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Geological evolution of the Chalk Group in the northern Dutch North Sea: inversion, sedimentation and redeposition

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Abstract – In contrast to the Norwegian and Danish sectors, where significant hydrocarbon reserves were found in chalk reservoirs, limited studies exist analysing the chalk evolution in the Dutch part of the North Sea. To provide a better understanding of this evolution, a tectono-sedimentary study of the Late Cretaceous to Early Palaeogene Chalk Group in the northern Dutch North Sea was performed, facilitated by a relatively new 3D seismic survey. Integrating seismic and biostratigraphic well data, seven chronostratigraphic units were mapped, allowing a reconstruction of intra-chalk geological events.

The southwestward thickening of the Turonian sequence is interpreted to result from tilting, and the absence of Coniacian and Santonian sediments in the western part of the study area is probably the result of non-deposition. Seismic truncations show evidence of a widespread inversion phase, the timing of which differs between the structural elements. It started at the end of the Campanian followed by a second pulse during the Maastrichtian, a new finding not reported before. After subsidence during the Maastrichtian and Danian, renewed inversion and erosion occurred at the end of the Danian. Halokinesis processes resulted in thickness variations of chalk units of different ages.

In summary, variations in sedimentation patterns in the northern Dutch North Sea relate to the Sub-Hercynian inversion phase during the Campanian and Maastrichtian, the Laramide inversion phase at the end of the Danian, and halokinesis processes. Additionally, the Late Cretaceous sea floor was characterized by erosion through contour bottom currents at different scales and resedimentation by slope failures.

Keywords: Late Cretaceous, Early Palaeogene, chalk, seismic interpretation, reflection truncations, channel incision, slumps

1. Introduction

During the Late Cretaceous and earliest Palaeogene (100–61 Ma) the Chalk Group sediments were deposited in the North Sea Basin (Ziegler, 1990). After several rifting pulses during the Triassic and Jurassic, post-rift thermal relaxation occurred in the North Sea Basin, starting in the Early Cretaceous (Coward *et al.* 2003; De Jager, 2007; Herngreen & Wong, 2007). Subsidence, combined with an eustatic sea-level rise, caused a transgression in NW Europe. From the Cenomanian onwards (earliest Late Cretaceous), large amounts of coccolith skeletons accumulated at the sea floor, forming the Chalk Group sediments (Hancock, 1975; Kennedy, 1987*a*). Continental convergence at the end of the Danian (Early Palaeogene) ended the chalk deposition. The influx of erosional material into the oceans increased, leading to less clear water conditions. From this time onward, siliciclastic sediments replaced the accumulation of chalk (Ziegler, 1990).

Many known large hydrocarbon fields in the Danish and Norwegian North Sea are situated in chalk reservoirs, for instance the Ekofisk, Dan and Kraka oil fields (Megson, 1992; Bramwell *et al.* 1999; Megson & Hardman, 2001; Gautier & Klett, 2005; Megson & Tygesen, 2005). These findings attracted attention to the Chalk Group in the central North Sea area. However, the Chalk Group remained a poorly understood and possibly underestimated hydrocarbon play in the Netherlands. Relatively little is known on the Late Cretaceous to earliest Palaeogene tectonics and related stratigraphic records. Therefore, this study examines the geological evolution of the Chalk Group in the northern Dutch North Sea by integrating seismic and well data. The study area covers parts of the D, E, F and G quadrants in the Dutch North Sea (Fig. 1). It contains parts of five structural elements

