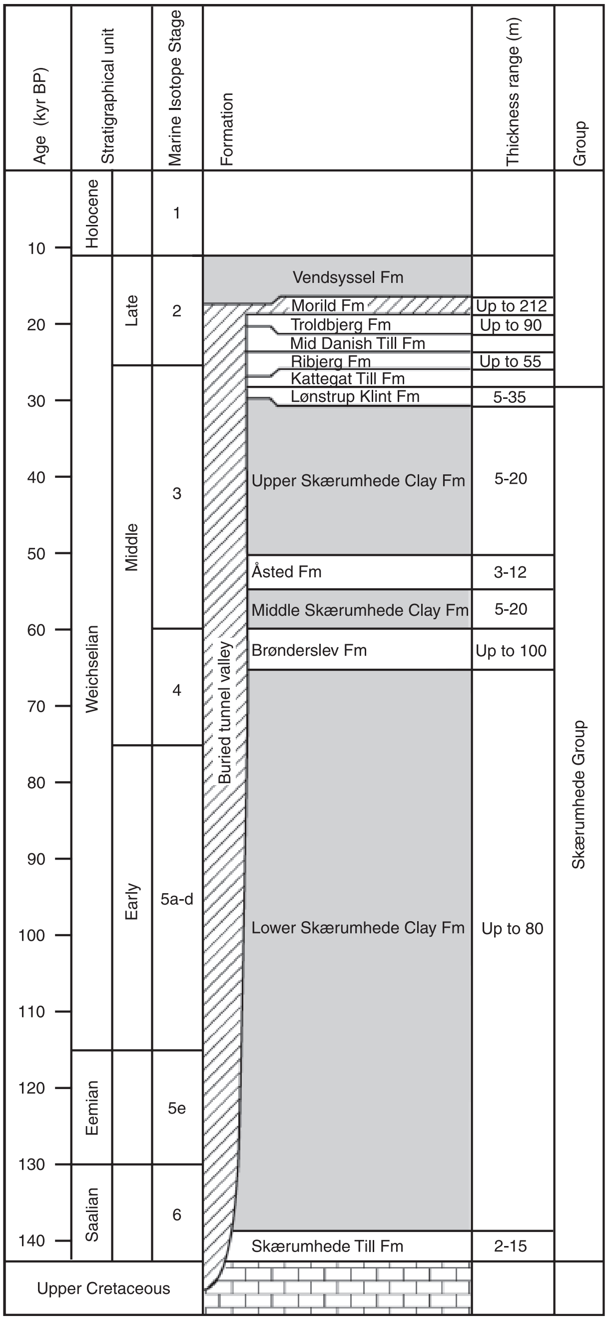

Fig. 2. Chronostratigraphical subdivision of the Quaternary sediments in Vendsyssel (after Krohn *et al*. 2009; Larsen *et al*. 2009b). Marine formations are shown in grey shading.

Till and Clay members, and by the Åsted Formation consisting mainly of a clayey till (Larsen *et al*. 2009b). The Brønderslev Till is dominated by erratics from a northern source and is correlated to the Sundsøre advance (*c*. 65–60 kyr BP). The marine Middle Skærumhede Clay Formation was deposited from *c*. 60 to 55 kyr BP and consists of up to 20 m dark clay with dropstones (Larsen *et al*. 2009b). The till of the Åsted Formation, between the Middle and Upper Skærumhede Clay formations, is from 3 to 12 m thick and is correlated to the Ristinge advance *c*. 55–50 kyr BP (Larsen *et al*. 2009a, b).

The marine Upper Skærumhede Clay Formation was deposited *c*. 50–30 kyr BP, and there is a gradual transition between this marine unit and the overlying up to 35 m thick glaciolacustrine Lønstrup Klint Formation (Larsen *et al*. 2009a, b). The Lønstrup Klint Formation represents a short interval from *c*. 30–29 kyr BP and is characterized by an upward-coarsening sequence from clay to sand. The Kattegat Till Formation, deposited during the Kattegat advance *c*. 29–27 kyr BP, is known from Lønstrup Klint (Houmark-Nielsen 2003; Pedersen 2005), but is not described in the deep boreholes (Larsen *et al*. 2009b).

Above the Lønstrup Klint Formation is the glaciolacustrine Ribjerg Formation deposited *c*. 27–23 kyr BP in front of the retreating ice sheet (Houmark-Nielsen 2003; Krohn *et al*. 2009). This formation attains thicknesses of up to 55 m and generally shows a coarsening upwards trend from clay and silt to sand (Fig. 4). The Mid-Danish Till Formation, deposited during the subsequent Main advance *c*. 23–21 kyr BP (Sadolin *et al*. 1997; Houmark-Nielsen 2003; Pedersen 2005), has not been found in the new boreholes in Vendsyssel (Krohn *et al*. 2009).

The predominantly sandy sediments of the up to 94 m thick Troldbjerg Formation are characterized by upward-fining or coarsening units in the boreholes (Fig. 4). The Troldbjerg Formation was deposited as glaciolacustrine sediments in an ice-dammed lake in front of the receding Scandinavian Ice Sheet (Krohn *et al*. 2009). Also the Morild Formation is interpreted as glaciolacustrine deposit. This up to 212 m thick formation shows a varied lithology from clay to coarse sand and is found in several boreholes (Krohn *et al*. 2009). The Vendsyssel Formation represents clayey, silty and sandy marine sediments deposited during the Lateglacial inundation, which was initiated *c*. 18 kyr BP (Richardt 1996; Pedersen 2005; Knudsen *et al*. 2009; Krohn *et al*. 2009).

Data and mapping methods

TEM

TEM data can be obtained either on the ground as single site soundings (e.g. Fitterman & Stewart 1986; Danielsen *et al*. 2003) or continuously measured from a helicopter using the SkyTEM method (Sørensen & Auken 2004). The penetration depth of the ground-based soundings is in the order of 130–150 m, whereas the SkyTEM system has a penetration of around 200 m.

The TEM method gives measurements of variations in the electrical resistivity of the subsurface and, given dense data coverage, a spatial model of resistivity variations is obtained. When combined with borehole

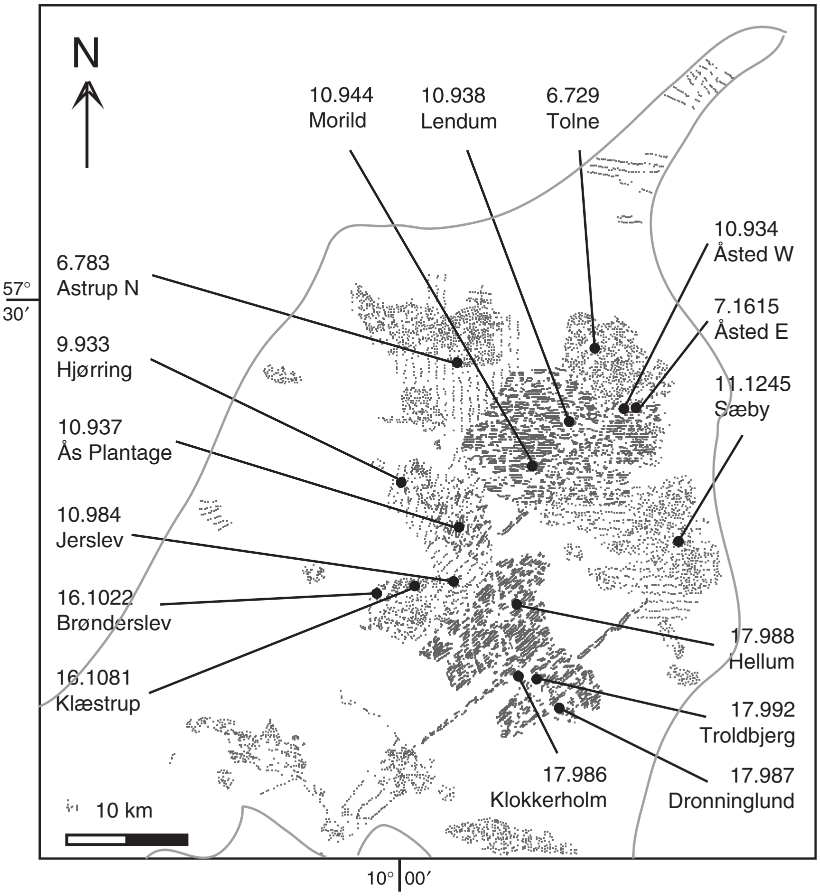

Fig. 3. Location of TEM soundings and boreholes. TEM soundings are shown as grey dots and boreholes as black spots labelled with borehole name and GEUS archive number.

data, the measured resistivities can be interpreted geologically. Variations in the formation resistivity mapped by the TEM method are mainly a result of varying clay mineralogy, clay content, porosity and ion content of the pore water. The method accurately maps deep layers with low resistivity, being either clay layers or layers with saline pore water. Numerous TEM surveys in Denmark have provided a listing of typical resistivity values as measured by TEM for different sediment types containing fresh pore water (Jørgensen *et al.* 2005). High-resistivity layers (> 60 ohmm) typically represent chalk, gravel, sand and silt, whereas low-resistivity layers typically represent clayey sediments and sediments containing saline pore water.

