Delineation of tunnel valleys across the North Sea coastline, Denmark based on reflection seismic data, boreholes, TEM and Schlumberger soundings.

Theis Raaschou Andersen*
VIA University College
C.M.Ostergaardsvej 4, Horsens, DK
Thra@via.dk

Flemming Jørgensen
Geological Survey of Denmark and Greenland, Aarhus, DK
flj@geus.dk

Steen Christensen
Geoscience, University of Aarhus
Aarhus, DK
sc@geo.au.dk

SUMMARY

Buried tunnel valleys are elongated depressions eroded into the substratum during the Pleistocene glaciations. Nine such valleys are mapped on- and offshore in a 300 km^2 area located at the Danish North Sea coast. The delineation of the buried valleys is based on an extensive data set consisting of on- and offshore 2D seismic data, TEM (Transient Electro-Magnetic) soundings, Schlumberger soundings, and boreholes. The valleys are observed as discrete incisions with three overall orientations: SSE – NNW, ESE – WNW, and SSW – NNE. They have depths between 75 and 185 m, widths up to 1.8 km, and lengths from 7 to 25 km. The infill comprises till, glaciofluvial sand, and glaciolacustrine clay and silt. Younger tunnel valleys are found to often re-use pre-established valleys generating cut-and-fill structures which are clearly revealed on the reflection seismic profiles. Cross-cutting relations, preferred orientations, and morphology support that three of the tunnel valleys cross the North Sea coastline. It is suggested that the nine valleys were formed during at least six events that occurred through one or more pre-Weichselian glaciations.

Key words: Pleistocene valleys, geophysical mapping, reflection seismic data, 3D geological models

INTRODUCTION

Tunnel valleys (TV) have been found throughout the lowlands of North Europe and North America which were covered by ice sheets during the Pleistocene (e.g. Wright, 1973, Huuse and Lykke-Andersen, 2000, Jørgensen and Sandersen, 2006, Kehew et al., 2012). Tunnel valleys are defined as large overdeepened elongated depressions eroded into bedrock or unconsolidated sediment (Ò Cofaigh, 1996). The valleys can be more than 100 km long, eight kilometres wide, 500 m deep, and their thalwegs typically undulate with multiple thresholds and hollows (e.g. Huuse and Lykke-Andersen, 2000, Jørgensen and Sandersen 2006, Andersen et al., 2012). The infill comprises glacial and/or interglacial deposits and can thus contain important aquifers (Sandersen and Jørgensen, 2003). The buried valleys have therefore been mapped intensively in Denmark during the last 20 years.

Over the past thirty years, there has been a significant advance in the application of geophysics to investigate the shallow geology, offshore as well as onshore. Offshore 2D high-resolution reflection seismic data and 3D reflection seismic volumes have provided new information on the occurrence and structural composition of buried valleys (e.g. Wingfield 1990, Huuse & Lykke-Andersen 2000, Praeg 2003, Kristensen et al. 2007). However, lithological information about the infill is sparse offshore due to the scarcity of boreholes.

Onshore, especially the Transient Electro-Magnetic (TEM) method (e.g. Christensen and Sørensen 1998) has provided comprehensive information about the existence and spatial distribution of tunnel valleys and indications about their formation and geomorphology (Jørgensen and Sandersen 2006). Extensive TEM data in combination with fairly extensive borehole data have provided evidence about the lithology of the infill in several buried tunnel valleys. However, detailed information about the valley structure and its infill can be difficult to obtain from the TEM soundings because at depth these measurements integrate over a large volume (West and MacNae 1991, Jørgensen et al. 2003a,b). Therefore, reflection seismic data has been utilized as a supplementary method in Denmark during the last 10-20 years in order to achieve detailed information on the internal structures of the tunnel valleys. However, the amount of onshore reflection seismic data is still sparse compared to the amount of e.g. TEM.

Little attention has been paid to comparing, correlating, and connecting onshore and offshore tunnel valleys in existing literature. From the Northern Netherlands Kluiving et al., (2003) used seismic data to correlate a series of tunnel valleys from the offshore part of the Dutch sector to onshore valleys from the Island of Ameland and the northern Netherland. From Denmark Andersen et al., (2012) correlated on- and offshore tunnel valleys with respect to their morphological and structural characteristics based on statically analysis.

The objective of this paper is to identify, compare, and connect on- and offshore tunnel valleys within a 300 km^2 area covering Holmsland, Denmark and the nearby offshore area (Figure 1). The study area comprises extensive datasets consisting of boreholes, geophysical soundings, and 2D reflection seismic data.