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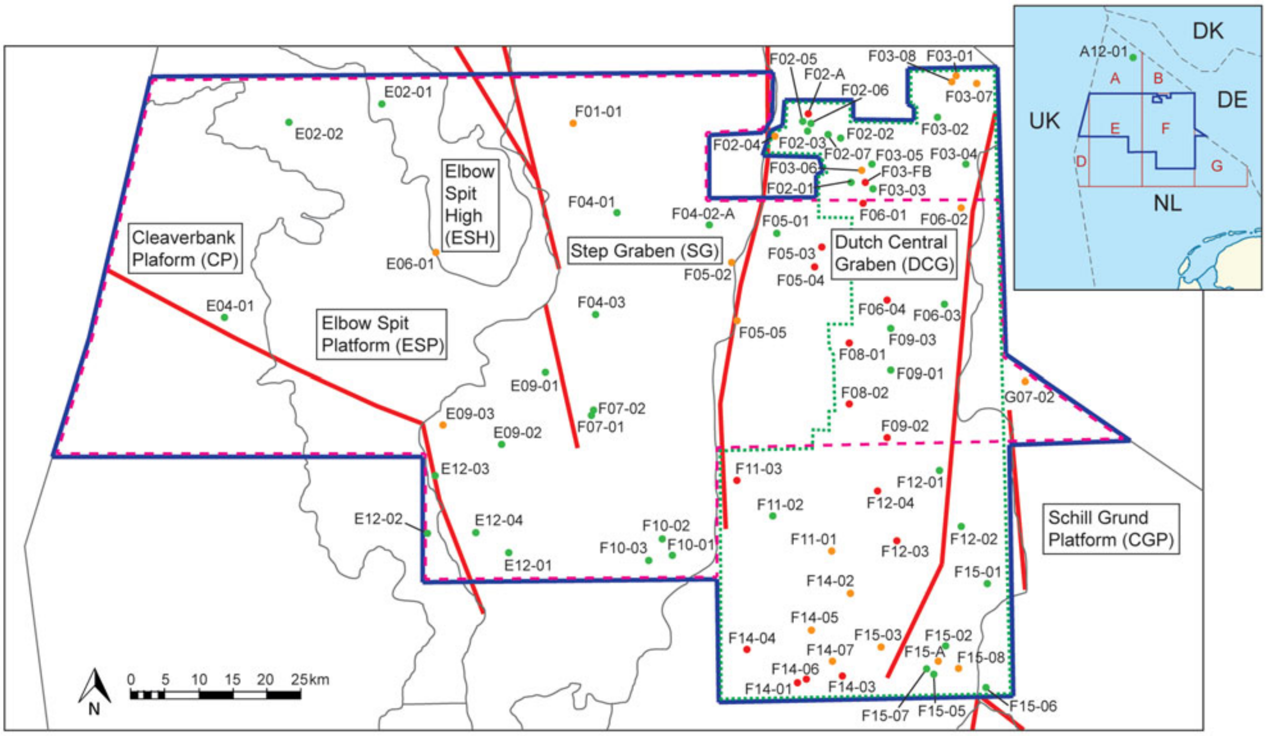

Figure 1. (Colour online) Location of the study area in the northern Dutch North Sea. The outline of the study area is indicated by the blue line and licence blocks are shown in the overview map in red. The names refer to the structural elements (after Kombrink *et al.* 2012), which are delineated by thin grey lines. The general Late Jurassic to Early Cretaceous fault framework identified by Kombrink *et al.* (2012) is shown as solid red lines. The wells that transected the Chalk Group are subdivided into groups with good (green), less good (orange) and poor (red) biostratigraphic information. Outline of the two seismic surveys: the DEF survey (dashed pink) and the Terracube Area 3 survey (dotted green).

characterizing the Mesozoic development: Cleaver Bank Platform, Elbow Spit High and Platform, Step Graben, Central Graben and Schill Grund Platform. All of these structural elements are approximately N–S oriented and are separated by faults and salt walls (Kombrink *et al.* 2012).

This seismic interpretation study re-evaluates geological events that influenced the stacking patterns and thickness variations of the Chalk sedimentary sequence in the Dutch North Sea.

2. Geological setting

The tectonic elements of the northern Dutch North Sea Basin consist of a range of sub-basins, platforms and highs that resulted from a series of tectonic phases of Palaeozoic to Palaeogene age (Kombrink *et al.* 2012). The above-mentioned structural elements are bounded by faults (Fig. 1) and salt structures. They characterized the morphology of the basin in the study area when the chalk deposition started.

During the Triassic, Pangaea started to break up. While the Southern Permian Basin was still subsiding, initial extensional faulting occurred in the Netherlands (Van Wijhe, 1987; Ziegler, 1990; De Jager, 2007).

In the middle Jurassic, the thermal Central North Sea Dome developed (Mid-Kimmerian phase) (Herngreen & Wong, 2007). This dome caused extensive uplift and erosion in the North Sea. During the Late Kimmerian Phase, major rifting took place and rift structures formed in the Southern North Sea; the Dutch Central Graben is one of them. Post-rift thermal relaxation combined with an eustatic sea-level rise caused the infill of the rift basins with Jurassic and Early Cretaceous sediments, overstepping the margins of the basins (Olsen, 1987; Ziegler, 1990; Herngreen & Wong, 2007). The transgression proceeded and at the end of the Early Cretaceous, large areas were flooded, which caused a reduced input of erosion material (Hancock, 1975; Ziegler, 1990). During that period the global sea level was *c.* 100–300 m higher than today. In the warm and clear seas of the wider Southern and Central North Sea area, large amounts of calcareous nannoplankton (coccoliths) were produced. The skeletons of these organisms accumulated on the sea floor, forming the Chalk Group sediments of Late Cretaceous to earliest Palaeogene age (Hancock, 1975; Hancock & Scholle, 1975).

During Oceanic Anoxic Events (OAEs) large amounts of organic material accumulated as a result of widespread anoxic conditions. One of these worldwide OAEs occurred at the Cenomanian to Turonian boundary, *c.* 93.5 million years ago (Schlanger & Jenkyns, 1976; Mort *et al.* 2007; Turgeon & Creaser, 2008). This episode is referred to as OAE2 and resulted in the deposition of the Plenus Marl Member. Turgeon & Creaser (2008) claim that OAE2 was triggered by a massive magmatic episode with the emplacement of

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large igneous provinces and/or development of mid-ocean ridges.

