**3D seismic geomorphology and sedimentology of the Chalk Group, southern Danish
North Sea**

Stefan Back¹, Heijn van Gent², Lars Reuning¹, Jürgen Grötsch³, Jan Niederau¹, Peter Kukla¹

¹ Geological Institute, RWTH Aachen University, Aachen, Germany

² Structural Geology – Tectonics - Geomechanics, RWTH Aachen University, Aachen,
Germany

³ Shell EP Europe, NAM, Assen, The Netherlands

contact: back@geol.rwth-aachen.de

Abstract

Classically, the North-Sea Chalk is assumed to have deposited under quiet, homogeneous pelagic conditions with local re-deposition in slumps and slides. However, recently the observation of highly discontinuous reflection patterns on 2D and 3D seismic data from the NW European Chalk Group initiated a revision of some general ideas of chalk deposition, assuming that long-lived, contour-parallel bottom currents exert a primary influence on the development of intra-chalk channels, drifts and mounds. In this study, an alternative explanation is suggested for the formation of many of the significant intra-chalk seismic and stratal discontinuities by interpreting these as being caused by gravity-driven processes developing in response to intense syndepositional tectonics. Submarine mass-transport systems identified in the study area include large-scale slumps, slides, debris flows and turbidites. The latter occur in sinuous channel systems flanked by large master overbanks, with the channel fill exhibiting well-developed secondary banks and overbanks on the respective outer bends of the inner channel thalweg. This first documentation of channelised density-flow deposits in the North-Sea Chalk has important consequences for the interpretation and prediction of re-deposited chalk units, emphasising at the same time the strength of vigorous 3D seismic discontinuity detection for subsurface sedimentary-systems analysis.

29 **Introduction**

30 The Upper Cretaceous to Lower Paleogene Chalk Group of NW Europe is a biogenic deposit
31 mainly of pelagic origin (e.g. Hancock 1975, Kennedy 1987, Surlyk 1997, Surlyk et al. 2003,
32 van der Molen et al. 2005, Esmerode et al. 2008, Surlyk et al. 2008). Its deposition is
33 classically assumed to represent the settlement of calcareous ooze from suspension, draping
34 pre-existing submarine morphology by a monotonous 'blanket deposit' with mainly parallel
35 bedding relationships and high lateral continuity (see e.g. Evans et al. 2003 and Surlyk et al.
36 2008 for a critical discussion). However, re-deposited, less homogenous chalk sediments
37 have also been identified in the past, mainly in and adjacent to tectonically active areas (e.g.
38 Hardman 1982, Brewster and Dangerfield 1984, Hatton 1986, Bromley and Ekdale 1987,
39 Cartwright 1989, Clausen and Huuse 1999, Skirius et al. 1999, Evans et al. 2003, Lykke-
40 Andersen and Surlyk 2004, van der Molen et al. 2005). Recently, the documentation of
41 significant intra-chalk erosional surfaces, channels, slump scarps and mass-transport
42 complexes on 2D and 3D seismic datasets offshore NW Europe (e.g. Lykke-Andersen and
43 Surlyk 2004, van der Molen et al. 2005, Surlyk and Lykke-Andersen 2007, Esmerode et al.
44 2007, Esmerode et al. 2008, Surlyk et al. 2008) initiated a revision of some general ideas of
45 chalk deposition, with the most recent publications strongly focusing on the argument that
46 powerful, lon-lived, contour-parallel bottom currents acted as the primary control for the
47 development of intra-chalk channels, drifts and mounds. This paper seeks an alternative
48 explanation for the formation of many of the significant intra-chalk seismic and stratal
49 discontinuities by interpreting these as being primarily caused by gravity-driven erosional and
50 sedimentary processes that developed in response to intense syndepositional tectonics.

51
52 The 3D seismic survey analysed in this study covers approximately 2000 km² of the Danish
53 North-Sea Central Graben, bound by the Ringkoebing-Fyn High in the east, extending in its
54 central part across the Bo-Jens, Gorm-Lola, Tyra-Igor, Igor-Emma and Adda Ridges, and
55 reaching in the south the Danish Salt Dome province (Fig. 1). The seismic character of the
56 Chalk Group reflections ranges from continuous to highly discontinuous. In the case of

pronounced discontinuity, the reflectors exhibit a multitude of terminations and truncations, are isolated and oblique with respect to the surrounding reflection packages, or show frequent polarity changes in lateral directions. To gain a basinwide overview of the 3D distribution of seismic discontinuity features throughout the Chalk Group, a fast-track 3D horizon framework was constructed comprising three iso-proportional surfaces between the Top- and Base-Chalk marker horizons (Fig. 2). This subdivision defined three coarse interpretation units, a basal Chalk I unit (Base-Chalk reflection to Iso-Surface 1), a central Chalk II unit (between Iso-Surfaces 2 and 3) and a topmost Chalk III interval (Iso-Surface 3 to Top-Chalk reflection; prime target interval for hydrocarbon exploration). In large parts of the study area, the iso-proportional surfaces honour the general trend of the subsurface stratigraphy; however, they crosscut seismic reflectors in the areas of pronounced stratal inhomogeneity (Fig. 2). Within and around these discontinuity zones, the projection of seismic discontinuity attributes (chaos, variance) was used as a first-pass indicator for the subsurface presence of channels and mass-transport complexes, features that were subsequently selected for a detailed 3D seismic-geomorphological analysis.

