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Buried and open tunnel valleys in Denmark—erosion beneath multiple ice sheets

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Abstract

Tunnel valleys are large, elongate and irregular depressions cut beneath the margin of former ice sheets. They are generally believed to play a substantial role for the entire hydraulic system beneath ice sheets and thus also for ice sheet behaviour. Their origin, however, remains poorly understood. Examination of newly collected Danish hydrogeophysical and lithological data has revealed numerous systems of buried valleys 50–350 m deep and 0.5–4 km wide. These valleys are similar to the open tunnel valleys found in the present-day landscape. Infills comprise a variety of sediments often with subglacial clay till and meltwater deposits. The incised substratum consists of limestone, heavy Paleogene clay, sand and silt. The tunnel valleys have preferred orientations and can be divided into several generations, each ascribed individual ice advances or ice sheets occurring during multiple glaciations. The processes forming the valleys appear to prefer pre-existing (open and buried) valleys for the renewed erosion. Thus, old subglacial erosion pathways have been re-used several times, and some of the present tunnel valleys may have been established in the middle or early Quaternary or even earlier. This valley-re-use effect causes apparently anastomosed valley systems to emerge in the data images. The valleys were mainly eroded by meltwater supposed to have drained from subglacially stored reservoirs, probably behind a frozen margin. The water was most likely released in repeated jökulhlaups and flowed in relatively small channels on the floors of the tunnel valleys, which gradually became ice-filled with the lowering of the bed. Selective linear, glacial erosion is also believed to have contributed to the erosion. This, however, was most pronounced for the widest valleys and is supposed to have played a secondary role.
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1. Introduction

Tunnel valleys are large elongated depressions of subglacial origin cut into both unconsolidated sediments and bedrock (e.g. ÓCofaigh, 1996). They occur with undulating longitudinal profiles and contain sections that slope upwards, sometimes to be terminated at the apex of an outwash fan. They are generally believed to have served as major subglacial drainage pathways for large volumes of meltwater, and are thus supposed to play a substantial role for the entire hydraulic system beneath glaciers. Because glacier behaviour largely reflects the subglacial hydraulic regime, the understanding of how tunnel valleys form and act is of crucial importance for the reconstruction and understanding of former ice sheets.

Tunnel valleys have been discussed intensely for more than a century, and agreement as to how they were formed remains poor. However, recent years have seen new research into this area owing both to a growing interest in subglacial processes and to the growing sophistication of investigation methods (e.g. geophysical and computational). Tunnel valleys are found in the present-day landscape and in the subsurface where they were created by the European Pleistocene ice sheets (e.g. Woodland, 1970; Ehlers et al., 1984; Ehlers and Linke, 1989; Huuse and Lykke-Andersen, 2000) and by the Laurentide Ice Sheet of North America (e.g. Wright, 1973; Mullins and Hinchey, 1989; Patterson, 1994; Clayton et al., 1999). However, tunnel valleys have also been formed elsewhere in the world, for instance beneath Paleozoic ice sheets as

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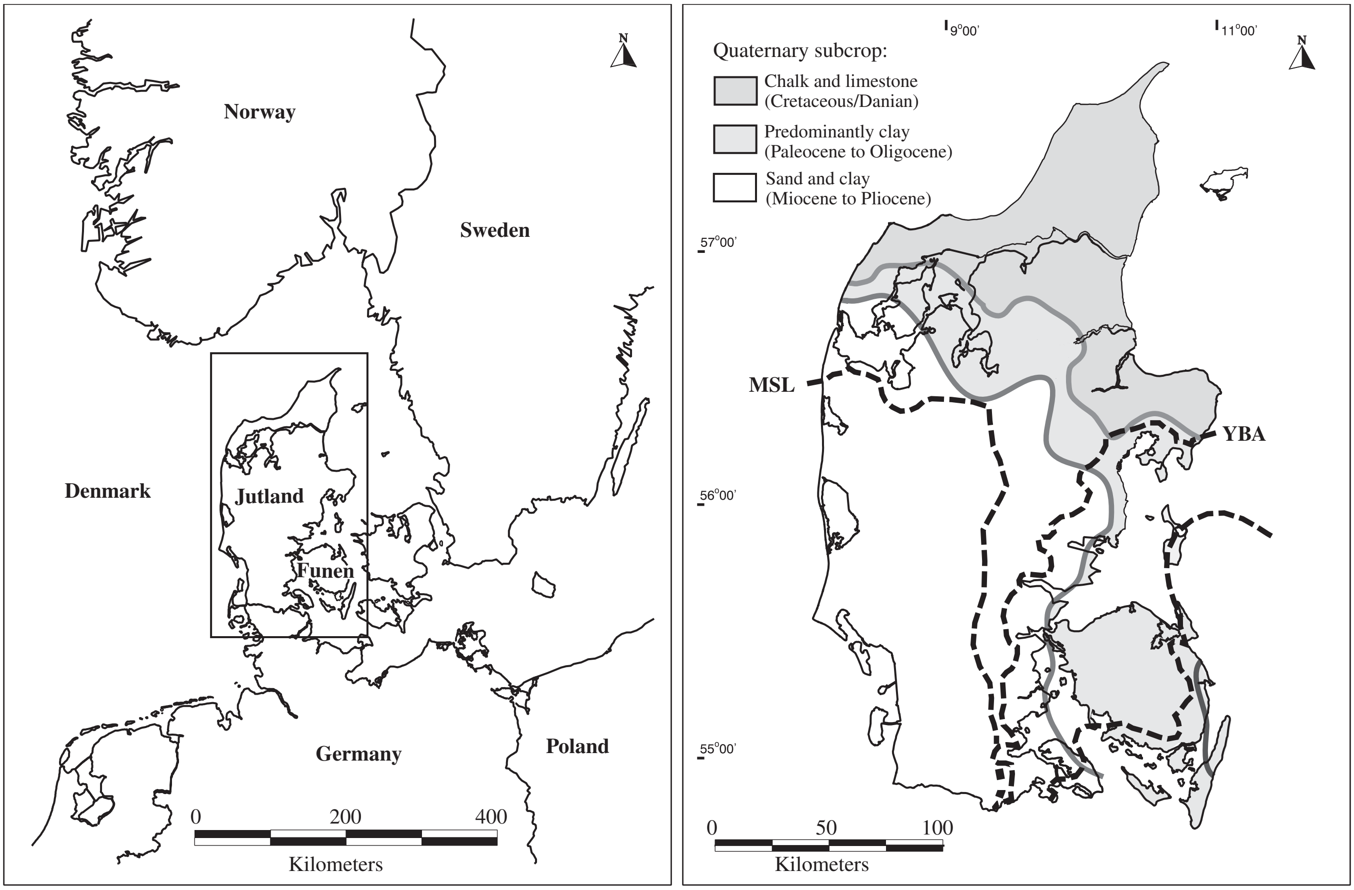


Fig. 1. Study area and the Quaternary subcrop. Dashed lines show major ice marginal lines. MSL: Main Stationary Line. YBA: Young Baltic Advance. Quaternary subcrop after Sorgenfrei and Berthelsen (1954).

reported by e.g. Visser (1988), Hirst et al. (2002), Eyles and de Broekert (2001) and Ghienne and Deynoux (1998). The difficulty of investigating tunnel valley formation processes lies mainly in the inaccessibility of the subglacial environment, but also in the fact that the conditions favouring these processes seem to be restricted under the present climatic conditions. The discussion of the tunnel valley formation processes mainly focuses on whether the valleys were eroded by subglacial meltwater or by a combination of meltwater and glacier ice erosion, and whether the eroding meltwater was discharged in catastrophic outbursts or by steady-state flows (cf. ÓCofaigh, 1996). Strong evidence backs these theories, and it is likely that there is no universal tunnel valley formation mode and that the valleys have a polygenetic origin (e.g. Huuse and Lykke-Andersen, 2000).

In this paper, we show the characteristics of buried valleys in Denmark (Fig. 1) by using newly collected hydrogeophysical data combined with lithological data. These are compared with the open tunnel valleys as described by other authors (e.g. Ussing, 1903, 1907; Milthers, 1935b, 1948; Nordmann, 1958; Smed, 1962, 1998; Nielsen, 1967; Sjørring, 1979). We find that the buried valleys and the open tunnel valleys share the same characteristics and most likely also the same origin. Tunnel valley genesis is discussed and a model for their origin is proposed.

2. Terminology

The term *tunnel valley* was coined by Madsen (1921) to describe subglacially melt-water-eroded valleys in Denmark as interpreted by Ussing (1903, 1907). These tunnel valleys are open features, but the term *tunnel valley* has also been used for buried features (e.g. Woodland, 1970).

The term *tunnel valley* is not entirely unproblematic and several objections have been raised against its use. A ‘valley’ is, for example, supposed to have a falling thalweg, but tunnel valleys defy this feature (Ehlers and Wingfield, 1991). A ‘valley’ is also expected to be occupied by a small stream on the valley floor only and not by a bank-full flow implied in the term ‘channel’. The terms *tunnel valley* and *tunnel channel* are often used synonymously, but Clayton et al. (1999) proposed that the latter should be used for elongate depressions subglacially carved by bank-full discharges, whereas the former should be used for elongate depressions carved by small subglacial conduits considerably narrower than the depression. According to Wingfield (1990), a ‘channel’ should be viewed as a continuous depression without closed endings, which is one of the main tunnel valley characteristics. The more neutral expression 'incisions' is accordingly preferred by Wingfield (1990), Ehlers and Wingfield (1991) and others. This term, however, implies that the features have been incised, but because at least one important theory for tunnel valley genesis addresses sediment deformation and not pure erosion (Boulton and Hindmarsh, 1987), this term is inadequate like the other proposed terms.

The well-known and widely used term *tunnel valley* has been used for almost a century to describe subglacially formed valleys. We accordingly prefer to use this term for the buried and open valleys of inferred subglacial origin in Denmark. The term 'channels' will be used for smaller melt-water-occupied, sediment-walled conduits (cf. Nye, 1973), and 'cut-and-fill structures' for larger erosive structures seen within the tunnel valleys.

3. Previous work on tunnel valleys in Denmark

The early descriptions of Danish tunnel valleys focused on valleys in the middle part of Jutland (Ussing, 1903, 1907), which were described as elongate depressions with undulating longitudinal profiles containing hollows and thresholds and without a continuously falling thalweg. Close to the maximum ice limit (the Main Stationary Line (MSL, Fig. 2)) at the Last Glacial Maximum (LGM) they were found to rise several tens of metres before terminating in large outwash fans. These characteristics constituted the basis for the theory that the tunnel valleys were formed by subglacial meltwater erosion driven by hydrostatic pressure gradients. It was also stated by Ussing that they were not buried by sediments during ice recession owing to dead ice abandoned in the valleys. Ussing's theory on tunnel valley formation was generally accepted for a long period (e.g. Andersen, 1931, 1933; Milthers, 1935, 1948; Nordmann, 1958; Smed, 1962; Nielsen, 1967). Parts of the theory, however, have been subject to further development. Andersen (1933) proposed that at least some of the valleys were established by earlier tectonic movements and later reshaped and overdeepened by the subglacial streams. Nordmann (1958) found it difficult to explain kilometre-wide tunnels below the glacier ice, and believed that the wide valleys must have been eroded by laterally migrating small streams on the valley floor. He proposed that the erosion could have been caused by one small stream steadily forced to move laterally due to blocking from falling ice blocks or by multiple streams flowing either parallel to each other or in anastomosing networks. This hypothesis was also advanced by Smed (1962), and recently further developed by Krüger (1989) and Smed (1998). Both Nordmann (1958) and Smed (1962) documented the potential of dead ice preservation of tunnel valleys.

The assumed problem of tunnel valleys too wide to be occupied by bank-full discharges was approached by Hansen (1971) in a different way. Based on a theory developed by Woldstedt (1952) and Gripp (1964), he proposed that the Danish tunnel valleys were mainly previously existing valleys subjected to direct glacial erosion and modification by outflowing glacier tongues. The influence from direct glacial erosion on previously existing valleys has later been supported by many Danish researchers (e.g. Berthelsen, 1972; Lykke-Andersen, 1973, 1986, 1988; Sjørring, 1979; Larsen and Kronborg, 1994); most of whom, however, also believed that meltwater erosion occurred as a secondary erosional agent. A mechanism that included the occurrence of permafrost was proposed by Berthelsen (1972) and Krüger (1983), who thought that restrained development of permafrost underneath previously existing valleys would intensify glacial erosion here in preference to the more deeply frozen higher ground outside the valleys.

The Danish glacial morphology has been thoroughly mapped by Smed (1979,1981a, b, 1982). Except for very small tunnel valleys that cannot be expressed by the scale of these maps (1:357 000), all Danish tunnel valleys (as inferred by Smed) are included. Recently, Smed continued the discussion of the mode of tunnel valley erosion by presenting evidence for the subglacial meltwater theory (Smed, 1998).

Sorgenfrei and Berthelsen (1954), Lykke-Andersen (1973, 1986, 1988), Lykke-Andersen and Schrøder (1974), Schrøder (1974), Kronborg et al. (1978) and others provided early descriptions that several of the large tunnel valleys were overlying deeper buried valleys. More recently, maps of the pre-Quaternary surface have confirmed that buried valleys are not only located beneath existing tunnel valleys (e.g. Binzer and Stockmarr, 1985,1994; Lykke-Andersen, 1988). The large amounts of newly collected hydrogeophysical data in Denmark, however, have made it possible to delineate and investigate buried valleys more thoroughly during the last 5–10 years. Careful examination of these data has revealed dense buried valley networks and thus improved our understanding of the upper part of the Danish subsurface (Sandersen and Jørgensen, 2003; Jørgensen and Sandersen, 2004; Jørgensen et al., 2005).

Also recently, Huuse and Lykke-Andersen (2000) presented buried valleys from the North Sea close to the Danish coast. These valleys were interpreted by the authors as subglacial tunnel valleys possibly connecting with buried onshore valleys; however, no data are available to validate this assumption. The valleys in the North Sea were mapped using seismic data alone, and no direct lithological information is therefore available. The scarcity of lithological information offshore, contrasts with the richness of such information onshore.

4. Regional geological setting

Denmark is characterized by large outwash plains, gently undulating moraines and diversified hummocky landscapes. At its maximum, the landscape rises to 173 m above sea level. The Quaternary subcrop of Denmark consists of limestones and chalk in the northern and eastern parts, heavy Paleogene clays in a zone from

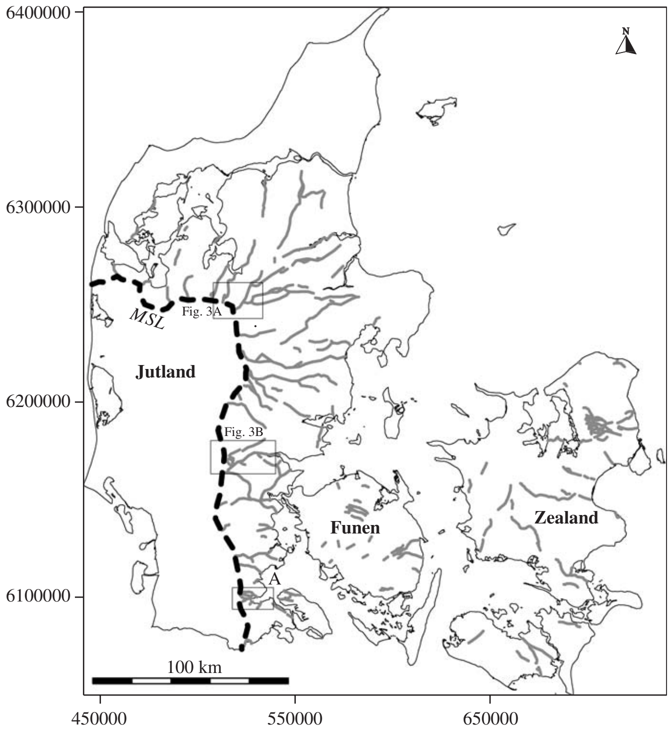


Fig. 2. Large, open tunnel valleys in Denmark (after Smed, 1979; 1981a, b; 1982). The tunnel valleys in Jutland terminate at the MSL. Some of the tunnel valleys on Funen and Zealand terminate at small outwash fans. Locations of tunnel valleys shown in Fig. 3 are indicated. Aabenraa Fjord is marked by the letter A. Coordinate system in metres (UTM zone 32/ED 50).

northwest towards southeast, and Neogene sands, silts and clays to the southwest (Fig. 1). The pre-Quaternary surface is covered by Quaternary sediments with a general thickness of 5–100 m. In most places, the surface of the pre-Quaternary sediments lies between 50 m below and 50 m above sea level, even if deviations from this general pattern are occasionally large (Binzer and Stockmarr, 1994).

The Quaternary sediments mainly comprise glacial and glaciofluvial sediments, but interglacial deposits also occur in scattered locations. Pre-Elsterian deposits have been described, but only at few localities (Andersen, 1965, 1979; Kronborg et al., 1990; Larsen and Kronborg, 1994). Deposits from the subsequent Elsterian and Saalian glaciations are more widespread and document at least three ice advances in each of the glaciations (Houmark-Nielsen, 1987; Larsen and Kronborg, 1994). Wide-spread occurrences of glaciolacustrine and glaciomarine clays from the Late Elsterian often followed by marine sediments from the Holsteinian are found in northwest and southwest Jutland (Jensen, 1985; Bruun-Petersen, 1987; Knudsen, 1987a, b; Ditlefsen, 1991). Holsteinian and Eemian freshwater deposits as well as Eemian marine deposits are also found at several locations (Andersen, 1965, Houmark-Nielsen, 1987; Knudsen, 1994; Larsen and Kronborg, 1994).