While Mesozoic times were dominated by rifting and sagging phases, compressional phases occurred during the Late Cretaceous and Palaeogene (Van Wijhe, 1987; Van der Molen, 2004; De Jager, 2007). During the deposition of the chalk, two important compressional phases occurred. The first phase is referred to as the 'Sub-Hercynian' phase, which started in the early Turonian and continued to the early Maastrichtian. The second phase took place during the middle Palaeocene (latest Danian and Selandian; Deckers, 2015), the so-called 'Laramide' pulse. During this phase, several Jurassic basins became inverted, while continental to shallow marine siliciclastics were deposited elsewhere (Deckers, 2015). In parts of the Dutch Central Graben, the entire chalk succession was eroded (Herngreen & Wong, 2007).

Continental convergence at the beginning of the Tertiary resulted in the influx of erosional material into the oceans, which terminated the chalk deposition and initiated widespread siliciclastic sedimentation (Ziegler, 1990).

3. Integrated stratigraphy of the North Sea

The Chalk Group in general has a very homogeneous lithology and is comprised of three formations in the northern Netherlands (Fig. 2): the Texel (Cenomanian), Ommelanden (Turonian to Maastrichtian) and Ekofisk formations (Danian) (Van Adrichem Boogaert & Kouwe, 1994; Van der Molen, 2004; Herngreen & Wong, 2007). In the Danish and Norwegian part of the North Sea, where the chalk is an important reservoir for hydrocarbon production, a more detailed subdivision is used (references below and Fig. 2).

Recently, a series of studies have been carried out on redefining the subdivision of the Chalk Group, not only in Norway and Denmark, but also in the United Kingdom, Germany and the Netherlands (references below and Fig. 2). These studies identified different units, mostly based on biostratigraphic and seismic data, which are summarized in Figure 2. Many subdivisions correlate to the chronostratigraphic stages (Cenomanian to Danian).

3.a. Denmark (columns 6 to 11 in Fig. 2)

Multiple seismic studies were carried out on the Chalk Group in Denmark. Subdivisions of seismic units were made by Kristensen *et al.* (1995) in the Dan Field, by Esmerode, Lykke-Andersen & Surlyk (2008) in the southern Danish Central Graben, by Klinkby *et al.* (2005) and Back *et al.* (2011) in the Danish Central Graben and by Larsen, Ineson & Boldreel, (2014) in SW Denmark. The unconformity best recognized on seismic in the Danish sector of the North Sea is likely of intra-Campanian age (Megson & Tygesen, 2005) and most likely comparable to the Late Campanian unconformity in the United Kingdom (Errat *et al.* 1999). Van Buchem *et al.* (2017) proposed the first formal lithostratigraphic subdivision of the Chalk Group in the Danish Central Graben, introducing two new formations: Kraka and Gorm.

3.b. Norway (columns 12 to 15 in Fig. 2)

The Shetland Group comprises the Cenomanian to Danian chalk deposits in the northern North Sea and is traditionally subdivided into five lithostratigraphic formations (Deegan & Scull, 1977; Surlyk *et al.* 2003): Ekofisk, Tor, Hod, Blod¢ks (which correlates to the Dutch Plenus Marl Member) and Hidra. Another subdivision of the chalk was proposed by Fritsen (1999) for the North Sea Eldfisk field and was based on the presence of four unconformities. Subdivisions of the Norwegian chalk based on seismic data, linked to litho- and biostratigraphic data, were made by Bramwell *et al.* (1999) for the Greater Ekofisk area and by Gennaro *et al.* (2013) for the southern Norwegian sector of the North Sea.

3.c. The United Kingdom (column 16 in Fig. 2)

Mortimore (2010) published a very detailed stratigraphic description and subdivision of the Late Cretaceous in England, based on biostratigraphic and wireline log data. He also compared the stratigraphy to global sea-level data and tectonic events, but did not use any seismic data.

3.d. Germany (column 17 in Fig. 2)

Surlyk, Jensen & Engkilde (2008) subdivided the Chalk Group of the German North Sea into eight seismostratigraphic sequences, based on mapping onlapping, downlapping and truncated reflectors.