3D Seismic Interpretation

In the Chalk I interval between the Base-Chalk reflection and Iso-Surface 1 (Fig. 2), most parts of the study area are characterised by continuous stratal configuration, as documented by a dominantly coherent lateral reflection distribution on seismic discontinuity data (Figs. 3A, B). However, the very south of the study area exhibits a sharply bounded, mildly sinuous to almost linear, fault-controlled channel feature (length ca. 10 km, width ca. 1 km) immediately west of the southernmost salt-rim syncline (Channel I; Figs. 3B, C). Another subtle channel system, over 20 km long, descends from the Tyra-Igor Ridge in the central part of the study area towards the southern Salt Dome province, feeding a triangular-shaped terminal fan of approximately 10 km² extent in the southernmost salt-rim syncline. This channel is also characterised by a low degree of sinuosity, a thickness of less than 20 ms two-way-time (TWT), possible crevasse splays in its central part (Channel II; Figs. 3A, B) and only very

85 little basal incision. More pronounced stratal discontinuity is observed in the hanging wall of
86 the Coffee-Soil fault in the very NE of the study area, where mildly mounded reflections with
87 a lobate termination suggest the occurrence of isolated, small-scale, fault-controlled mass-
88 transport complexes (Fig. 3D).

89
90 In the Chalk II interval (Iso-Surfaces 1 to 3; see Fig. 2), large parts of the survey area are
91 characterised by highly discontinuous stratal configuration (Fig. 4). The surface-slice analysis
92 of seismic discontinuity data (Figs. 4A, B) documents that subparallel, continuous reflection
93 patterns are generally rare; instead, a multitude of reflection discontinuities occurs, including
94 seismic irregularities associated with large-scale mass transport systems (slides and
95 slumps), and a variety of channels. The channel systems observed are oriented in different
96 directions, including channel systems that trend mainly southward (Channels III and IV on
97 the eastern flank Bo-Jens Ridge; Figs. 4B, C, D), to the east (Channel V on the northeastern
98 flank Tyra-Igor Ridge; Fig. 4B), and westward (Channel VI in the northern part of Salt-Dome
99 province; Fig. 4B). The vertical display of reflectivity data documents pronounced channel
100 amalgamation, channel stacking and the incision and truncation of older channel segments
101 by younger successors, locally preserving deposits interpreted as former channel fill, inner
102 banks and overbank units (Fig. 4D). The sidewalls of the major sediment-pathways are
103 locally influenced by slope instability, as indicated by the occurrence of small-scale faults
104 trending parallel to the channel axis that are associated with stratal discontinuities interpreted
105 as small-scale slides or slumps (e.g. western flank of Tyra-Igor Ridge, Figs. 4A, B). On the
106 southwestern and northeastern flanks of the Tyra-Igor Ridge, extensive ($>150 \text{ km}^2$), arcuate-
107 shaped zones of highly discontinuous seismic facies are the result of the subsurface
108 presence of large-scale mass-transport complexes (Fig. 4A, B). Vertical reflectivity sections
109 show depositional units of significant stratal distortion that descend from the Tyra-Igor Ridge
110 both into southwestern direction into the Salt-Dome province (MTC A; Fig. 4E), and towards
111 the northeast into the Coffee-Soil fault zone (MTC B; Fig. 4F). The observation of

pronounced cut-and-fill features above both mass transport complexes (Figs. 4E, F) suggests that channel incision succeeded sliding and slumping.

In the Chalk III interval between Iso-surface 3 and the Top-Chalk reflection (Fig. 2), the survey-wide seismic discontinuity data documents that the major seismic discontinuity signature of the preceding interval is waning (Figs. 5A, B). In contrast to the multitude of linear seismic features observed so far, the presence of a horizontally dendritic to circular (Fig. 5A), vertically often mound-like seismic discontinuity facies (Fig. 5C) dominates this interval, characterising large areas of the Adda and Igor-Emma Ridges. Outside of these areas, the Chalk III strata is rather homogenous and of high lateral reflection continuity (Fig. 5A).

3D Seismic Geomorphology of Key Stratal Discontinuities

In the study area, the occurrence of seismic discontinuity facies seems almost as common as seismic continuity, which is in line with previous studies that identified significant intra-chalk stratal inhomogeneity (e.g. Evans et al. 2003, Lykke-Andersen and Surlyk 2004, van der Molen et al. 2005, Surlyk and Lykke-Andersen 2007, Esmerode et al. 2007, Esmerode et al. 2008, Surlyk et al. 2008). At Chalk II level (Fig. 4), stratal discontinuity seems even dominant with the multitude of preserved channels and mass-transport complexes witnessing significant erosion, transport and re-deposition of chalk material. The following paragraphs provide a more detailed description of the geomorphology and seismic expression of the most prominent erosional and depositional features identified in the study area, focusing on (1) submarine channels; (2) depositional bodies interpreted as slides, slumps, and debris flows; (3) the pronounced seismic discontinuity facies that characterises extensive areas at the Chalk III level.

