1 Middle Pleistocene landforms in the Danish Sector of the southern North Sea

2 imaged on 3D seismic data

3

4 Dagmar Mütter¹, Stefan Back¹, Lars Reuning¹, Peter Kukla¹, Frank Lehmkuhl²

5 ¹RWTH Aachen University, Department of Geology, Wüllnerstr. 2, D-52062 Aachen

6 ²RWTH Aachen University, Department of Geography, Templergraben 55, D-52056 Aachen

7 email: westerschulte@geol.rwth-aachen.de

8

9

10 **Abstract**

11 Despite a long history of investigation, several critical issues regarding the glacial history of
12 Northwest Europe, particularly in currently marine areas, remain unsolved. In this study we
13 present a comprehensive 3D seismic interpretation of an area of 2,000 km² in the western
14 part of the Danish North Sea that exhibits several buried, Quaternary landforms. Well data
15 are used to assign minimum and maximum ages for the studied sedimentary succession.
16 The most prominent buried landforms are three large-scale tunnel valleys of probable
17 Saalian age that extend over more than 20 km across the western and southern part of the
18 study area. These valleys most likely formed by subglacial meltwater erosion close to the
19 termination of a former ice sheet. In the southern part of the study area, an extensive
20 network of small-scale, dendritic seismic lineations interpreted as a paleo-drainage system
21 characterises the landward termination of one major tunnel valley. This drainage system was
22 active either contemporaneously or shortly after the development of the tunnel valley.
23 Interpretation of this system as contemporaneous to tunnel-valley formation suggests that
24 steady-state subglacial meltwater discharge was funneled through a drainage system into
25 the main tunnel valley; in contrast, the interpretation of the drainage network as post-
26 incisional points to the development of a post-glacial river system re-using the pre-existing
27 tunnel valley as downstream fluvial pathway. The above interpretation uncertainty has

important consequences for the prediction of the rock content and reservoir characteristics of the tunnel-valley infill in that either meltwater deposits or fluvial sediments form a considerable part of the tunnel-valley infill.

31

32 **Introduction**

33 At the beginning of the Quaternary, climate changed to cooler and more variable conditions.

34 During the Pleistocene the climate all over Europe was characterized by an alternation
35 between glacial and interglacial conditions, which was the main prerequisite for several
36 advances and retreats of continental ice sheets (e.g. Ehlers 1994; Velichko *et al.* 1997;
37 Ehlers & Gibbard 2003). During the peak of glacial conditions, maximum ice cover reached
38 45 million km², about three times as much as today (e.g. Reinwarth 1972).

39

40 Three extensive glaciations of north-west Europe are known from the Middle and Late
41 Pleistocene: the Elsterian, the Saalian and the Weichselian, each of these likely
42 characterised by multiple ice advances. These glaciations were separated by interglacial
43 periods marked by considerable transgressions. The size and location of pre-Elsterian ice
44 sheets are poorly known (e.g. Ehlers 1994, Ehlers & Gibbard 2004, Kristensen *et al.* 2007)
45 as the landscape of northern Europe was completely rearranged by the Elsterian ice sheet,
46 which is the first – today traceable – ice cover over entire northern Europe. During this
47 glaciation, most older landforms were remodeled and the fluvial systems were re-oriented.
48 Subglacial meltwater channels (tunnel valleys) of this age reach onto the European mainland
49 as far as the Netherlands (e.g. Ehlers 1994). The Elsterian and the Saalian glaciations were
50 separated by the Holsteinian interglacial period. The youngest Quaternary glacial period, the
51 Weichselian, had the least southward extension of the three major glacial intervals. For long
52 time, the question was unsolved if northern Europe was covered during Weichselian by one
53 ice sheet or two separate ones, one covering Scandinavia and one covering Scotland and
54 Great Britain (Boulton *et al.* 1985, 2001; Bowen *et al.* 1986; Long *et al.* 1988; Ehlers 1990;
55 Ehlers & Wingfield 1991; Karabanov *et al.* 1996; Coles 1998; Sejrup *et al.* 1998, 2005).

56 However, it was recently clarified that the Weichselian ice sheets of Scandinavia and Great
57 Britain had been connected at least temporarily during the Weichselian (Bradwell *et al.* 2008;
58 Sejrup *et al.* 2009).

59

60 This study provides new information on the landscape evolution of the North Sea area during
61 the Pleistocene based on the analysis of a large 3-D seismic data volume offshore Denmark.
62 The dataset allows the detailed mapping of the distribution and internal geometry of
63 morphological features located in the uppermost 600 m of the sedimentary column. The
64 interpretation of the seismic reflectors of the 3D seismic volume revealed the subsurface
65 presence of several tunnel valleys and of a paleo-drainage system that characterises the
66 landward termination of one of the tunnel valley. The valleys encountered are several tens of
67 kilometres long, up to a few kilometres wide and several hundred metres deep and most
68 likely a product of subglacial meltwater erosion and therefore glacio-hydropneumatic
69 processes (Ehlers *et al.* 1984; Ehlers & Wingfield 1991; Ó Cofaigh 1996; Huuse & Lykke-
70 Andersen 2000; Praeg 2003; Stackebrandt 2009).