4. Methodology

4.a. Seismic reflection data

Parts of two 3D seismic surveys were studied, namely the DEF survey and the Terracube Area 3 survey. The DEF survey (acquired in 2012) is a survey of *c.* 150 by 80 km, located in the D-, E- and F-blocks of the Dutch North Sea, and includes a small part of the G-block (Fig. 1). The second 3D seismic cube is called Terracube Area 3 (2011) and covers the F- and G-blocks of the study area (Fig. 1). The part of this cube that was used for this study is *c.* 100 by 70 km and partly overlaps with the DEF survey. Only seismic data between *c.* 1 and 3 s two-way travel time (TWT) were used. The Petrel software (Schlumberger) was used for the seismic interpretation. An increase in acoustic impedance results in a positive seismic response (peak) and a blue loop (polarity standard of the Society of Exploration Geophysicists; SEG). The average resolution of the seismic data on the chalk level is *c.* 16–20 m.

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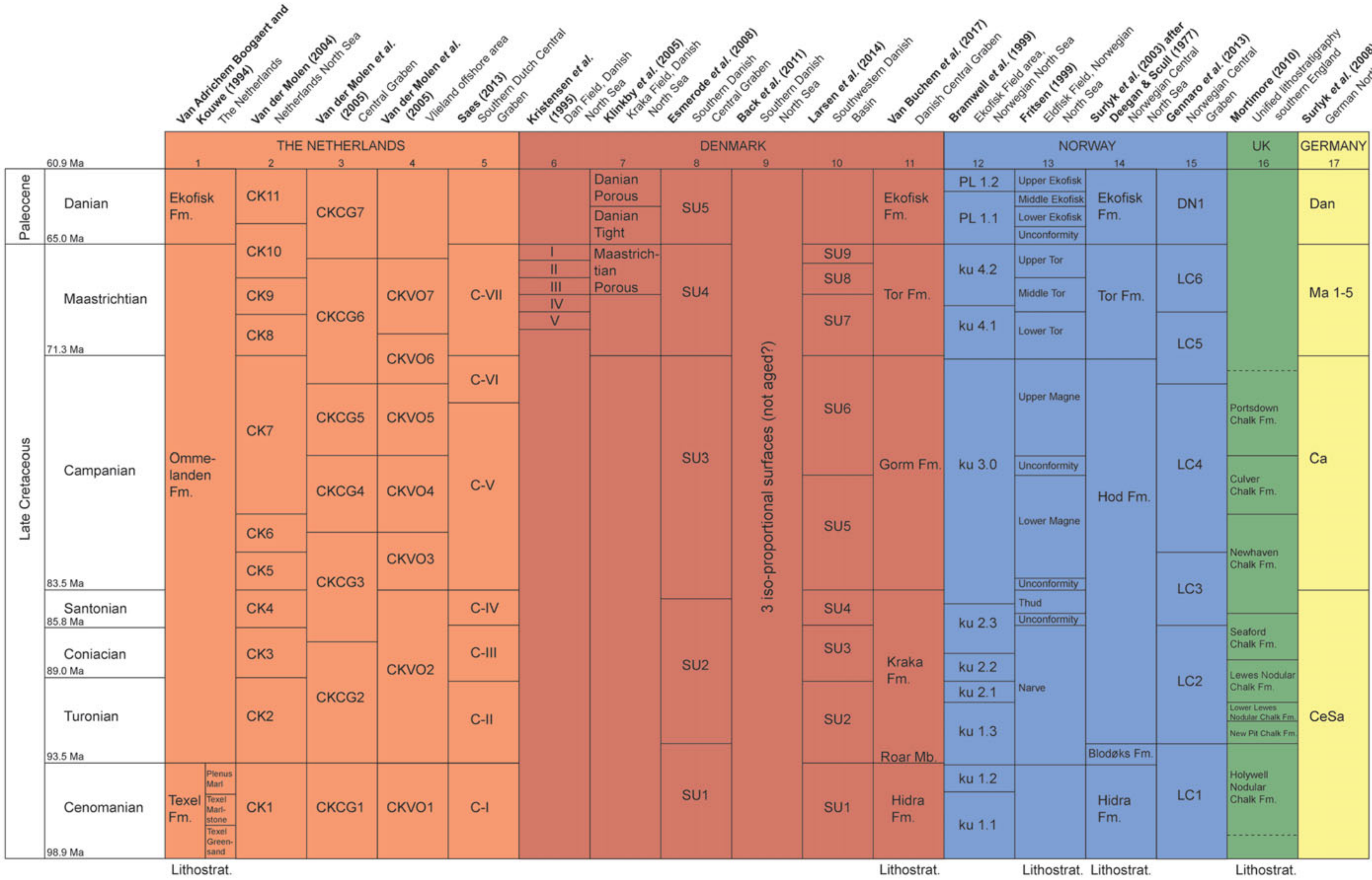

Figure 2. (Colour online) Comparison of the multiple biostratigraphic and/or seismic subdivisions of the North Sea Chalk in the Netherlands, Denmark, Norway, the United Kingdom and Germany. Four of the subdivisions are based on lithostratigraphy (as indicated on the previous page).