Denmark was totally covered by the glaciers several times during the Pleistocene (Houmark-Nielsen, 1987; Larsen and Kronborg, 1994). Some glaciers came through the Baltic depression thus overriding Denmark from southeasterly directions, whereas others came from northern or northeastern directions. Till fabric, striations and glaciotectonic deformation indicate Weichselian ice advances from directions ranging from north over east to south–southeast (Larsen and Kronborg, 1994; Houmark-Nielsen, 1999, 2003; Houmark-Nielsen and Kjær, 2003; Kjær et al., 2003). During the LGM, the ice sheet covered the northern and eastern part of Denmark from northeastern directions. The ice margin (MSL) was situated from south to north through Jutland to the upper middle part of the peninsula where it bends and makes a right angle E–W turn towards the North Sea (Figs. 1 and 2). Large outwash plains were formed in the proglacial environment and tunnel valleys were incised in the subglacial environment (Ussing, 1903,1907; Smed, 1998). Before retreating entirely, the ice sheet readvanced several times (Harder, 1908; Smed, 1962; Houmark-Nielsen and Kjær, 2003). During the first major readvance, the Young Baltic Advance (YBA; Fig. 1), an ice stream moved rapidly across the north-eastern part of Funen, indicating a subglacial environment dominated by basal water pressures close to the flotation point (Jørgensen and Piotrowski, 2003). This is in contrast to the behaviour of the Main Advance, where the flow has been claimed to be slower (Kjær et al., 2003).

5. Database and methods

5.1. Data

Buried valleys are mapped primarily on the basis of comprehensive geophysical and lithological data collected by the Danish counties. These data mainly comprise TEM data, shallow seismic data and borehole data. The primary aim for the counties to collect the data is to delineate site-specific groundwater protection zones with a view to regulating land use and securing groundwater protection (Thomsen et al., 2004). They therefore need spatially dense, high-quality geophysical data to supplement existing borehole data. To our knowledge, Denmark is the first country to launch a mapping campaign of this magnitude. The mapping of buried valleys is continuously updated and extended in ongoing studies performed by the counties in Jutland and Funen (Sandersen and Jørgensen, 2003; Jørgensen and Sandersen, 2004; Jørgensen et al., 2005).

Procedures, techniques and methodology used for the delineation of the buried valleys have been described in Jørgensen et al. (2003a–c), Sandersen and Jørgensen (2003) and Jørgensen et al. (2005), and will only be briefly mentioned here. Measurement and comparison of the buried valleys is performed by using a fixed set of criteria. The most important criterion used is that the lateral extent and the orientation of the valleys must be unambiguously expressed in the data. Accordingly, no extrapolations between surveyed areas and no delineations of valleys on the basis of topography have therefore been made.

The open tunnel valleys used for comparison in this paper originate from the maps produced by Smed (1979, 1981a, b, 1982) and from new topographic maps in scales of 1:25 000 and 1:100 000 (National Survey and Cadastre). Digital elevation models have been constructed on the basis of elevation data in 25×25 m grids (National Survey and Cadastre).

5.2. Boreholes

The national archive of well data, *Jupiter*, served by the Geological Survey of Denmark and Greenland comprises water well construction reports, lithological logs, and hydraulic data, among other data sets. Due to a generally poor spacing between the boreholes, the well data only precisely delineates buried valleys at a limited number of locations, but the borehole data can usually be used to verify the presence of valleys delineated from geophysical data. The well data give valuable information about the valley-fill properties of the mapped valleys.

Existing well data have been supplemented by data obtained from new exploratory drillings performed in buried valleys. Serving hydrogeological investigatory purposes, these drillings were performed by the air-lift drilling technique, which can produce useful samples for the construction of detailed lithological logs (Jørgensen et al., 2003b). All exploratory drillings were logged with gamma and resistivity tools.

5.3. Transient electromagnetic data (TEM)

The TEM method is widely used in Danish hydrological surveys (Thomsen et al., 2004). TEM surveys are performed with different instrumentations, especially the conventional 40×40 TEM, the HiTEM, the PATEM and the SkyTEM methods (e.g. Danielsen et al., 2003; Sørensen and Auken, 2004). The penetration depth varies between 120 and 250–300 m depending on the instrumentation and the lithology. Since the resolution capability of the TEM method decreases with depth, only thick layers can be resolved at large depths. The method is particularly useful for mapping of electrically conducting layers and surfaces like Paleogene clay or glaciolacustrine clays in Denmark. The TEM data are inverted by one-dimensional modelling into sounding models containing 2–5 layers (Effersø et al., 1999). Their use for the construction of geological models and mapping of buried valleys is thoroughly described in Jørgensen et al. (2003c, 2005). The electrical resistivities are normally below 12 Ω m for Paleogene clay layers, between 15 and 40 Ω m for glaciolacustrine clay, between 30 and 60 Ω m for clay till and above 60–80 Ω m for sandy, gravely and limestone layers.

5.4. Reflection seismic data

Over the last few years the counties have performed multi-channel seismic reflection surveys to supplement the hydrogeological models. These surveys are either performed using dynamite and grounded geophones, or by a towed land-streamer system with a vibrator as the energy source (Doll et al., 1998; Veen and Green, 1998; Vangkilde-Pedersen et al., 2003). Both methods are capable of resolving the outline of valley structures and, under ideal circumstances, the internal structures of the infill as well (e.g. Jørgensen et al., 2003b). The buried valleys are generally identified by the presence of lateral changes in seismic reflection patterns, truncation of underlying strata and onlapping infill strata.

Onshore seismic investigations generally produce poorer data quality than offshore investigations, which hampers their geological interpretation. In combination with borehole and TEM data, it is, however, possible to construct detailed geological models (Jørgensen et al., 2003a, b). A combination of the different data sets hence provides the best basis for mapping of buried valleys.

6. Open tunnel valleys—description

6.1. Occurrence and patterns

Fig. 2 shows the open tunnel valleys in Denmark as mapped by Smed (1979, 1981a, b, 1982). In the northwestern part of Denmark, the valleys are generally arranged in a convergent pattern pointing towards the sharp re-entry into the MSL and further south they head more or less perpendicular to the MSL. The large tunnel valleys are most pronounced in Jutland, but smaller tunnel valleys are also evident on Funen and Zealand (e.g. Andersen, 1931; Milthers, 1935; Smed, 1962; Nielsen, 1967). Most tunnel valleys in Jutland terminate at the apex of large MSL outwash fans (Ussing, 1903, 1907; Smed, 1998), whereas the island valleys usually terminate into small outwash plains in front of recessional lines. Some valleys, however, lack the relation to outwash plains. Valleys with general rising thalwegs towards the terminus at the ice margin can be observed in some cases.

Digital elevation models of two large tunnel valleys in Jutland are shown in Fig. 3. The first valley (A) is the otherwise thoroughly described example of Hald Sø (i.e. Ussing, 1903, 1907; Milthers, 1948; Woodland, 1970; Hansen, 1971; Smed, 1998) and the second valley (B) is Vejle Tunnel Valley (Milthers, 1925; Nordmann, 198); both terminating at large outwash fans at the MSL.

The open tunnel valleys typically appear as individual, segmented elements. At some places, however, they branch and join, and apparently anastomosing patterns occasionally seem to occur. Individual segments can be up to 30 km long, but mostly do not exceed 20 km. In Jutland, the individual segments are in general aligned in chains with total lengths reaching 70 km. Most tunnel valleys can be described as rectilinear or slightly sinuous, occasionally showing abrupt, but low-angle bends.

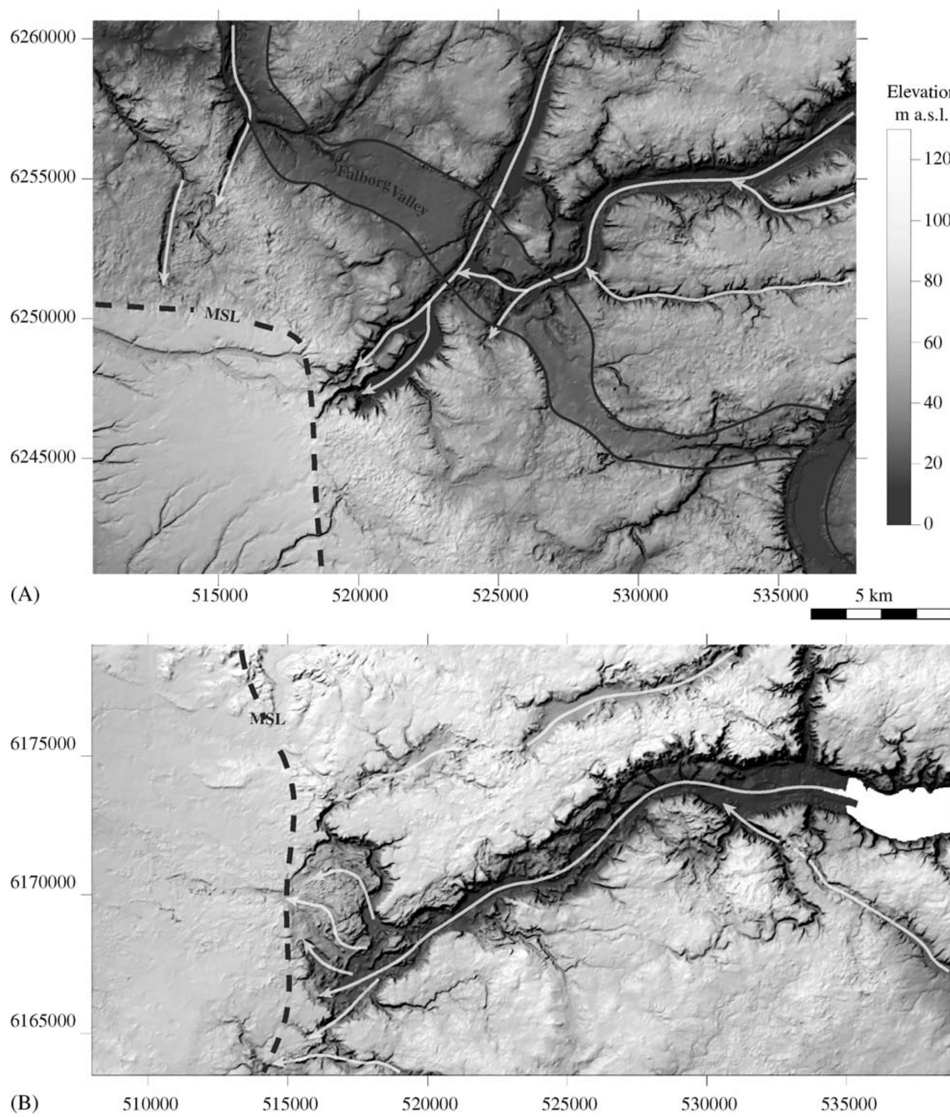


Fig. 3. Digital elevation models showing two examples of open tunnel valleys in Denmark. (A) The Hald Sø area. (B) Vejle Tunnel Valley. See Fig. 2 for locations. Grey arrow-lines indicate inferred meltwater flow pathways. The younger proglacial Falborg Valley is delineated in A. *Data source*: National survey and Cadastre (KMS). Coordinate system in metres (UTM zone 32/ED 50).

6.2. Morphology

Maximum depths of open tunnel valleys reach about 80 m, but in general they are not more than 20–60 m deep. Valley width is often 0.5–1.5 km, but may range up to 4 km (see detailed examination below). Their cross-sections can be described as U-shaped with rather steep sides and flat floors, and most often they contain postglacial streams in parts of the valley. The hollows along the irregular tunnel valley floors are normally occupied by lakes or bogs. Small valleys or channels, sometimes observed on the floor of the main tunnel valley, have been referred to as 'handles' in cases where they branch and rejoin the main valley (Smed, 1998, Fig. 14). They have been thought to produce the relatively frequent pseudo-eskers within the tunnel valleys (e.g. Milthers, 1948; Smed, 1962). The pseudo-eskers are interpreted as erosional remnants between two channels incised parallel and close to each other.

Many eskers seem to co-exist with tunnel valleys (Andersen, 1931; Milthers, 1935, 1948; Nielsen, 1967; Smed, 1979, 1981a, b, 1982, 1998; Krüger, 1983). They are often confined to the pathways of individual valleys; sometimes following the valley floors, sometimes lying upon their shoulders, and occasionally crossing valleys at rather sharp angles. Sometimes, eskers seem to replace a piece of a tunnel valley if the tunnel valley disappears over a short distance (e.g. Andersen, 1931; Milthers, 1948; Smed, 1962, 1979, 1981a, b, 1982, 1998). The relationship between eskers and tunnel valleys is most pronounced for the small tunnel valleys on Zealand, Funen and the eastern part of Jutland, which was covered by the Young Baltic Advance and later readvances. Outside these areas eskers are infrequent.

Several authors have shown that many of the Danish tunnel valleys were occupied by remnants of dead ice subsequent to their formation (e.g. Ussing, 1907; Andersen, 1931; Smed, 1962). The dead ice prevented the valleys from being filled by outwash deposits from the receding glacier and perhaps from later readvances. An example of such preservation of valleys by dead ice can be observed in Fig. 3A. The Falborg Valley is crossed by two tunnel valleys and subsequently, during ice recession, it was partly filled by outwash. Pro-glacial meltwater streams must have crossed the two tunnel valleys at higher levels, while dead ice occupied these valleys shortly after recession from the MSL (Ussing, 1907; Milthers, 1935a). Subsequently, the covering outwash plain in the Falborg Valley collapsed into the tunnel valleys during decay of the dead ice. A similar example of tunnel valleys preserved by dead ice in Poland has been described by Galon (1983).

7. Buried valleys—description

7.1. Occurrence

All buried valleys mapped in accordance with the criteria described above are shown in Fig. 4. Their distribution presented on the map, however, does not reflect their real distribution in Denmark, because (1) no interpolation between the identified valleys has been made, (2) the density of useful data is unevenly distributed, (3) regional variations in the character of the subsurface (Fig. 1) make it difficult to achieve distinct results with the geophysical methods and to interpret borehole logs in some sub-areas. The map accordingly offers only a fractured picture of the buried valleys. In areas where the valleys are easily identified, the density often appears to be high. Such areas can for instance be observed northwest of Aarhus (Fig. 5) and on the island of Mors (Jørgensen et al., 2005). A very high data density is required for delineating the outline and orientation of the buried valleys in complicated systems like these and obviously it is impossible to establish the connection between individual buried valleys from different survey areas.

Some buried valleys seem to be arranged in anastomosing networks, whereas others occur as individual elements. Apparently anastomosing networks are seen at several locations (Fig. 4) and typically appear in the morphology of the incised substratum. The completely buried Hornsyld Valley (Fig. 6A), which primarily is incised into Paleogene clay layers, appears to form such an apparently anastomosing network. However, as shall be shown below, this network consists of a series of individual incisions. Individual valleys can be characterized as rectilinear to slightly sinuous (e.g. Figs. 6 and 8), even if abrupt low-angle bendings can occasionally be observed.

7.2. Morphology

At some locations the depths of the buried valleys are recorded to exceed 300–350 m, but most of the valleys are between 100 and 200 m deep. Valley longitudinal profiles are highly irregular with multiple occurrences of lows and thresholds (Figs. 5 and 6). Differences between highs and lows along the valley floors can exceed 50–100 m (Fig. 6C). It is difficult to describe a general longitudinal profile trend for the valley floors, but in some valleys it has been observed that the deepest part is situated close to the southerly or westerly ends of the valleys (Figs. 6A and B).

The valley width is often 0.5–1.5 km, but it may range up to around 4 km (see detailed examination below). Valley lengths are difficult to determine from the data, because the individual valleys mostly extend beyond the relatively small survey areas. However, where large-scale surveys have been carried out, or where valley extensions over longer distances have been mapped by other means, they can be followed for up to 25–30 km (Fig. 4). Shorter valleys of only a few kilometres in length also appear. A rather conspicuous characteristic of the buried valleys is that they sometimes terminate abruptly. At Stilling (Fig. 6B) the over 100 m deep valley terminates over a distance of 1–2 km.

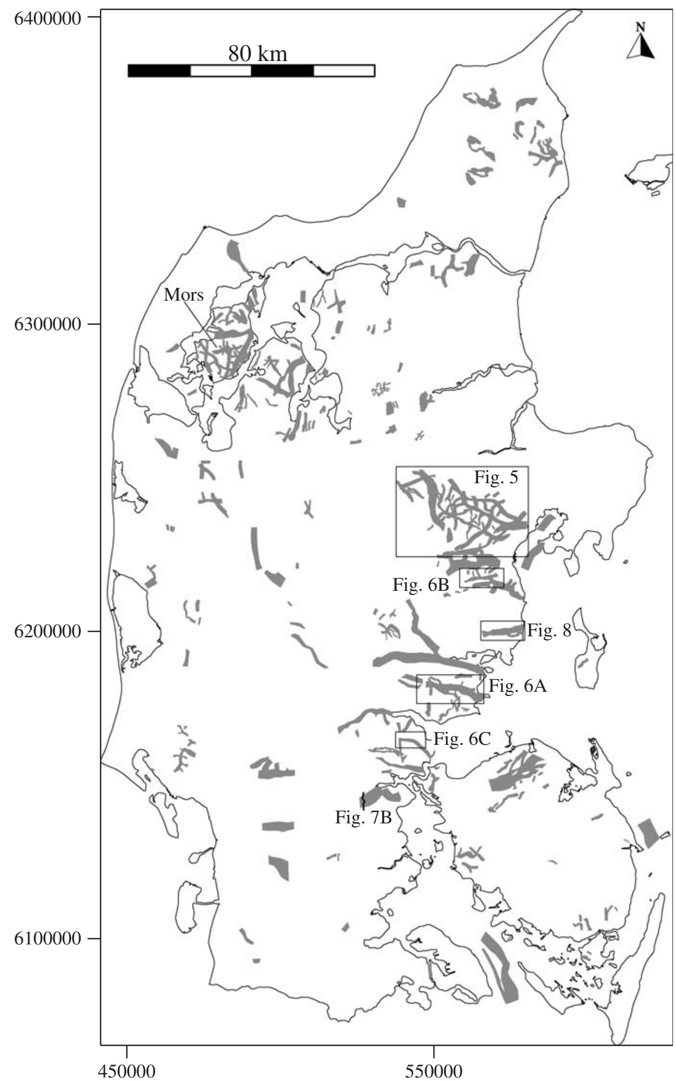


Fig. 4. Mapped buried valleys in Jutland and Funen. Locations of the described buried valleys in Figs. 5, 6, 7 and 8 are indicated. Coordinate system in metres (UTM zone 32/ED 50).