The vertical resolution of the TEM method is limited and decreasing with depth. Normally, up to five major layers can be resolved from the ground surface down to 200 m depth; a resolution of this magnitude is generally inadequate for a detailed description of the geology. As the method determines the electrical resistivity of layers, it cannot distinguish between geological layers with comparable electric resistivities. The limitations of the TEM method imply that a TEM survey cannot resolve stratigraphical detail, but the limitations of the method are usually greatly overshadowed by its strengths (e.g. Jørgensen *et al.* 2005). The TEM method is therefore widely used in hydrogeological investigations in Denmark (e.g. Thomsen *et al.* 2004; Jørgensen *et al.* 2005).

Formerly collected ground-based TEM data as well as the newly collected SkyTEM data make up the TEM database for Vendsyssel (Fig. 3). The number of soundings amounts to about 5800 ground-based TEM soundings and 9050 SkyTEM soundings (1250 profile kilometres). All TEM data have been processed and inverted using a 1D earth model description (Auken *et al.* 2003; Danielsen *et al.* 2007). The inversion model typically consists of 4–5 layers, each described by an electric resistivity and a thickness. Based on the inverted TEM models, a series of average resistivity maps at 10 m intervals is generated (Figs 5–8). The stratigraphical interpretations of 16 new boreholes within the study area (Fig. 3) (Knudsen *et al.* 2009; Krohn *et al.* 2009; Larsen *et al.* 2009b) have been used for the geological interpretations of the TEM data.

Wire-line logging

In order to obtain detailed and continuous physical measurements of the drilled succession, wire-line

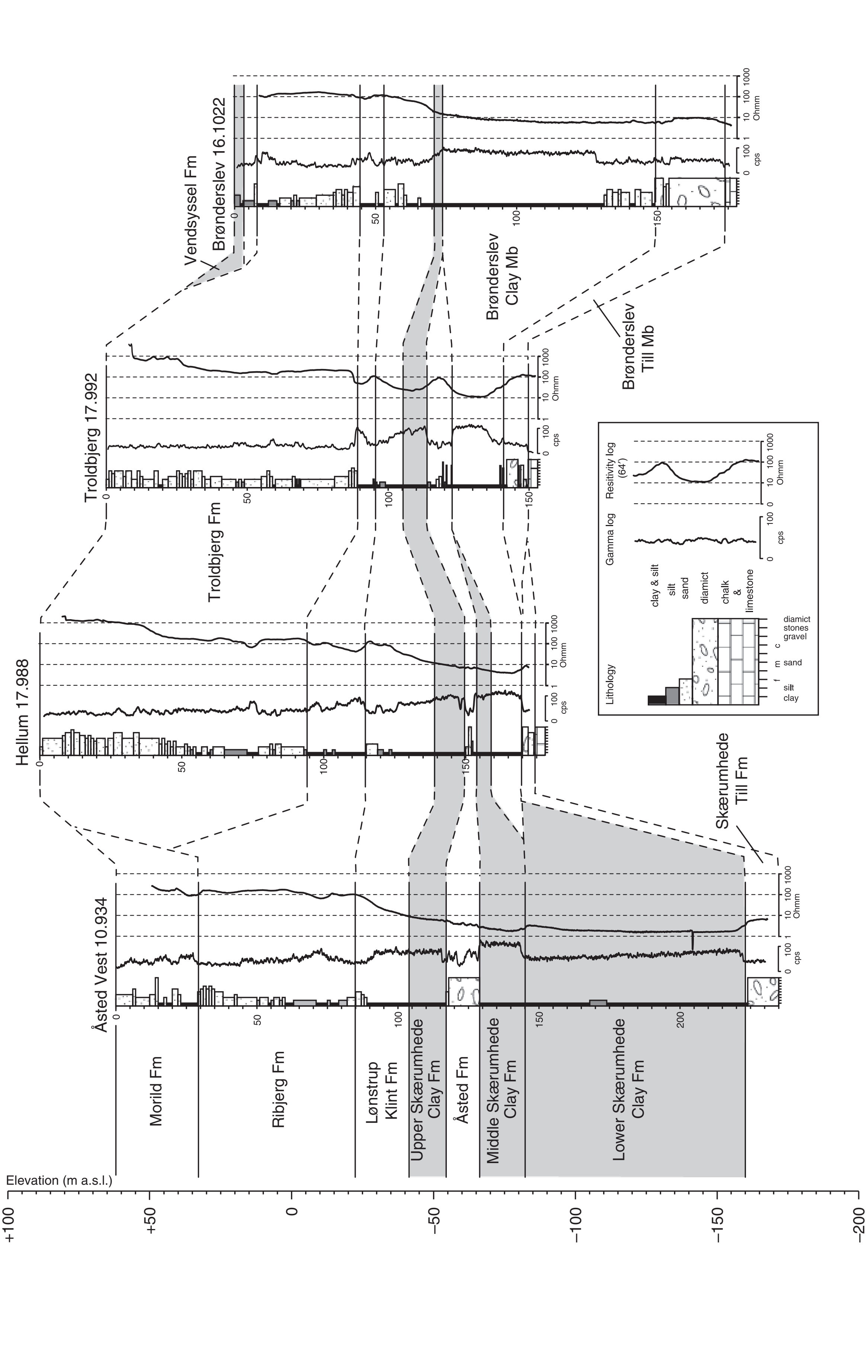

Fig. 4. Resistivity and gamma logs, lithology and stratigraphical subdivision of selected boreholes. Lithological and stratigraphical interpretations after Larsen *et al.* (2009b) and Krohn *et al.* (2009). CPS: Counts Per Second (gammalog). Resistivity is shown in ohmm.

Table 1. Resistivity ranges of lithostratigraphical formations as measured with '64 resistivity logging tool in boreholes.

Formation	Lithology	Resistivity intervals (ohmm)															Thick-ness (m)
		0-1	1-2	2-3	3-5	5-10	10-20	20-30	30-40	40-50	50-60	60-80	80-100	100-120	120-160	160-200	
Morild	Sand/silt							■	■	■	■	■	■	■	■	■	Up to 212
Troldbjerg	Sand											■	■	■	■	■	Up to 95
Ribjerg	Clay/sand							■	■	■	■	■	■	■	■	■	Up to 55
Lønstrup Klint	Clay/sand						■	■	■	■	■	■	■	■	■	■	Up to 35
Upper Skærumhede Clay	Clay				■	■	■	■	■				■				5 - 20
Åsted	Till				■	■				■	■	■	■				3 - 12
Middle Skærumhede Clay	Clay			■	■	■											5 - 20
Brønderslev Clay Member	Clay/sand				■	■	■	■	■	■	■	■					10 - 55
Brønderslev Till Member	Till, sandy					■	■						■				5 - 30
Lower Skærumhede Clay	Clay, silty			■													Up to 85
Skærumhede Till	Clay till					■				■	■						5 - 15
Upper Cretaceous	Chalk					■				■			■				-

logging has been carried out in 11 of the 16 boreholes shown in Fig. 3. The resistivity logs were used to define the typical resistivity ranges of the individual formations and members (Table 1).

Spatial distribution of the formations

In order to utilize the TEM data to outline the spatial distribution of the formations, a model for the electrical resistivity characteristics of the succession has been established (Table 1). This has been done on the basis of the resistivity log data, which provide a detailed picture of the resistivity variations of the penetrated formations in the boreholes (Fig. 4). As we describe resistivity values in broad intervals, a probable minor influence from formation anisotropy and borehole mud is considered to be insignificant, allowing us to compare the resistivity ranges of the geological formations from the wire-line logs (Table 1) with the resistivities measured by TEM. In the following, the electrical resistivity characteristics of the formations and the overall outline of the spatial distribution of the formations are described.