71

72 Today, the investigation of glacial valleys is not merely of scientific interest. Instead,
73 knowledge on the infill of buried glacial valleys becomes increasingly important as these form
74 important groundwater reservoirs (e.g. BurVal 2006; 2009); can contain exploitable
75 hydrocarbon accumulations (Levell *et al.* 1988, Le Heron *et al.* 2004, Ghienne & Deynoux
76 1998); or can serve while drilling deep-seated hydrocarbon accumulations as shallow-seated
77 storage sites for e.g. drilling fluid. Since located in a classic region for hydrocarbon
78 exploration and production, the geomorphological and seismic-sedimentological observations
79 presented in this North Sea case study can be readily used to identify such near-field storage
80 sites; at the same time, the results of the study might provide analogue data for the reservoir
81 characteristics of buried glacial valleys at a distance containing exploitable water or
82 hydrocarbon resources.

83

84 **Data Base**

85 This study is based on the analysis of a 3D seismic volume that covers an area of approx.
86 2,000 km² in the central part of the Danish North Sea sector (Fig. 1). The target area is
87 located about 200 km westward of the Danish mainland between 4° to 5° eastern longitude
88 and close to 56° northern latitude. The seismic survey has an inline and crossline spacing of
89 25 m, and a vertical seismic resolution of about 25 m in the uppermost one second (TWT)
90 under study. For stratigraphic calibration, sedimentological and palaeontological reports and
91 logs of 15 offshore wells were used (unpublished well completion reports; Knudsen 1985;
92 Pedersen 1995). Integration of the available welldata, particularly of the wells Skjold 21 and
93 TWB-12 (Fig. 2), into an approximated time-depth model (based on an average seismic
94 velocity of 1,500 m/sec in the water column; 1,750 m/sec in the substratum) results in the
95 prediction of the topmost continuous seismic reflector at ca. 85 m ($\approx$ 100 ms TWT) below the
96 present-day sea floor. A well-to-seismic correlation indicates that the uppermost seismic
97 reflection that can be traced throughout the entire 3D survey corresponds to Saalian
98 sediments at the well Roar 41 (Salomonsen & Jensen, 1994). The youngest Quaternary
99 sediments (Holocene - Eemian and at least parts of the Saalian) are therefore missing from
100 the dataset due to seismic processing issues that focused on deeper geological targets for
101 hydrocarbon exploration. This correlation provides an approximate age framework for the
102 interpretations of this study in that all reflection features incising into this horizon are either
103 late middle Pleistocene or younger in age; in turn, all seismic features encountered below
104 this horizon level, if unaffected by incision, are older. Thus, all seismic information imaging
105 the earlier parts of the Quaternary remains valid, and time- and horizon slices from this
106 interval form the base of the seismic-geomorphological interpretation presented in this paper.

107

108 **Geological Setting**

109 During the Cenozoic, the North Sea was an epicontinental basin bound by the
110 Fennoscandian landmasses to the northeast, the British Isles to the west and the Central
111 European landmass to the south (Nielsen *et al.* 1986; Ziegler 1990; Andresen *et al.* 2008).

The central and eastern part of the Cenozoic North Sea overlies Paleozoic and Mesozoic structures such as the Central Graben and the Ringkøbing-Fyn High (Fig. 1; Michelsen *et al.* 1998; Andresen *et al.* 2008). Of these deep-seated structures mainly the salt diapirs of the Salt-Dome Province in the south of the study area influenced the overlying Cenozoic sedimentary record.

During the Pliocene, generally warm climatic conditions affected NW Europe and the North Sea region. Sedimentation in the southern North Sea basin was dominantly siliciclastic and characterised by the progradation of deltas originating from mainland Europe as well as from the Scandinavian Shield (Salomonsen 1994; BurVal 2009, Møller *et al.* 2009). In the Quaternary, climate conditions deteriorated and large parts of North West Europe including the North Sea were affected by glaciation. During the Elsterian, Saalian and Weichselian glacial intervals, main ice-sheet advances into the study area were southward from southern Norway, south-westward from southern Sweden and westward through the Baltic Sea area (Bowen *et al.* 1986; Long *et al.* 1988; Ehlers 1990; Karabanov *et al.* 1996; Kristensen *et al.* 2007). During the last glacial maximum the sea level fall was about 130 meters (Fairbanks 1989) and the shorelines proceeded considerably northwards in comparison to today (Jelgersma 1979). During the Elsterian and Saalian glaciations, the North Sea recorded sea-level falls of more than 100 meters (Cameron *et al.* 1987; Shackleton 1987; Coles 1998).

Seismic Analysis

The focus of this study are Quaternary landforms that were interpreted on 3D seismic data of the Danish part of the North Sea Central Graben. For the analysis of the uppermost 1 s TWT of the seismic data, vertical sections as well as time and horizon slices were used. The uppermost seismic reflector of the survey is a strong negative seismic event, corresponding in well Roar 41 to the middle Pleistocene “erosional surface 1” of Salomonsen & Jensen (1994). Figure 3 documents the presence of three prominent, incised valleys or valley segments in the subsurface of the studied dataset. The observed landforms are different in