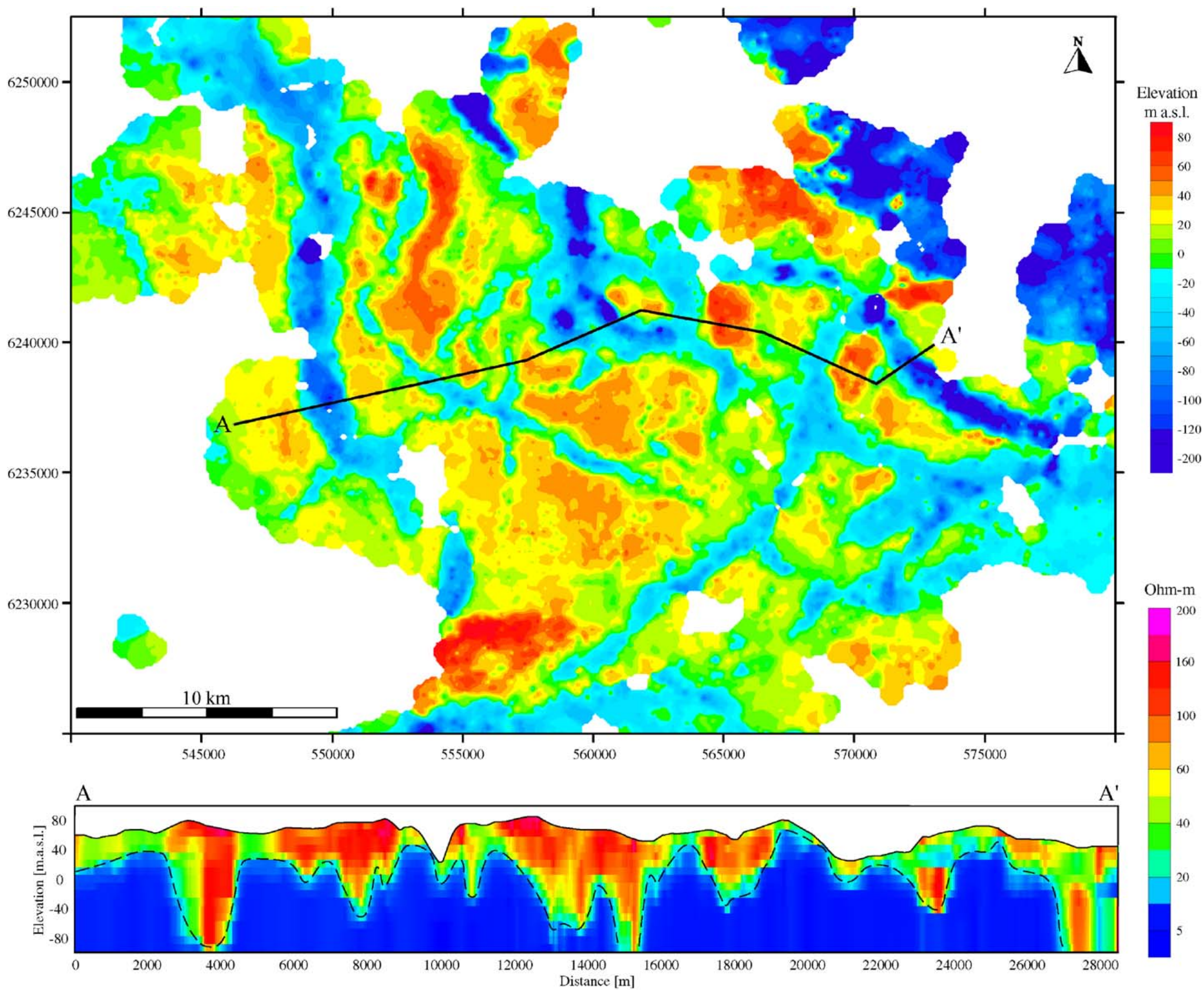


Fig. 5. Contoured surface of the low-resistive bottom layer ($<12\,\Omega$m) in all 1-D TEM sounding models in the area NW of Aarhus (1100 km^2), see Fig. 4 for location. The surface largely coincides with the surface of the Paleogene clay and the pre-Quaternary surface. Kriging with 500 m search distance and 100 m cell spacing is used for contouring. A profile section A–A′ through the area is seen below the contour map. The resistivity distribution above the low-resistive layer is shown by the cross-section, in which a succession of 10-m interval resistivity grids calculated from the TEM sounding models is cut. Buried valleys are clearly seen to cut the subsurface. They are mainly filled with coarse-grained meltwater sediments as indicated by the high resistivities. *Data source*: The counties of Viborg and Aarhus. Coordinate system in metres (UTM zone 32/ED 50).

Some valley cross-profiles are U-shaped and generally have steep sides and rather flat or curved floors (e.g. Figs. 7A,B and 8). Other cross-profiles, however, are more V-shaped than U-shaped (e.g. Fig. 5). The inclination of the valley sides cannot be precisely detected by TEM (Danielsen et al., 2003), but steepness estimates can be given. Based on the TEM soundings, the sides of the Stilling valley (Fig. 6B) can be measured to 20–25°, but this inclination is a minimum value, which, in reality, may be somewhat higher. Steeper slopes than those occurring in the TEM surveys have been observed in seismic surveys (e.g. the Vonsild Valley, Fig. 7B), but determination of exact inclinations in seismic data is problematic, too (e.g. Badley, 1985). We evaluate that valley slopes in general vary in steepness; from rather gentle slopes, as for instance for some segments of the Hornsyld valley (Fig. 6A), to steep slopes of 45° or more.

7.3. Internal structures

The examination of the geophysical data has shown that the buried valleys often are composed of a series of cut-and-fill structures. Such structures can only be observed in high-quality data. When observed, 2–4 sets of cut-and-fill structures can often be distinguished. Cut-and-fill structures can be seen in Fig. 7A showing a crossing seismic section of the Hornsyld Valley. The seismic interpretations presented in the figure have been supported by TEM

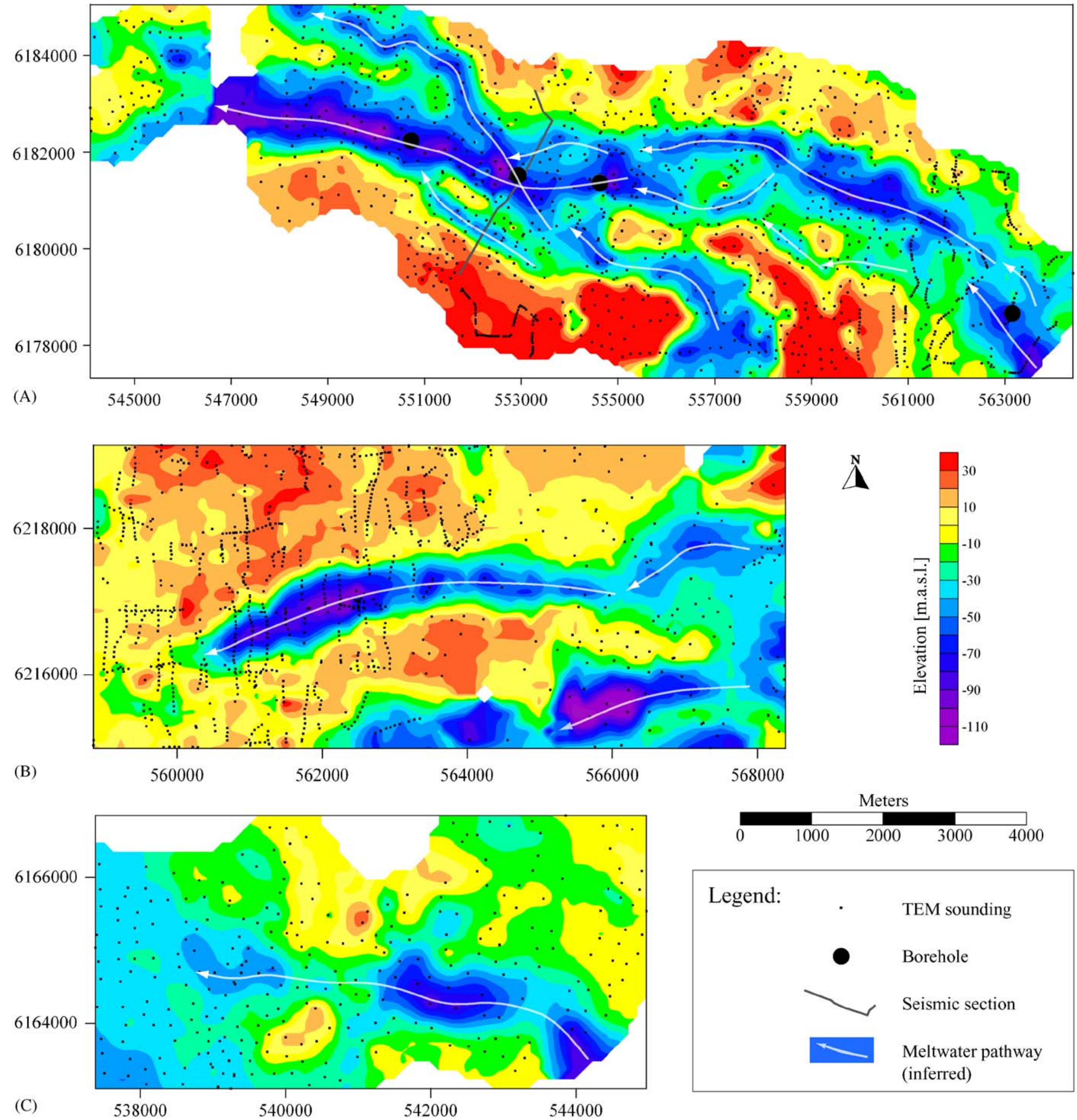
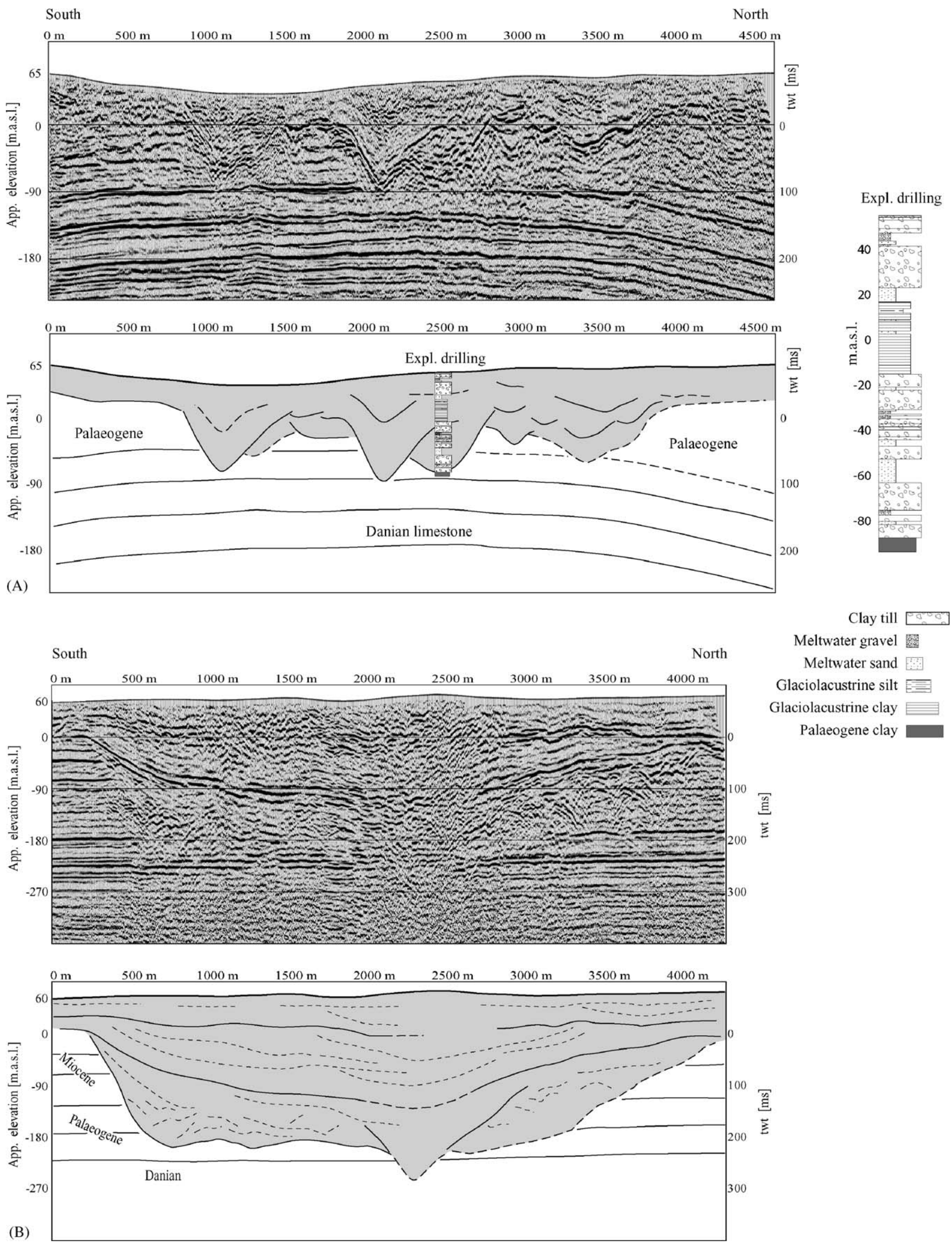


Fig. 6. Contoured surfaces of low-resistive bottom layers, showing three examples of buried valleys, see Fig. 4 for locations. (A) The Hornsyld Valley ($<8\,\Omega$m). (B) The Stilling Valley ($<12\,\Omega$m). (C) The Rands Valley ($<8\,\Omega$m). The surfaces largely coincide with the surface of the Paleogene clay and the pre-Quaternary surface. Grey arrow-lines indicate inferred meltwater flow pathways. The exploratory drillings shown in Fig. 9 and the seismic section shown in Fig. 7A are marked on the Hornsyld Valley map. Kriging with 650 m search distance and 125 m cell spacing is used for contouring. *Data source*: The counties of Aarhus and Vejle. Coordinate system in metres (UTM zone 32/ED 50).

soundings (data not shown). The buried valley consists of 3–4 cut-and-fill structures, each 500–1000 m wide. Two of these structures cross-cut in the central part of the valley. An exploration drilling here (see Fig. 6A for location) shows that the oldest structure mostly contains clay till and that the younger structure contains glaciolacustrine clay. The two cut-and-fill structures penetrated by the drilling can also be observed in Fig. 6A. The oldest is most likely oriented ESE–WNW, whereas the youngest is oriented E–W (marked by white arrows). The apparently anastomosing network is hence composed of cut-and-fill structures.


South
North
0 m
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
4500 m
App. elevation [m.a.s.l.]
twt [ms]
65
0
-90
-180
100
200
Expl. drilling
Palaeogene
Palaeogene
Danian limestone
(A)
m.a.s.l.
40
20
-20
-40
-60
-80
Clay till
Meltwater gravel
Meltwater sand
Glaciolacustrine silt
Glaciolacustrine clay
Palaeogene clay
60
-270
300
Miocene
Palaeogene
Danian
(B)

Most cut-and-fill structures are narrower than the overall buried valley, but in some places very wide structures that span the entire valley width occur. The seismic section shown in Fig. 7B crosses the entire Vonsild Valley from shoulder to shoulder, but the valley is somewhat narrower (about 3.2 km) than apparent on the profile section because it is not crossed perpendicularly. The valley comprises two, equally wide, cut-and-fill structures clearly exposed in the section. In addition, one narrow cut-and-fill structure in the deepest part probably also occurs. The deeper of the two wide structures cuts into Miocene and Paleogene layers, whereas the younger wide structure above mainly cuts the older one.