The Upper Cretaceous chalk and the Skærumhede Till Formation (generally below 80 m b.s.l.) show both high and low resistivities in the boreholes (Table 1). The values between 40 and 100 ohmm are within the expected range for sediments of these types (Jørgensen *et al.* 2005), but in some boreholes the measured resistivities are below 10 ohmm. These low resistivities are caused by saline pore water, as confirmed by water samples from the boreholes. The saline pore water, however, makes it difficult for the TEM method to separate the chalk and the till from the clayey sediments of the Skærumhede Clay Formation above, as the resistivities are similar. Primarily due to presence of saline pore water, the TEM data do not provide details of this part of the sedimentary succession.

The Lower and Middle Skærumhede Clay Formations show resistivities between 2 and 20 ohmm, most often below 10 ohmm, in the boreholes (Fig. 4) (e.g. Åsted Vest). The low resistivities are mainly due to high clay content but can also be caused by presence of saline pore water. The Upper Skærumhede Clay Formation ranges from very low to intermediate resistivity, corresponding to the general upwards-coarsening trend, but typically the resistivities are below 10 ohmm (Fig. 4). The coarse parts of the tills and the glaciolacustrine deposits in the Skærumhede Clay Formation (the Brønderslev and Åsted Formations) occasionally show moderate to high resistivities (Table 1). These high-resistivity layers are typically thin and may contain saline pore water.

From *c.* 30 m b.s.l. downwards, the TEM data show narrow and elongated areas of high resistivity surrounded by low resistivities (Figs 7, 8). As discussed below, these features are buried tunnel valleys. According to borehole samples, the sediments in the buried tunnel valleys predominantly consist of sand and silt in the Morild Formation (Krohn *et al.* 2009).

Between 50 and 30 m b.s.l., the TEM data show a gradual change from dominance of low resistivities to dominance of high resistivities (Figs 6, 7). In the Åsted Vest borehole, this shift from around 10 ohmm to 100 ohmm occurs between 30 and 40 m b.s.l. In this interval of the borehole, there is a lithological change from clay to sand in the Lønstrup Klint Formation (Fig. 4). The change from low to high resistivities is seen in several boreholes and throughout the study area in the TEM data and is therefore generally interpreted as a gradual shift from clay to sand within the uppermost part of the Skærumhede Group.

From 30 to 50 m b.s.l. and upwards, the Ribjerg, Troldbjerg and Morild formations generally show high resistivities in the boreholes (Table 1, Fig. 4). Coarsening upwards sequences from clay to sand in the formations are reflected in the upwards increasing log resistivities (e.g. the Åsted Vest borehole) (Fig. 4). The sand-dominated Troldbjerg Formation generally reveals high resistivity, whereas the heterogeneous Morild Formation shows a wide resistivity range (Table 1), reflecting the variations in clay content as described for the boreholes. Above 30 m b.s.l., the TEM data generally show resistivities higher than 50 ohmm and only

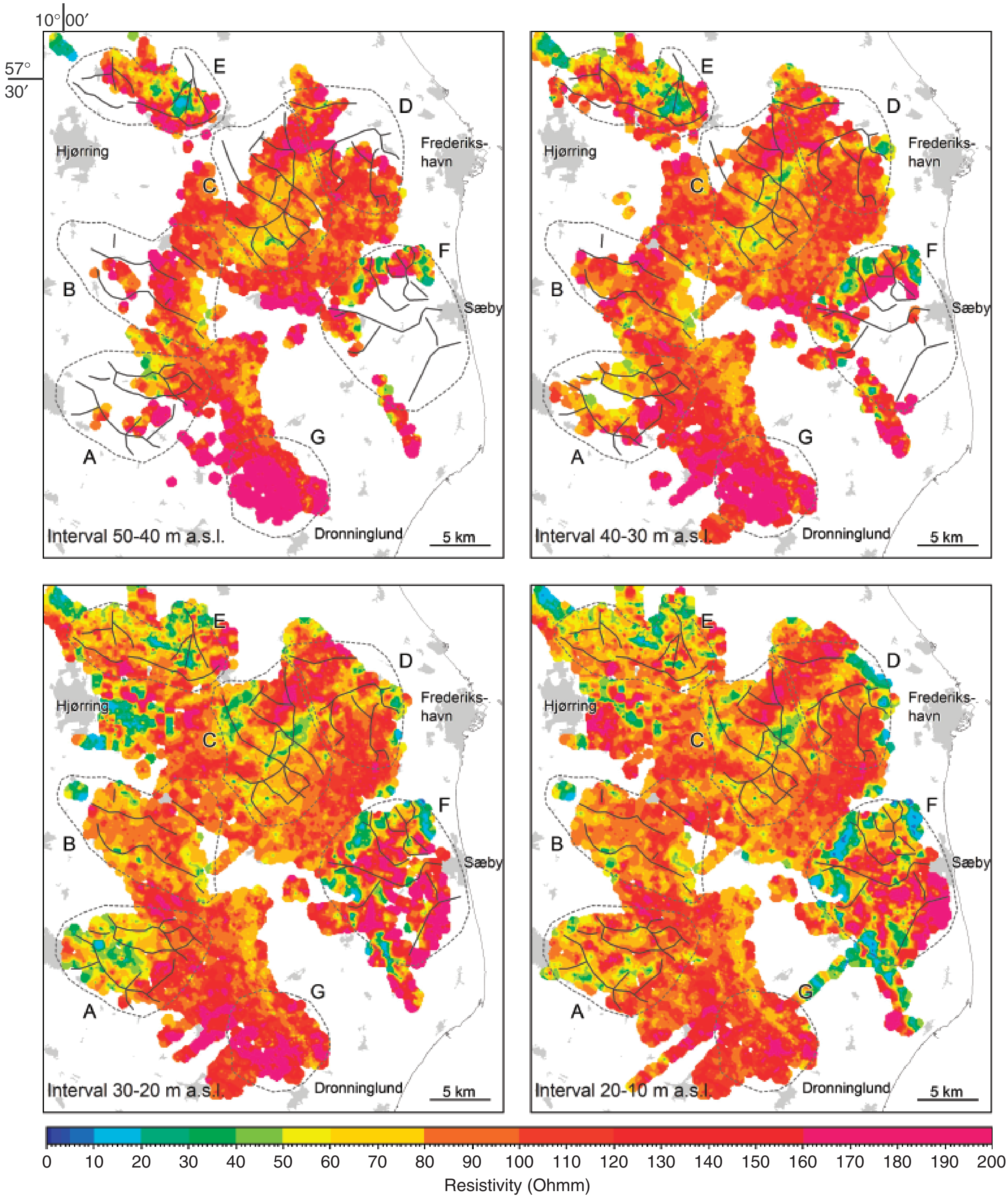

Fig. 5. Average TEM resistivity in intervals from 50 m a.s.l. to 10 m a.s.l. Hatched polygons are sub-areas referred to in the text. Buried tunnel valleys are shown with dark grey lines. Towns are shown in light grey shading.

sporadic occurrences of resistivities below 50 ohmm (Figs 5, 6). This is in accordance with the resistivity values of the Morild, Troldbjerg and Ribjerg formations measured in the boreholes. The TEM data show that these formations are widely distributed within the study area.

Geological interpretation of sub-areas A–G with focus on buried tunnel valleys

The major part of the narrow high-resistivity features seen in the TEM data at levels below 30 m b.s.l. (Figs 7, 8) consist of rectilinear segments with widths between