4.b. Well data

In the study area, 82 wells are present which contain at least some lithostratigraphic and/or biostratigraphic information on the Chalk Group. Well logs were available for almost all of these wells (see NLOG database, www.nlog.nl). An internal report of Wintershall Noordzee (WINZ) (J. P. G. Fenton *et al.* 2014) provided additional biostratigraphic information on 11 wells.

All wells contain at least two lithostratigraphic tops (i.e. the top of the underlying formation at the location of the well). The mapped lithostratigraphic tops are based on the subdivision of the chalk by Van Adrichem Boogaert & Kouwe (1994), being: Top Chalk, Top Ekofisk Formation, Top Ommelanden Formation, Top Plenus Marl Member, Top Texel Formation and Base Chalk (Fig. 2).

Subsequently, chronostratigraphic 'tops' of the Cenomanian, Turonian, Coniacian, Santonian, Campanian, Maastrichtian and Danian were deduced from biostratigraphic data. For several wells, exact depths of these horizons are unavailable, but ranges are reported. When this uncertainty applied, the mid value of the range was used as the 'top' and a lower confidence level was assigned to this data point. Each top was evaluated with one of the three confidence levels, one being a top that is located no more than 10 m higher or lower than the depth that is given to it; two or three could be 50 and 100 m higher or lower, respectively.

Only the density, gamma-ray and sonic logs were used for this study. To correlate possible lithological changes or erosional events with the seismic response, both the density and gamma-ray logs were studied as an extra indication for the location of these transitions.

Time–depth relations were used for the well-to-seismic match to correlate reflections to the tops of the units. For wells without checkshot or Vertical Seismic Profile (VSP) data, the sonic log was the most important source of time–depth information. The easily recognizable top and base of the Chalk Group itself were also used to tie the wells to the seismic. The TWT and the depth of the top and the base of the chalk were extracted from the seismic and the well tops. The sonic log was used for time–depth conversion within the chalk.

4.c. Seismic interpretation

The aim of the seismic interpretation was to identify the distribution and thickness variations of the sedimentary sequences within the Chalk Group and to determine the age of unconformities that link to geological events. To achieve this, the seven chronostratigraphic tops of Van Adrichem Boogaert & Kouwe (1994) were interpreted throughout the study area (Fig. 2). These horizons were chosen because of their relatively good biostratigraphic well ties and regional correlation. Furthermore, the mapped seismic horizons could also help improve the time–depth conversion within the chalk in order to predict the depth of certain formations.

Flattening of an under- or overlying surface was used for interpretation purposes. Tuning occurrences were interpreted as an indication of the vicinity of a reflection termination. Several seismic attributes were extracted at different surfaces, for instance Root Mean Square Amplitude and Average Negative Amplitude to reveal thickness variations of seismic units. Anomalies on these attribute maps were compared to the seismic. If the anomaly was caused by tuning, it was used to define the boundaries of an interpreted horizon. In other cases, the anomalies were assigned to a lithology change. The interpreted horizons were used to produce thickness maps of the seismic units (Fig. 3).

5. Results of seismic interpretation

The seismic characteristics of the seven interpreted horizons are described in Figure 4. The seismic facies were also analysed in detail, resulting in a subdivision of 17 sub-units (Fig. 5). The seismic character of the Cleaverbank Platform chalk differs significantly from the other structural elements, showing very continuous and parallel reflections.

Figure 3 shows the thickness maps of the units that could be interpreted throughout the study area. Due to limited biostratigraphic information on the Coniacian and Santonian, unit 3 shows the combined thickness of the Coniacian, Santonian and Campanian. The Chalk Group is the thickest on the Schill Grund Platform and absent in a few parts of the Dutch Central Graben. At the western and eastern boundaries of the Step Graben, close to the salt walls that form the boundaries of the Step Graben, the Chalk Group is thicker than in the centre.

The Cenomanian unit is generally very thin, mostly only one reflection, and onlaps onto pre-chalk deposits at the Elbow Spit High. The Turonian sequence is thickest in the SW and becomes gradually thinner towards the NE, with an exception at the boundary between the Elbow Spit Platform and Step Graben (Figs 3 and 6). Similar to the Cenomanian, Turonian deposits onlap onto a part of the Elbow Spit High. Turonian reflections are truncated by Campanian/Maastrichtian reflections in the central Step Graben. Coniacian and Santonian deposits could only be interpreted in a relatively small part of the study area, due to limited biostratigraphic well control. However, the Coniacian and Santonian are interpreted to be absent or thinner than the seismic resolution (16–20 m) at the Cleaverbank Platform (Fig. 7). In the Chalk Group of the Elbow Spit Platform, the Step Graben and the Dutch Central Graben, clear reflection truncations were recognized within the chalk. In the Step Graben (Fig. 8) and western Dutch Central Graben (Fig. 9) truncations occur below and within the Campanian chalk. At the Elbow Spit Platform (Fig. 10) and in the eastern Dutch Central Graben