Submarine Channels

Both the north and south of the study area exhibit extensive zones of recurrent channel incision and infill. In the northern part of the study area, the prime location for channelling is between the Bo-Jens and Adda Ridges (Fig. 4; also see Esmerode et al., 2008). With a width of around 7 km, the main channelised area extends for over 30 km into a region west of Gorm-Lola Ridge. In the southern part of the study area, the main location for channel development is located east of Gorm-Lola Ridge (Fig. 4). The largest channels observed in this part trend in western direction on the southwestern flank of Tyra-Igor Ridge, turning southward where entering the structural depression east of Gorm-Lola Ridge.

Figure 6 is a detailed geomorphological interpretation of the proximal master valley of the most prominent Channel II between the Bo-Jens, Tyra-Igor and Adda Ridges (see Figs. 4B, C, D). The master valley has an average width of 2.5 km, with basal incision of up to 150 ms TWT into the underlying chalk substratum. Large master overbanks flank the valley in the northern (proximal) part of the system (Fig. 6, sections A-A' to C-C'), decreasing in height towards the south (sections D-D' to E-E'). In places, secondary banks and overbanks (inner levees) are developed (Fig. 6, sections B-B' and C-C'), features that dominantly mark the outer bends of the inner channel thalweg. Vertical reflectivity displays along the main channel axis (Section F-F') document that pronounced reflection discontinuities (onlap, downlap, truncation) characterise the channel fill. Figure 7 illustrates the variability of the master valley fill through time by a projection of successive reflectivity time-slices into the main channel container. At the lowest stratigraphic level (ca. 20 ms TWT above the master-valley base, Fig. 7A), the channel thalweg is restricted to the central part of the master valley, and inner levees occur at their respective outer bend locations. In the very south, the master valley is entered by slump units derived from the eastern master overbank. Up section, around 40 ms TWT above the valley base (Fig. 7B), both the inner channel thalweg and the inner levees are broadened, with overbank deposition remaining confined to the inner part of the master valley. In contrast, the secondary overbanks associated with the upper portion of the sinuous channel system (ca. 60 ms TWT above the master-valley base, Fig. 7C) extend beyond the

confines of the master valley and overlie the master overbanks. This suggests that the valley was filled by this time and that channelised flows could no longer be contained.

In comparison to the northern part of the study area, intra-chalk channels in the south are generally less confined, less incised and thus more difficult to detect. Figure 8 is a representative example of a southern channel descending the southwestern flank of Tyra-Igor Ridge in western direction. The channel truncates the northern flank of a rising salt structure, before turning into SSE-direction when entering the structural depression east of Gorm-Lola Ridge (see Fig. 4B, Channel VI). The geomorphology and internal seismic character of this channel is fundamentally different from the northern system described above. The southern example lacks an internal sinuosity and is strongly asymmetric. Its southern flank is generally steep and erosive, whereas its northern flank is only weakly confined to partly unconfined. As a consequence of the weak confinement, master levees are generally lacking and there is no indication of secondary banks and overbanks within the channel fill. Instead, the channel deposits are rather well-layered forming depositional sheets that are difficult to detect seismically if their polarity matches that of the surrounding strata. However, the generally low-amplitude, semi-transparent seismic facies of the channel fill (Fig. 8) supports the detection of this example and similar systems on vertical and horizontal reflectivity data.

Slides, slumps and debris flows

A key observation in the study area is that the majority of large-scale seismic discontinuity features interpreted as gravity-driven mass-transport systems are located on, or in the immediate vicinity of the flanks of rising structures (inversion ridges, diapirs). These features can be very diverse in external form, size and internal architecture (e.g. Figs. 3D, 4E and 4F). Probably the most obvious and with an extent of around 150 km² also the largest mass-transport complex is observed in the lower Chalk II interval east of a series of major headwall scarps (sensu Bull et al. 2009) between the Tyra-Igor and Igor-Emma Ridges (Figs. 4A, B,

F). Although close to the limit of seismic resolution, vertical displays across the mass transport complex indicate the presence of compressional ridges, irregular bedding contacts and internal high-amplitude reflections, classifying the deposit as slump (*sensu* Moscardelli and Wood 2008). The second largest mass transport complex of the study area is located at the same stratigraphic level on the southwestern flank of Tyra-Igor Ridge (Figs. 4A, B, E), covering an area of around 100 km² (Fig. 9). Internally, this mass transport complex exhibits trains of compressional ridges characterised by prominent negative amplitudes. In comparison to the large-scale slump of the on the eastern side of Tyra-Igor Ridge (Fig. 4F), the reflections of the southwestern slump are of higher lateral continuity suggesting less brittle deformation of the internal bedding. Another significant difference is that this slump lacks a sharp, well-defined headwall scarp in its most proximal portion. Because of its clear internal deformation, this system is also classified as slump accumulation (*sensu* Moscardelli and Wood 2008), although the relatively high reflection continuity in the most proximal portion might indicate only minor downslope sliding.