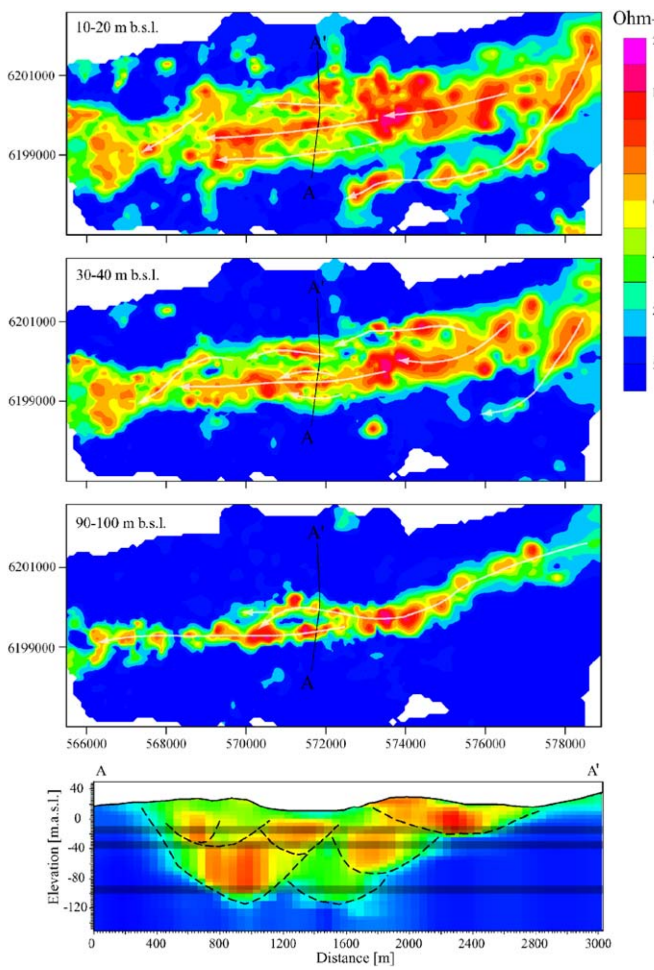


Fig. 8. Selected interval resistivity maps and a cross-section of the Boulstrup–Hundslund Valley. The cross-section A–A′ is marked on the maps. The interval resistivity maps shows average resistivities for 10-m intervals calculated from SkyTEM data in the western part and ground-based TEM data in the eastern part. The cross-section shows the succession of the interval resistivity grids down to 150 m below sea level. The three selected intervals shown by the maps are marked as shaded horizons on the cross-section. Inferred meltwater pathways are shown by grey arrow-lines on the maps, and inferred cut-and-fill structures are shown by hatched lines on the cross-section. The valley is around 2 km wide and more than 14 km long. At least 5 cut-and-fill structures can both be identified in the maps and the cross-section. *Data source*: The county of Aarhus. Coordinate system in metres (UTM zone 32/ED 50).

The seismic section across the Vonsild Valley (Fig. 7B) indicates the presence of glaciotectonic activity. The irregular seismic patterns situated at 500–1500 m and 2750–3750 m at depths between 100 and 200 m most likely represent strongly disturbed and dipping sequences either in or outside the plane of the seismic section. The strong irregularity of the valley fill generates diffraction hyperbola; especially between 3000 and 3750 m. This phenomenon hampers delineation of the exact position of the northern valley flank, but the interpretation shown is supported by TEM soundings and by migrated seismic data. The TEM soundings confirm the position of the valley base along the entire section (as shown for other seismic sections in Jørgensen et al. (2003b)), whereas the migrated stack does not eliminate the disturbed reflectors; except for the diffraction hyperbola. Glacially thrusted infill sediments are also indicated by frequent occurrences of rafts of pre-Quaternary material in the glacial sediments in several boreholes from within the buried valleys. Glaciotectonically disturbed sequences within two other buried valleys have previously been interpreted from a combination of seismic surveys, drillings and TEM soundings by Jørgensen et al. (2003b).

The buried Boulstrup-Hundslund Valley (Fig. 8), mapped by the use of SkyTEM and ground-based TEM, harbours more than five cut-and-fill structures. The entire valley is around 2 km wide, whereas the structures in the valley are 0.3–1.3 km wide. The individual cut-and-fill structures occur as elongate features on the interval resistivity maps and as U-shaped incisions on the cross-section in Fig. 8. The red colours indicate coarse meltwater sediments, green colours clayey glacial deposits. The valley is incised into Paleogene clay (blue colour). The individual cut-and-fill structures can occasionally be followed for several kilometres within the valley; however, some only appear as rather short features, presumably because of their undulating longitudinal trend, which makes them difficult to trace in the thin elevation slices. Most of the structures follow the overall valley pathway.

Examples of esker-like structures situated on the Hornsyld valley floor are presented in Jørgensen et al.

Fig. 7. (A) Seismic section across the Hornsyld Valley (immigrated 30-fold stack). See Fig. 6A for location of the section. The lower panel shows the interpreted section. The buried valley is coloured in grey. An exploratory drilling is superimposed onto the section by assuming a seismic velocity of 1850 m/s (obtained from VSP measurements). See Fig. 6A for location of this drilling and Fig. 9 for a detailed view and legend. App. vertical exaggeration is 5×. (B) Seismic section across the Vonsild Valley (unmigrated 32-fold stack). See Fig. 4 for location of the section. The lower panel shows the interpreted section. The buried valley is coloured in grey. App. vertical exaggeration is 3.7×. Data collection and processing of both sections was performed by Rambøll (Vangkilde-Pedersen et al., 2003). *Data source*: Vejle County.

(2003b) and from the Tørring-Horsens valley by Foldager (2003). In both cases the structures were interpreted from crossing seismic sections.

7.4. Lithology

The buried valleys are filled with a variety of glacial and interglacial deposits, most commonly meltwater sand and gravel, glaciolacustrine clay and silt and clay till. Other frequent deposits are heterogeneous, sandy diamictons, marine clay and peat. Comparisons of available borehole log information in the western part of Denmark (Jutland and Funen) show only minor differences between valley-fill deposits and other Pleistocene deposits (Jørgensen and Sandersen, 2004). Meltwater sand/gravel account for 50%, glaciolacustrine silt/clay for 17% and till/diamictons for 33% of the total amount of these three types of valley-fill deposits. For Pleistocene deposits in the western part of Denmark outside the mapped buried valleys, the same distribution is 52%, 13% and 35%. These valley-fill deposits accordingly do not differ distinctly from other Pleistocene deposits.

Tills are found as thick or thin layers in all parts of the buried valleys. They mostly appear as coherent, homogeneous and clayey tills, and can be interpreted as subglacially deposited (Jørgensen et al., 2003b; Jørgensen and Sandersen, 2004; Kronborg et al., 2003; Sørensen et al., 2004). Based on fine gravel counts, clay content and grain size distribution analyses, it has been shown that the till deposits found in the valleys can be used as a stratigraphical correlation tool (Kronborg et al., 2003, 2004). This indicates the subglacial origin of the till deposits because uniform, correlatable subglacial till units are expected to occur much more widespread than other types of till.

Exploration drillings in buried valleys often show thick sequences of waterlaid deposits (e.g. Foldager, 2003; Jørgensen and Sandersen, 2004; Sørensen et al., 2004), but frequent shifts in lithofacies are also commonly found (Fig. 9). Sandersen and Jørgensen (2003, Fig. 9) and Jørgensen and Sandersen (2004) showed that the local, incised substratum clearly influences the character of the infill sediments. Clay till is much more common as a part of the infill in valleys incised in clayey deposits. The relative proportion of till to clay/silt and sand/gravel in such areas is 40–50% compared with 5–15% in sandy areas. The proportion of sand/gravel is 60–80% in valleys incised into a sandy substratum, but only 40–50% in clay areas.

Fig. 9 shows lithological logs and gamma ray logs from 4 exploratory drillings performed along the central part of the Hornsyld Valley (drilling locations marked in Fig. 6A). This valley is incised into clayey Miocene and Paleogene sediments and the infill sediments are dominated by clayey Quaternary sediments. Most of these clayey sediments are clay till, frequently occurring in all drillings. Apart from some few relatively thick layers, a high frequency of vertical lithofacies shifts is seen in most parts of the drillings. The drillings show that the infill is difficult to correlate, which indicates a pronounced complexity of the valley infill.

The buried valleys occur in all regions of the mapped area, and they are thus incised into a variety of sediments. In the eastern and northwestern parts of Denmark, the incised pre-Quaternary substratum is composed of heavy Paleogene clay, in the northern parts of Danien and Selandien chalk and limestone and towards the west and southwest of a variety of Miocene sands, silts and clays (Fig. 1). The present data set does not allow us to determine whether the substratum sediment type has any significant effect on valley morphology, valley distribution or valley patterns.

7.5. Generations and ages

The buried valleys in the area NW of Aarhus (Fig. 5) can be divided into at least three generations on the basis

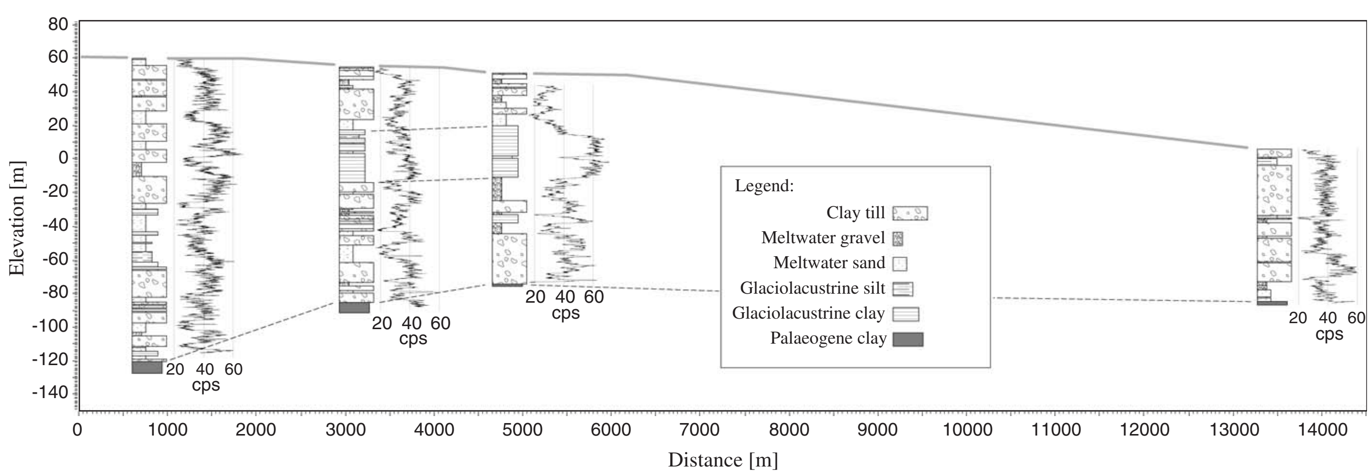


Fig. 9. Cross-section through four exploration drillings aligned along the thalweg of the Hornsyld Valley. See Fig. 6A for location of the drillings. Lithological logs are shown along with gamma ray logs for each drilling. The drillings illustrate the structural complexity of the valley infill.

of their orientations. Cross-cutting relationships can be determined from the TEM data at a number of crossings, indicating that the oldest is a SE–NW generation and the youngest a generation of valleys striking NE–SW (Fig. 10). Between these two, a N–S generation seems to exist. The relations between the three mentioned generations are, however, more complicated, because more than one incision (cut-and-fill structures) can be found within some of the valleys. There may, therefore, be even more generations in the area, but they cannot be distinguished on the basis of their orientations, because they line up with the pre-existing orientations or re-use older valley traces. Almost all valleys are completely buried and there are therefore no significant signs left in the present-day landscape. Lithostratigraphic investigations recently carried out on borehole samples from several exploration drillings located in the valleys support the proposed age relationships by showing the presence of old, probably pre-Elsterian, glacial sediments within one of the valleys from the oldest generation, and probably Saalian and Weichselian deposits in the younger generations (Sørensen et al., 2004). The pre-Elsterian age of the SE–NW generation is also indicated by datings of samples from a borehole at Hadsten (see Fig. 10 for location). Marine silty clay and sand from this borehole (Geol. Surv. file no. 78 458, 1976) were examined for foraminifera by Knudsen (1987a, b) and ostracoda by Penney (1987). The marine sequence found 31–36 m below present day sea level was found to be of Late Elsterian and Holsteinian age. The TEM investigations (Fig. 5) reveal that the drilling penetrates a large buried valley, and that these marine sediments are valley infill sediments. According to Knudsen (1987a), the sediments may have been glaciotectonically disturbed and they could therefore have been displaced from somewhere outside the valley. Despite this uncertainty, it seems reasonable that the valley existed as an open fjord in the Holsteinian Interglacial. The buried valley can be followed almost to the present-day seashore some 20 km towards the southeast.

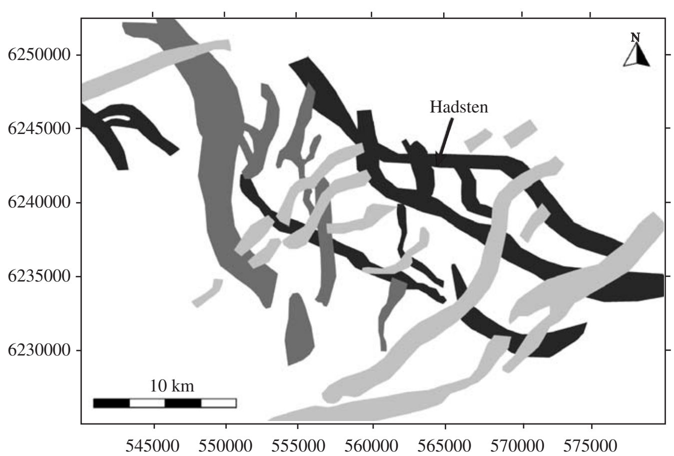


Fig. 10. Three buried valley generations in the area NW of Aarhus (area identical to Fig. 5). The oldest generation of valleys (dark grey valleys) are oriented SE–NW, a younger generation (grey valleys) is oriented N–S and the youngest generation (light grey valleys) is oriented NE–SW. The arrow shows the location of drilling no. 78 458, see text. Coordinate system in metres (UTM zone 32/ED 50).

Multiple generations of buried valleys are also found on the island of Mors in the northwestern part of Jutland, where it has been possible to distinguish at least four generations and to determine their age relationships (Jørgensen et al., 2005). Presumed Holsteinian sediments found within the youngest generation indicate a relatively old minimum age of the valleys. The occurrence of multiple valley generations has also been observed in some other places in Denmark and cross-cutting relationships have occasionally been determined (Jørgensen and Sandersen, 2004). However, it is not possible to establish a valid 'valley-stratigraphy' throughout the Danish region.

As described for the area NW of Aarhus, multiple valley generations do not always show different orientations. New generations can be formed with orientations similar to existing generations and in such cases individual valleys are commonly incised into each other. This is exemplified in Fig. 11, where a buried valley (the Rands valley, Fig. 6C) is found underneath Vejlby, which is the key locality for the early Saalian Vejlby substages. Deposits of diatom and silicic gyttja at Vejlby were described and dated to the Holsteinian Interglacial and Early Saalian (Vejlby 1 and Vejlby 2 interstadials) by use of pollen analysis (Andersen, 1965). The extension of the buried valley outside the TEM survey area is mapped by the inspection of borehole logs from water wells. Here, diatomaceous deposits and other interglacial and interstadial deposits are found in several boreholes and exposures along the valley. Fig. 11 shows the extension of the valley beneath Vejlby oriented towards the NW and W. Several other buried valleys in the region show a similar trend with westerly directions and slight southward bends: the Hornsyld Valley (Fig. 6A), the Viuf Valley (Jørgensen et al., 2003b), the Tørring-Horsens Valley (Foldager, 2003; Jørgensen and Sandersen, 2004) and a valley, over 150 m deep, beneath the Vejle Tunnel Valley (Jørgensen and Sandersen, 2004). Based on the similarity of their orientations, it can be assumed that these buried valleys belong to the same generation. This assumption is supported by the occurrence of diatomaceous deposits in boreholes located not only in the Rands Valley, but also in the buried valley beneath the Vejle Tunnel Valley and in the Tørring-Horsens Valley (Fig. 11). This implies that the Vejlby Valley and all other valleys belonging to this generation pre-date the early Saalian. It is, however, evident that the Vejle Tunnel Valley, which can be observed in the present-day landscape, is much younger (Late Weichselian) due to its relation to the MSL and the outwash fan (Fig. 3B). The old, pre-existing buried valleys were apparently re-incised/re-used by the Vejle Tunnel Valley and other young tunnel valleys, at least during the Late Weichselian.