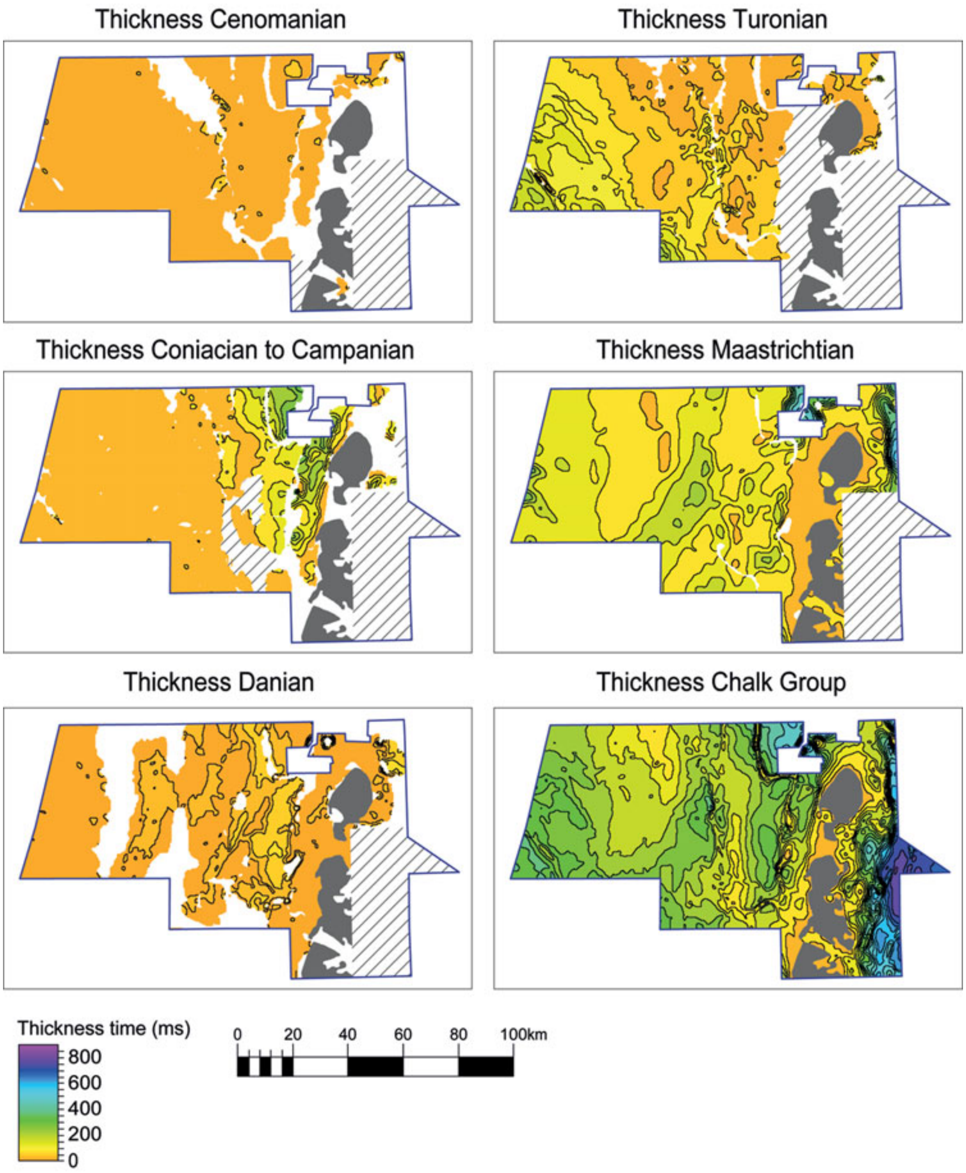

Figure 3. (Colour online) Thickness maps of five (combinations of) units and the complete Chalk Group, measured in two-way travel time (TWT; ms). No thickness maps were created for the separate Coniacian unit and Santonian unit because the areal extent of these units is very limited. The Chalk Group is absent in the grey areas, and the grey striped areas indicate where no reliable thicknesses could be interpreted. The particular units are absent in the white areas.

(Fig. 11), truncations are present below and within the Maastrichtian chalk. The Maastrichtian is generally the thickest unit of the Chalk Group in the study area. In contrast, the Danian unit is very thin, mostly only one reflection. Distinct reflection terminations are also visible in the upper part of the Chalk Group below the Palaeogene clastics (Fig. 12). In many parts of the study area, the Danian reflection is truncated at the top of the chalk. On parts of the Cleaverbank Platform and Elbow Spit Platform, the Danian is absent and even upper Maastrichtian reflections are truncated.