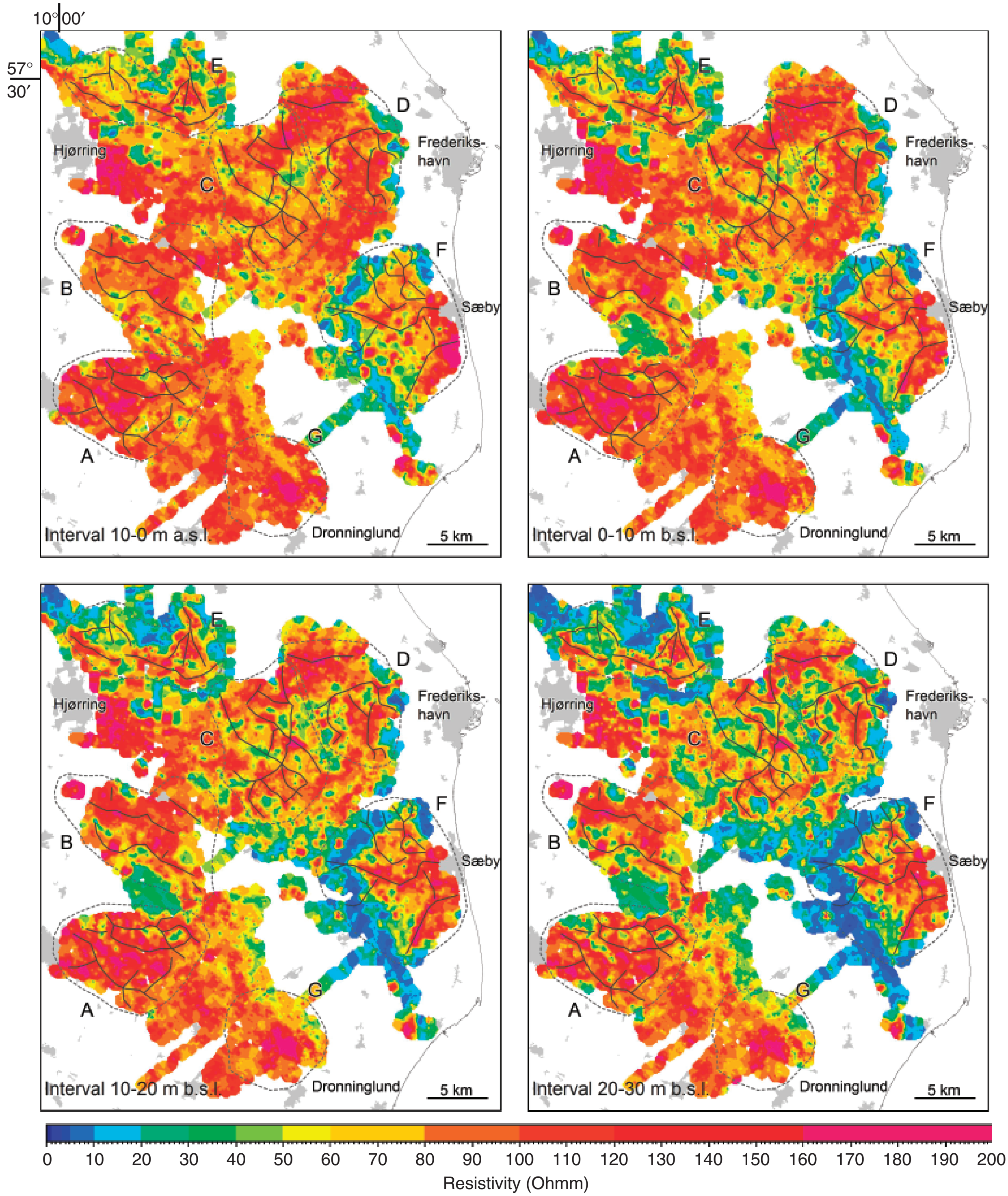

Fig. 6. Average TEM resistivity in intervals from 10 m a.s.l. to 30 m b.s.l. Hatched polygons are sub-areas referred to in the text. Buried tunnel valleys are shown with dark grey lines. Towns are shown in light grey shading.

0.5 and 2 km and with dominant orientations around NW–SE. In the intervals deeper than 30 m b.s.l., the high-resistivity features gradually narrow; they often disappear or become diffuse, terminate abruptly at one or both ends and show signs of varied bottom topography. As the shape, size and infill of the high-resistivity features in Vendsyssel are comparable to the buried tunnel valleys elsewhere in Jutland (Jørgensen & Sandersen 2006), we apply the same interpretation to these. Figure 9 shows a profile across two representative buried tunnel valleys in Vendsyssel. The shape and size of the two buried valleys vary, but they

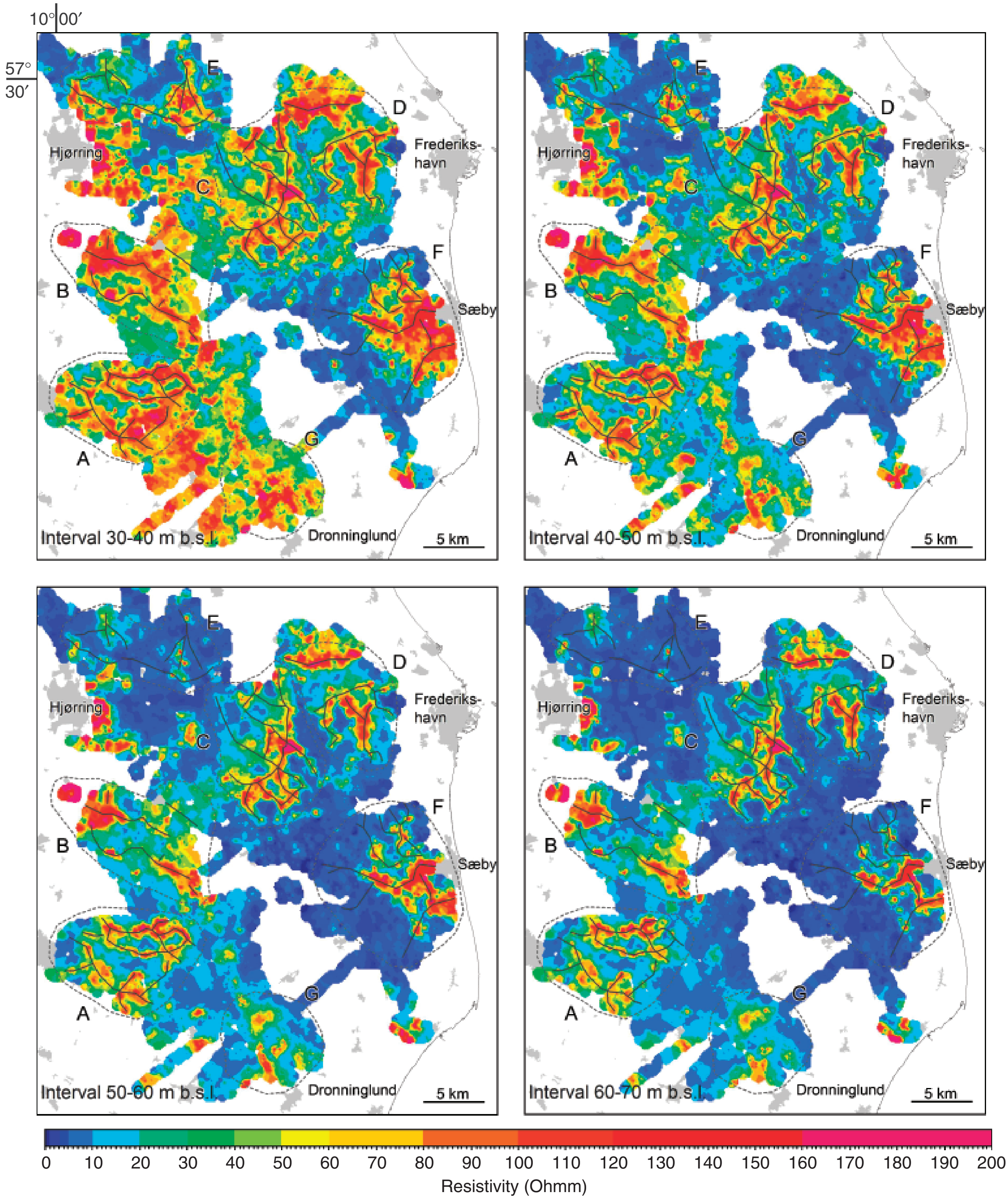

Fig. 7. Average TEM resistivity in intervals from 30 m b.s.l. to 70 m b.s.l. Hatched polygons are sub-areas referred to in the text. Buried tunnel valleys are shown with dark grey lines. Towns are shown in light grey shading.

share a number of similarities; they are eroded into the sediments of the Skærumhede Group and the younger formations above, they gradually narrow downwards, and they are filled with sediments of the Morild Formation.