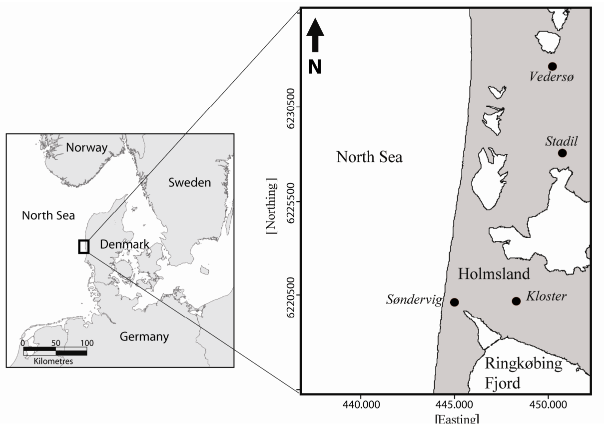

Figure 1: Study area

GEOLOGICAL SETTING

Throughout the Cenozoic the North Sea Basin was dominated by subsidence and accumulation of more than three kilometers of sediments from the surrounding landmasses that were uplifted and eroded (Nielsen et al., 1986). During the Oligocene and Miocene the eastern North Sea Basin and the western Denmark were covered by a series of depositional sequences due to tectonic movements and eustatic sea-level changes. The successions consist of sandy fluvio-deltaic deposits alternating with more clayish marine deposits (Rasmussen, 2010).

During the Pleistocene, Denmark and the eastern North Sea were covered by multiple glaciations expanding from the Scandinavian highlands (Houmark-Nielsen, 1987, Carr et al., 2006). During the glaciations the sea level was at least 120 m lower than today and large areas of the North Sea were probably subaerial (Cameron et al. 1987, Shackleton 1987). The Elsterian and Saalian ice sheets covered north-western Europe, including the study area, and large parts of the North Sea (Ehlers, 1990, Carr et al., 2006). The Weichselian glaciation, however, is not believed to have covered the study area. The glaciations were characterized by multiple ice advances and retreats and the formation of intricate systems of tunnel valleys (Huuse and Lykke-Andersen, 2000, Jørgensen and Sandersen 2006, Andersen et al., 2012). During the glaciations, glaciofluvial sand and gravel, tills and glaciolacustrine sediments were deposited.

DATA

Transient Electro-Magnetic (TEM) surveys
A total of 150 TEM soundings have been carried out in the study area (Figure 2). The TEM method is a time-domain electromagnetic method, which has been used successfully in Denmark during the past decades in hydrogeophysical investigations (e.g. Auken et al., 2003, Jørgensen et al. 2003a,b). A TEM measurement is conducted by sending a steady current through a transmitter loop which creates a magnetic field. The current is turned off abruptly whereby the magnetic field decays and induces a secondary current that diffuses into the ground. The secondary current creates a secondary magnetic field that is measured by a receiver coil on the surface.

The TEM method has proven successful for mapping the near-surface Danish sedimentary environments, and has therefore often been used with success to locate buried tunnel valleys (Auken et al. 2003, Jørgensen et al. 2003a,b), especially in areas where the resistivity contrast between the substratum and the valley infill is high. In some cases TEM measurements have provided valuable information about the morphology and the lithology of buried tunnel valleys (Høyer et al., 2015). However, the resolution capabilities of the TEM soundings decrease with depth. In practice, the lithological layers at a depth of 100 m has to be at least 20 – 50 m thick to be resolved properly by the TEM soundings (Jørgensen et al. 2003a,b, Jørgensen et al., 2005). Furthermore, the lateral resolution also decreases with the depth which makes deep interpretations of 3-D structures based exclusively on TEM soundings weak (e.g. West and MacNae 1991, Danielsen et al. 2003).

The TEM measurements were conducted utilizing a Geonics PROTEM 47 receiver with a 40 x 40 m^2 transmitter loop. The transmitted current was between 1 and 3 ampere yielding a penetration depth of 120–150 meters depending on the background noise and the resistivity of the subsurface layers (Spies, 1989, Auken et al., 2003). The TEM measurements were inverted by one-dimensional modelling into layered soundings (Effersø et al., 1999, Danielsen et al., 2003, Auken et al., 2003).

Schlumberger soundings
The 115 Schlumberger soundings located within the study area (Figure 2) were conducted using an ABEM SAS-300C Terrameter with an ABEM booster. The transmitted current was between 10 and 200 mA, the maximum distance between the current electrodes was 500 m, and the distance between the potential electrodes was varied between 1, 10 and 50 m. Ten measurements were made per decade distance. The data were inverted into layered soundings.