Other buried valley systems in Denmark pre-dating the Holsteinian Interglacial have been reported in south-

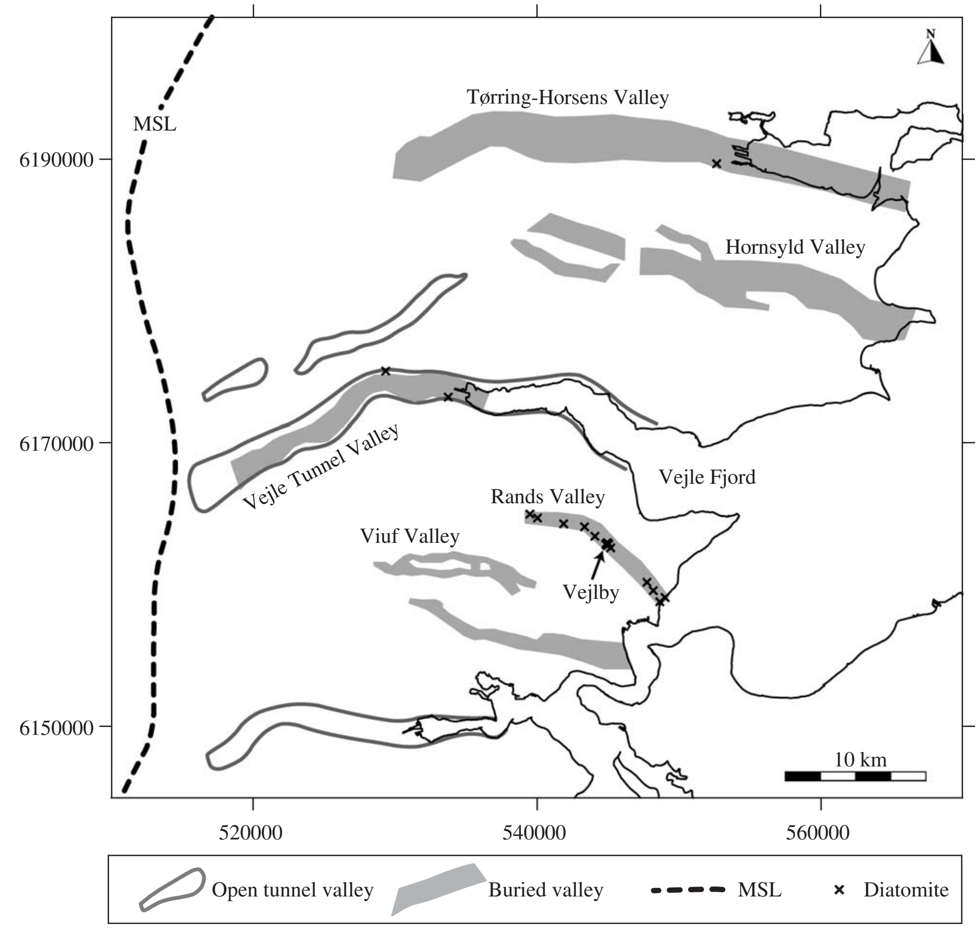


Fig. 11. Map showing the tendency of tunnel valleys to re-use older valleys traces. The Vejle Tunnel Valley is aligned above an older buried valley supposed to be a member of a pre-Holsteinian generation of buried valleys. The Hornsyld Valley and the Rands Valley are among the members of this generation. Coordinate system in metres (UTM zone 32/ED 50).

western Jutland (Bruun-Petersen, 1987; Knudsen, 1987a, 1994; Sandersen and Jørgensen, 2002), where borehole data show widely distributed Late Elsterian–Holsteinian marine deposits as part of the infill in assumed systems of buried valleys. The data coverage is, however, too sparse to allow accurate delineation of these systems.

Although infill sediments can be dated in some cases, the age of the buried valleys cannot be precisely determined. The time gap between the dated infill and the incised substratum is normally too large for precise determinations of the time of the valley incision.

8. Comparison between the buried valleys and the open tunnel valleys

The above examination shows that the buried valleys and the open tunnel valleys share several morphological characteristics: (1) They are arranged individually or appear in anastomosing patterns, (2) individual valley segments are generally straight or slightly sinuous, (3) the irregular longitudinal profiles with hollows and thresholds are typical for both, (4) both often have U-shaped profiles with rather steep sides, (5) eskers are common within the open tunnel valleys and their presence is indicated in the buried valleys as well and (6) both sets of valleys occasionally show abrupt terminations.

Furthermore, the widths of both valley types seem to be identical. Valley width is a parameter that can be determined relatively precisely and consistently for both data sets. Widths of open tunnel valleys and the mapped buried valleys (Fig. 4) were therefore measured systematically in Jutland and on Funen. For open tunnel valleys we used the valleys delineated by Smed (1979, 1981a, b, 1982) to avoid the subjective dimension, which often lies at the root of the distinction between tunnel valleys and other types of valleys in the landscape. The widths of the tunnel valleys, however, were not measured directly upon Smeds' maps. Their locations were transferred to topographic maps in order to obtain precise measurements. The widths of both valley types were measured from shoulder-to-shoulder perpendicularly to the valley orientation. One measurement was made for every third kilometre, and one measurement was made for valleys or valley segments shorter than 3 km.

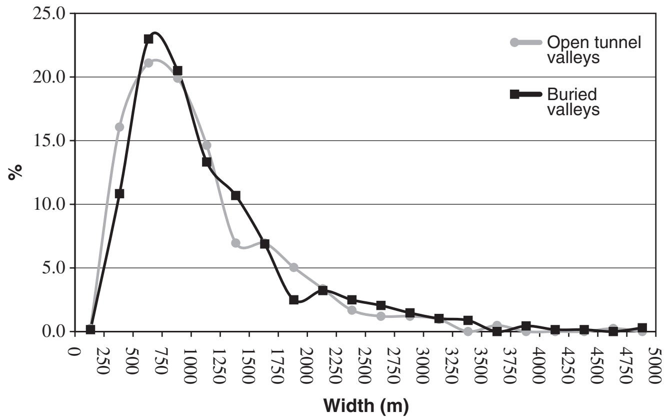


Fig. 12. Widths of tunnel valleys and buried valleys. Frequency distributions for intervals of 250 m. Note that narrow valleys may be underestimated.

Table 1
Main characteristics of the open and buried tunnel valleys in Denmark

Characteristics	Description
Width	Max: 4000 m; typical: 500–1500 m
Depth	Max. observed: 350 m; typical: 20–200 m
Length	Undefined
Morphology	Irregular; undulating longitudinal profiles with thresholds; mostly U-shaped cross-profiles
Patterns	Apparently anastomosing or parallel, rectilinear to slightly sinuous valleys
Orientations	Multiple, preferred orientations in sub-areas
Generations	Min: 4–5
Internal structure	'Cut-and-fill', occasionally glaciotectonized
Infill	Typical ratio between meltwater sand/gravel; till and glaciolacustrine silt/clay: 3:2:1.
Substratum	Sand, silt, clay, till, limestone, chalk
Ages	Weichselian, Saalian, Elsterian, pre-Elsterian?

We obtained 417 observations for the open tunnel valleys and 683 observations for the buried valleys. The results are shown as frequency distributions for intervals of 250 m in Fig. 12. The two distributions are almost identical: the frequency reaches a maximum close to 750 m for both data sets, drops abruptly between 750 and 2000 m and descends slowly to a maximum width of around 3500–4000 m. The mean values are 1068 m for the open tunnel valleys and 1148 m for the buried valleys.

The distributions are not expected to be valid for valleys narrower than about 500 m. Small tunnel valleys were not delineated by Smed (1979, 1981a, b, 1982) and narrow buried valleys are difficult to map using borehole data and geophysical data. The 'narrow' part of both populations is therefore underestimated. This limitation, however, does not influence the distribution for the wider part of the valleys (>500–750 m), which can still be considered identical for the two valley types.

The comparison indicates a close relationship between the two valley types. All data point to the fact that the buried valleys can be considered tunnel valleys now buried in the subsurface by glacial sediments. Hence, it follows that we can expect the buried valleys to have been formed in the same way as the open tunnel valleys, which allows us to integrate the data sets in an attempt to formulate a hypothesis about their common origin.

Data and typical characteristics of the Danish tunnel valleys are summarized in Table 1.

9. Comparison with tunnel valleys at other locations

Multiple tunnel valleys generations are also found elsewhere in Northern Europe and are mostly attributed to the last three glaciations (Wingfield, 1989; Piotrowski, 1994; Dobracki and Krzyszkowski, 1997; Glasser et al., 2004). Weichselian tunnel valleys are commonly preserved in the present-day landscape (e.g. Ussing, 1907; Galon, 1965) or on the sea floor (e.g. Long and Stoker, 1986), but tunnel valleys can also be buried in the subsurface (Woodland, 1970), which is typically seen for valleys of the Saalian and Elsterian glaciations (e.g. Ehlers et al., 1984). Especially the Elsterian valleys form comprehensive networks of deep-cut valleys both onshore and offshore (e.g. Ehlers et al., 1984; Piotrowski, 1994; Dobracki and Krzyszkowski, 1997; Huuse and Lykke-Andersen, 2000; Praeg, 2003). Except for the Late Weichselian valleys, the precise age of the Danish tunnel valleys is difficult to assess. We can, though, identify several generations, which are expected to be relatively old. It is likely that one of these generations is identical to the generation of Elsterian valleys found in the neighbouring countries and in the North Sea. In Germany this generation is oriented approximately N–S (e.g. Ehlers et al., 1984) as is also at least one of the old generations in Denmark.

The largest tunnel valleys in Europe are found in the North Sea Basin and the neighbouring regions (Huuse and Lykke-Andersen, 2000). Their maximum depths exceed 500 m in the North Sea (Praeg, 2003); and about 400 m in North Germany (Lüttig, 1972; Ehlers and Linke, 1989). Deep tunnel valleys (100–300 m) have also been reported from North America (Boyd et al., 1988; Mullins and Hinchey, 1989; Pugin et al., 1999; Smith, 2004). The widths of the large tunnel valleys in Europe and North America normally vary between 1 and 4 km and the length ranges from a few km to around 100 km or more (e.g. Kuster and Meyer, 1979; Brennand and Shaw, 1994; Huuse and Lykke-Andersen, 2000; Praeg, 2003). The reported lengths are not measurements of individual valley segments, but merely reflect the lengths of anastomosing valley networks. The lengths of individual valley segments normally do not exceed 20–30 km. The described dimensions for tunnel valleys in general are comparable with those of the Danish tunnel valleys.

Most tunnel valleys outside Denmark seem to occur in anastomosing networks (e.g. Boyd et al., 1988; Brennand and Shaw, 1994; Pugin et al., 1999; Huuse and Lykke-

Andersen, 2000; Glasser et al., 2004). Sometimes, however, the valleys are primarily found as individual, sub-parallel elements (e.g. Mooers, 1989; Cutler et al., 2002; Smith, 2004). Tunnel valleys are often found to have rectilinear or slightly sinuous segments (e.g. Long and Stoker, 1986; Eyles and McCabe, 1989; Mooers, 1989; Wingfield, 1989; Patterson, 1994; Praeg, 2003), sometimes arranged in a radial pattern (e.g. Galon, 1983; Mullins and Hinchey, 1989; Ehlers and Gibbard, 1991; Patterson, 1994; Dobracki and Krzyszkowski, 1997; Clayton et al., 1999). Although some of the Danish tunnel valleys are arranged in anastomosing networks, they are interpreted to have been formed as individual, independent valleys. This inference has also been proposed for apparently anastomosing networks outside Denmark (Mooers, 1989; Ehlers and Linke, 1989; Salomonsen, 1995; Ehlers, 1996; ÓCofaigh, 1996; Huuse and Lykke-Andersen, 2000).

One of the most significant universal characteristics of tunnel valleys is their irregular, undulating profiles along the thalwegs locally with differences between sills and hollows higher than 50–100 m (e.g. Woodland, 1970; Patterson, 1994; Pugin et al., 1999; Huuse and Lykke-Andersen, 2000; Smith, 2004). Convex-up longitudinal profiles of valleys/channels that cross-thresholds have been reported in several studies in North America (e.g. Beaney and Shaw, 2000; Beaney, 2002; Sjogren et al., 2002; Rains et al., 2002) and some in Europe (Glasser et al., 2004). Others studies, especially from North Europe, find that the valleys are formed as elongated, enclosed and overdeepened depressions (e.g. Ehlers et al., 1984; Wingfield, 1989; von Schwab and Ludwig, 1996; Huuse and Lykke-Andersen, 2000; Praeg, 2003). It is difficult to describe a general profile for the Danish tunnel valleys, but we usually do not find the convex-up longitudinal profiles.

Tunnel valley cross-profiles have mostly been described as U-shaped or as both U-shaped and V-shaped often with steep walls (e.g. Bjarkeus et al., 1994; Piotrowski, 1994; Eyles and de Broekert, 2001). Such cross-profiles are consistent with the observations for Danish tunnel valleys and the same is the frequent occurrence of eskers in tunnel valleys. As probably found in some of the buried tunnel valleys in Denmark, eskers have also been observed on seismic sections from buried valleys in North America (Mullins et al., 1996; Pugin et al., 1996).

The infill lithology generally described from buried tunnel valleys is also comparable to the Danish tunnel valleys. A great lithological variety prevails both within individual valleys (e.g. Piotrowski, 1994) and between different valleys and valley systems (e.g. Grube, 1979). Lithofacies associated with glaciofluvial, lacustrine or marine sedimentation are found as part of the infill in most of the European buried tunnel valleys (e.g. Woodland, 1970; Ehlers et al., 1984; Ehlers and Linke, 1989; Dobracki and Krzyszkowski, 1997; Kluiving et al., 2003; Praeg, 2003), but also in buried valleys outside Europe (e.g. Mullins and Hinchey, 1989; Evans and Campbell, 1995; Pugin et al., 1999; Hirst et al., 2002; Russell et al., 2003). As in the Danish tunnel valleys, infill sediments associated with direct glacial sedimentation have also been described elsewhere. Tills, for instance, are reported from valley fills, e.g. by Grube (1979), Visser (1988), Ehlers and Linke (1989), Piotrowski (1994), Dobracki and Krzyszkowski (1997), Eyles and de Broekert (2001), Gabriel et al. (2003) and Kluiving et al. (2003) and rafts displaced by glaciotectonic activity are described by e.g. Ehlers and Linke (1989), Piotrowski (1994) and Eissmann et al. (1995).

The comparison above shows that the tunnel valleys in Denmark and elsewhere in Europe and North America share basic features and therefore may be of the same origin(s).

10. Origin of the tunnel valleys—discussion

10.1. Tunnel valleys formed by multiple glaciations

The main tunnel valley formation hypotheses focus on subglacial meltwater erosion and the way the subglacial meltwater carves the substratum (cf. ÓCofaigh, 1996; Huuse and Lykke-Andersen, 2000). As already inferred by Ussing (1903,1907), tunnel valley formation by subglacial meltwater erosion can also be attributed to the open tunnel valleys in Denmark, but a debate as to whether the valleys possibly formed by direct glacial erosion also is still thriving.

We agree that the tunnel valleys were primarily formed subglacially. Their subglacial origin or at least an enhanced subglacial resculpturing of the valleys is indicated by: (1) their abrupt terminations at former ice margins, (2) their irregular longitudinal profiles, (3) the occurrence of small channels and eskers in the valleys and (4) the non-meandering and non-dendritic appearance of the relatively straight-segmented valleys.

Having included the buried valleys into the tunnel valley category, it follows that several generations of tunnel valleys exist. The generational dimension is backed by the existence of patterns of valley systems with different preferred orientations and by the occurrence of cut-and-fill structures within the valleys. Also the presence of open tunnel valleys above older buried tunnel valleys and the apparently anastomosing systems show the multiple generations. The apparently anastomosing valley patterns as for example seen for the Hornsyld Valley (Figs. 6A and 7A) reflected individual valleys belonging to different generations.

We can distinguish at least four generations of buried tunnel valleys from the preferred orientations, but open valley generations should be added to this number and we may have to add even more generations because of the difficulty of distinguishing generations with identical preferred orientations. As the generations are expected to have formed during different ice advances, tunnel valley generations can be considered as footprints left by several glaciations, but since it has not yet been possible to date any of the erosional events that created the buried tunnel valley generations it has not been possible to place them into the established Quaternary stratigraphy. Most of the generations are supposed to be of pre-Late Weichselian age, and because only little is known about ice margin positions prior to the Late Weichselian, the relationships between buried valleys and ice margin positions have not yet been established.

Valley re-usage has caused valleys to be eroded over and over again during several glaciations. It is probable that the pathways used by the tunnel valleys were established during the early Quaternary glaciations or even earlier, and it cannot be ruled out that parts of the pre-glacial, perhaps fluvially eroded landscape in this way 'survived' the Pleistocene glaciations by being reused as subglacial drainage pathways or by being re-sculptured or preferentially eroded several times.

10.2. The role of direct glacial erosion versus subglacial meltwater erosion

Three main categories of erosional processes occur within a subglacial environment: quarrying, abrasion and meltwater erosion (e.g. Benn and Evans, 1998; Glasser and Bennett, 2004). Quarrying and abrasion will here be referred to as direct glacial erosion. The role of direct glacial erosion relative to meltwater erosion in the formation of the open tunnel valleys in Denmark was recently discussed by Smed (1998). Smed claimed that tunnel valley formation by meltwater erosion was primary, and that direct glacial erosion only occurred in cases where very wide valleys could be re-sculptured by small ice lobes advancing into open tunnel valleys left by former ice sheets. His arguments were that most of the valleys were too small to be able to produce and confine outlet glaciers and if projected outlet glaciers occurred in the tunnel valleys, the MSL would not have been as straight as it is (Smed, 1998). As an example of a wide valley resculptered by an outlet glacier, Smed (1998) discussed the Aabenraa Fjord (for location, see Fig. 2). This fjord valley is around 4 km wide and 13 km long. Its inner part is surrounded by an end moraine (Hansen, 1978; Smed, 1998, Fig. 17) indicating the presence of a short ice lobe projected into the valley during the Young Baltic Advance. This lobe is thought to have widened a pre-existing tunnel valley formed during the Main Advance by direct glacial erosion (Smed, 1998). Although the fjord valley is wide (compared with the tunnel valleys), the form of the end moraine shows that only a short lobe was projected into the valley while the main part was covered by the Young Baltic Advance. This supports the hypothesis that topographically confined outlet glaciers in Denmark only occurred as small lobes and within the widest tunnel valleys.

A number of wide valleys in Denmark that have not been interpreted as tunnel valleys on Smed's maps can probably be attributed to glacial erosion. These valleys are significantly wider, shorter and, unlike the Aabenraa Fjord valley, more diffusely expressed in the landscape than the tunnel valleys.