Sub-area A. – The TEM data in sub-area A show two valley systems with E–W to SE–NW orientations. The individual valleys become wider upwards through the intervals shown in Figs 6–8. The valleys are most clearly seen in the interval 30–70 m b.s.l. (Fig. 7), but from this

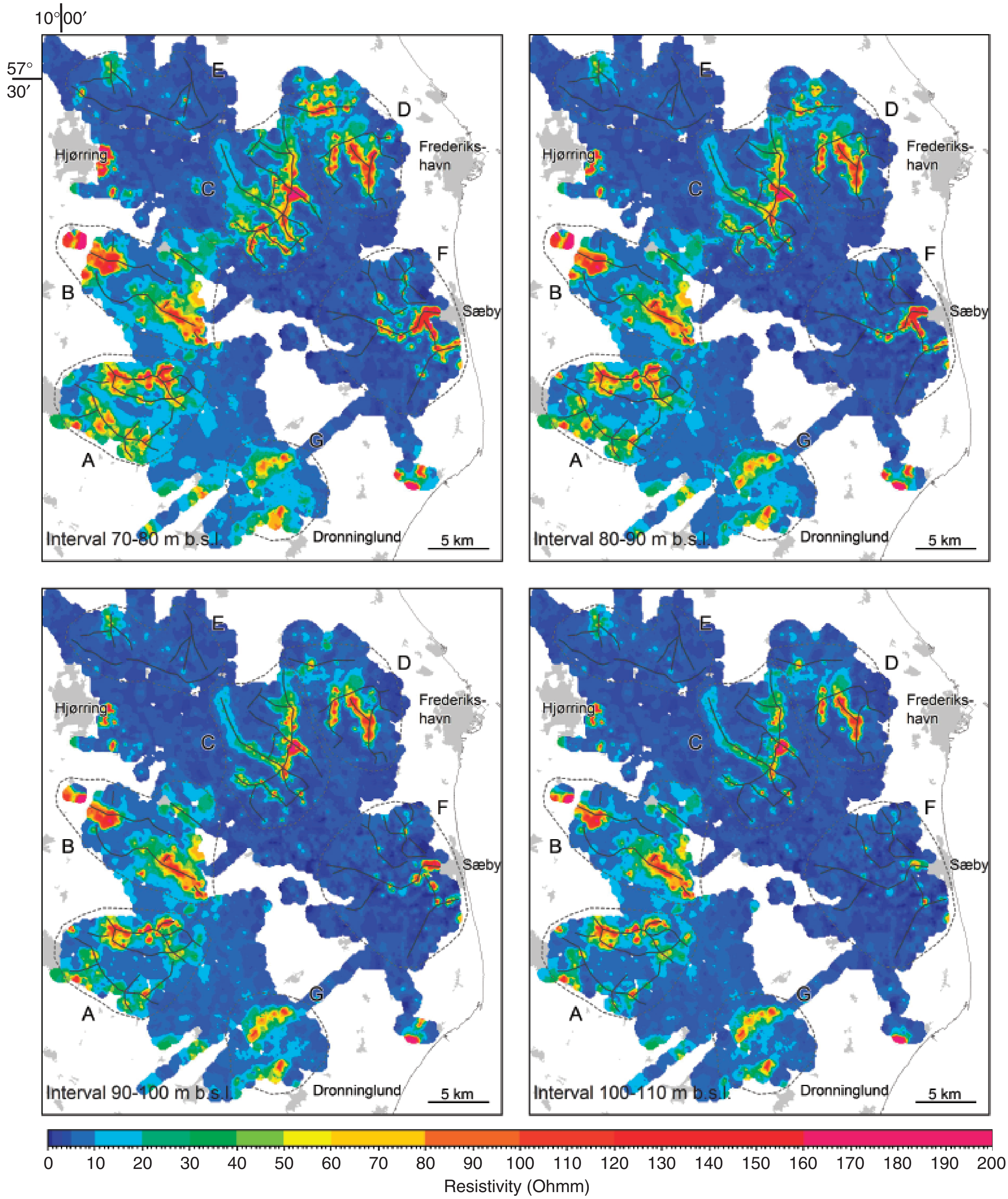

Fig. 8. Average TEM resistivity in intervals from 70 m b.s.l. to 110 m b.s.l. Hatched polygons are sub-areas referred to in the text. Buried tunnel valleys are shown with dark grey lines. Towns are shown in light grey shading.

level and upwards the valley boundaries generally become diffuse because the surrounding layers change from a dominance of low resistivities to high resistivities (Figs 5, 6). However, the flanks of the northernmost valleys can locally be followed upwards to at least the sea level (Fig. 6). The valleys terminate abruptly towards both the east and the west (e.g. intervals below 40 m b.s.l.) (Fig. 7), and seem to converge towards the west.

According to the TEM data, the valleys are locally eroded to below 100 m b.s.l. The Klæstrup borehole

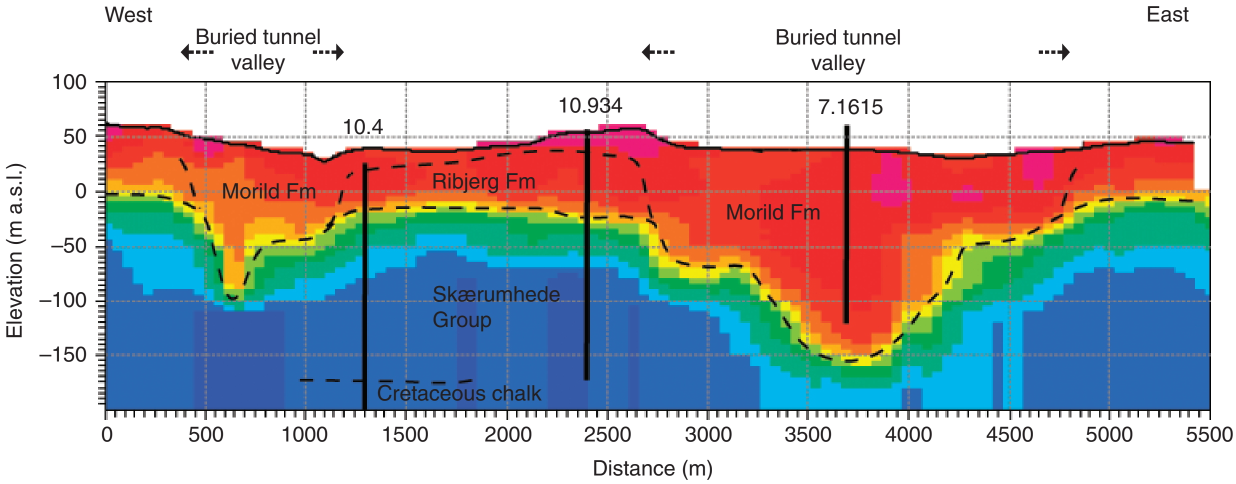

Fig. 9. TEM profile through the southern part of sub-area D. See Fig. 10 for location of profile and Table 1 for colour scale. Boreholes are shown as black vertical bars with GEUS archive number. Borehole stratigraphy from Krohn *et al.* (2009) and Larsen *et al.* (2009a, b). Ground surface is modelled from TEM data.

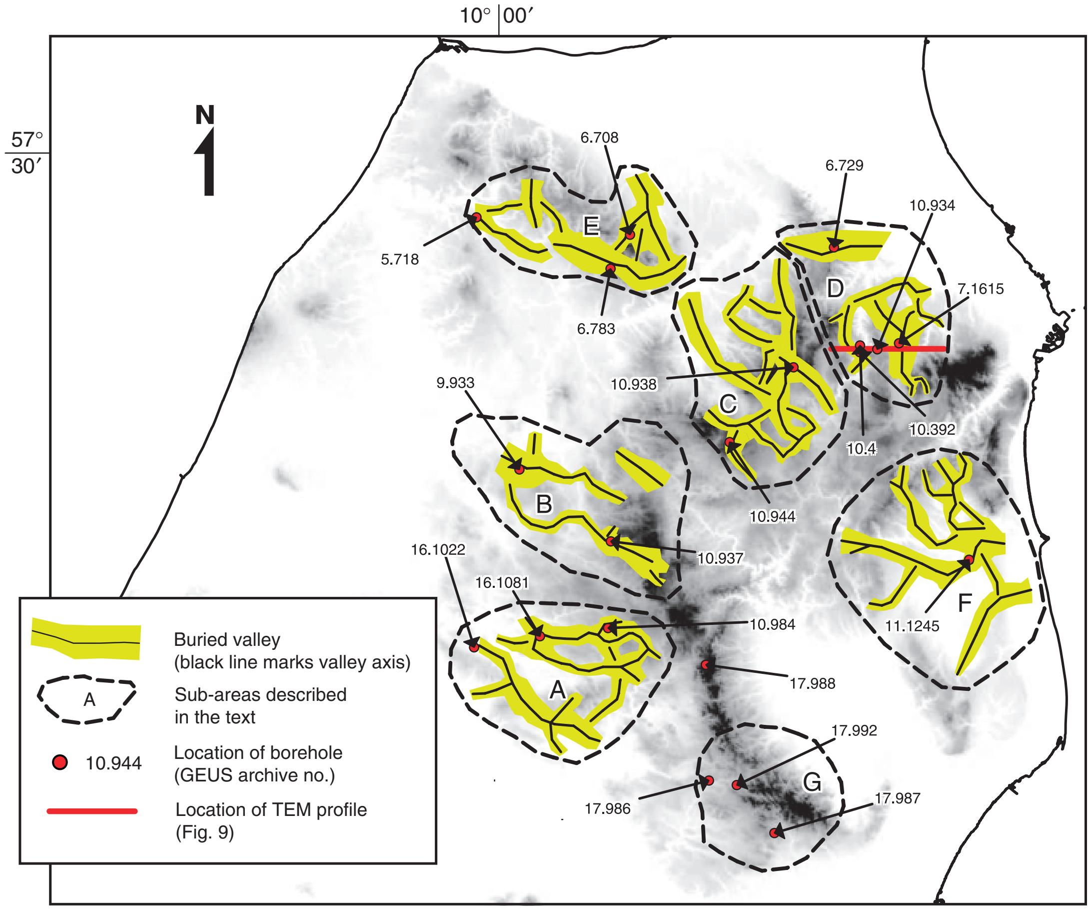

Fig. 10. Buried tunnel valleys. The topography is shown as background with dark grey colours representing the highest areas (up to 136 m a.s.l.).