Reflection seismic data
In this study both on- and offshore data were analysed (Figure 2). Offshore, 60 km of seismic data measured along eight lines situated close to the coastline (DA95_05, DA95_l21, DA95_l22, DA96_06, GR9712_1, GR9712_2, GR9716, and GR9717) were

interpreted. The post-stack bandwidth of the migrated data is 40-250 Hz for DA 95, DA 96, GR 97 and GR 98, and 40-180 Hz for DA 94. For the upper 400 m, which is the focus depth of this study, this gives a vertical resolution of the seismic surveys of 20-30 m and 5-10 m, respectively.

The onshore seismic surveys were acquired by two different setups both using the common mid-point technique with a small vibrator as the source and a towed geophone land-streamer. One survey (6 km) was made with an IVI Minivib T7000 and 101 geophones. The second survey (9 km) was made with an IVI Minivib and 72 geophones with 2.5 meters spacing (the first author). In the latter survey the near-offset from the first shot to the vibration point was 20 m giving a total tow length of 200 meters; the spacing between the vibration points was 10 meters and the vertical resolution around 5-10 m in the focus depth. In both surveys, the seismic lines are mainly oriented perpendicular to the buried tunnel valley, identified from the TEM- and Schlumberger surveys.

The post-processing includes import of field geometry, trace editing and muting, bandpass filtering, velocity analysis, residual static, normal-moveout correction, CMP stacking, and migration.

For depth conversion an average interval velocity of 1750 m/s was assumed for the on- and offshore reflection seismic data (Jørgensen et al. 2003b).

Boreholes

Lithological information from boreholes is available from the national borehole database, Jupiter, hosted by The Geological Survey of Denmark and Greenland (GEUS). A total of 577 boreholes are available for interpretation onshore. The density of boreholes changes significantly with depth from a total of 3.85 boreholes per km^2 to 0.38 boreholes per km^2 with depths of more than 50 m (Figure 2). For boreholes deeper than 150 m, the density reduces to only 0.04 boreholes per km^2.

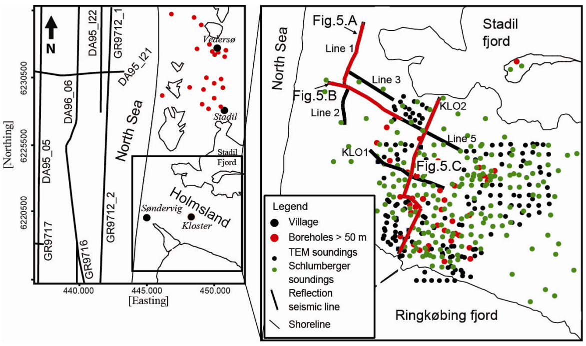

Figure 2: Map showing the data within the study area.

Geological interpretation procedure

This section describes the procedures used to identify, characterize, and interpolate buried tunnel valleys within the study area.

For the onshore part the inverted TEM- and Schlumberger data were used to identify the spatial extension of the buried tunnel valleys. This was done by presenting the resistivity in thematic maps in 10 m depth intervals reaching from the ground surface to the maximum penetration depth of the geophysical soundings. The tunnel valleys are identified as channel-shaped bodies showing resistivities that differ significantly from the surroundings on the thematic maps. For similar geological environments this has previously been found to be a good approach (Jørgensen et al., 2003b). A first rough interpretation of the lithology was made on basis of the typical resistivity ranges from Danish sediments (Jørgensen et al., 2005). This interpretation was subsequently re-evaluated against the lithological borehole information and a preliminary 3D geological model was thus constructed on basis of both resistivity and borehole data.

A geological interpretation was then performed on the seismic data, in which the base-quaternary surface and the internal valley structures were identified. In sections where the reflections were vague or missing the horizons were estimated from truncations of the substratum, reflection terminations, onlap of tunnel valley infill, velocity-induced structures in the underlying strata, and changes in the lateral reflections indicating changes in the sediment.

The preliminary geological model was finally adjusted and refined on basis of the reflection seismic data to obtain a final 3D model for the onshore buried tunnel valleys.

Due to the lack of boreholes offshore the geological interpretation was here based on information from the seismic data. Noise and multiples from the sea bed prevented the upper 40-50 m of the substratum to be resolved in detail and many shallow tunnel valleys may therefore not have been identified.