Whereas erosion of tunnel valleys by projected outlet glaciers is limited, other indications, as discussed below, indicate selective linear erosion (cf. Sugden and John, 1976). The product of selective linear erosion is directly glacially eroded troughs and valleys beneath ice sheets. Pre-existing valleys may also be selectively eroded and changed into larger valleys, troughs or fjords (e.g. Hall and Glasser, 2003; Brook et al., 2004). Selective linear erosion requires tunnel valleys to have been ice-filled during their formation and this is indicated by the presence of glaciotectonized sediments and frequent and widespread occurrence of subglacial till as part of the buried valley-fill sequences. Furthermore, the common occurrence of dead ice-preserved tunnel valleys indicates that the valleys most likely became ice-filled during, or maybe shortly after, their formation. The occurrence of ice-filled valleys can be observed in some of the buried valley data; for instance in the Vonsild Valley. Here two, 3.2 km-wide erosional unconformities were found as smooth, curved surfaces covering the entire valley from shoulder to shoulder (Fig. 7B). Such km-wide features, approximately parabolically U-shaped, are considered to be typical for glacial troughs produced by direct glacial erosion (e.g. Benn and Evans, 1998). The interpreted glaciotectonic structures between the two unconformities further supports that selective linear erosion may have taken part in the formation of this particular valley by indicating the presence of ice in the valley.

Selective linear erosion is thus believed to have played an important role for the formation of at least some of the wider tunnel valleys. Thicker ice over the valley floors may have augmented basal melting rates and thereby increased sliding velocities and erosion rates (e.g. Benn and Evans, 1998; Hall and Glasser, 2003). Another possibility is that taliks and thinner permafrost below lakes and streams in the valleys in an otherwise continuously permafrozen region may have facilitated higher erosion rates (e.g. Berthelsen, 1972; Krüger, 1983; Ehlers et al., 1984). Conditions favourable for selective linear erosion can also arise owing to differences in the substratum lithology (e.g. Brook et al., 2004). Such conditions could probably be expected in buried valleys filled with sediments other than those found in its surroundings because of the differences in kinematic resistance or hydraulic conductivity of different sediments (e.g. Piotrowski, 1994; Taylor and Wilson, 1997).

In Poland, Niewiarowski (1995) showed that several of the widest tunnel valleys were invaded, resculptured and supposedly also eroded by ice tongues and ice streams. He states, in agreement with the interpretations here, that tunnel valleys that were formed or partly formed by direct glacial erosion are generally wider (1–4 km) than those carved by subglacial meltwater (less than 1 km). The width frequency distribution of the Danish valleys (Fig. 12) shows that most of the valleys are less than 1.5–2 km wide.

However, a significant portion of the valleys is wider than this. It can be speculated whether this distribution represents two, perhaps partly related populations; a 'narrow', and frequently occurring population of meltwater eroded valleys (up to 1.5–2 km in width) and a 'wide' population of direct glacially eroded valleys (more than 1.5–2 km in width). Two independent valley populations cannot be clearly distinguished, however; probably because the valley-forming process is a combination of the two modes of erosion, where the relative importance of direct glacial erosion is greater for the wide, than for the narrow valleys. Other researchers have also discussed the possibility that direct glacial erosion may occur in co-operation with meltwater erosion. Lowering of the porewater pressure in the surroundings of subglacial channels (Piotrowski, 1994, 1997b) is for instance thought to facilitate preferential erosion of valley edges (Iverson, 2000; Piotrowski et al., 2002). van Dijke and Veldkamp (1996) proposed that meltwater erosion causes valley beds to be lowered, whereas direct glacial erosion widens the valleys by eroding the valley walls.

Although direct glacial erosion may have played an important role for the formation of the wider tunnel valleys, the relationship between the open tunnel valleys and the outwash fans along the MSL testifies that the valleys must have acted as subglacial conduits under hydrostatic pressure, and the erosional power of the flow in these conduits is indicated by the very large amounts of outwash incorporated in the outwash fans. Subglacial meltwater flow is therefore expected to be responsible for the main part of the erosion. The frequent occurrence of cut-and-fill structures inside the valleys that do not span shoulder-to-shoulder can, furthermore, be taken as evidence for meltwater erosion rather than direct glacial erosion because direct glacial erosion is expected to produce the more infrequent shoulder-to-shoulder unconformities as seen in the wide Vonsild Valley (Fig. 7B). Also the presence of channels and 'handles' in open tunnel valleys demonstrates the erosion by pressurized meltwater. They can be considered as N-channels (Nye, 1973). Although eskers are not erosive features, their occurrence in relation to tunnel valleys is another strong indicator of confined, subglacial meltwater flow in the valleys.

10.3. Steady-state versus catastrophic meltwater releases

The subglacial meltwater erosion hypotheses proposed for tunnel valley formation can largely be divided into two variants: (1) the steady state, progressive formation (e.g. Boulton and Hindmarsh, 1987; Mooers, 1989; Smed, 1998; Huuse and Lykke-Andersen, 2000; Praeg, 2003), and (2) the sudden (near-synchronous) formation exerted by catastrophic outbursts (jökulhlaup) of subglacially accumulated meltwater (e.g. Wright, 1973; Ehlers and Linke, 1989; Brennand and Shaw, 1994; Patterson, 1994; Piotrowski, 1994; Björnsson, 1996; Clayton et al., 1999; Beaney, 2002).

The former includes theories of sediment deformation and small migrating erosive channels. The sediment deformation theory as inferred by Boulton and Hindmarsh (1987), predicts sediment creep towards small R-channels (cf. Röthlisberger, 1972) accommodating steady-state meltwater flow. The creeping sediments are gradually washed out by the flowing meltwater and, if this process continues for a long period, the deformable bed will be lowered and a large valley occupied by ice will form. However, this hypothesis does not account for valleys cut in lithified bedrock (ÓCofaigh, 1996) and is therefore not directly applicable to the Danish tunnel valleys, which are cut into limestone at several locations. The theory of Boulton and Hindmarsh (1987) has also been considered problematic regarding its general implication for subglacial hydrology (Piotrowski et al., 2001, 2002). With reference to Clark and Walder (1994) and Walder and Fowler (1994), who estimated that channelized sub-glacial drainage over deforming beds will tend to occur in uniformly distributed, wide and shallow channels, Piotrowski et al. (2002) questioned that the large and deep tunnel valleys in Europe could have been formed in this way. Identical considerations can be applied to the Danish tunnel valleys, which are comparable to tunnel valleys elsewhere in Europe. Extensive deforming bed conditions like those expected for the model predicted by Boulton and Hindmarsh (1987) would also imply that the valley surroundings must have been deformed and the original bedding destroyed. Such deformation has not been identified in our data. By contrast, our high-quality data allows identification of relatively sharp bedding planes in the surroundings close to the valleys (e.g. Fig. 7).

Contrary to the steady-state theory, other tunnel valleys (tunnel channels) are interpreted to have been formed by sudden releases of subglacially stored meltwater (jökulhlaups) that simultaneously occupied entire channel systems by bank-full discharges (e.g. Brennand and Shaw, 1994; Beaney and Shaw, 2000; Beaney, 2002). The strongest indications for catastrophic outbursts to be responsible for tunnel channel incision are (1) the occurrence of boulder accumulations in tunnel valley-related out-wash fans, (2) the anastomosing valley patterns and (3) bedforms indicative of subglacial meltwater floods (e.g. Wright, 1973; Ehlers and Linke, 1989; Brennand and Shaw, 1994; Piotrowski, 1994; Björnsson, 1996; Clayton et al., 1999; Beaney and Shaw, 2000; Beaney, 2002; Cutler et al., 2002). It has also been proposed that the channels are the products of broad subglacial meltwater floods that occurred initially during the peak of the flooding event and during waning flows integrated valley systems were formed by progressive flow channelization (Shoemaker, 1992; Brennand and Shaw, 1994). The simultaneous occupancy of anastomosing systems of tunnel channels requires outbursts of huge dimensions (e.g. ÓCofaigh, 1996) and there is no evidence for the occurrence of such outbursts in Denmark. On the contrary, the apparently anastomosing systems observed in our investigation are composed of individual and internally independent tunnel valleys.

The common appearance of cut-and-fill structures indicate a repeated process of meltwater erosion intervened by deposition. The repeated meltwater erosion may reflect repeated meltwater discharges below the same glacier or meltwater erosion below different glaciers. The hypothesis of repeated discharges below the same glacier is problematic, since the observed infill sequences, must have required a significant amount of subglacial sedimentation. Although subglacial lake sedimentation in valleys or basins connected to subglacial drainage systems is reported by several authors (e.g. McCabe and ÓCofaigh, 1994; Munro-Stasiuk, 2003; Russell et al., 2003; Smith, 2004), the bank-full filling of the single cut-and-fill structures is taken to indicate a recession of the glacier and melting of the ice that occupied the valleys before space for the sedimentation was created. Bank-full subglacial sedimentation immediately after erosion is thought to be unlikely because the majority of valleys were evidently left ice-filled, thus indicating ice creep into the valleys during or after erosion. Ice creep may have closed the valleys rapidly before they were filled with sediment after cessation of the flow. Consequently, it is suggested that the observed cut-and-fill architecture was created by the erosive forces of multiple glacier advances and intervening intervals of sedimentation.

The eskers and channels on the floors of the open tunnel valleys are much smaller than the cut-and-fill structures. They are most likely the remnants of the single conduits that discharged the eroding meltwater. Hence, the meltwater flowed in rather small conduits relative to the entire sizes of the tunnel valleys and cut-and-fill structures. These channels could either have been eroded by steady-state flows in small channels steadily migrating laterally on the valley floors or by repeated discontinuous flows in shifting channels on the valley floors. Several authors have invoked the former scenario to explain tunnel valley formation (Gripp, 1964; Krüger, 1989; Mooers, 1989; Jeffery, 1991; Smed, 1998; Huuse and Lykke-Andersen, 2000).

Boulders are a common constituent of Danish tills which are very widespread in the Danish subsurface. Almost all tunnel valleys must have incised till layers and erosional remnants such as large boulders would therefore be expected in the valleys at relatively low flow velocities. There is, however, no distinct evidence for widespread boulder lags in the Danish tunnel valleys. A large number of boreholes penetrate buried tunnel valleys, but boulder lags or boulder layers are seldom found. Nor have widespread occurrences of stony or bouldery ground been reported from floors of open tunnel valleys. The apparent lack of such remnants could hence indicate high flow velocities sufficient to transport large boulders uphill towards the ice margin and out of the subglacial system. If the boulders were washed out, they would, however, be expected to be a common component of the outwash fan. The occurrence of accumulated large boulders and boulder gravel in outwash fans or other lithofacies indicative of jökulhlaup episodes in the outwash (cf. Maizels, 1997) has been used as sedimentological indication for large-scale catastrophic outbursts (e.g. Piotrowski, 1994; Cutler et al., 2002; Russell et al., 2003). However, widespread boulder facies within the Danish outwash fans like those found in Wisconsin (Cutler et al., 2002) have not been reported on the outwash fans, but jökulhlaup lithofacies in the upper part of a large outwash fan just in front of the mouth of one of the large tunnel valleys that terminate at the MSL have been described by Olsen and Andreasen (1995). Although, the widespread boulder gravels in the outwash fans seem to be missing, the reported lithofacies sequences and the apparent absence of boulder lags within the valleys point towards the operation of catastrophic outbursts of meltwater in the tunnel valleys. The expected high flow velocities in the conduits require high discharges and support at the same time the assumption of rather small conduits. It is, therefore, considered most likely that the tunnel valleys were eroded by meltwater outbursts confined to relatively small conduits. For such small meltwater conduits to erode the larger cut-and-fill structure outbursts must have occurred repeatedly to successively cut the structures.

10.4. The role of time-transgressive formation

A time-transgressive origin of some North American tunnel valley systems has been claimed based on relationships between tunnel valley segments, recessional moraines and outwash fans (Mooers, 1989; Patterson, 1994). No such evidence presently supports time-transgressive formation of the Danish tunnel valleys. The Main Advance peaked at the MSL at rather stationary conditions (Houmark-Nielsen and Kjær, 2003). Although it may, during early times, have reached limits beyond the MSL (e.g. Kjær et al., 2003), the Main Advance is believed to have resided in close vicinity of the MSL for about 2000 years (22–20 kyr BP, Houmark-Nielsen and Kjær, 2003). It was most likely a sluggish ice compared with the subsequent fast-moving re-advances reaching the recession lines (e.g. Kjær et al., 2003; Jørgensen and Piotrowski, 2003). The re-advances were short-lived, spending only limited time at the recessional lines, thus showing an apparent relationship between the time of still-stand of the ice margin and the tunnel valley size (Smed, 1998). This indicates that the tunnel valleys were successively cut while the ice margin was at a stationary position and not during recession.

A number of the small tunnel valleys, however, do not terminate at the apex of outwash fans or at distinct, traceable ice margins. Some have been assigned to a formation prior to the maximum extent of the Main Advance (Smed, 1998). They were thus preserved by dead ice during the subsequent ice transgression, but their related outwash fans were buried by younger glacial deposits, making them difficult to detect in the present-day landscape. The same reasoning could probably be applied to the large open tunnel valleys in Jutland, which appear to be segmented by elements of 20–30 km in length. The inner, up-ice segments should then have been formed at still-stands during the transgressional phase of the Main Advance. Such valleys formed during a transgressional phase of an ice sheet were also reported in Poland by Galon (1965, 1983). However, the individual segments of open tunnel valleys aligned to one another to produce connected meltwater pathways reaching 70 km in total length could otherwise be of time-transgressive origin like the one documented for some tunnel valleys in Minnesota (Mooers, 1989; Patterson, 1994). But since no distinct outwash fans seem to occur at the mouths of the individual segments except for those terminating at the MSL, this formation mode does not apply for the tunnel valleys related to the Main Advance.

The application of the time-transgressive formation theory was recently extended to the North Sea owing to the identification of large clinoform reflectors in a 3D seismic survey interpreted as glaciofluvial backfill (Praeg, 2003). Tunnel valleys were supposed to have emerged from a receding glacier and valley erosion to have taken place contemporaneously with the backfilling. Praeg (2003) proposed that time-transgressive backfilling should be applicable to tunnel valleys elsewhere, for instance to the ones found along the MSL in Jutland. However, we consider this rather doubtful; mostly for the following reasons: (1) no evidence of backfill deposits within the valleys has been found, (2) at some locations the outwash fan is situated at higher positions than the moraine behind the MSL, thus documenting a still-stand of the margin that enabled the fan to accumulate, (3) dead ice was left in the tunnel valleys preventing glaciofluvial sediments from backfilling the valleys during the recession from the MSL, (4) there is no evidence that the tunnel valleys extend as buried tunnel valleys beneath the outwash fans outside the MSL, and finally, (5) the frequent occurrence of till and the great variety of sediments within the buried tunnel valleys do not support the proposed formation process. We believe that the tunnel valley erosion along the MSL ceased rather abruptly and that the valleys were preserved by the ice filling them at that stage. Later, during the recession or perhaps at the time when the meltwater flow ceased, this ice was frequently disintegrated from the active ice, thus preserving the valleys from being buried by outwash.

10.5. Subglacial bed properties and hydrology

The extent to which the substratum controls tunnel valley formation is not thoroughly described in the tunnel valley literature. However, a number of studies indicate some degree of relationship between: (1) tunnel valley occurrence and substrate lithology (e.g. Hinsch, 1979; Bjarkeus et al., 1994; Piotrowski, 1994; Evans and Campbell, 1995; Dobracki and Krzyszkowski, 1997; Taylor and Wilson, 1997; Huuse and Lykke-Andersen, 2000), (2) tunnel valley size and shape and substrate lithology (e.g. Woodland, 1970; Ehlers, 1996) and (3) tunnel valley location/orientation and bedrock structures/fault zones (e.g. Johannsen, 1960; Woodland, 1970; Long and Stoker, 1986; Lykke-Andersen et al., 1993; Brennand and Shaw, 1994; von Schwab and Ludwig, 1996; Dobracki and Krzyszkowski, 1997). In previously glaciated areas in North Europe, the tunnel valleys are found in poorly consolidated sedimentary bedrock only and not in areas of crystalline bedrock (e.g. Huuse and Lykke-Andersen, 2000). Variations in erodibility may also explain why tunnel valleys in northeast Europe with mainly lithified sedimentary bedrock seem to be smaller and shallower than valleys cut in the unconsolidated sediments in the North Sea Basin (Ehlers, 1996). Thus, subglacial bed properties clearly play a distinct role in tunnel valley formation. As discussed above, one important controlling factor is the erodibility of the bed; another is its hydraulic conductivity and the possible occurrence of permafrost.

The importance of meltwater drainage through the subglacial substratum for the entire hydrological regime was recently documented by means of hydraulic modelling (Boulton et al., 1993, 1995; van Dijke and Veldkamp, 1996; Piotrowski, 1997a, b; Breemer et al., 2002). The ability of the substrate to discharge meltwater from the glacier bed was shown to play a substantial role in controlling tunnel valley formation beneath glaciers (Piotrowski, 1997a, b) and the role of permafrost blocking groundwater discharge was also identified as an important factor (Piotrowski, 1997a, b; Cutler et al., 2002). Frozen ice margins are supposed to have forced subglacial water pressures to build up in aquifers or lakes until one or more outbreaks through the frozen-bed zone carved the valleys (e.g. Wright, 1973; Attig et al., 1989; Piotrowski, 1994, 1997a, b; Clayton et al., 1999; Cutler et al., 2002).