Other mass transport complexes in the study area include e.g. the small-scale mounded features (< 20 km² extent) documented in the Chalk I interval in the very northeast of the study area (Figs. 3A, B, D). These deposits accumulated in the hanging wall of the Coffee-Soil Fault, and are characterised by irregular bedding contacts, lateral reflection pinch-outs, lobate terminations as well as downslope-oriented ridges and scours (e.g. Fig. 3D). Based on the classification scheme of Moscardelli and Wood (2008), these small-scale mass-transport deposits fall into the category debris flows.

Seismic discontinuity facies at Chalk III level

A seismic discontinuity facies associated with a generally rugged morphology characterises the strata immediately below and at Top-Chalk level (Fig. 5; Fig. 10A; see Huuse (1999) for interpretation of comparable Top-Chalk features on 2D seismic data). Figures 5C and 5D illustrate the lateral and vertical character of this facies that is particularly present on the

Adda and Igor-Emma Ridges. If compared against the distribution of seismic discontinuity facies in the preceding Chalk II (see Fig. 4) and Chalk I (see Fig. 3) levels, the location of this distinct Chalk III discontinuity facies approximately corresponds to the sites of former mass wasting, although much larger in area. In order to test whether the Chalk III discontinuity facies could also be related to gravity-driven processes, the approximate paleo-relief at Chalk III times was restored by flattening an auxiliary intra-Tertiary horizon immediately above Top Chalk (Figs. 10B, C). The resulting eastward inclination (ca. 1-2°) of the underlying Chalk III unit suggests that the discontinuity facies originally formed on a paleo-slope, an area that was post-depositionally uplifted and tilted to its present-day position at the crest of Tyra-Igor Ridge. In the context of the multitude of gravity-driven deposits documented in the preceding Chalk intervals, it seems very likely that an Chalk III slope setting facilitated gravity-driven downslope movement (sliding or creep?) generating the irregular Chalk III morphology and seismic facies (Fig. 10D).

Discussion

The seismic data and interpretations presented in this paper document that the North-Sea Chalk in the Central Graben offshore Denmark contains a multitude of mass-transport deposits. The majority of these is located on, or in the immediate vicinity of tectonically active structures, in particular on the flanks of ridges that formed in response to Late Cretaceous inversion (e.g. Vejbaek and Andersen 1987, 2002; Esmerode et al. 2008). The most obvious mass-transport units are the large-scale slumps and slides on the flanks of the Tyra-Igor and Igor-Emma Ridges (e.g. Figs. 4, 9, 10); more subtle units are e.g. slump and debris flow deposits in the vicinity of the Coffee-Soil Fault (e.g. Fig. 3D). Stratal thinning towards former structural highs suggests that horizon flattening can be used as a first-pass indicator for paleo-slope settings (e.g. Fig. 10), but the lack of well-defined paleo-bathymetric reference data for the Chalk Group limits a more detailed 3D-restoration of the paleo-morphology (e.g. *sensu* Back et al. 2008). However, the widespread inhomogeneity of seismic facies still documents that much of the Chalk Group material was re-mobilized after deposition and

transported either by sliding, slumping, or as channelised density flow (e.g. Figs. 3, 4, 5). This clearly contrasts the classical view of a highly continuous, dominantly parallel-bedded North-Sea Chalk, but supports studies that previously identified considerable intra-chalk erosion, sediment re-working and re-deposition (e.g. Quine and Bosence 1991, Evans et al. 2003, Lykke-Andersen and Surlyk 2004, van der Molen et al. 2005, Jarvis 2006, Esmerode et al. 2007, Surlyk and Lykke-Andersen 2007, Esmerode et al. 2008, Surlyk et al. 2008).

A significant part of the very recent work on dynamic sedimentation processes during the development of the North-Sea Chalk (e.g. Esmerode et al. 2007, Surlyk and Lykke-Andersen 2007, Esmerode et al. 2008, Surlyk et al. 2008) has stressed the influence of powerful, long-lived, contour-parallel bottom currents for the development of many of the intra-chalk stratal irregularities, an interpretation particularly relying on the analysis of channel geometries (see Esmerode et al. 2008, Surlyk et al. 2008, and discussions therein). However, the quantity, extent, spatial distribution, variability in transport direction and seismic character of unambiguously gravity-driven mass-transport complexes (i.e. slides, slumps) and the channel systems documented in this study suggests a critical re-evaluation of the main controlling factors for the deposition of the North Sea Chalk of the Central Graben. With gravity-driven sediment transport as common as observed, it seems very likely that turbid density flows contributed to the re-deposition of chalk strata, currents that could have formed e.g. from the dispersed head-parts of debris flows (Nemec 1990), or simply evolved from such flows whenever these accelerated sufficiently to become fully turbulent (Hampton 1972, Ferentinos et al. 1988, Weirich 1989, Nemec 1990).