The final geological model, including both the onshore and offshore areas, was constructed using a 3D geological modelling software program (GeoScene3D; http://www.i-gis.dk) where the onshore tunnel valleys were connected with the offshore tunnel valleys from similarities in valley orientation, relative time of formation and morphological and structural characteristics. The final geological model was utilized to estimate the minimum number of events necessary to create the identified tunnel valleys and to describe the morphology such as depth from shoulders to bottom, width from shoulder to shoulder, average dip of the flanks, length, and longitudinal tunnel valley shape.

RESULTS

Nine tunnel valleys (TV1-TV9) were interpreted within the study area (Figure 3). Although there is only sparse data coverage along the coastline three of the nine valleys were connected from the onshore area across the coastline into the offshore area (Figure 3). The interpretations and the 3D model will be carefully described in the following sub-chapters.

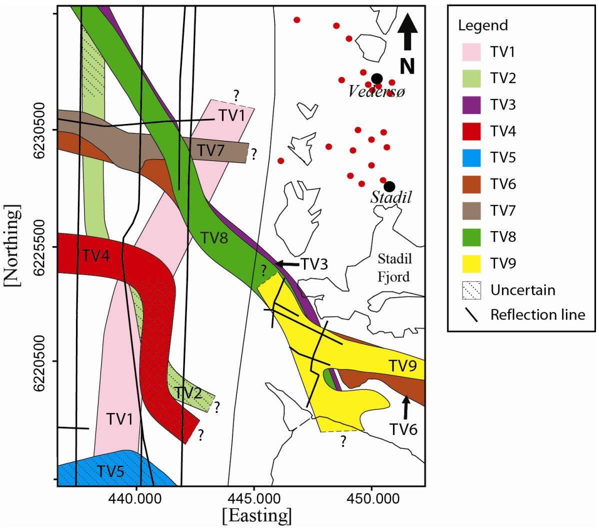

Figure 3: The nine tunnel valleys (TV1 to TV9) found in the area. The black box shows the area where TV6 reoccupy the trace of TV3 and thereby change orientation from ESE-WNW to SE-NW.

Onshore interpretation

Figure 4 shows the electrical resistivity maps for selected depth intervals as estimated from the TEM- and Schlumberger soundings.

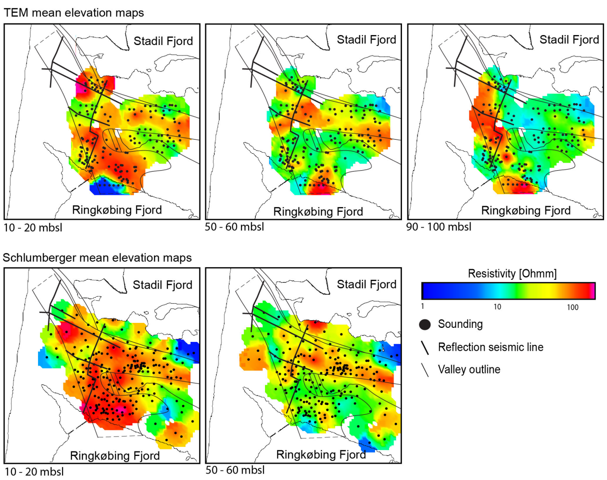

Figure 4. Interval resistivity maps based on 1-D inverse models of the TEM and Schlumberger soundings.

Several elongated features of high resistivity (> 80 ohmm) can be identified within the otherwise low-resistive environment (Figure 4). These features represent sandy infill in tunnel valleys that are eroded into the Neogene substratum of marine clayey deposits. This is supported by boreholes in the area, showing that high resistivities generally correspond to sandy glacial sediments while the medium and low resistivities correspond to clayey Neogene deposits.

The TEM data (Figure 4) supplemented by borehole data support an interpretation with three high resistivity sand units. The first unit is found within the southern and eastern part of the Holmsland area from the surface down to about 40 meters below sea level (mbsl). The second unit is found from 50 to 80 mbsl in the eastern and northern part of the area with an ESE – WNW direction. The third unit is found between 90 and 120 mbsl in the western part of Holmsland with a SSE – NNW direction. The interpretation of the high-resistive features as buried tunnel valleys are also supported by the onshore reflection seismic lines (Figure 5).

The seismic data furthermore contributes with a more precise delineation of the valleys at the intersections. The onshore seismic lines reveal four incisions that can each be interpreted as tunnel valleys. The deepest incision (TV3) is seen around 165-175 mbsl on KLO1, KLO2 (Figure 5), Line 1 (Figure 5), Line 3, and Line 5 (Figure 5). The second incision (TV6) is seen at about 125-155 mbsl on the northern part of KLO2 (Figure 5), on Line 1 (Figure 5), Line 3, and Line 5 (Figure 5). The third incision (TV8) occurs about

95-105 mbsl on KLO1, KLO2 (Figure 5), Line 1 (Figure 5), Line 2, Line 3, and Line 5 (Figure 5). The fourth and shallowest (TV9) is seen at 70-90 mbsl on all the onshore lines.