Permafrozen conditions prior to and perhaps during the Main Advance were demonstrated on the basis of frost wedge casts for the Danish area by Kolstrup (1986). Similar conditions for the Main Advance in Northern Germany have also been considered (e.g. Fränzle, 1988; Piotrowski, 1994, 1997a). Thus, it seems likely that the Main Advance had a frozen toe and perhaps large parts of the ice sheet were more or less cold-based in the Danish region, as indicated by its supposed sluggish behaviour here. As the frozen ground was overridden by the ice, meltwater discharge through subglacial aquifers was impeded or partly impeded and this may then have led to meltwater outbursts and incision of tunnel valleys. The existence of numerous subglacial lakes beneath the Antarctic Ice Sheet has been described by Siegert (2000) and such meltwater accumulations may also have existed beneath the Pleistocene ice sheets in North Europe. Piotrowski (1997a, b) designed a model for an area in Northern Germany comparable to Denmark, showing that the groundwater transmissivity through the bed was sufficient to drain only about 25% of the basal meltwater. This model did not account for the probable presence of permafrost conditions and meltwater may therefore even have accumulated without a frozen margin.

The general occurrence of permafrost may have led to development of open hydrothermal taliks (cf. van Everdingen, 1976) in the pro-glacial environment during the ice advance. As also proposed by Berthelsen (1972) and Krüger (1983), taliks could have occurred below pro-glacial lakes and rivers in pre-existing valleys. When these taliks were covered by the advancing ice, they were probably maintained subglacially by pressurized groundwater that steadily flowed in the often coarse-grained valley infill sediments that may partly have filled the valleys. It is also possible that taliks occurred not only within pre-existing valleys, but also along completely buried valleys. Such taliks may have occurred owing to elevated hydraulic conductivity in the valley infill deposits, thus promoting enhanced groundwater flow. Close to the LGM, when the glacier bed attained temperatures above the pressure melting point and the glacier became wet-based at the margin, the subglacial permafrost started to decay. Once the catastrophic drainage event was triggered, the proposed pre-established steady-state aquifer drainage pathways were preferred by the catastrophic drainage and meltwater erosion occurred along these pathways during successive outbursts. Predetermined meltwater pathways for subglacially stored meltwater were also proposed by Cutler et al. (2002) as so-called ‘focal points’. Piotrowski (1997b) also inferred that tunnel valleys in northern Germany were initiated along high-energy groundwater flow paths, which, however, were not connected to permafrost and subglacial taliks.

The here discussed mechanism of pre-determined meltwater pathways controlled by hydraulic conductivity and/or permafrost may explain the observed tendency for tunnel valleys to re-use older tunnel valley traces, as may also the process of selective linear erosion discussed above. The two processes may even co-operate. However, erosion is also affected by the morphology at the ice-bed interface which tends to control subglacial meltwater flow (cf. Shreve, 1985; Booth and Hallet, 1993), thus exposing the valleys to preferential meltwater erosion. It is, however, not possible to assess the relative importance of the different processes/mechanisms proposed for the re-erosion of pre-existing valleys.

11. Conclusions

Extensive systems of buried tunnel valleys in Denmark were mapped by means of newly collected hydrogeophysical data. These data were evaluated along with lithological data and valley characteristics were investigated and compared with those of open tunnel valleys in Denmark and tunnel valleys in other parts of the world. The main conclusions of this work are stated in the following:

- Buried valleys in Denmark can be considered tunnel valleys formed subglacially beneath multiple glaciers. They are comparable to the open tunnel valleys seen in the present-day terrain. Regarding their morphology, infill sediments, infill structures, substratum, etc., the tunnel valleys are also comparable to tunnel valleys elsewhere in Europe and in North America. The width distribution of the valleys is distinct: Most are around or just below 1 km in width, whereas relatively few have a width exceeding 2 km. The maximum width seems to be around 3.5–4 km.
- Several generations of tunnel valleys are found. They appear with various preferred orientations signifying that multiple glaciers covered Denmark during the Weichselian, Saalian, Elsterian and perhaps pre-Elsterian.
- There is a marked tendency for the tunnel valleys to have re-used older pre-existing valleys, open as well as buried. Pre-existing valleys were re-used if the ice moved parallel or near-parallel to these valleys. This re-usage is documented by the frequently found cut-and-fill structures inside buried valleys and by the open tunnel valleys situated above old buried tunnel valleys. Some of the tunnel valley pathways may have been established already during the earliest Quaternary glaciations or even earlier.
- The tunnel valleys were primarily eroded by subglacial meltwater and direct glacial erosion is considered to have played an important, but secondary, role. The importance of direct glacial erosion increases with valley width. The two types of subglacial erosional processes most likely collaborated.
- The main part of the meltwater erosion is supposed to have been the product of outbursts of sub-glacially stored meltwater. This meltwater was probably stored in subglacial basins somewhere up-ice, most likely restrained by a frozen toe. We envisage a model of repeated, relatively small outbursts while the ice margin resided at relatively stable positions. The tunnel valleys were ice-occupied and the discharge occurred in small channels situated on the tunnel valley floors. Once the outburst events were triggered, the discharges preferred to follow pre-defined meltwater path-ways along existing tunnel valleys. A steady-state discharge of meltwater in laterally migrating conduits cannot be excluded as a contributor to the erosion.
- The main part of the direct glacial erosion is supposed to have occurred as selective linear erosion within the ice sheet. This erosion was controlled by the morphology and erodibility of the substratum and occurred along pre-existing open as well as buried valleys.
- The valley re-usage tendency is most likely caused by differences in hydraulic conductivity (increased groundwater flow controlled by coarse valley infill or subglacial taliks), variation in the subglacial morphology and the selective linear erosion.

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References

Andersen, S.A., 1931. Om Aase og Terrasser inden for Susaa's Vandområde og deres Vidnesbyrd om Isafsmelt-ningens Forløb. Geological Survey of Denmark (Series II) 54, 1–167.

Andersen, S.A., 1933. Det danske landskabs historie. Danmarks geologi i almenfattelig fremstilling. Levin og Munksgaard, København, 276pp.

Andersen, S.T., 1965. Interglacialer og interstadialer i Danmarks Kvartær. Medd. Dansk Geologisk Forening 15, 486–504.

Andersen, S.T., 1979. Istider og mellemistider. In: Nørrevang, A., Lundø, J. (Eds.), Danmarks Natur 1, Bind 1: landskabernes opståen. Politikens forlag and Gads Natur Forum, Copenhagen, pp. 199–250.

Attig, J.W., Mickelson, D.M., Clayton, L., 1989. Late Wisconsin landform distribution and glacier-bed conditions in Wisconsin. Sedimentary Geology 62, 399–405.

Badley, M.E., 1985. Practical Seismic Interpretation. International Human Resources Development Corporation, Boston, 266pp.

Beaney, C.L., 2002. Tunnel channels in southeast Alberta, Canada: evidence for catastrophic channelized drainage. Quaternary International 90, 67–74.

Beaney, C.L., Shaw, J., 2000. The subglacial geomorphology of southeast Alberta: evidence for subglacial meltwater erosion. Canadian Journal of Earth Sciences 37, 51–61.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London 734pp.

Berthelsen, A., 1972. Flod-, fjord- og tunneldale. Dansk Geologisk Forening (Årsskrift for 1971) 101–104.

Binzer, K., Stockmarr, J., 1985. Geologi i Midtjylland. Prækvartæroverfladens højdeforhold og landskabets udformning, kortbladet 1214, Silkeborg. Geological Survey of Denmark, 28pp.

Binzer, K., Stockmarr, J., 1994. Prækvartæroverfladens højdeforhold, 1:500 000. Geological Survey of Denmark, Map Series No. 44.

Bjarkeus, M., Gelumbauskaite, Z., Sturkell, E., Flodén, T., Grigelis, A., 1994. Paleochannels in the East Central part of the Baltic Proper. Baltica 8, 15–26.

Björnsson, H., 1996. Scales and rates of glacial sediment removal: a 20 km long, 300 m deep trench created beneath Breidamerjökull during the Little Ice Age. Annals of Glaciology 22, 141–146.

Booth, D.B., Hallet, B., 1993. Channel networks carved by subglacial meltwater: observations and reconstruction in the Eastern Puget Lowland of Washington. Geological Society of America Bulletin 105, 671–683.

Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and geological consequences. Journal of Geophysical Research 92, 9059–9082.

Boulton, G.S., Slot, T., Blessing, K., Glasbergen, P., Leijnse, T., Van Gijssel, K., 1993. Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences. Quaternary Science Reviews 12, 739–745.

Boulton, G.S., Caban, P.E., van Gijssel, K., 1995. Groundwater flow beneath ice sheets: Part I—large scale patterns. Quaternary Science Reviews 14, 545–562.

Boyd, R., Scott, D.B., Douma, M., 1988. Glacial tunnel valleys and quaternary history of the outer Scotian shelf. Nature 333, 61–64.

Breemer, C.W., Clark, P.U., Haggerty, R., 2002. Modeling the subglacial hydrology of the late Pleistocene Lake Michigan Lobe, Laurentide Ice Sheet. Geological Society of America Bulletin 114, 665–674.

Brennand, T.A., Shaw, J., 1994. Tunnel channels and associated landforms, south-central Ontario: their implications for ice-sheet hydrology. Canadian Journal of Earth Sciences 31, 505–522.

Brook, M.S., Kirkbride, M.P., Brock, B.W., 2004. Rock strength and development of glacial valley morphology in the Scottish Highlands and northwest Iceland. Geografiska Annaler Series A 86A, 225–234.

Bruun-Petersen, J., 1987. Prækvartæroverfladen i Ribe Amt, dens højdeforhold og dannelse samt indflydelse på vandindvindingsmulighederne. Dansk Geologisk Forening (Årsskrift for 1986) 35–40.

Clark, P.U., Walder, J.S., 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. Geological Society of America Bulletin 106, 304–314.

Clayton, L., Attig, J.W., Mickelson, D.M., 1999. Tunnel channels formed in Wisconsin during the last glaciation. Geological Society of America (Special Paper) 337, 69–82.

ÓCofaigh, C., 1996. Tunnel valley genesis. Progress in Physical Geography 20, 1–19.

Cutler, P.M., Colgan, P.M., Mickelson, D.M., 2002. Sedimentologic evidence for outburst floods from the Laurentide Ice Sheet margin in Wisconsin, USA: implications for tunnel-channel formation. Quaternary International 90, 23–40.

Danielsen, J.E., Auken, E., Jørgensen, F., Søndergaard, V., Sørensen, K.I., 2003. The application of the transient electromagnetic method in hydrogeophysical surveys. Journal of Applied Geophysics 53, 181–198.

van Dijke, J.J., Veldkamp, A., 1996. Climate-controlled glacial erosion in the unconsolidated sediments of northwestern Europe, based on a genetic model for tunnel valley formation. Earth Surface Processes and Landforms 21, 327–340.

Ditlefsen, C., 1991. Luminescence dating of Danish Quarternary sediments. Unpublished Ph.D. Thesis, Aarhus University, Århus, Denmark, 116pp.

Dobracki, R., Krzyszkowski, D., 1997. Sedimentation and erosion at the Weichselian ice-marginal zone near Golczewo, northwestern Poland. Quaternary Science Reviews 16, 721–740.

Doll, W.E., Miller, R.D., Xia, J.H., 1998. A noninvasive shallow seismic source comparison on the Oak Ridge Reservation, Tennessee. Geophysics 63, 1318–1331.

Effersø, F., Auken, E., Sørensen, K.I., 1999. Inversion of band-limited TEM responses. Geophysical Prospecting 47, 551–564.

Ehlers, J., 1996. Quaternary and Glacial Geology. Wiley, Chichester 578pp.

Ehlers, J., Gibbard, P., 1991. Anglian glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L., Rose, J. (Eds.), Glacial Deposits in Great Britain and Northern Ireland. A.A. Balkema, Rotterdam, pp. 17–24.

Ehlers, J., Linke, G., 1989. The origin of deep buried channels of Elsterian age in NW Germany. Journal of Quaternary Science 4, 255–265.

Ehlers, J., Wingfield, R., 1991. The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. Journal of Quaternary Science 6, 313–326.

Ehlers, J., Meyer, K.-D., Stephan, H.-J., 1984. Pre-Weichselian glaciations of north-west Europe. Quaternary Science Reviews 3, 1–40.

Eissmann, L., Litt, T., Wansa, S., 1995. Elsterian and Saalian deposits in their type area in central Germany. In: Ehlers, J., Kozarski, S., Gibbard, P. (Eds.), Glacial Deposits in North-east Europe. Balkema, Rotterdam, pp. 439–464.

Evans, D.J.A., Campbell, I.A., 1995. Quaternary stratigraphy of the buried valleys of the lower red deer river, Alberta, Canada. Journal of Quaternary Science 10, 123–148.

van Everdingen, R.O., 1976. Geocryological terminology. Canadian Journal of Earth Sciences 13, 862–867.

Eyles, N., de Broekert, P., 2001. Glacial tunnel valleys in the Eastern Goldfields of Western Australia cut below the Late Paleozoic Pilbara ice sheet. Palaeogeography Palaeoclimatology Palaeoecology 171, 29–40.

Eyles, N., McCabe, A.M., 1989. Glaciomarine Facies Within Subglacial Tunnel Valleys—the Sedimentary Record of Glacioisostatic Downwarping in the Irish Sea Basin. Sedimentology 36, 431–448.

Foldager, C., 2003. En begravet kvartær dal ved Horsens: Geologi og oprindelse. M.Sc. Thesis, Aarhus University, Denmark, 113pp.

Fränzle, O., 1988. Periglaziale Formung der Altmoränengebiete Schleswig-Holsteins. Berliner Geographische Abhandlungen 47, 23–35.

Gabriel, G., Kirsch, R., Siemon, B., Wiederhold, H., 2003. Geophysical investigation of buried Pleistocene subglacial valleys in Northern Germany. Journal of Applied Geophysics 53, 159–180.

Galon, R., 1965. Some new problems concerning sub-glacial channels. Geographia Polonica 6, 19–28.

Galon, R., 1983. On the origin of subglacial channels. In: Briggs, D.J., Waters, R.S. (Eds.), Studies in Quaternary Geomorphology. Proceedings of the Sixth British—Polish Seminar, Institute of British Geographers. Geo. Books, Norwich, pp. 85–95.

Ghienne, J.F., Deynoux, M., 1998. Large-scale channel fill structures in late Ordovician glacial deposits in Mauritania, western Sahara. Sedimentary Geology 119, 141–159.

Glasser, N.F., Bennett, M.R., 2004. Glacial erosional landforms: origins and significance for palaeoglaciology. Progress in Physical Geography 28, 43–75.

Glasser, N.F., et al., 2004. Glacial meltwater erosion and sedimentation as evidence for multiple glaciations in west Wales. Boreas 33, 224–237.

Gripp, K., 1964. Erdgeschichte von Schleswig-Holstein. Wachholtz Verlag Neumünster, 411pp.

Grube, F., 1979. Übertiefte Täler im Hamburger Raum. Eiszeitalter und Gegenwart 29, 157–172.

Hall, A.M., Glasser, N.F., 2003. Reconstructing former glacial basal thermal regimes in a landscape of selective linear erosion: Glen Avon, Cairngorm Mountains, Scotland. Boreas 32, 191–207.

Hansen, K., 1971. Tunnel valleys in Denmark and Northern Germany. Bulletin of the Geological Society of Denmark 20, 295–306.

Hansen, S., 1978. Sidste nedisnings maksimum-udbredelse i Syd- og Midtjylland. Danmarks Geologiske Undersøgelse (Årbog 1976) 139–152.

Harder, P., 1908. En østjysk Israndslinie og dens Indflydelse paa Vandløbene. Danmarks Geologiske Undersøgelse, II. rk, vol. 19, pp. 1–227.

Hinsch, W., 1979. Rinnen an der Basis des glaziären Pleistozäns in Schleswig-Holstein. Eiszeitalter und Gegenwart 29, 173–178.

Hirst, J.P.P., Benbakir, A., Payne, D.F., Westlake, I.R., 2002. Tunnel valleys and density flow processes in the upper Ordovician glacial succession, Illizi Basin, Algeria: influence on reservoir quality. Journal of Petroleum Geology 25, 297–324.

Houmark-Nielsen, M., 1987. Pleistocene stratigraphy and glacial history of the central part af Denmark. Bulletin of the Geological Society of Denmark 36, 1–189.

Houmark-Nielsen, M., 1999. A lithostratigrafy of the Weichselian glacial and interstadial deposits in Denmark. Bulletin of the Geological Society of Denmark 46, 101–114.

Houmark-Nielsen, M., 2003. Signature and timing of the Kattegat Ice Stream: onset of the Last Glacial Maximum sequence at the southwestern margin of the Scandinavian Ice Sheet. Boreas 32, 227–241.

Houmark-Nielsen, M., Kjaer, K.H., 2003. Southwest Scandinavia, 40–15 kyr BP: palaeogeography and environmental change. Journal of Quaternary Science 18, 769–786.

Huuse, M., Lykke-Andersen, H., 2000. Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quaternary Science Reviews 19, 1233–1253.

Iverson, N.R., 2000. Sediment entrainment by a soft-bedded glacier: a model based on regelation into the bed. Earth Surface Processes and Landforms 25, 881–893.

Jeffery, D.H., 1991. The origin of major incisions within the Pleistocene deposits of the North-Sea—comment. Marine Geology 96, 125–126.

Jensen, J.B., 1985. Sen-Elster smeltevandsler-en mulig ledehorisont i det vestlige Jylland. Dansk Geologisk Forening (Årsskrift for 1984) 21–35.

Johannsen, A., 1960. Ur-anlagen pleistozäner Förden und Rinnen in Schleswig-Holstein. Geologisches Jahrbuch 77, 271–307.

Jørgensen, F., Piotrowski, J.A., 2003. Signature of the Baltic Ice Stream on Funen Island, Denmark during the Weichselian glaciation. Boreas 32, 242–255.