Following this line of argument, it is significant that the orientation of the interpreted channel systems varies throughout the study area, with the channels of the Chalk I interval trending into southwestern, southeastern and northwestern direction (Fig. 3), and the channels of the Chalk II interval oriented towards the south, east, southwest and north (Fig. 4). No channels were detected in the Chalk III level. All channels of the Chalk I and Chalk II trend

approximately perpendicular to the paleo-slope (see e.g. channel base of section F-F', Figure 6, in relation to the Top Chalk reflection); however, it has been noted before that an unambiguous paleo-slope restoration in the Chalk is difficult in the absence of a clear paleo-bathymetric datum. The most prominent channel of the study area is a major southward-trending system at Chalk II level shown on Figures 4, 6 and 7, which is partly the same system as analysed and described by Esmerode et al. (2008). The channel is branched in its upper part, with individual tributaries descending the Bo-Jens Ridge in the west and the Adda Ridge in the northeast, before combining into one large channel that follows the course of the structurally defined depression between the Bo-Jens and Tyra-Igor Ridges (Figs. 2, 4). A key departure from the interpretation of Esmerode et al. (2008) is the documentation of a clear sinuosity of the master valley (Fig. 6) that is flanked by large master overbanks. The valley fill comprises well-defined secondary banks and overbanks (inner levees) on the respective outer bends of the inner channel thalweg (see Figs. 6 and 7), which strongly indicates that the master valley served as a conduit for turbulent density flows. Towards the top of the channel system, the secondary overbanks extend beyond the confines of the master valley covering the master overbanks (Fig. 7C). This is interpreted to reflect that most of the valley was filled by this time and channelised flows could no longer be contained. The systems starting points on the flanks of Bo-Jens and Adda-Ridges (Fig. 4) witness that it was primarily fed by slumped material from the actively rising and locally failing ridge slopes, being further downslope supported by mass-wasted material derived from channel-wall collapses. The considerable erosive power of the system is witnessed by its strong incision, possibly resulting from the incorporation of failed chalk hardgrounds in the density flows passing through. Thus, the northern channel system of the Chalk II interval displays all architectural elements of a gravity-driven deepwater turbidite system proper (e.g. *sensu* Deptuck et al. 2007, Kolla et al. 2007), leaving little support for its interpretation as a contour-current feature.

In comparison to the northern system, the channels in the south of the study area (e.g. Figs. 4, 8) are less confined and less incised. An important discussion point is that the southern channel VI documented on Figure 8 trends in its proximal portion in western direction (also see Fig. 4), which is highly oblique to the general southeast direction of the long-lived, contour-parallel bottom currents proposed by Esmerode et al. (2008) and Surlyk et al (2008). However, after truncating the northern flank of a rising salt structure, the channel turns into a SSE-direction (see Fig. 4B), a flow direction that is in line with the proposed bottom currents. A detailed view into the geomorphology of the southern channel example reveals that the system lacks an internal sinuosity, and is strongly asymmetric. Its southern side appears steep and erosive, whereas the northern side is only weakly confined. This lack of confinement seems to have limited the development of channelised flows flanked by overbanks, instead resulting in the accumulation of subparallel- to parallel-bedded sheet deposits. The rather conformable interbedding of the channel fill with the surrounding strata on its northern flank (Fig. 8) indicates that re-deposited (allochthonous) chalk sheets might tightly alternate and laterally interfinger with autochthonous pelagic chalk, a genetic succession probably difficult to interpret as such if encountered on wireline-log and core data.

In summary, the observation of significant stratal discontinuity in the Chalk Group of the Danish part of the North Sea Central Graben documents that submarine erosion, sediment transport and re-deposition highly influenced chalk sedimentation. The mass-transport systems analysed in this study are only mildly developed in the Chalk I interval, but reach a maximum in the Chalk II and lower Chalk III (Fig. 11). The major Chalk II slumps and slides located alongside tectonically active inversion structures indicate that tectonically-induced, gravity-driven mass transport contributed significantly to the re-distribution of chalk sediment. Additionally, the detailed analysis of the orientation, geomorphology and internal architecture of selected intra-chalk channels documents that these systems formed important conduits for density flows that transported failed chalk material into the deeper chalk depocentres, a

334 primarily gravity-driven process that is distinctly different from the contour-current model
335 proposed by e.g. Lykke-Andersen and Surlyk (2004), Surlyk and Lykke-Andersen (2007),
336 Esmerode et al. (2008) and Surlyk et al. (2008). However, irrespective of the ultimate cause
337 for chalk re-working, the results of this study document that re-deposited chalk strata can
338 occur in a highly variable depositional fashion at many locations, possibly associated with a
339 prominent seismic discontinuity, but maybe only as subtle seismic irregularity. Inferences
340 whether the re-worked chalk units have reservoir properties different from autochthonous
341 chalk deposits clearly cannot be made from the use of seismic data alone, but the delineation
342 of key study sites for integrating seismic interpretation results with high-resolution wireline-
343 log and core data is very well possible. A study such as this will have the potential to identify
344 unconventional hydrocarbon traps in deeper chalk layers.