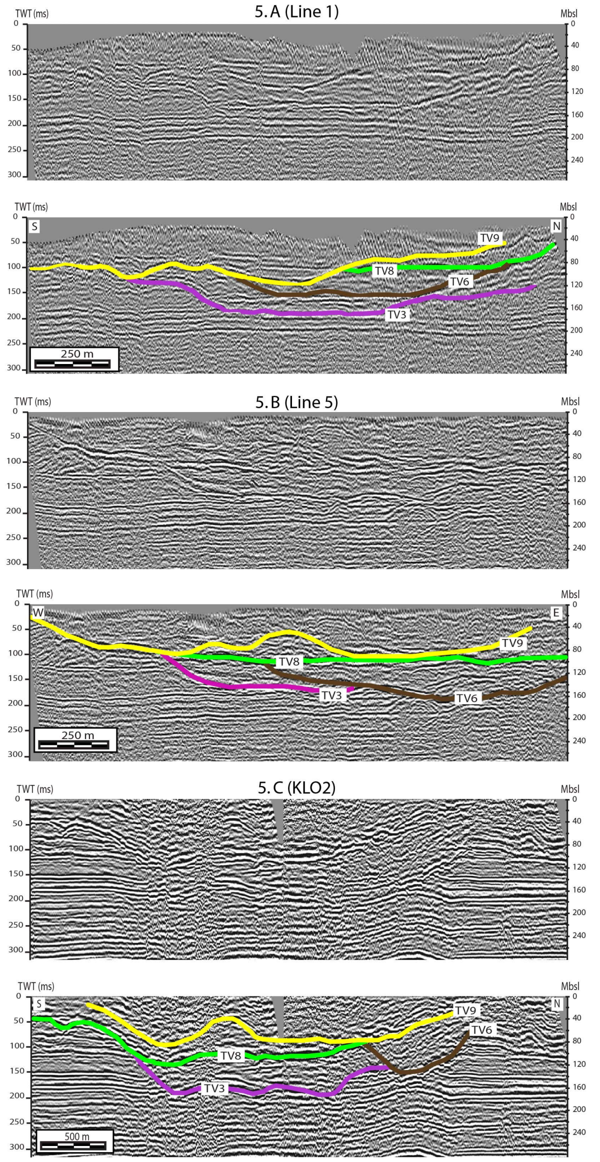

Figure 5. Onshore seismic lines (Line1, Line 5 and KLO2) with interpretations of TV3, TV6 TV8 and TV9. The positions of the reflection seismic lines are shown on Figure 2.

The deepest valley (TV3) runs NNW–SSE through the area, and deep boreholes (e.g. DGU no. 82.320) show that the infill comprises clay and fluvial sand. The second, slightly shallower valley (TV6) is oriented NW–SE in the eastern and northern part of the area. The valley is mainly identified from the seismic data and the boreholes, but to a limited degree also in the resistivity data.

The third valley (TV8) runs NNW – SSE through the area. Boreholes show that the infill mainly comprises clay and glaciofluvial sand. The sandy fill can also be inferred from the resistivity level in the high-resistive feature observed between 90-100 mbsl on Figure 4. The fourth and shallowest valley (TV9) covers large parts of the Holmsland area and reaches depths around 50-80 mbsl. The infill of TV9 mostly consists of glaciofluvial sand which is also supported by the resistivity distribution (Figure 4, 50-60 mbsl), but till and clay also occurs.

The tunnel valleys in the area are often incised into the deposits of older tunnel valleys. A part of TV6 is cut into TV3; TV8 is cut into TV3 and TV6; and large parts of TV9 are cut into TV6 and TV8.

In the northern and southern parts of the area there is a lack of geophysical and seismic data. No tunnel valleys have therefore been interpreted in these areas but a few deep boreholes indicate that valleys may exist here.

Offshore interpretation

A total of eight tunnel valleys are mapped within the offshore area (Figure 3). This was done based on morphological and structural characteristics, valley orientations, and cross-cutting relationships. All valleys are completely buried and do not show any sea-floor expression.