Besides thickness variations, smaller-scale structures such as incision features are also recognized in the study area at different scales. Relatively small structures are *c.* 300 m wide and are present in the Dutch Central Graben as well as on the Elbow Spit High (Fig. 13a). Larger incision features were found mainly in the Dutch Central Graben, for instance in the F2 block (Fig. 13b). The variance attribute map (Fig. 13c) visualizes these structures, which are oriented parallel to the contours of the slope and are up to 1200 m wide. The features are sinuous and V-shaped or W-shaped and seem to be mostly present in Maastrichtian and Danian sequences but were also recognized in older structures. In a zone of *c.* 2–10 km width, stretching from north to south to southwest along the central part of the Step Graben, the Danian thickness shows a clear positive anomaly with respect to the rest of the study area. Well F04-03 is located in the middle of this feature and contains a Danian sequence of *c.* 90 m thick (Figs 8 and 14). Another relatively thick Danian sequence is located in a N–S-trending zone of *c.* 10 km wide on the Elbow

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Horizon	Extent	Reflection phase	Reflection continuity	Reflection amplitude	Depth range (time)
Top Danian	Entire study area except E-CP, W-ESP, ESH, small part of SG, large parts of DCG and on and around salt structures	Blue (positive, peak)	Very continuous	High to very high amplitude	1000-2200 ms
Top Maastrichtian	Entire study area except large parts of DCG and on and around salt structures	Red (negative, trough)	Continuous	Low to very high amplitude (tuning effect)	1100-1700 ms
Top Campanian	Entire study area except part of ESH, S-SG, M-DCG and on and around salt structures	Red (negative, trough)	Not very continuous, especially in SG and ESP/ESH	Low to medium amplitude	1200-1800 ms
Top Santonian	Parts of DCG and SGP, rest unknown due to limited biostratigraphic information	Red (negative, trough)	Not continuous	Low to medium amplitude	1800-2200 ms
Top Coniacian	Parts of DCG and SGP, rest unknown due to limited biostratigraphic information	Blue (positive, peak)	Not continuous	Low to medium amplitude	1800-2200 ms
Top Turonian	Parts of DCG and SGP, rest unknown due to limited biostratigraphic information	Blue (positive, peak)	Rather continuous	Mostly low, locally up to high	1100-1700 ms
Top Cenomanian	Entire study area except parts of ESP, large parts of DCG and on and around salt structures	Red (negative, trough)	Continuous	Varying low to high amplitude	1200-2200 ms
Base Chalk Group	Entire study area	Red (negative, trough)	Very continuous	High to very high amplitude	1300-2300 ms

Figure 4. (Colour online) Seismic reflectivity characteristics of the interpreted horizons and their extent and depth range (ms) throughout the study area.

Spit Platform. Unfortunately, no wells have been drilled in this particular feature. The thickness map of the Danian clearly shows these anomalies (Figs. 3 and 14).

Complexes of chaotic and distorted reflections were found in many parts of the Dutch Central Graben. Two examples of such chaotic and distorted reflection features are shown in Figure 15. Such complexes are up to 7 km in length along the axis of displacement.

6. Discussion of intra-chalk geological events

Based on the seismic interpretation, a series of intra-chalk events were discovered in the study area.

6.a. Turonian tilting

The gradual thickening of the Turonian deposits towards the SW is interpreted as the result of tilting during the Turonian. The SW part of the Cleaverbank Platform subsided with respect to the NE part. Van der Molen (2004) proposed a sea-level rise during the Turonian that could have caused the thick Turonian sequence in the western part of the study area, but did not discuss a tilting or subsidence process that could explain the thickness differences observed in this study.

6.b. Halokinesis

During the deposition of the Chalk Group, local subsidence mainly resulted from halokinesis processes related to the Zechstein salt (Remmelts, 1996; Ten Veen, Van Gessel & Den Dulk, 2012; Van Winden *et al.* 2018). The salt diapirs and walls are located mainly in the Step Graben and Dutch Central Graben. During the development of these structures, salt was removed from the adjacent areas, which led to local subsidence at those positions. Accommodation space in these rim synclines was filled up with sediments, resulting in a thicker sequence (Ten Veen, Van Gessel & Den Dulk, 2012; Van Winden *et al.* 2018). At the western and eastern boundaries of the Step Graben, the Chalk Group is thicker than in the centre (Fig. 8). This is mainly the result of Campanian inversion and erosion (see discussion below), but the effect was possibly strengthened by rim synclines of the salt structures. Halokinesis also resulted in erosion of the chalk on top of the salt diapirs (Ten Veen, Van Gessel & Den Dulk, 2012; Van Winden *et al.* 2018).

In the SW Cleaverbank Platform, a major salt wall is present. Salt activity started here during the late Turonian, creating onlap structures onto a local high (Fig. 7). This salt wall continued growing until the earliest Maastrichtian.