size: two larger valleys (valleys 1 and 2) occur in the south and northwest of the study area, whereas a smaller valley or valley segment (valley 3) is observed to the south of valley 2. In detail, valley 1 can be traced for about 18 km in N-S orientation reaching to the southern boundary of the 3D dataset and possibly beyond that so the full length of the valley is unknown (Fig. 3). From north to south the valley broadens from about 500 m to its maximum width of up to 1.8 km. The valley reaches a maximum depth of ca. 130 m in its central-southern part, but shallows towards the southern boundary of the study area. Valley 1 is neighbored in the south by a sinuous seismic reflection feature of approximately 5 km length with a width of ca 500 m (Figs. 3 and 4). Figure 4 shows four cross sections A-A' to D-D' that cut vertically through the central to southern parts of valley 1. The valley infill is imaged only by few seismic reflections, rarely exceeding four seismic loops; thus individual seismic reflections might represent an aggregation of a variety of depositional layers below seismic resolution. However, what can be clearly seen is that the studied system is partly asymmetric concerning the incision geometry and architecture of the sedimentary fill; that the centre of incision and maximum infill shifts downslope from one valley flank to the other (Figs. 4b,c,d); and that the subsurface incision geometry might reflect multiple phases of cut and fill (Figs. 4b, c). With respect to the infill architecture of valley 1, all vertical sections exhibit two to three relatively continuous seismic reflections associated with high amplitudes immediately above the valley floor. These reflections are overlain by several discontinuous reflectors with low amplitudes that are in turn covered by few continuous, medium-amplitude reflections. Hence, the seismic facies of the valley can be subdivided into three different types that are imaged horizontally on a series of infill sections (timeslices at 300, 265 and 225 ms TWT depth, respectively). Infill section 1 at 300 ms TWT (Fig. 4f) shows a basal high-amplitude seismic facies 1 in the southernmost 5 km of valley 1. Infill section 2 at 265 ms TWT depth (Fig. 4g) shows considerable polarity changes within the overlying facies 2 both along the valley trend and between the flanks and the inner valley thalweg. The uppermost facies 3 is finally imaged at 225 ms TWT in infill section 3 as laterally relatively continuous with medium amplitudes (Fig. 4h). The analysis of vertical reflectivity data along the valley trend (see

longitudinal section E-E' on Fig. 5) provides further information on the downslope facies variations within valley 1: seismic facies 1 primarily includes very strong, at the base partly discontinuous reflections immediately above the main incision surface. Facies 2 is a partly discontinuous fill preserved with variable thickness in the northern, proximal parts of valley 1. Further south, seismic facies 2 progrades with a slight sigmoidal shape into the deepest part of valley 1. At the top of the succession, the homogenous, medium-amplitude reflections of seismic facies 3 onlap onto and cover facies 2 in the distal parts of valley 1.

Valley 2 of the northwestern part of the study area (Figs. 3, 6a) consists in its northern part of several segments that combine southward into one major valley. Valley 2 has a total length of 27 km, a maximum depth of 100 m and a width of 2.5 to 1.7 km for the western main branch, whilst the northeastern branch is about 1 km wide. Figure 6 shows the location of the vertical cross sections F-F', G-G' and H-H' that image the detailed reflection content of this valley. The fill of valley 2 is imaged at maximum by eight seismic reflectors. From bottom to top, the lowest reflectors are more continuous than the overlying, stratigraphically higher reflections. The longitudinal profile cross section I-I' (Fig. 6e) shows a subparallel bedding of the reflections over the entire length of the valley. In comparison to valley 1, the infill of valley 2 belongs to only one seismic facies which is similar to reflectivity facies 3 of valley 1.

6 km south of valley 2 is a third valley or valley segment, about 7.6 km in length and with a depth of 80 m. This valley may be a continuation of valley 2 (Figs. 3, 7) but this assumption is difficult to prove since the reflector pattern between the mapped valleys is affected by a deteriorating seismic signal most likely caused by faulting and fracturing above an underlying salt diapir. Valley 3 reaches the boundary of the data set at the border between the Danish and German part of the southern North Sea. Cross sections J-J' and K-K' (Fig. 7b, c) provide vertical seismic information on valley 3 in that the northern cross section J-J' depicts up to 15 subparallel, rather subtle reflections that have a slightly higher amplitude than the surrounding reflections. Section K-K' is located southward and shows a part of valley 3

196 where it is less incised into the surrounding strata. At this location, the valley is imaged by
197 only 6 reflections. However, in comparison to the surrounding deposits these reflections
198 show a clearly different geometry and a significantly stronger reflectivity response. The
199 downslope cross section L-L' indicates a dominant parallel bedding of the valley fill as
200 documented previously for valley 2.

201
202 Figure 8 shows a series of successive amplitude time slices at depths of 265, 235, 220 and
203 195 ms TWT of the southern part of the study area in the vicinity and above valley 1. Imaged
204 are linear seismic features that show the transition of an isolated, single-branch seismic
205 incision feature at the lowest and oldest stratigraphic level towards into a northwards
206 growing, dendritic line network that mimics in shape and size the drainage network of a
207 fluvial system. Figure 8a shows the initial main branch of this system immediately north of
208 valley 1 (also see Figs. 3, 4, 5), locally supplemented on its western and northern sides by
209 isolated distributaries. This main branch trends southward into the south-eastern valley 1. In
210 its lower reaches close to the entrance into valley 1, this main branch is approximately 400 m
211 wide, which is less than one-fifth of the valley's width, whilst its central part has a width of
212 100 to 200 m. Figures 8b and 8c document that the northward extent of the now dendritic
213 system increases with time, as does the number of its branches. This particularly concerns
214 the northwestern part of the system, in which several eastward-oriented linear features feed
215 into the main branch. Fig. 8d documents that the dendritic system finally lost its importance
216 over time, and that many of the older features were not longer active. The two easternmost,
217 originally parallel branches seem to have their maximum development at this time, thus after
218 the maximum extent of the central part of the system. This is the only part of the system
219 where two branches amalgamate to one system in which linear seismic features cross each
220 other several times.