TV1 appears from cross-cutting patterns to be the oldest identified valley. From DA95_l21, GR9712_1 and DA96_06 it is interpreted to cross the offshore area in a NNE–SSW direction (Figure 3), and to reach a depth of around 160 mbsl (Figures. 6A and 7C). In the southern part of GR9717, GR9716 and DA96_06 the north flank of TV5 is observed at depths of about 140 - 150 mbsl.

However, the orientation and morphology are unclear due to insufficient data. Two tunnel valleys (TV2 and TV4) with depths of around 155-165 mbsl can be seen north of TV5 on GR9712_1. TV4 also appears on DA95_05 and DA96_06 as a deep (160 – 170 mbsl) and well-defined valley with an ESE–WNW orientation (Figure 6). On DA96_06 it is seen to cut TV1. From this point the course of the valley is very uncertain, but due to similarities in morphology it is proposed that it correlates with an incision observed on GR9712_1/GR9712_2 in the southern part of the investigation area (Figure 6). TV2 is observed on DA95_l21 in the northern part of the study area. From here it correlates with a younger incision than that of TV1 found on DA96_06. Its further course towards the SE is uncertain, but it is proposed that it should be correlated to an incision found on GR9712_1/ GR9712_2 in the southern part of the area.

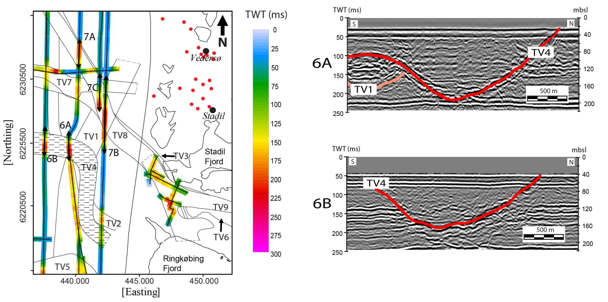

Figure 6: (Left) The correlations of tunnel valleys TV4 in the North Sea. (6A): An interpreted section of DA96_06 where TV4 is observed to erode in TV1. (6B) An interpreted section of DA95_05 where the presence of TV4 is observed.

Northwest of Holmsland, the high-resolution seismic lines DA95_l22, GR9712_1, DA96_06 and DA95_121 reveal a system of six tunnel valleys with four different orientations (Figure 3). TV1 is seen with a SSW - NNE orientation, TV2 with a N–S orientation, TV7 with an E–W orientation, and TV3, TV6 and TV8 all with NNW–SSE orientations. Seismic sections with interpretations are shown in Figures 6 and 7 (their connections to onshore valleys are discussed below). East of DA95_l22, in the north-western part of the study area, the three valleys split into two systems with different orientations: TV6 is observed to turn towards WNW crossing DA96_06 and DA95_l21, where it is followed by the younger TV7, whereas TV3 and TV8 more or less follow the initial NNW - SSE orientation to cross DA95_l21 and DA96_06 (Figures. 3 and 7).

Correlation of tunnel valleys across the coastline

The correlation of the suite of NNW-SSE oriented valleys TV3, TV6 and TV8 between the on- and offshore areas (Figures 3) is primarily based on valley orientation and cross-cutting relationships but also to some degree on morphological and structural characteristics.

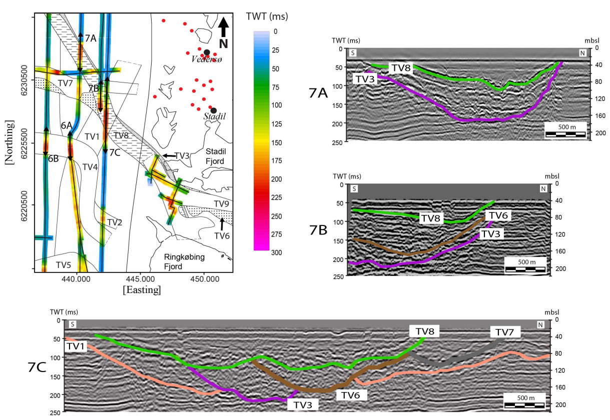

Figure 7: (Left) The three correlated valleys TV3, TV6 and TV8 are shown. (7A): An interpreted section of DA96_06 where the presence of TV3 and TV8 can be observed (7B): An interpreted section of Da95_l22 where the presence of TV3, TV6 and TV8 can be observed. (7C): an interpreted section of GR9712_1 where the presence of TV1, TV3, TV6, TV7 and TV8 can be observed.