346 **Conclusions**

- 347 1. The development of the Chalk Group of the North-Sea Central Graben was significantly
348 influenced by mass-transport processes. Slope instability of the flanks of tectonically active
349 structures (inversion ridges) generated in many places oversteepened ridge flanks that
350 failed, triggering gravity-driven deepwater mass transport ranging from sliding and slumping
351 to the generation of high-energy, sediment-laden density flows.
- 352 2. The detailed analysis of selected intra-chalk channels of varying orientation documents for
353 the first time the subsurface presence of a large-scale, sinuous, leveed intra-chalk sediment-
354 transport system that displays all architectural elements typical for a deepwater turbidite
355 system. This system seems to have formed an important conduit for density flows that
356 transported failed chalk material into the deeper chalk depocentres.
- 357 3. The quantity, extent, orientation, spatial distribution and type of mass-transport systems
358 encountered in the study area emphasises the importance of gravity-driven processes for
359 downslope sediment transport. In contrast to previous studies on the re-working of chalk
360 strata in and around the North-Sea Central Graben, the results of this study do not provide

evidence for contour-parallel bottom currents influencing intra-chalk sediment mobilization and re-deposition.

4. The interpretation approach used in this study emphasises the value of initially coarse, 3D-seismic discontinuity-highlighting techniques that subsequently support target-oriented, detailed depositional-systems analyses. The interpretation results presented enable at many locations a differentiation between original, autochthonous chalk strata and re-worked, re-deposited chalk units. If systematically calibrated against high-resolution wireline and core data, this seismic-based differentiation might become important for the prediction of potential hydrocarbon reservoir facies.

Acknowledgements

The authors thank Maersk Olie og Gas, Shell EPE Geological Services and the DUC partners for initiating and supporting this study. The contributions of many of their staff technically and/or by discussion is particularly acknowledged. Schlumberger is thanked for providing 'PETREL' under an Academic User License Agreement. Seismic Micro-Technology is gratefully acknowledged for providing 'KINGDOM Software' under an Educational User License Agreement. This study is a spin-off of project DINGO (RE 2697/3-1) funded by the Deutsche Forschungsgemeinschaft (DFG).

References

- Back, S., Strozyk, F., Kukla, P.A. and Lambiase, J.J. 2008. 3D restoration of original sedimentary geometries in deformed basin fill, onshore Brunei Darussalam, NW Borneo. Basin Research, v. 20, 99-117.
- Brewster, J. and Dangerfield, J.A. 1984. Chalk fields along the Lindesnes Ridge, Eldfisk. Marine and Petroleum Geology, 1, 239-278.
- Bromley, R.G. and Ekdale, A.A. 1987. Mass transport in European Cretaceous chalk; fabric criteria for its recognition. Sedimentology, 34, 1079-1092.

388 Bull, S., Cartwright, J. and Huuse, M. 2009. A review of kinematic indicators from mass
389 transport complexes using 3D seismic data. *Marine and Petroleum Geology*, 26, 1132-1151.

390 Cartwright, J. 1989. The kinematics of inversion in the Danish Central Graben. In: Cooper,
391 M.A. & Williams, G.D. (eds), *Inversion Tectonics*. Geological Society, London, Special
392 Publications, 44, 153-175.

393 Cartwright, J. 1991. The kinematic evolution of the Coffee Soil Fault. In: Roberts A. M.,
394 Yielding, G. & Freeman, B. (eds), *The Geometry of Normal Faults*, Geological Society
395 London, Special Publication 56, 29-40.

396 Clausen, O. R. and Huuse, M. 1999. Topography of the Top Chalk surface on- and offshore
397 Denmark. *Marine and Petroleum Geology*, 16, 677-691.

398 Deptuck, M.E., Syvester, Z., Pirmez, C. and O'Byrne, C. 2007. Migration–aggradation history
399 and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major
400 Canyon, western Niger Delta slope. *Marine and Petroleum Geology*, 24, 406-433.

401 Esmerode, E. V., Lykke-Andersen, H. and Surlyk, F. 2008. Interaction between bottom
402 currents and slope failure in the Late Cretaceous of the southern Danish Central Graben,
403 North Sea. *Journal of the Geological Society*, London, 165, 55-72.

404 Evans, D.J., Hopson, P.M., Kirby, G.A. and Bristow, C.R. 2003. The development and
405 seismic expression of synsedimentary features within the Chalk of southern England. *Journal*
406 *of the Geological Society*, London, 160, 797-813.

407 Ferentinos, G., Papatheodorou, G. and Collins, M.B. 1988. Sediment transport processes on
408 an active submarine fault escarpment, Gulf of Corinth, Greece. *Marine Geology*, 83, 43-61.

409 Hampton, M.A. 1972. The role of subaqueous debris flow in generating turbidity currents.
410 *Journal of Sedimentary Petrology*, 42, 775-793.

411 Hancock, J.M. 1975. The petrology of the Chalk. *Proceedings of the Geologists' Association*,
412 86, 499-535.

413 Hardman, R.F.P. 1982. Chalk reservoirs of the North Sea. *Bulletin of the Geological Society*
414 *of Denmark*, 30, 119-137.

415 Hatton, I.R. 1986. Geometry of allochthonous Chalk Group members, Central Trough, North
 416 Sea. *Marine and Petroleum Geology*, 3, 79–98.

417 Huuse, M. 1999. Detailed morphology of the Top Chalk surface in the eastern Danish North
 418 Sea. *Petroleum Geoscience*, 5, p. 303-314.