Jørgensen, F., Sandersen, P.B.E., 2004. Kortlægning af begravede dale i Jylland og på Fyn. Opdatering 2003–2004. De jysk-fynske amters grundvandssamarbejde. Vejle Amt, Watertech a/s, 224pp.

Jørgensen, F., Auken, E., Lykke-Andersen, H., Sørensen, K.I.S., 2003a. Groundwater exploration by the use of TEM, reflection seismic surveys and drillings, EEGS-ES, Ninth Annual Meeting, Prague, Czech Republic. Proceedings, vol. O-063, 4pp.

Jørgensen, F., Lykke-Andersen, H., Sandersen, P.B.E., Auken, E., Normark, E., 2003b. Geophysical investigations of buried Quaternary valleys in Denmark: an integrated application of transient electromagnetic soundings, reflection seismic surveys and exploratory drillings. Journal of Applied Geophysics 53, 215–228.

Jørgensen, F., Sandersen, P.B.E., Auken, E., 2003c. Imaging buried Quaternary valleys using the transient electromagnetic method. Journal of Applied Geophysics 53, 199–213.

Jørgensen, F., Sandersen, P.B.E., Auken, E., Lykke-Andersen, H., Sørensen, K., 2005. Contributions to the geological mapping of Mors, Denmark—a study base don a large-scale TEM survey. Bulletin of the Geological Society of Denmark 52, 53–75.

Kjær, K.H., Houmark-Nielsen, M., Richardt, N., 2003. Ice-flow patterns and dispersal of erratics at the southwestern margin of the last Scandinavian Ice Sheet: signature of palaeo-ice streams. Boreas 32, 130–148.

Kluiving, S.J., Bosch, J.H.A., Ebbing, J.H.J., Mesdag, C.S., Westerhoff, R.S., 2003. Onshore and offshore seismic and lithostratigraphic analysis of a deeply incised Quaternary buried valley-system in the Northern Netherlands. Journal of Applied Geophysics 53, 249–271.

Knudsen, K.L., 1987a. Elsterian–Holsteinian Foraminiferal Stratigraphy in the North Jutland and Kattegat areas, Denmark. Boreas 16, 359–368.

Knudsen, K.L., 1987b. Foraminifera and ostracoda in late Elsterian–Holsteinian deposits at Tornskov and adjacent areas in Jutland, Denmark. Geological Survey of Denmark (Series B) 10, 7–32.

Knudsen, K.L., 1994. The marine Quaternary in Denmark: a review of new evidence from glacial–interglacial studies. Bulletin of the Geological Society of Denmark 41, 203–218.

Kolstrup, E., 1986. Reapraisal of the upper Weichselian periglacial environment from Danish frost wedge casts. Palaeogeography Palaeoclimatology Palaeoecology 56, 237–249.

Kronborg, C., Bender, H., Larsen, G., 1978. Tektonik som mulig medvirkende årsag til daldannelsen i Midtjylland. Danmarks Geologiske Undersøgelse (Årbog 1977) 63–76.

Kronborg, C., Bender, H., Bjerre, R., Friborg, R., Jacobsen, H.O., Kristiansen, L., Rasmussen, P., Sørensen, P.R., Larsen, G., 1990. Glacial stratigraphy of East and Central Jutland. Boreas 19, 273–287.

Kronborg, C, Nielsen, O.B., Sørensen, J., Kragelund, A., Hartvig, L., 2003. Boring DGU nr. 97.951 og 97.952. 03VE-01, Department of Earth Sciences, Aarhus University, 85pp.

Kronborg, C, Nielsen, O.B., Sørensen, J., Krohn, C., Kragelund, A., 2004. Kortlægning og korrelation af grundvandsførende sedimenter i Jylland og på Fyn, Vintermøde om jord- og grundvandsforurening. ATV Jord og Grundvand, Vingstedcentret, Denmark, pp. 253–266.

Krüger, J., 1983. Glacial morphology and deposits in Denmark. In: Ehlers, J. (Ed.), Glacial Deposits in North-west Europe. A.A. Balkema, Rotterdam, pp. 181–191.

Krüger, J., 1989. Gletscheren og landskabet—i nutid og istid. Geografiske temahæfter. Gyldendal, Nordisk For-lag, Copenhagen, 77pp.

Kuster, H., Meyer, K.-D., 1979. Glaziäre Rinnen im mittleren und nordöstlichen Niedersachsen. Eiszeitalter und Gegenwart 29, 135–156.

Larsen, G., Kronborg, C., 1994. Geologisk Set. Det mellemste Jylland. Geografforlaget, Brenderup, Denmark, 272pp.

Long, D., Stoker, M.S., 1986. Channels in the North Sea: the nature of a hazard. Proceedings of Oceanology International'86, Oceanology, vol. 6. Graham and Trotman, London, pp. 339–351.

Lüttig, G., 1972. Die Bodenschätze des Nordsee-Küstenraumes und ihre Bedeutung für Landesplanung und Raumordnung. Neues Archiv für Niedersachsen 21, 13–25.

Lykke-Andersen, H., 1973. En begravet dal i Præ-kvartæret ved Århus. Dansk Geologisk Forening (Årsskrift for 1972) 111–118.

Lykke-Andersen, H., 1986. On the buried Nørreå Valley: a contribution to the geology of the Nørreå Valley, Jylland—and other overdeepened valleys. In: Møller, J.T. (Ed.), Twentyfive Years of Geology in Aarhus. Geoskrifter, pp. 211–223.

Lykke-Andersen, H., 1988. Viborgegnens geologi. Viborg Leksikon 6, 40p.

Lykke-Andersen, H., Schrøder, N., 1974. Et begravet landskab ved Århus. Varv 4, 110–113.

Lykke-Andersen, H., Seidenkrantz, M.-S., Knudsen, K.L., 1993. Quaternary sequences and their relations to the pre-Quaternary in the vicinity of Anholt, Kattegat, Scandinavia. Boreas 22, 291–298.

Madsen, V., 1921. Terrainformerne på Skovbjerg Bakkeø. Danmarks Geologiske Undersøgelse (IV. rk.) 1 (12), 1–24.

Maizels, J., 1997. Jökulhlaup deposits in proglacial areas. Quaternary Science Reviews 16, 793–819.

McCabe, A.M., ÓCofaigh, C.O., 1994. Sedimentation in a Subglacial Lake, Enniskerry, Eastern Ireland. Sedimentary Geology 91, 57–95.

Milthers, V., 1925. Beskrivelse til Geologisk Kort over Danmark. Kortbladet Bække. Danmarks Geologiske Undersøgelse, (I. rk) 15, 175pp.

Milthers, K., 1935a. Landskabets Udformning mellem Alheden og Limfjorden. Danmarks Geologiske Undersøgelse (II. rk) 56, 1–32.

Milthers, V., 1935b. Nordøstsjællands Geologi. Danmarks Geologiske Undersøgelse (V. rk), 3, 186pp.

Milthers, V., 1948. The morphology and genesis of the glacial landscape in Denmark. Geological Survey of Denmark (Series III) 28, 1–233.

Mooers, H.D., 1989. On the Formation of the Tunnel Valleys of the Superior Lobe, Central Minnesota. Quaternary Research 32, 24–35.

Mullins, H.T., Hinchey, E.J., 1989. Erosion and infill of New York Finger Lakes—implications for Laurentide ice-sheet deglaciation. Geology 17, 622–625.

Mullins, H.T., Hinchey, E.J., Wellner, R.W., Stephens, D.B., Anderson Jr., W.T., Dwyer, T.R., Hine, A.C., 1996. Seismic stratigraphy of the Finger Lakes; a continental record of Heinrich event H-1 and Laurentide ice sheet instability. In: Mullins, H.T., Eyles, N., (Eds.), Subsurface Geologic Investigations of New York Finger Lakes; Implications for Late Quaternary Deglaciation and Environmental Change Special Paper—Geological Society of America, No. 311. Geological Society of America, Boulder, Boulder, CO, United States, pp. 1–35.

Munro-Stasiuk, M.J., 2003. Subglacial Lake McGregor, south-central Alberta, Canada. Sedimentary Geology 160, 325–350.

Nielsen, A.V., 1967. De geologiske forhold i naturparken, Naturparken mellem Farum og Slangerup. C.E.C. Gad, Copenhagen, pp. 133–178.

Niewiarowski, W., 1995. Diagnostic features of sub-glacial channels of glacial and fluvio-glacial origin, exemplified by channels of the Chelmo-Dobrzyn and the eastern Gniezo lakelands. Questiones Geographicae 4, 225–231.

Nordmann, V., 1958. Beskrivelse til Geologisk kort over Danmark. Kortbladet Fredericia. A: Kvartære aflejringer. Geological Survey of Denmark (Series I) 22-A, 1–125.

Nye, J.F., 1973. Water at the bed of a glacier. International Association of Scientific Hydrology 95, 189–193.

Olsen, H., Andreasen, F., 1995. Sedimentology and ground-penetrating radar characteristics of a Pleistocene sandur deposit. Sedimentary Geology 99, 1–15.

Patterson, C.J., 1994. Tunnel-valley fans of the St. Croix moraine, east-central Minnesota, USA. In: Warren, W.P., Croot, D.G. (Eds.), Formation and Deformation of Glacial Deposits. Balkema, Rotterdam, pp. 69–87.

Penney, D.N., 1987. Foraminifera and ostracoda in late Elsterian–Holsteinian deposits at Tornskov and adjacent areas in Jutland, Denmark. Geological Survey of Denmark (Series B) 10, 33–67.

Piotrowski, J.A., 1994. Tunnel-valley formation in Northwest Germany—geology, mechanisms of formation and subglacial bed conditions for the bornhoved tunnel valley. Sedimentary Geology 89, 107–141.

Piotrowski, J.A., 1997a. Subglacial groundwater flow during the last glaciation in northwestern Germany. Sedimentary Geology 111, 217–224.

Piotrowski, J.A., 1997b. Subglacial hydrology in north-western Germany during the last glaciation: groundwater flow, tunnel valleys and hydrological cycles. Quaternary Science Reviews 16, 169–185.

Piotrowski, J.A., Mickelson, D.M., Tulaczyk, S., Krzyszkowski, D., Junge, F.W., 2001. Were deforming subglacial beds beneath past ice sheets really widespread? Quaternary International 86, 139–150.

Piotrowski, J.A., Mickelson, D.M., Tulaczyk, S., Krzyszkowski, D., Junge, F.W., 2002. Reply to the comments by G.S. Boulton, K.E. Dobbie, S. Zatsepin on: deforming soft beds under ice sheets: how extensive were they? Quaternary International 97, 173–177.

Praeg, D., 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin-high resolution from low frequencies. Journal of Applied Geophysics 53, 273–298.

Pugin, A., Pullan, S.E., Sharpe, D.R., 1996. Observation of tunnel channels in glacial sediments with shallow land-based seismic reflection. Annals of Glaciology 22, 176–180.

Pugin, A., Pullan, S.E., Sharpe, D.R., 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario. Canadian Journal of Earth Sciences 36, 409–432.

Rains, R.B., Shaw, J., Sjogren, D.B., Munro-Stasiuk, M.J., Skoye, K.R., Young, R.R., Thompson, R.T., 2002. Subglacial tunnel channels, Porcupine Hills, southwest Alberta, Canada. Quaternary International 90, 57–65.

Röthlisberger, H., 1972. Water pressure in intra- and subglacial channels. Journal of Glaciology 11, 177–203.

Russell, H.A.J., Arnott, R.W.C., Sharpe, D.R., 2003. Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, Southern Ontario, Canada. Sedimentary Geology 160, 33–55.

Salomonsen, I., 1995. Origin of a deep buried valley system in Pleistocene deposits of the eastern Central North Sea. In: Michelsen, O. (Ed.), Proceedings of the Second Symposium on Marine Geology—Geology of the North Sea and Skagerrak. Geological Survey of Denmark, pp. 7–19.

Sandersen, P., Jørgensen, F., 2002. Kortlægning af begravede dale i Jylland og på Fyn. Opdatering 2001–2002. De jysk-fynske amters grundvandssamarbejde. Vejle Amt, Watertech a/s, 189pp.

Sandersen, P.B.E., Jørgensen, F., 2003. Buried Quaternary valleys in western Denmark—occurrence and inferred implications for groundwater resources and vulnerability. Journal of Applied Geophysics 53, 229–248.

Schrøder, N., 1974. De geofysisk-geologiske undersøgelser af området nord for Århus. In: Frederiksen, E., Hastrup, H.F., Saxov, S. (Eds.), Undersøgelser af Århusegnens undergrund. Laboratoriet for Geofysik, Århus Universitet, pp. 11–55.

von Schwab, G., Ludwig, A.O., 1996. Zum Relief der Quartärbasis in Norddeutschland. Bemerkungen zu einer neuen Karte. Zeitschrift für Geologische Wissenschaften 24, 343–349.

Shoemaker, E.M., 1992. Water sheet outburst floods from the Laurentide Ice-Sheet. Canadian Journal of Earth Sciences 29, 1250–1264.

Shreve, R.D., 1985. Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. Geological Society of America Bulletin 96, 639–646.

Siegert, M.J., 2000. Antarctic subglacial lakes. Earth-Science Reviews 50, 29–50.

Sjogren, D.B., Fisher, T.G., Taylor, L.D., Jol, H.M., Munro-Stasiuk, M.J., 2002. Incipient tunnel channels. Quaternary International 90, 41–56.

Sjørring, S., 1979. Tunneltäler in Dänemark. Eiszeitalter und Gegenwart 29, 179–188.

Smed, P., 1962. Studier over den fynske øgruppes glaciale landskabsformer. Medd. Dansk Geologisk Forening 15, 1–74.

Smed, P., 1979. Landskabskort over Danmark, Blad 1, Nordjylland. Geografforlaget, Brenderup, Denmark.

Smed, P., 1981a. Landskabskort over Danmark, Blad 2, Midtjylland. Geografforlaget, Brenderup, Denmark.

Smed, P., 1981b. Landskabskort over Danmark, Blad 4, Sjæjlland, Lolland, Falster, Bornholm. Geografforlaget, Brenderup, Denmark.

Smed, P., 1982. Landskabskort over Danmark, Blad 3, Sønderjylland, Fyn. Geografforlaget, Brenderup, Denmark.

Smed, P., 1998. Die Entstehung der dänischen und norddeutschen Rinnentäler (Tunneltäler)—Glaziologische Gesichtspunkte. Eiszeitalter und Gegenwart 48, 1–18.

Smith, L.N., 2004. Late Pleistocene stratigraphy and implications for deglaciation and subglacial processes of the Flathead Lobe of the Cordilleran Ice Sheet, Flathead Valley, Montana, USA. Sedimentary Geology 165, 295–332.

Sorgenfrei, T., Berthelsen, O., 1954. Geology and Water Well Boring. Geological Survey of Denmark (Series III) 31, 1–60.

Sugden, D.E., John, B., 1976. Glaciers and landscape: a geomorphological approach. Edward Arnol, London 376pp.

Sørensen, K.I., Auken, E., 2004. SkyTEM—a new high-resolution helicopter transient electromagnetic system. Exploration Geophysics 35, 191–199.

Sørensen, J., Kronborg, C, Nielsen, O.B., Krohn, C., Kragelund, A., 2004. Petrografisk korrelation af 9 boringer fra Århus Nord. Fase 2. Department of Earth Sciences, Åarhus University, 26pp.

Taylor, W.P., Wilson, C.D.V., 1997. Tectonically influenced glacial erosion, and ensuing valley infill: a geophysical survey. Quarterly Journal of Engineering Geology 30, 97–113.

Thomsen, R., Søndergaard, V.H., Sørensen, K.I., 2004. Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark. Hydrogeology Journal 12, 550–562.

Ussing, N.V., 1903. Om Jyllands hedesletter og teorierne for deres dannelse. Oversigt over Det Kongelige danske Videnskabernes Selskab Forhandlinger 2, 99–152.

Ussing, N.V., 1907. Om floddale og randmoræner i Jylland. Oversigt over Det Kongelige danske Videnskabernes Selskab Forhandlinger 4, 161–213.

Vangkilde-Pedersen, T., Skjellerup, P., Ringgaard, J., Jensen, J.F., 2003. Pulled array seismic (PAS)—a new method for shallow reflection seismic data acquisition. European Association of Geoscientists & Engineers, 65th EAGE Conference & Exhibition, Stavanger 2003, Norway, P201, 4pp.

Veen, M.V.D., Green, A.G., 1998. Land-streamer for shallow seismic data acquisition: evaluation of gimbal mounted geophones. Geophysics 63, 1408–1423.

Visser, J.N.J., 1988. A permo-carboniferous tunnel valley system east of Barkly West, northern Cape Province. South African Journal of Geology 91, 350–357.

Walder, J.S., Fowler, A., 1994. Channelized Subglacial Drainage over a Deformable Bed. Journal of Glaciology 40 (134), 3–15.

Wingfield, R., 1990. The origin of major incisions within the Pleistocene deposits of the North sea. Marine Geology 91, 31–52.

Wingfield, R.T.R., 1989. Glacial incisions indicating middle and upper Pleistocene ice limits off Britain. Terra Nova 1, 538–548.

Woldstedt, P., 1952. Die Entstehung der Seen in den ehemals vergletscherten Gebieten. Eiszeitalter und Gegenwart 2, 146–153.

Woodland, A.W., 1970. The buried tunnel-valleys of East Anglia. Proceedings of the Yorkshire Geological Society 37, 521–578.

Wright, H.E., 1973. Tunnel valleys, Glacial surges, and subglacial hydrology of the superior lobe, Minnesota. In: Black, R.F., Goldthwait, R.P., Willman, H.B. (Eds.), The Geological Society of America, Memoir 136, pp. 251–276.