TV3 is observed on the onshore reflection seismic data as the deepest and oldest valley with depths around 165-175 mbsl and an NNW – SSE orientation (Figures 3 and 5). Similar depth and orientation are seen for TV3 offshore (Figure 7). TV3 is relative oldest on Figure 7A and 7B whereas it is eroded into TV1 on Figure 7C. Onshore, TV6 is observed to have a depth around 135-165 mbsl (which is between TV3 and TV8) and an overall NW–SE orientation. This is similar to the offshore observations of this valley (Figure 7). TV8 is observed offshore as the shallowest and youngest valley with depths of 80-100 m. It follows TV3 and is eroded into TV1, TV3, TV6 and TV7 (Figure 7). Onshore, TV8 is observed to have depths within the same range (Figure 5), and again to follow TV3 and to be eroded into TV3 and TV6.

The extension of TV7 onshore is unknown due to poor data cover. However, some boreholes indicate the presence of one or more tunnel valleys in the northern part of the study area by showing glacial sediments at large depths, but as previously mentioned proper delineation of the valley is not possible. TV9, the youngest onshore tunnel valley identified on Holmsland, cannot be correlated to any offshore valleys. This is not possible because of the low quality of the upper 40-50 meters of offshore reflection seismic data. Shallow tunnel valleys can occasionally be observed offshore but they cannot be resolved laterally.

Cross-cutting relationships and valley generations

Based on cross-cutting relationships between the nine tunnel valleys their relative ages were evaluated. A model for their successive formation is proposed based on the cross-cutting relationships between the nine tunnel valleys. At least six valley-forming events are required in order to create the nine tunnel valleys (Figure 8).

A proposed model for the six events forming the nine valleys are shown in Figure 8 and can be shortly described as follows.

TV1 was formed during the first event and is incised by most of the other valleys. TV1 is characterized by being the only valley with a NNE – SSW orientation and by having a greater width than the others. TV2 and TV3 were formed by the second event. These two valleys are characterized by being deep (up to 185 m), and having a general NNW - SSE orientation. They incise TV1 and are themselves incised by the valleys belonging to the later events 3, 4 and 5. TV4, TV5 and TV6 were formed during event 3. The valleys of this generation are generally oriented SE – NW. From the cross-cutting relations and orientation it cannot be ruled out that TV5 is a member of event 4 instead. It is suggested to belong to event 3 because it has similar depth as TV4, TV5 and TV6. TV 7 was formed during event 4 and strikes E-W. It is about 80 m deep, incises TV1, TV2, TV3 and TV6, and it is incised by TV8. TV8 was formed by event 5. It is about 120 m deep and incises valleys from events 1 to 4. The youngest valley, TV9, was formed during event 6 and incises TV8 and TV6.

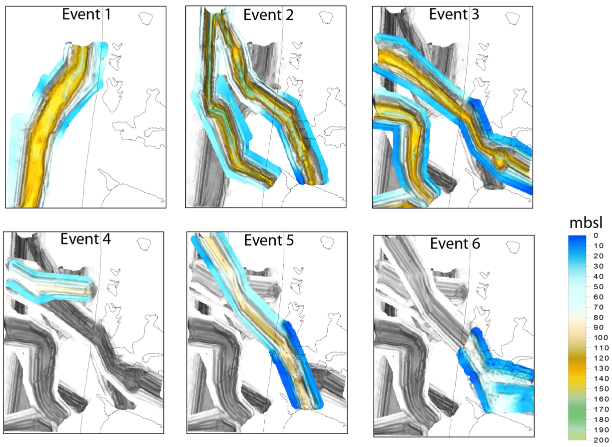

Figure 8: Model showing the six glacial events and the pre-Quaternary surface from the study area. The coloured tunnel valleys were the active tunnel valleys during the event whereas the grey are older valleys formed during earlier events.

Discussion

For the studied onshore area we find that a credible and detailed model of the tunnel valleys can only be developed for sub-areas covered by all three types of data, i.e. boreholes, soundings, and seismic data. Lack of soundings and seismic data prevent us from mapping and characterizing tunnel valleys in the southern and northern parts of the Holmsland area. For the remaining area the TEM- and Schlumberger soundings can be utilized for horizontal delineation of the tunnel valleys but not always in depth due to a low resistivity contrast between the valley infill and the Neogene substratum. Furthermore, due to the complex system of cross-cutting tunnel valleys in the Holmsland area and a lack of resistivity contrasts between the individual valleys infill, it is not possible to differentiate individual tunnel valleys and resolve their internal structures on basis of resistivity soundings alone. The deep boreholes located in the tunnel valleys compensate for the limited resolution of the soundings and provide detailed information about the infill, but the number of such boreholes is limited. The picture of several generations of cross-cutting valleys could first be drawn in detail by supplementing the borehole data and the soundings with careful analysis of the reflection seismic lines.