419 Jarvis, I., 2006, The Santonian–Campanian phosphatic chalks of England and France:
 420 *Proceedings of the Geologists' Association*, 117, p. 219-237.

421 Japsen, P., Britze, P. and Anderson, C. 2003. Upper Jurassic – Lower Cretaceous of the
 422 Danish Central Graben: structural framework and nomenclature. *Geological Survey of*
 423 *Denmark and Greenland Bulletin*, 1, 233-246.

424 Kolla, V., Posamentier, H. W., and Wood, L. J. 2007. Deep-water and fluvial sinuous
 425 channels – Characteristics, similarities and dissimilarities, and models of formation. *Marine*
 426 *and Petroleum Geology*, 24, 388-405.

427 Kennedy, W.J. 1987. Sedimentology of Late Cretaceous–Paleocene chalk reservoirs, North
 428 Sea Central Graben. In: Brooks, J. & Glennie, K.W. (eds), *Petroleum Geology of North West*
 429 *Europe*. Graham & Trotman, London, 469- 481.

430 Lykke-Andersen, H. and Surlyk, F. 2004. The Cretaceous–Palaeogene boundary at Stevns
 431 Klint, Denmark: inversion tectonics or sea-floor topography? *Journal of the Geological*
 432 *Society*, London, 161, 343-352.

433 Moscardelli, L. and Wood, L. 2008. New classification system for mass transport complexes
 434 in offshore Trinidad. *Basin Research*, 20, 73–98.

435 Nemec, W. 1990. Aspects of sediment movement on steep delta slopes. In: Colella, A. &
 436 Prior, D.B. (eds), *Coarse-grained deltas: The International Association of Sedimentologists*,
 437 *Special Publication 10*, 29-73.

438 Quine, M. & Bosence, D. 1991. Stratal geometries, facies and sea-floor erosion in Upper
 439 Cretaceous chalk, Normandy, France. *Sedimentology*, 38, 1113-1152.

440 Skirius, C., Nissen, S., Haskell, N., Marfurt, K., Hadley, S., Ternes, D., Michel, K., Reglar, I.,
 441 D'Amico, D., Deuencourt, F., Romero, T., D'Angelo, R. And Brown, B. 1999. 3-D seismic
 442 attributes applied to carbonates. *The Leading Edge*, 18, 384-393.

Surlyk, F., T. Dons, C. K. Clausen, and J. Higham, 2003. Upper Cretaceous. In D. Evans, C. Graham, A. Armour, and P. Bathurst (eds), *The millennium atlas: Petroleum geology of the central and northern North Sea*: The Geological Society (London), 213-233.

Surlyk, F. and Lykke-Andersen, H. 2007. Contourite drifts, moats and channels in the Upper Cretaceous Chalk of the Danish Basin. *Sedimentology*, 54, 405-422.

Surlyk, F., Jensen, S.K. and Engkilde, M. 2008. Deep channels in the Cenomanian–Danian Chalk Group of the German North Sea sector: Evidence of strong constructional and erosional bottom currents and effect on reservoir quality distribution. *American Association of Petroleum Geologists Bulletin*, 92, 1565-1586.

Van der Molen, A. S., Dudok van Heel, H. W., Wong, T.E. 2005. The influence of tectonic regime on chalk deposition: examples of the sedimentary development and 3D-seismic stratigraphy of the Chalk Group in the Netherlands offshore area. *Basin Research*, 17, 63-81.

Vejbaek, O.V. and Andersen, C. 1987. Cretaceous–early Tertiary inversion tectonism in the Danish Central Trough. *Tectonophysics*, 137, 221-238.

Vejbaek, O.V. and Andersen, C. 2002. Post mid-Cretaceous inversion tectonics in the Danish Central Graben—regionally synchronous tectonic events? *Bulletin of the Geological Society of Denmark*, 49, 129-144.

Weirich, F.H. 1989. The generation of turbidity currents by subaerial debris flows. *Bulletin of the Geological Society of America*, 101, 278-291.

Figure Captions

Figure 1. Regional map showing the location of the study area in the North-Sea Central Graben offshore Denmark and the key structural elements of the Central Graben area (modified after Cartwright 1991, Vejbaek and Andersen 2002; Esmerode, 2008). 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.

Figure 2. Fast-track 3D-seismic interpretation framework based on the calculation of three iso-proportional surfaces (phantom horizons) between the Top-Chalk and Base-Chalk

marker reflections. This interpretation approach subdivides the Chalk Group into three coarse interpretation units, a Chalk I unit (Base-Chalk reflection to Iso-Surface 1), a Chalk II unit (between Iso-Surfaces 2 and 3) and a Chalk III interval (Isosurface 3 to Top-Chalk reflection).

Figure 3. (A) Chaos attribute extracted in Chalk I interval, and **(B)** interpretation. The discontinuity-slice data shows that vast areas are characterised by highly continuous stratal configuration (white areas; laterally discontinuous seismic signature shown in black). **(C)** Vertical seismic display of the mildly sinuous, fault-controlled Channel I (length ca. 10 km, width ca. 1 km) in the very south of the study area. **(D)** Additional stratal discontinuity along the Coffee-Soil fault in the very NE of the study area where mildly mounded reflections suggest the occurrence of small-scale, fault-controlled mass-transport complexes.