221
222 Figure 9 provides a series of cross sections through the dendritic seismic discontinuity facies
223 described above. Seismic section A-A' (Fig. 9b) follows the main southerly trend of the

224 branched system in downslope direction, illustrating the transition from its only slightly
225 incised (in places unincised) proximal part into the distal, strongly incised part corresponding
226 to valley 1 (also see Fig. 5). Cross sections B-B' and C-C' in the north (Figs. 9c, d) are
227 perpendicular to the main trend of the system, documenting the subtle vertical expression of
228 various small-scale seismic discontinuities (width < 250m) that combine into the dendritic
229 discontinuity network. Cross section D-D' (Fig. 9e) images a seismic discontinuity feature at
230 the base of the topmost reflection that is ca. 400 m wide. This feature is interpreted as the
231 most proximal part of the incised valley 1, which further deepens and widens (500 – 700 m)
232 southwards (Figs. 9f, g). A prominent amplitude anomaly westward of the incised valley 1 in
233 cross section F-F' (location f1 on Fig. 9g) corresponds to an eastward trending branch of the
234 system (also see Fig. 8c).

236 Measurements of the sinuosity of the dendritic discontinuity features encountered show that
237 the individual branches of the system are only slightly sinuous (Fig. 10): of ten measured
238 branches, only two exhibit a sinuosity P above 1.2 (P = actual path length divided by shortest
239 path length; P = 1: linear river; P > 1.5: sinuous river; sensu Ahnert 1996), with the mean
240 sinuosity of the measured branches at P = 1.147. Such low sinuosity is commonly interpreted
241 to characterise streams with a high water flow velocity (Ahnert 1996). In addition to the
242 connected seismic lineations described above, there are four isolated, sub-parallel branch
243 features located in the very east of the study area (Figs. 8b, c). Three of these systems exit
244 the study area at its southern boundary.

246 Discussion

247 The following paragraphs discuss the relationship between the observed seismic features
248 with respect to their formation, possible lithological content, the timing of their development,
249 and finally their comparability to other Quaternary incision features known from regions
250 adjacent to or documented previously within the study area. The seismic interpretation
251 results document the presence of three valley systems of kilometre-scale in the shallow

subsurface of the North Sea Central Graben area offshore Denmark, for which a subglacial origin can be assumed. The observed valleys match the scale and morphology of subglacial meltwater valleys (tunnel valleys) that have been previously documented in the subsurface of northern Europe by e.g. Ehlers *et al.* (1984), Ehlers (1990), Salomonsen (1993, 1995), Smed (1998), Huuse & Lykke-Andersen (2000), Sandersen & Flemming (2003), Kristensen *et al.* (2007), and Lutz *et al.* 2009).

The seismic interpretations presented also reveal the presence of reflection irregularities that form a dendritic line network around the northern termination of valley 1 (Fig. 8), possibly feeding into the main valley incision. The dendritic, locally braided geometry of this system is suggestive of a drainage network of a fluvial system that seems to have enlarged its catchment area northwards through time (Figs. 8 a-c). The presence of fluvial systems in the immediate geographic and stratigraphic vicinity of tunnel valleys has – to our knowledge – only been rarely documented in the literature. E.g. Fitch *et al.* (2005) interpreted fluvial branch features on 3D seismic reflection data of the Dogger Bank of the British North Sea Sector that extend over 28 km in a northwest-southeast orientation in the vicinity of a buried tunnel valley. However, this fluvial system is dated as Holocene (Fitch *et al.* 2005). By the time of its activity the Dogger Bank tunnel valley was completely filled and there seems no genetic connection between earlier subglacial meltwater erosion and the subsequent fluvial development. In contrast, the proximity of the dendritic discontinuity features to valley 1 on the studied data suggests that the interpreted drainage system was active either at the same time or shortly after the development of the tunnel valley. If the two systems had been active at the same time, the observed drainage system would have developed subglacially. This means that the drainage network formed a subglacial catchment system for tunnel valley 1, developing time-transgressively (see Figs. 8a-d) by steady-state subglacial meltwater drainage (e.g. sensu Boulton & Hindmarsh 1987). An important pre-condition for such a scenario would be a warm-based ice-sheet. In contrast, the interpretation of fluvial activity under subaerial conditions after a glacial retreat would imply that tunnel valley 1 remained an

unfilled, open landform attracting surface drainage. Erosion associated with such a scenario must have been significant, as the dendritic discontinuity features incise up to 50 ms TWT (e.g. Figs. 8, 9) into the underlying substratum. A final statement whether the dendritic discontinuity features developed by subglacial meltwater erosion or subaerial fluvial processes cannot be made. However, in the case of a subglacial meltwater origin, the preservation of a tunnel valley catchment area would be unexpected given the wealth of previous tunnel-valley studies.