Only 2D reflection seismic data were available for the studied offshore area. The density and quality of the seismic data was observed to be decisive for the delineation and characterization of the buried tunnel valleys. That small line spacing is more important for delineation than vertical resolution was discussed by Praeg (2003) who compared valley mapping by using a line spacing of 1 km and 5 km, respectively. Our line spacing varies from 400 m to 2500 m. Besides having fairly close lines it is found helpful to also have perpendicular seismic lines. However, even in sub-areas with high density data the lack of good quality data for the upper 40-50 m of the seabed prevent us from delineating shallow tunnel valleys. The best supported interpretations are for valleys TV3, TV6, and TV8 whereas TV1, TV2 and TV4 are least certain.

Correlation across the coast line

Three valleys (TV3, TV6 and TV8) have been be correlated across the coastline over a distance of 4 km. Correlation over such distance can be questioned, since previous Danish on- and offshore investigations with dense data sets have shown that tunnel valleys can change orientation abruptly (e.g. Jørgensen and Sandersen, 2006, Kristensen et al., 2007), or they can terminate over short distances of 1-2 km (Huuse and Lykke-Andersen, 2000, Jørgensen and Sandersen, 2006, and Kristensen et al., 2007). We have also interpreted TV4 to make a 90° change of direction over a 1 km distance (Figure 3). We cannot rule out that abrupt termination or change of direction occurs for TV3, TV6 and TV8. However, several observations support our correlations:

Most of the investigated valleys are generally interpreted to be linear to slightly curving for long sections and to have orientations mainly between NNW-SSE and WNW-ESE. Similar orientations have been observed for nearby tunnel valleys both in the western part of Jutland (Sandersen and Jørgensen, 2003) and in the eastern part of the Danish North Sea (Huuse and Lykke-Andersen, 2000).

Jørgensen and Sandersen (2009) analysed a dense SkyTEM and seismic data set from a large area east of Holmsland and interpreted multiple tunnel valleys. One of these correlates with our TV6. Pooling our observations with theirs, TV6 can be followed 20 km on land (Jørgensen and Sandersen 2009 Appendix 3, Figure 11). Along its entire course it appears to be relatively straight with an overall ESE – WNW orientation.

Provided that the quality of a 2D seismic data section is high, any deep tunnel valley will be revealed by this. Such data are available from the two offshore seismic lines closest to the coast (GR9712_1 and GR9712_2, Figure 2). These lines do not reveal any tunnel valleys until 7 km north of our study area (Huuse and Lykke-Andersen, 2000). With respect to the possibility of abrupt valley termination falsifying our correlations, we find it quite unlikely that three onshore valleys as well as three offshore valleys, up to 170 m deep and with similar orientations, all should terminate within a distance of 4 km and thus not be connected across the coastline. Hence we find the suggested valley correlations across the coast line to be credible.

CONCLUSIONS

Based on seismic data, TEM- and Schlumberger soundings, and boreholes a total of nine tunnel valleys have been described from a 300 km^2 study area located at the Danish North Sea coast. The valleys are longitudinally linear to slightly curving over longer distances, and they have three major orientations (SSE - NNW, ESE – WNW and NNE – SSW), undulating thalwegs, widths from 1 to 1.8 km, and depths from 75 to 180 meters. All the tunnel valleys seem to extend beyond the boundaries of the study area, but the lengths inside the study area vary from 7 to 25 km. Younger tunnel valleys are found to often re-use and incise older tunnel valleys creating a cut-and-fill structure on the reflection seismic profiles.

There is support in the data to connect three valleys (TV3, TV6 and TV8) from the Holmsland area beyond the coastline and into the North Sea area. The onshore-offshore connections were established on the basis of valley orientation, relative time of formation, and morphological and structural characteristics.

The relative ages of the nine buried tunnel valleys were inferred from a 3D geological model based on the data. This leads us to suggest that the nine valleys were formed during at least six events, and that a maximum of three valleys were formed during the same event. It cannot be derived from this investigation whether the events all occurred during one or several glaciations.

The experience from this study suggests that on land a credible and detailed model of tunnel valley(s) and infill structure can best be built on basis of a combination of dense geophysical soundings, borehole information, and reflection seismic data. Using only the first two types of data can lead to a smooth model that lack important details about structure and variability inside the valleys. Offshore, where boreholes and soundings are not available, the spacing between the reflection lines has to be low in order to correlate and connect the observed tunnel valleys.

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