(GEUS no. 16.1081; Fig. 10) shows coarse meltwater sediments of the Morild Formation extending down to the bottom of the borehole at approximately 107 m b.s.l. (Krohn *et al.* 2009). The borehole has not penetrated the bottom of the buried valley at this depth.

In the Brønderslev borehole (GEUS no. 16.1022) located close to the valley (Fig. 10), the change from high to low resistivities (below 10 ohmm) is close to the top of the Upper Skærumhede Clay Formation around 50 m b.s.l. (Fig. 4). This surface is seen in the TEM data as a change from green to blue colours (Fig. 7). The succession consists of the Lønstrup Klint, Ribjerg and Troldbjerg formations in the interval from 50 m b.s.l. to 14 m a.s.l. (Fig. 4) (Krohn *et al.* 2009; Larsen *et al.* 2009b). Because the valleys locally can be seen in the TEM data at elevations close to the sea level, they are obviously eroded into these formations and consequently are younger than the Troldbjerg Formation.

Sub-area B. – The buried tunnel valleys in sub-area B are most clearly seen in the interval from 30 to 50 m b.s.l. (Fig. 7). The valleys have an overall SE–NW orientation, and the upper parts locally reach intervals higher than the sea level (Fig. 6). Below 50 m b.s.l., the valleys appear as deep high-resistivity segments towards the NW and SE (Figs 7, 8).

The Hjørring borehole (GEUS no. 9.933), which terminates at 186 m b.s.l. in the northwestern buried valley (Fig. 10), comprises 212 m of fine-grained glaciolacustrine sediments (Krohn *et al.* 2009). In boreholes outside the valley, the surface of the Upper Cretaceous chalk is found around 100 m b.s.l. (e.g. GEUS no. 10.61; DGU 1984), implying that the buried valley is eroded at least 86 m into the chalk.

As in sub-area A, the valley surroundings from *c.* 40 m b.s.l. and downwards consist of layers with low electrical resistivities (Figs 7, 8). There are no detailed lithological descriptions of the layers outside the valleys in sub-area B, but based on the TEM data it is assumed that the succession resembles the succession outside the valleys in sub-area A.

Sub-area C. – Sub-area C shows a complicated pattern of 1–1.5 km wide buried valleys. The valleys are seen as elongate segments, typically with higher resistivities than the surroundings (Figs 6–8). The orientations are generally SE–NW or N–S/NE–SW. The majority of the valleys can be seen from 0–30 m b.s.l. to below 100 m b.s.l.

The succession outside the valleys shows low resistivities from around 30 m b.s.l. and downwards (Fig. 7). A comparison with the nearby Åsted Vest borehole (Fig. 4) suggests that the low-resistivity layers (resistivity below 20 ohmm) consist of the clayey parts of the Lønstrup Klint Formation and the Skærumhede Clay Formation. According to the data from the Åsted Vest borehole (Krohn *et al.* 2009; Larsen *et al.* 2009b), the layers from 30 m b.s.l. to sea level consist of the sandy upper part of the Lønstrup Klint Formation and part of the Ribjerg Formation (Fig. 4). This implies that the valleys are eroded into the Ribjerg Formation and the underlying Skærumhede Group.

The alternating high- and low-resistivity areas above sea level have irregular boundaries and cover relatively large areas (Fig. 5). These areas are interpreted as alternating sandy and clayey layers of the Morild Formation above the buried valleys.

The Morild and Lendum boreholes (GEUS no. 10.944 and 10.938) are both located inside the buried valleys (Fig. 10). In the Morild borehole, the Morild Formation extends down to 29 m b.s.l., and underneath, down to more than 100 m b.s.l., the succession is dominated by clays in the Ribjerg Formation and the Skærumhede Group (Krohn *et al.* 2009). This is inconsistent with the TEM data, which show high resistivity down to 70 to 80 m b.s.l. (Fig. 8). This may be caused by flushing of saline pore water in the sandy parts of the generally clayey Skærumhede Group underlying the valley. As this gives way to high resistivity, the buried valley appears deeper than it actually is. The Lendum borehole shows that the valley bottom is not reached at the terminal depth of 112 m b.s.l. (Krohn *et al.* 2009), which is in accordance with the TEM data (Fig. 8).

Sub-area D. – Towards the north in sub-area D, a high-resistivity buried valley structure with an E–W orientation can be seen in the interval 30 to 90 m b.s.l. (Figs 7, 8). The structure is wide in the upper parts and narrow in the deeper parts (Fig. 7). The buried valley is between 1.5 and 2 km wide at 50 m b.s.l. The Tolne borehole (GEUS no. 6.729) at the centre of the valley (Fig. 10) contains clay and fine-grained sand (Krohn *et al.* 2009). The low-resistivity layers surrounding the buried valley from 30 m b.s.l. and downwards is interpreted to represent the clayey part of the Lønstrup Klint Formation and the sediments of the Skærumhede Group below (Figs 7–9). This is confirmed by results from the Åsted Vest borehole (Fig. 4) (Larsen *et al.* 2009b).

In the southern part of the sub-area, a number of buried valleys are also seen as high-resistivity structures. Two valleys are oriented N–S and WSW–ENE. A TEM profile perpendicular to the two N–S oriented buried valleys can be seen in Fig. 9. At levels deeper than 70 m b.s.l., only the N–S valleys are seen in the TEM data, and the valley floor has apparently not been reached at 110 m b.s.l. (Figs 7, 8). The Åsted Øst borehole (GEUS no. 7.1516), located in the N–S valley to the southeast, contains a variable succession of sand, silt and clay (Krohn *et al.* 2009). The floor of the valley rises towards the south.

Sub-area E. – The buried valleys in sub-area E are seen in the TEM data as irregular areas of high resistivity from 10 to 30 m b.s.l. (Fig. 6). The valleys, locally reaching down to 60 m b.s.l. (Fig. 7) and as high as 20 m a.s.l. (Fig. 5), are arranged in two groups: 1) valleys with orientations around N–S in the northern part of the sub-area and 2) a long ESE–WNW oriented valley to the south.

The N–S oriented valleys seem to diverge towards the south. At the southern end, narrow ESE–WNW oriented bodies with low resistivities can be seen (e.g. interval 0 to 10 m b.s.l.) (Fig. 6). Some of these narrow structures occur from 30 to 40 m b.s.l. (Fig. 7) and as high as 30 m a.s.l. (Fig. 5). They are thus at least 60–70 m high and around 0.5–0.75 km in width. Downwards, the structures merge with the low resistivities of the clayey Skærumhede Group. Owing to their shape, location and orientation, the narrow low-resistivity structures are most likely glaciotectonically dislocated rafts of clay layers originating from the Skærumhede Group. The orientation of the structures coincides with a large end moraine, pointing to glacial deformation from a northerly direction. The buried valleys are oriented approximately perpendicular to the rafts and the end moraine.

The long ESE–WNW oriented valley is seen as high-resistivity areas between 0 and 40 m b.s.l. (Figs 6, 7). A borehole located on the valley flank (Astrup Nord; GEUS no. 6.783) shows the presence of predominantly clayey Ribjerg and Lønstrup formations below and the mainly sandy Morild Formation above 10 m a.s.l. (Krohn *et al.* 2009). The low-resistivity areas at levels above 20 m a.s.l. (Fig. 5) are interpreted as clay in the Morild Formation.

Sub-area F. – The TEM data show that sub-area F is dominated by a conspicuous crescent-shaped structure with low resistivities from 50 m a.s.l. to 30 m b.s.l. (Figs 5, 6). The structure broadens downwards and merges with a large area with resistivities below 10 ohmm (Figs 7, 8). The buried valleys in sub-area F are generally irregularly shaped and diffuse. They are located to the east of the crescent-shaped structure and appear as high-resistivity structures diverging towards the west. The valley floors rise towards the west, where they occasionally cross-cut the crescent-shaped low-resistivity structure at levels between 0 and 50 m a.s.l. (Fig. 5).