With respect to the infill of the tunnel valley, it is known that meltwater sands commonly form the basal sediments of tunnel valleys (Ehlers & Linke 1989), but that glaciolacustrine and glaciomarine sand, silt, clay and glacial till (Long *et al.* 1988; Smed 1998) can also occur. The reflection strength of the valley-fill facies interpreted in this study is generally high if compared to the surrounding deposits. This can be explained by a change of the material properties, e.g. a compaction difference, a variation in grain size, or even a difference in the intra-formational fluid content. Besides the differences of the valley fill to the neighbouring strata, the infill of valley 1 can be further subdivided into three different facies types. The high amplitude facies 1 at the valley base seems to characterise predominantly deeply incised areas at the channel base (Fig. 5, bottom), suggesting the presence of remnant pockets of high-impedance material, e.g. boulder fill or even diamictite (see e.g. Erohina *et al.* 2004). In contrast, the seismically discontinuous, more transparent seismic facies 2 can be interpreted as having formed under fluvial or subglacial stream conditions. The lithological content of facies 2 can be approximated with lithology data of well Skjold 21 (for location see Fig. 9a). Within this well, the rock content from 73 m down to the total depth of 98.9m is reported as fine sand (Knudsen 1985). This zone is immediately above the dendritic seismic discontinuity system encountered in this study, and defined as “presumably non-marine” (Knudsen 1985). Facies 3, in turn, covers the previous facies associations with more continuous, commonly parallel low-amplitude reflections pointing to a low-energy depositional environment that could have been lacustrine or marine. In contrast to valley 1, the infill of the tunnel valleys 2

and 3 in the west of the study area exhibits only one seismic facies type that matches facies 3 of valley 1. Yet, the reflection intensity within valleys 2 and 3 remains above that of the neighbouring deposits, thus differences in rock properties to the surrounding strata – and consequently differential reservoir characteristics - can be expected.

In order to approximate the age of the landforms and strata of the study area, well data were used (Figs. 11). A detailed stratigraphy for the Late Pleistocene and Saalian in the study area was published for core samples of several shallow boreholes, e.g. Skjold-21, Roar 41 and Roar 43 (Knudsen 1985; Sejrup & Knudsen 1993; Salomonsen & Jensen 1994). A complete biostratigraphic framework of the middle Pleistocene was only published for cutting samples of the oil well TWB-12 (Pedersen 1995). In this well, sediments of Cromerian age (zone T2, Fig. 11) are directly overlain by Saalian sediments (zone T1, Fig. 11), implying that Elsterian and Holsteinian sediments are lacking. Pedersen (1995) divided zone T2 in a lower non-marine to brackish and an upper normal marine interval that was interpreted to correlate with the marine Zone R6 of the geotechnical borehole Roar 41 (Fig. 11), which was attributed to the Saalian period by Sejrup & Knudsen (1993). The Saalian/Cromerian boundary in TWB-12 therefore is either situated directly at the T1/T2 boundary or at the normal marine to non-marine, brackish transition within T2.

A seismic-to-well tie of the strata at well TWB-12 carried over to tunnel valleys 1 and 2 associates the stratigraphy around and immediately above the studied tunnel valleys 1 and 2 with zone T2 of Pedersen (1995) (Fig. 11). The lack of Elsterian sediments at well TWB-12 suggests that these deposits were eroded during the Saalian glacial period. This indicates that possible Elsterian tunnel valleys may have been overprinted and deepened during the Saalian, or that the observed tunnel valleys formed entirely during the Saalian glacial interval. An interpretation of the glacial meltwater valleys as Saalian would be in line with Salomonsen & Jensen (1994). However, Lutz *et al.* (2009) assume an Elsterian age for tunnel valleys that they have interpreted immediately southward of the study area in the

German North Sea sector. The age of these valleys that very likely form the continuation of our systems (Fig. 12); is interpreted from possibly correlative tunnel valleys located immediately offshore the Danish coast (Huuse & Lykke-Anderson 2000; tunnel-valley age: Elsterian and possibly Saalian) and onshore Germany (Ehlers *et al.* 1984).

Conclusions

1. The analysis of the uppermost 600 m of a large 3D seismic dataset in the western Danish North Sea sector revealed the shallow subsurface presence of three north-south trending valleys of up to 27 km length, a width between several hundreds of metres and a few kilometres, and an incision depth of up to 150 m. The incised valleys match the scale and morphology of subglacial meltwater valleys (tunnel valleys) that have been previously documented in the subsurface of onshore and offshore northern Europe, and seem to extend in southerly directions beyond the study area into the German sector of the North Sea.

2. Seismic interpretation also revealed the subsurface preservation of a dendritic drainage network around the northern termination of the second largest tunnel valley of the study area. This drainage system could have been active either at the same time or shortly after the development of the tunnel valley. Interpretation of the development of this system as contemporaneous to the tunnel-valley formation is suggestive of steady-state subglacial meltwater drainage in the proximal parts of a major subglacial meltwater stream. However, the observed drainage network can also be interpreted as the catchment area of a palaeo-river developing after glacial retreat under subaerial conditions, with the northern termination of the pre-existing tunnel valley attracting surface drainage. Fluvial erosion associated with this scenario must have been considerable, as the dendritic discontinuity features incise up to 70 m into the underlying substratum.

3. The reflection signature of the infill of the studied tunnel valleys is variable. Tunnel valley 1 comprises a basal, high-amplitude reflection unit covered by a seismically discontinuous,

transparent seismic facies and finally continuous, low-amplitude reflections. In contrast, the infill of tunnel valleys 2 and 3 exhibits solely continuous, low-amplitude reflections. The observed variations indicate that the valley infill can vary considerably even between neighbouring tunnel valleys, making a generalised prediction of its lithological content and reservoir characteristics difficult.

4. Seismic-to-well correlations indicate that the studied tunnel valleys likely record Saalian subglacial meltwater erosion, possibly re-using pre-existing Elsterian tunnel valleys. A firm age for both, incision and valley infill can only be established by direct dating of both the valley fill and the surrounding strata.