Figure 4. (A) Chaos attribute extracted in Chalk II interval, documenting that most of the survey area is characterised by discontinuous stratal configuration (grey to black areas). **(B)** Interpretation of discontinuity-slice data. Channels in blue, mass-transport complexes in red. Blue arrows show downstream direction of channels indicated by dendritic channel patterns upstream; red arrows indicate mass-transport direction indicated by upslope headwall scarps and/or downslope folds and thrusts. **(C)** Close-up on sinuous channel segments located between Adda and Bo-Jens Ridges (chaos attribute; location of close-up indicated on Fig. 4A). **(D)** Vertical reflectivity images along sections W-W' and X-X' (location indicated on Fig. 4C). **(E)** SW-oriented mass-transport complex with major internal folding observed on southern Tyra-Igor Ridge along section Y-Y' (location indicated on Fig. 4B). Yellow crosses indicate cut-and-fill features above mass-transport complex. **(F)** ENE-oriented mass-transport complex on eastern flank of Tyra-Igor Ridge along section Z-Z' (location indicated on Fig. 4B). Yellow crosses as on Figure 4E.

Figure 5. (A) Chaos attribute extracted in Chalk III interval, and **(B)** interpretation. The discontinuity-slice data shows a decrease of seismic discontinuity facies if compared to the preceding Chalk II interval (Fig. 4). Hatched areas on Igor-Emma, Bo-Jens and Adda Ridges correspond to the dendritic to circular seismic discontinuity facies characterising vast parts of

the Chalk III interpretation level. **(C)** Close-up of the dendritic to circular, vertically often mounded seismic discontinuity facies (chaos attribute; location of close-up indicated on Fig. 5A). **(D)** Vertical reflectivity section along section X-X' (location indicated on Fig. 5C).

Figure 6. Detailed interpretation of the main container of a sinuous master valley in the northern study area (for location of system see Figs. 4C, D; for location of horizon picks on vertical sections see yellow crosses). The master channel has an average width of 2.5 km, incising up to 150 ms TWT into the underlying chalk substratum. Vertical reflectivity sections perpendicular to the master valley document master overbanks flanking the valley in the northern (proximal) part (e.g. sections A-A' to C-C'), and the presence of secondary banks and overbanks (inner levees) that mark the outer bends of the inner channel thalweg. At section D-D', the master valley is joined by a tributary valley descending the eastern flank of Bo-Jens Ridge (also see Fig. 4C). The vertical reflectivity display F-F' along the main channel axis documents pronounced reflection discontinuity within the channel fill.

Figure 7. Projection of successive reflectivity time-slices into the main container of Channel II. **(A)** Time slice ca. 20 ms TWT above the master-valley base, indicating that the channel thalweg is restricted to the central part of the master valley, and inner levees occur at their respective outer bend locations. In the very south, the master valley is entered by a slump derived from the eastern master overbank. **(B)** Time slice ca. 40 ms TWT above the master-valley base, in which both the inner channel thalweg and the inner levees are broadened, with overbank deposition remaining confined to the inner part of the master valley. **(C)** Time slice ca. 60 ms TWT above the master-valley base, indicating that secondary overbanks associated with the upper portion of the channel extend beyond the confines of the master valley and overlie the master overbanks. This suggests that the valley was filled by this time and that channelised flows could no longer be contained.

Figure 8. Representative example of a channel in the south of the study area descending the southwestern flank of Tyra-Igor Ridge in western to southwestern direction (for approximate location see Fig. 4B). This channel is characterised by a steep and erosive southern flank and a gentle northern flank that is only weakly confined (partly unconfined). In this and

comparable systems, primary levees are lacking and there is no indication of secondary banks and overbanks within the channel fill.

Figure 9. Depth map of the top of the second largest mass-transport complex in the study area, located on the SW flank of Tyra-Igor Ridge. Cross sections A-A' and B-B' document prominent compressional ridges within the mass-transport complex. For cross section Y-Y' see Figure 4E. Horizon picks indicated on vertical sections by yellow crosses.

Figure 10. Seismic discontinuity facies associated with a generally rugged morphology immediately below and at Top-Chalk level. **(A)** Landmark structure attribute map, corresponding in location to Figure 5C. **(B)** Unflattened vertical reflectivity display along section X-X' (section location indicated on Fig. 10A). **(C)** Vertical reflectivity section flattened on auxiliary horizon above Top Chalk. **(D)** Interpretation of the Chalk III discontinuity facies to have formed by gravity-sliding in a paleo-slope setting.

Figure 11. Summary diagram of the various gravity-driven depositional systems encountered at different stratigraphic levels in the North-Sea Chalk Group offshore Denmark. Mass-transport systems are only mildly developed in **(A)** the Chalk I interval, but reach a maximum in the **(B)** Chalk II and **(C)** Chalk III. The major slump and slide units are all located alongside tectonically active inversion ridges indicating that tectonically-induced, gravity-driven mass transport contributed significantly to the re-distribution of chalk sediment.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 8

Figure 9

ca. 10 km

100 ms
TWT

Figure 10

Figure 11