The Sæby borehole (GEUS no. 11.1245), situated in one of the buried valleys to the east (Fig. 10), contains the sandy part of the Morild Formation between *c.* 22 m b.s.l. and *c.* 110 m b.s.l. with the Lower Skærumhede Clay Formation underneath (Krohn *et al.* 2009). This is in accordance with the TEM soundings that show predominantly high-resistivity layers above 110 m b.s.l. and low-resistivity layers below (Fig. 8).

The buried crescent-shaped structure coincides with an ice margin described by Jessen (1936), primarily interpreted from the topography. Jessen (1936) describes a series of hills as a push moraine made up of rafts of deeper-lying clay. This description is in accordance with the TEM data, which show low-resistivity layers within the structure. The low-resistivity layers most likely represent the clayey part of the Skærumhede Group. The top of these layers is typically found around 40 m b.s.l. in the area, and because the dislocated layers occur as high as 50 m a.s.l., the vertical dislocation of the marine sediments is at least 90 m.

Sub-area G. – Elongated areas of high resistivity can also be seen in sub-area G. These areas occur below 40 m b.s.l. (Figs 7, 8); they are approximately 1 km wide and have orientations around N–S and NE–SW. Because the Skærumhede Group and the Ribjerg and Troldbjerg formations occur in boreholes inside as well as outside these high-resistivity areas (GEUS no. 17.986, 17.987, 17.992) (Krohn *et al.* 2009; Larsen *et al.* 2009b), the high-resistivity areas do not represent eroded structures and therefore cannot be interpreted as buried valleys. Water samples from the boreholes locally show high chloride contents in the pore water, and thus the resistivity variations most likely represent layers with fresh pore water side by side with layers containing saline pore water.

The distinct elongated hill, which passes through the sub-area and further to the north (Fig. 10), is crescent-shaped, asymmetric and shows suites of subparallel ridges and depressions. A large depression is located on the concave east side of the hill. This morphology has the typical characteristics of a hill-hole pair (Aber *et al.* 1989) indicating a glacier advancing from the east. In the northeastern part of sub-area G, the TEM data show low-resistivity layers parallel to the NW–SE outline of the hill (interval 10–30 m b.s.l.) (Fig. 6). The low-resistivity layers predominantly occur in the eastern parts of the hill, and are interpreted as dislocated rafts of deeper-lying clayey layers. This complies with Andersen (1961), who describes northeasterly inclined rafts of clay and sand in the uppermost layers in this area.

Relations between buried tunnel valleys and ice margins

There is a clear correlation between the location of tunnel valleys and the position of the ice margins, particularly in sub-areas E and F. This indicates that the valleys must have formed beneath the outermost kilometres of the ice sheet. The buried tunnel valleys in sub-area F rise towards the recessional moraine and terminate at the former ice margin, which suggests that the valleys formed subglacially during or immediately after formation of the recessional moraine.

In the other sub-areas, the correlation between buried tunnel valleys and the topography is less explicit, but the valleys are often located close to hill ridges and hilly areas (Fig. 10). If the valleys terminate close to the ice margin, as seen in sub-areas F and E, the terminations of tunnel valleys define former ice-marginal positions. Former ice-marginal positions can therefore be outlined on the basis of the valleys, even when the ice margins cannot be traced in the terrain.

The orientation of the buried tunnel valleys in sub-area A points to an ice movement towards the west and northwest (Fig. 10). The valleys here cannot be related to existing topographic highs, but if the valleys terminate along a former ice margin this must have been situated immediately to the west of the mapped valleys (Fig. 11B).

In sub-area B, the buried tunnel valleys cannot with any certainty be related to an ice margin in the topography. However, corresponding to sub-area A, the valleys are located close to the western rim of the hilly area (Fig. 10), and a connection with the interpreted ice margin of sub-area A is therefore proposed. The valleys in sub-area B reach the deepest levels towards the northwest and the southeast, respectively, and appear as separated high-resistivity areas from 50 m b.s.l. downwards (Figs 7, 8). The deep valley segment to the southeast is situated right underneath the pronounced hills in the eastern part of the sub-area. This valley segment possibly formed as the ice margin was in the eastern part of sub-area B.

The long ESE–WNW oriented tunnel valley in sub-area E is parallel to the margin of the ice sheet that formed the N–S valleys and is not crossed by the N–S valleys. This could imply that the ESE–WNW oriented valley is younger than the N–S oriented valleys, and was formed when the ice margin was situated to the west, just outside the mapped area.

In summary, the orientations of the buried tunnel valleys fall within two groups: a group with ESE–WNW to SE–NW orientations and a group with orientations around N–S to NE-SW. The buried tunnel valleys have been ascribed to specific ice margins on the basis of the interpretations described above. The two valley groups represent: buried tunnel valleys formed under ice margins formed at temporary standstills during the recession of an ice sheet towards the north (N) (Fig. 11A) and buried tunnel valleys formed under ice

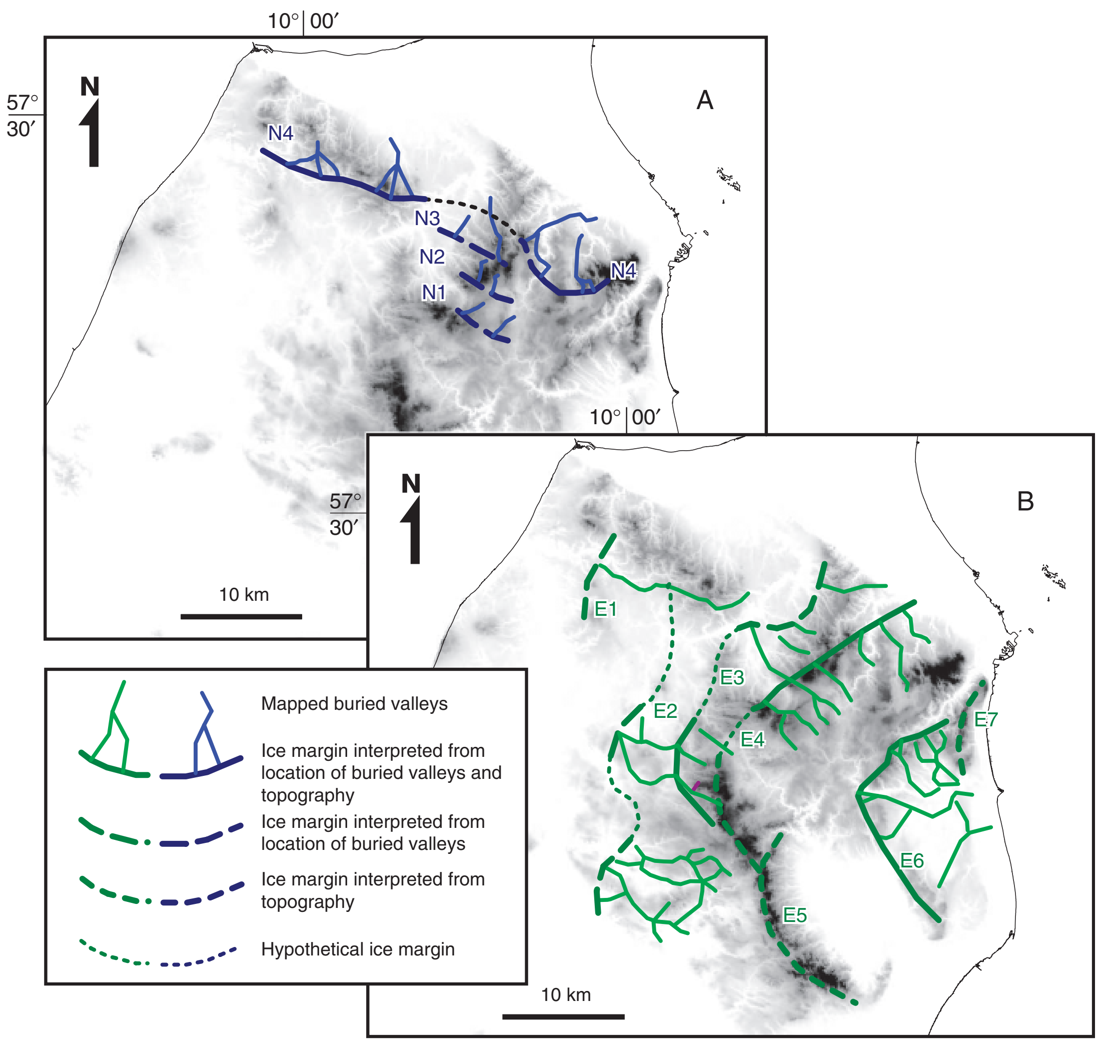

Fig. 11. Ice-margin positions inferred from buried tunnel valleys and the topography. The topography is shown as background with dark grey colours representing the highest areas (up to 136 m a.s.l.).

margins formed at temporary standstills during the recession of an ice sheet towards the east (E) (Fig. 11B).