Acknowledgements

This study is funded by a scholarship of RWTH Aachen University. We thank Maersk Oil and Gas and DUC partners for kindly providing the 3D seismic volume. Marianne M. Hansen, GEUS, is thanked for her support with the well data. Schlumberger is acknowledged for providing the seismic interpretation software Petrel. The corrections, comments and suggestions by reviewers Thomas B. Kristensen, an anonymous reviewer and GSL editor Mads Huuse significantly improved an earlier version of this manuscript, and their contribution to the final paper is highly appreciated.

References

- Ahnert, F. 1996. *Einführung in die Geomorphologie*, UTB, Stuttgart, 440 pp
- Andresen, K.J., Huuse, M. & Clausen, O.R. 2008. Morphology and distribution of Oligocene and Miocene pockmarks in the Danish North Sea – implications for bottom current activity and fluid migration. *Basin Research*, **20**, 445-466
- Back, S., van Gent, H., Reuning, L., Grötsch, J., Niederau, J. & Kukla, P. in press 2011. 3D seismic geomorphology and sedimentology of the Chalk Group, southern Danish North *Journal of the Geological Society of London*

- Boulton, G.S., Smith, G.D., Jones, A.S. & Newsome, J. 1985. Glacial geology and glaciology of the last mid-latitude ice sheets. *Journal of the Geophysical Society*, **142**, 447-474
- Boulton, G.S. & Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: Rheology and geological consequences. *Journal of Geophysical Research*, **92 (B9)**, 9059-9082.
- Boulton, G.S., Dongelmans, P., Punkari, M. & Broadgate, M. 2001. Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet trough the Weichselian. *Quaternary science Reviews*, **20**, 591-625
- Bowen, D.Q., Rose, J., McCabe, A.M. & Sutherland, D.G. 1986. Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales. In: Sibrava V., Bowen D.Q., Richmond G.M. (eds) *Quaternary Glaciations in the Northern Hemisphere*, *Quaternary Science Reviews*, Oxford, 299–340
- Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G. & Mathers, H.E. 2008. The northern sector of the last British Ice Sheet: Maximum extent and demise. *Earth-Science Reviews*, **88**, 207-226
- BurVal Working Group 2006. *Groundwater Resources in Buried Valleys – a Challenge for Geosciences*, Hannover, 303 pp.
- BurVal Working Group 2009. Buried Quaternary valleys – a geophysical approach. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **160**, 237-247
- Cameron, T.D.J., Stoker, M.S. & Long, D. 1987. The history of Quaternary sedimentation in the UK sector of the North Sea Basin. *Journal of the Geological Society of London*, **144**, 43–58
- Coles, B.J. 1998: Doggerland: a Speculative Survey. *Proceedings of the Prehistoric Society*, **64**, 45-81
- Ehlers, J., Meyer, K.D. & Stephan, H.J. 1984. The pre-Weichselian glaciations of North-West Europe. *Quaternary Science Reviews*, **3**, 1-40
- Ehlers, J. & Linke, G. 1989. The origin of deep buried channels of Elsterian age in north-west Germany. *Journal of Quaternary Science*, **4**, 255-265

- Ehlers, J. 1990. Reconstructing the dynamics of the north-west European Pleistocene ice sheets. *Quaternary Science Reviews*, **9**, 71-83
- 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. 1994. *Allgemeine und historische Quartärgeologie*, Stuttgart, 358 pp
- Ehlers, J. & Gibbard, P.L. 2003. Extent and chronology of glaciations. *Quaternary Science Reviews*, **22**, 1561-1568
- Ehlers, J. & Gibbard, P.L. (eds) 2004. *Quaternary glaciations - extent and chronology; Part I – Europe*. Development in Quaternary Science, Vol. 2a, Amsterdam, 475 pp
- Erohina, T., Cooper, A., Handwerger, D. and Dunbar, R. 2004. 8. Seismic stratigraphic correlations between ODP sites 742 and 1166: implications for depositional paleoenvironments in Prydz Bay, Antarctica. In: Cooper, A.K., O'Brien, P.E. and Richter C. (eds.) *Proceedings of the Ocean Drilling Program*, Scientific Results Volume, **188**, 1-21
- Fairbanks, R.G. 1989. A 17000-year glacio-eustatic sea level record: influence of glacial melting rates on the younger Dryas event and deepocean circulation. *Nature*, **342**, 637– 642
- Fitch, S., Thomson, K. & Gaffney, V. 2005. Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research*, **64**, 185-196
- Ghienne, J.F. & Deynoux, M. 1998. Large-scale channel fill structures in Late Ordovician glacial deposits in Mauretania, western Sahara. *Sedimentary Geology*, **119**, 141-159
- Huuse, M. & Lykke-Anderson, H. 2000. Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. *Quaternary Science Reviews*, **19**, 1233-1253
- Jelgersma, S. 1979. Sea-level changes in the North Sea basin. In: Oele, E., Schüttenhelm, R.T.E. & Wiggers, A.J. (eds.) *The Quaternary History of the North Sea*, Acta. Ups. Symp. Univ. Annum Quingentesimum Celebrantis, **2**, Uppsala, 233-248
- Karabanov, A.K, Ludvig, A.O. & Schwab, G. 1996. Base of Quaternary deposits of the Baltic Sea depression and adjacent areas, 1:1,500,000. *Neogeodynamica Baltica Project No. 346*

447 Knudsen, K.L. 1985. Foraminiferal stratigraphy of Quaternary deposits in the Roar, Skjold
 448 and Dan fields, central North Sea. *Boreas*, **14**, 311-324

449 Kristensen, T.B. & Huuse, M. 2007. Seismic characterization of buried pleistocene tunnel
 450 valleys in the North Sea basin – implications for infill lithology and seismic velocity effects.
 451 submitted for publication in *Marine and Petroleum Geology*

452 Kristensen, T.B., Huuse, M., Piotrowski, J.A. & Clausen, O.R. 2007. A morphometric analysis
 453 of tunnel valleys in the eastern North Sea based on 3D seismic data. *Journal of Quaternary*
 454 *Science*, **22**, 801-815

455 Le Heron, D., Sutcliffe, O., Bourgig, K., Craig, J., Visentin, C. & Whittington, R. 2004.
 456 Sedimentary Architecture of Upper Ordovician Tunnel Valleys, Gargaf Arch, Libya:
 457 Implications for the Genesis of a Hydrocarbon Reservoir. *GeoArabia*, **9**, 137-160

458 Levell, B.K., Braakman, J.H. & Rutten, K.W. 1988. Oil-bearing sediments of Gondwana
 459 glaciation in Oman. *AAPG Bulletin*, **72**, 775 - 796

460 Long, D., Laban, C., Streif, H., Cameron T.D.J. & Schüttenhelm, R.T.E. 1988. The
 461 sedimentary record of climatic variation in the southern North Sea. *In*: Shackleton N.J., West
 462 R.G., Bowen D.Q. (eds), *The Past Three Million Years; Evolution of Climatic Variability in the*
 463 *North Atlantic Region; a Discussion*, Philosophical Transactions of the Royal Society of
 464 London, Series B: Biological Sciences, 523–537

465 Lutz, R., Kalka, S., Gaedicke, C., Reinhardt, L. & Winsemann, J. 2009. Pleistocene tunnel
 466 valleys in the German North Sea: spatial distribution and morphology. *Zeitschrift der*
 467 *Deutschen Gesellschaft für Geowissenschaften*, **160**, 225-235

468 Michelsen, O., Thomsen, E., Danielsen, M., Heilmann-Clausen, C., Jordt, H. & Laursen, G.
 469 1998. Cenozoic sequence stratigraphy in the eastern North Sea. *In*: de Graciansky, P.C.,
 470 Jacquin, T. & Vail, P.R. (eds) *Mesozoic and Cenozoic Sequence Stratigraphy of European*
 471 *Basins*, SEPM Spec. Publ., **60**, 91-118

472 Møller, L.K., Rasmussen, E.S. & Clausen, O.R. 2009. Clinoform migration patterns of a Late
 473 Miocene delta complex in the Danish Central Graben; implications for relative sea-level
 474 changes. *Basin Research*, **21**, 704-720

- 475 Nielsen, O.B., Sørensen, S., Thiede, J. & Skarbø, O. 1986. Cenozoic differential subsidence
476 of North Sea. *AAPG Bulletin*, **70**, 276-298
- 477 Ó Cofaigh, C. 1996. Tunnel valley genesis. *Progress in Physical Geography*, **20**, 1-19
- 478 Pedersen, A. 1995. Pliocene – Middle Pleistocene Biostratigraphy in the Central Danish
479 North Sea wells E-1, P-1 and TWB-12. *Danmarks Geologiske Undersøgelse*, Serie C, No. 13
- 480 Praeg, D. 2003. Seismic imaging of mid-Pleistocene tunnel-valleys in the North Sea Basin –
481 high resolution from low frequencies. *Journal of Applied Geophysics*, **53**, 273-298
- 482 Rheinwarth, O. 1972. Die Kryosphäre. *Würzburger geographische Arbeiten*, **36**
- 483 Salomonsen, I. 1993. *Quaternary buried valley systems in the eastern North Sea*. PhD
484 thesis, University of Copenhagen
- 485 Salomonsen, I. 1994. A seismic stratigraphic analysis of Lower Pleistocene deposits in the
486 western Danish sector of the North Sea. *Geologie en Mijnbouw*, **72**, 349-361
- 487 Salomonsen, I. & Jensen, K.A. 1994. Quaternary erosional surfaces in the Danish North Sea.
488 *Boreas*, **23**, 244-253
- 489 Salomonsen, I. 1995. Origin of a deep buried valley system in Pleistocene deposits of the
490 eastern central North Sea. In: Michelsen, O. (eds) *Proceedings of the 2nd symposium on*
491 *Marine geology; geology of the North Sea and Skagerrak*; DGU-Series, C. Danmark og
492 Grønlands Geologiske Undersøgelser (DGU), Copenhagen, Denmark, 7-19
- 493 Sandersen, P.B.E. & Flemming, J. 2003. Buried Quaternary valleys in western Denmark -
494 occurrence and inferred implications for groundwater resources and vulnerability. *Journal of*
495 *Applied Geophysics*, **53**, 229-248
- 496 Sejrup, H.P. & Knudsen, K.L. 1993. Paleoenvironments and correlations of interglacial
497 sediments in the North Sea. *Boreas*, **22**, 223-235
- 498 Sejrup, H.P., Landvik, J.Y., Larsen, E., Janocko, J., Eriksson, J. & King, E. 1998. The Jæren
499 area, a border zone of the Norwegian Channel ice stream. *Quaternary Science Reviews*, **17**,
500 801-812

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S. & Vorren, T.O. 2005. Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*, **22**, 1111-1129

Sejrup, H.P., Nygård, A., Hall, A.M. & Haflidason, H. 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. *Quaternary Science Reviews*, **28**, 370-380

Shackleton, N.J. 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, **6**, 183-190