According to the topography, the ice margins of E6 and E5 (Fig. 11B) are young and, as E6 does not show any signs of having been overridden by glaciers, this ice margin is interpreted as the younger of the two. Just northeast of E6, a very distinct N–S oriented hill is interpreted as an even younger ice margin (E7). The topographically less distinct ice margins situated further to the west and northwest pre-date the ice margins of E5, E6 and E7.

The ice margin E4 (Fig. 11B) is situated along an arc-formed series of hills. In the northern part of this ice margin, several buried tunnel valleys terminate close to the culmination of the hills. The ice margin E3 further to the west is connected to several buried tunnel valleys with a similar orientation as those connected to E4, but the expression of the ice margin in the topography here is more subtle, at least in the northern part. Further to the west, the ice margin E2 connects the buried tunnel valleys of sub-areas A and B to the same event.

The westernmost ice margin E1 (Fig. 11B) is interpreted on the basis of the ESE–WNW oriented buried tunnel valley in sub-area E. The interpretation of this ice margin is thus based on a single valley, and there is only limited topographical control.

The N–S oriented buried tunnel valleys in the southern part of sub-area D are situated close to hills towards the southwest and southeast. These hills are possibly remnants of an E–W oriented ice margin that connects with the ice margin further to the west (N4). The N–S to NE–SW oriented valleys to the south of N4 likely relate to three temporary ice margins pre-dating the N4.

Timing of the tunnel-valley formation

It has been shown that the buried tunnel valleys are eroded into the Skærumhede Group and often also into the younger Ribjerg and Troldbjerg formations. As none of the valleys are overlain by marine sediments of the Skærumhede Group, it is unlikely that the valleys were formed during the Sundsøre and the Ristinge advances and deglaciations (*c.* 65–60 kyr BP and *c.* 55–50 kyr BP, respectively). Furthermore, none of the valleys is formed in connection with the Kattegat advance *c.* 29 kyr BP, because the Ribjerg Formation is not found in any borehole within the buried tunnel valleys. Thus, all the mapped valleys appear to post-date the Kattegat advance and must be related to the Main advance *c.* 23–21 kyr BP and to the re-advance over Vendsyssel from easterly directions *c.* 19 kyr BP.

However, the formation of the buried tunnel valleys must have taken place within an even shorter time interval. The relative age of the valleys and ice margins related to the re-advance from the east (Fig. 11B) shows that the valleys formed during temporary standstills and minor re-advances during the overall recession of the ice sheet from *c.* 19 kyr to 18 kyr BP. This is contemporaneous with the deposition of the Morild Formation (Krohn *et al.* 2009). Likewise, it is suggested that the N–S valleys were formed during the deglaciation of the Main advance, contemporaneously with the deposition of the Troldbjerg Formation *c.* 20–19 kyr (Krohn *et al.* 2009). Accordingly, the four generations of the N–S valleys (Fig. 11A) and the five generations of E–W valleys (Fig. 11B) were formed between *c.* 20 and 18 kyr BP. Thus, only a few hundred years or less may have been available for the formation of the buried tunnel valleys at each ice margin.

Implications for the formation of the tunnel valleys

In places, the valleys are eroded to depths of more than 180 m b.s.l. and to widths of up to 2 km. Erosion to great depths close to the ice margin would imply large quantities of meltwater and high subglacial water pressures. Based on the investigations of buried valleys in other parts of Jutland it is considered unlikely that the formation of such large valleys took place in one single meltwater outburst (Jørgensen & Sandersen 2006). For the Danish and German tunnel valleys, the difficulty of explaining kilometre-wide tunnels below the glacier has been the subject of discussion in the literature. Nordmann (1958) believed that the wide valleys were eroded by laterally migrating small streams on the valley floor. This hypothesis was further elaborated by Smed (1962, 1998), Krüger (1989) and Huuse & Lykke-Andersen (2000).

Jørgensen & Sandersen (2006) suggested that tunnel valleys in Denmark were generated by repeated erosion of meltwater in channels of limited dimensions within a larger valley tract. The individual meltwater channels subsequently became closed by ice as the water pressure dropped. Repeated outbursts of meltwater would then be able to erode successively broader and deeper ice-filled valley structures.

As we have no indications that the tunnel valleys in Vendsyssel differ from those typically observed in Denmark, the hypothesis of Jørgensen & Sandersen (2006) may also be valid for the formation of the valleys in this study. If valleys of the described dimensions are formed along each of the outlined ice margins within a few hundred years, the valley erosion must be a result of powerful and recurring outbursts of meltwater. The hypothesis implies that the eroded valleys became exposed and subject to proglacial infilling as the ice sheet retreated. This is supported by investigations of the infill sediments showing proglacial rather than subglacial sedimentation (Krohn *et al.* 2009).

There is a remarkable difference between the E5 and E6 ice margins, because several tunnel valleys have been formed along the E6 ice margin, whereas no valleys are found along the E5 ice margin (Fig. 11B). However, the E5 ice margin is probably only a few hundred years older than the E6, and the expressions of the two ice margins in the topography share many similarities. There is also a difference in the lithological composition of the recessional moraines. The end moraine of E5 comprises the predominantly sandy Troldbjerg Formation (Krohn *et al.* 2009), whereas the end moraine of ice margin E6 is predominantly composed of clayey parts of the Skærumhede Group.

Studies by, for example, Piotrowski (1997a, b) have shown that the hydraulic conductivity of the substratum plays an important role in the control of tunnel-valley formation beneath glaciers. It is likely that the absence of valleys along the coarse-grained E5 can be explained by sufficient drainage of subglacial meltwater through the coarse-grained layers under the ice margin. This would have prevented high subglacial water pressures and storage of subglacial meltwater at this specific ice margin, and consequently less meltwater erosion occurred here.

A large number of buried valleys in Denmark have been used as preferred pathways for meltwater drainage beneath successive ice sheets (Jørgensen & Sandersen 2006). None of the buried valleys in Denmark have hitherto been dated precisely, mainly because of extensive re-use of valley pathways (Sandersen & Jørgensen 2003); the exact time of the tunnel-valley formation therefore remains undetermined. Only relative ages between valleys and minimum ages, determined on the basis of the infill sediments, have been estimated (e.g. Sandersen & Jørgensen 2003).

The buried valleys in Vendsyssel are unique, because they can be attributed to the recession of two specific Late Weichselian ice advances, and because the individual valleys represent erosive episodes during temporary standstills over a time span of a few hundred years or less. As the valleys are attributed to the recession of the last ice sheet, no extensive re-use of the valleys has taken place.

Conclusions

- A relation between the resistivities measured by the geophysical methods and the lithostratigraphical formations has been established.
- The TEM data combined with results from geophysical well logging have provided an overview of the spatial distribution of predominantly high-resistivity buried valleys surrounded by generally thick and regionally distributed low-resistivity sediments.
- The buried tunnel valleys are typically 5–10 km long, 1 km wide and are locally eroded to depths of more than 180 m b.s.l.
- The TEM surveys have provided evidence of glaciotectonically dislocated layers in recessional moraines. At some locations, the morphology and the lithology of the recessional moraines are clearly seen in the TEM data and in the topography, showing a causal relationship between the location of the tunnel valleys and the position of the ice margin.
- The buried tunnel valleys formed by subglacial meltwater erosion beneath the outermost kilometres of the ice sheet, most likely during temporary standstills and minor re-advances during the overall recession of the ice sheet.
- Formation of the tunnel valleys is constrained to the deglaciation of the Main advance and to the re-advance from easterly directions within the time interval *c.* 20 to 18 kyr BP.
- Based on the occurrences of the buried tunnel valleys and the topography, four ice-marginal positions have been interpreted during the deglaciation of the Main ice advance from the north and seven ice-marginal positions during the deglaciation of the re-advance from the east.
- All buried tunnel valleys were formed within a time interval of a few thousand years, giving only a few hundred years or less for the formation of the buried tunnel valleys at each ice-marginal position.
- Formation of the buried tunnel valleys is suggested to be the result of repeated outbursts of meltwater that eroded narrow subglacial meltwater channels within larger valley tracts. When the water pressure decreased after each outburst, the meltwater channels were closed by ice and broader and deeper valley structures were gradually formed.

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