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

Stackebrandt, W. 2009. Subglacial channels of Northern Germany – a brief review. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **160**, 203-210

Velichko, A.A., Kononov, Y.M. & Faustova, M.A. 1997. The last glaciation of earth: size and volume of ice-sheets. *Quaternary International*, **41/42**, 43-51

Ziegler, P.A. 1990. Geological Atlas of Western and Central Europe. *Shell Internationale Petroleum Maatschappij BV*, The Hague

Figure captions

Fig. 1 - Regional map showing the location of the study area in the North-Sea Central Graben offshore Denmark (modified after Back *et al.*, in press 2011). The main fault zone separating the Ringkøbing-Fyn High from the Central Graben is shown in dark grey. Salt structures are indicated in grey and Pleistocene tunnel valleys in light grey. The location of the 3D seismic dataset analysed in this study is indicated by the dashed outline. The black horizontal line indicates the position of the seismic line shown on Figure 2. The black boxes indicate the location of Figure 8 and 9. Location of wells used for seismic to well tie are given as black dots.

Fig. 2 – Seismic cross section through parts of the study area from west (W) to east (E) (VE = 13.3) (for location see Fig. 1). In the western part the seismic line cuts through tunnel valley 2 (interpreted valley floor is marked by black crosses), the chronostratigraphic zones of well TWB-12 are tied to the seismic line. .

Fig. 3 – Seismic geomorphology of the tunnel valleys 1, 2 and 3 superimposed on a coherency time slice (200 ms TWT). The tunnel valleys are color coded according to depth in TWT (ms). Position of wells are indicated as blue dots.

Fig. 4 – a) Orientation of cross sections A-E and timeslices 1-3 (infill sections) relative to outlines of valley 1, valley location is indicated in Fig. 3. b)-e) cross sections A-D perpendicular to the long axis of tunnel valley 1, Repeated phases of cut and fill are indicated by the interpretation of two valley floor generations (orange and yellow crosses) f)-h) infill sections through tunnel valley 1 displaying amplitude variations on timeslices cutting through the valley infill in a depth of 225, 265 and 300 ms TWT. The dotted line shows the tunnel valley outline.

Fig. 5 – Top: Perspective view of the 3D seismic morphology of valley 1 (view from south); dotted line shows location of section E. (Z-axis in ms TWT.); Middle: cross section E-E' parallel to the long axis of the tunnel valley, showing different generations of valley fill. Repeated phases of cut and fill are indicated by the interpretation of two valley floor generations (orange and yellow crosses) Bottom: Interpreted cross section E.

Fig. 6 – a) Orientation of cross sections F-H and section I relative to outlines of valley 2 (valley location is indicated in Fig. 3). b)-d) cross sections F-H through tunnel valley 2, Interpreted valley floor is marked by yellow crosses. e) section I parallel to the long axis of the tunnel valley I, Interpreted valley floor is marked by yellow crosses.

Fig. 7 – a) Orientation of cross sections J and K and section L relative to outlines of valley 3 (valley location is indicated in Fig. 3). b)-c) cross sections J and K through tunnel valley 3, Interpreted valley floor is marked by yellow crosses. d) section L parallel to the long axis of the tunnel valley 3, Interpreted valley floor is marked by yellow crosses.

Fig. 8 – Left: A-D uninterpreted timeslices (amplitudes) from the southeastern part of the study area in a depth of 265, 235, 220 and 195 ms TWT; for location see Fig. 1. Right: interpretation of a dendritic drainage system on timeslices A, B, C and D. Black lines show parts of the drainage system that are interpreted to be active at the time. Grey lines: abandoned parts of the drainage system. Dotted lines: seismically less well defined parts of the drainage system.

Fig 9 – a) Timeslice in a depth of 220 ms TWT for orientation of cross sections A-F; for location see Fig. 1.; b) longitudinal cross sections A through the main branch of the dendritic network and the northernmost part of the tunnel valley; cutting points with cross sections B-E are indicated; c)-g) cross sections perpendicular to the long axis of branch and the tunnel valley 1; cutting points with the longitudinal section A and distributaries are indicated; f) and g) tunnel valley bottom is indicated by black crosses.

Fig. 10 – Sinuosity measured for 10 branches of the drainage system (actual path length divided by shortest path length). Mean 1.147 (linear = 1; sinuous > 1.5).

Fig. 11 – European Stages for wells Skjold 21 (Knudsen 1985), TWB-12 (Pedersen 1995) and Roar 41 and 43 in the Roar field (Knudsen 1995, Sejrup & Knudsen 1993, Salomonsen & Jensen 1994, GEUS unpublished well completion reports). Further foraminiferal zones and environmental interpretation (Pederson, 1995) for well TWB-12. The marine part of Zone T2 was correlated by Pederson (1995) to the Zone R6 in the Roar field. The stratigraphic position of this interval is disputed, since Pedersen (1995) attributed the entire T2 Zone to

the Cromerian, whereas Zone R6 was interpreted as Saalian by Sejrup & Knudsen (1993).
The seismic event (wavy line) represents a seismic-to-well tie of the uppermost reflector that
was cut by tunnel valleys 1 and 2 to the strata at well TWB-12. Depth in m below sea floor
(for well location see Fig. 1).

Fig. 12 – Comparison of tunnel valley outlines mapped in this study with literature data.
Previously valleys were mapped from 2D- (Salomonsen, 1993; 1995) and 3D seismic data
(Kristensen & Huuse 2007, Lutz *et al.* 2009).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 6

Fig. 7

• well

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12