6.c. Coniacian–Santonian uplift of the Cleaverbank platform

The absence of Coniacian and Santonian deposits on the Cleaverbank Platform (Figs. 6 and 7) probably resulted from non-deposition, caused by tectonic

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Stage	Unit	Location seismic facies	Reflection configuration	Reflection continuity	Reflection amplitude and frequency	Lateral relationships	Depth range (time)	Image
7: DANIAN	(a)	CP, ESP/ESH, SG, DCG and SGP	Only 1 reflection thick, see description Top Danian	Very continuous	High amplitude	In SG merges into (b) and if absent, truncated by Top Chalk	1000-2200 ms	
	(b)	Parts of SG and ESP	Maximum 3 reflections thick, parallel	Very continuous to not very continuous due to thin unit	Low to high amplitude, medium frequency	In west and east merges into (a)	1600-1900 ms	
6: MAASTRICHTIAN	(c)	Western CP and western ESP/ESH	Parallel, folded reflections	Very continuous	Medium amplitude, medium frequency	In east truncated by Top Chalk	1100-1700 ms	
	(d)	Eastern CP, eastern ESP/ESH and SG	Not parallel, onlap structures, bifurcations and merging refl.	Alternation of continuous and non-continuous	High amplitude, medium frequency	In west truncated by Top Chalk, in east bounded by salt	1600-1900 ms	
	(e)	DCG and SGP	Upper part parallel, lower part also truncated refl. in DCG (transparent)	Alternation of continuous and non-continuous	Low amplitude, transparent, medium to high frequency	In west bounded by salt, in center DCG truncated by Top Chalk	1500-2000 ms	
5: CAMPANIAN	(f)	CP and western ESP/ESH	Only 1 or 3 ref. thick, see description Top Campanian	Very continuous	Medium amplitude	In east merges into (g)	1200-1800 ms	
	(g)	Eastern ESP/ESH and western SG	Not parallel, many onlap structures and also truncations	Non-continuous	Alternation of low and high amplitudes, low to medium frequency	In west merges into (f), in east merges into (h)	1600-1800 ms	
	(h)	Eastern SG and western DCG	Rather parallel, locally chaotic seismic response in lower part	Rather continuous, lower part non-continuous	Low to medium amplitude, low to medium frequency	In west merges into (g), in east truncated by Top Chalk	1800-2300 ms	
	(i)	SGP	Parallel, folded at many locations	Rather continuous, also truncated reflections	Medium amplitude, medium to high frequency	In west bounded by salt	1700-2100 ms	
4: SANTONIAN	(j)	Western SG and northwestern DCG	Only 1 refl. thick, see description Top Santonian	Rather continuous	Low amplitude	In west bounded by salt, in east truncated by Campanian (h)	1800-2200 ms	
	(k)	Eastern SG, SGP and eastern DCG	Mostly parallel, some onlap structures	Rather continuous	Medium to high amplitude, medium frequency	In west bounded by salt	1900-2100 ms	
3: CONIACIAN	(l)	Eastern SG, western DCG and south-eastern DCG	Rather parallel, some onlap structures	Not very continuous	Alternation of low and high amplitudes, medium to high frequency	In west onlap onto Turonian, in center disrupted by salt, in east onlap onto pre-chalk	1800-2200 ms	
2: TURONIAN	(m)	CP	Parallel reflections	Very continuous	Medium to high amplitude, high frequency	In west partly bounded by salt, in east merges into (n)	1100-1700 ms	
	(n)	ESP/ESH and western SG	Mostly parallel, some onlap structures	Very continuous	High amplitude, medium frequency	In west merges into (m), in east merges into (o)	1800-2000 ms	
	(o)	Eastern SG and SGP	Only 2 or 4 reflections thick	Rather continuous	High amplitude, medium frequency	In west mergesinto (n), towards DCG onlap onto Cenomanian (p)	1800-2000 ms	
1: CENOMANIAN	(p)	CP, ESP, SG, western DCG and SGP	Only 1 reflection thick, see description Top Cenomanian	Very continuous	Low to high amplitude	Locally disrupted by salt, in ESH onlap onto Base Chalk, in center DCG onlap onto pre-chalk	1200-2200 ms	
	(q)	Southeastern DCG	Parallel reflections	Rather continuous	Low to medium amplitude, medium to high frequency	In west bounded by salt	1700-2300 ms	

Figure 5. (Colour online) Seismic facies subdivision of the seven chronostratigraphic units with their locations in the study area, lateral relationships, reflection characteristics and depth range (ms). Each seismic facies is illustrated with an image from the study area.

uplift of the Cleaverbank Platform from Coniacian time onwards. The alternative explanation of uplift during the Campanian and erosion of Coniacian to Santonian deposits seems less likely in the absence of evidence of erosion in seismic and well data.

Van der Molen (2004) stated that at least the southern Cleaverbank Platform (K-quadrant, outside the study area) subsided rapidly during Coniacian to Campanian times and that the entire Cleaverbank Platform was tilted south-southeastwards during the early

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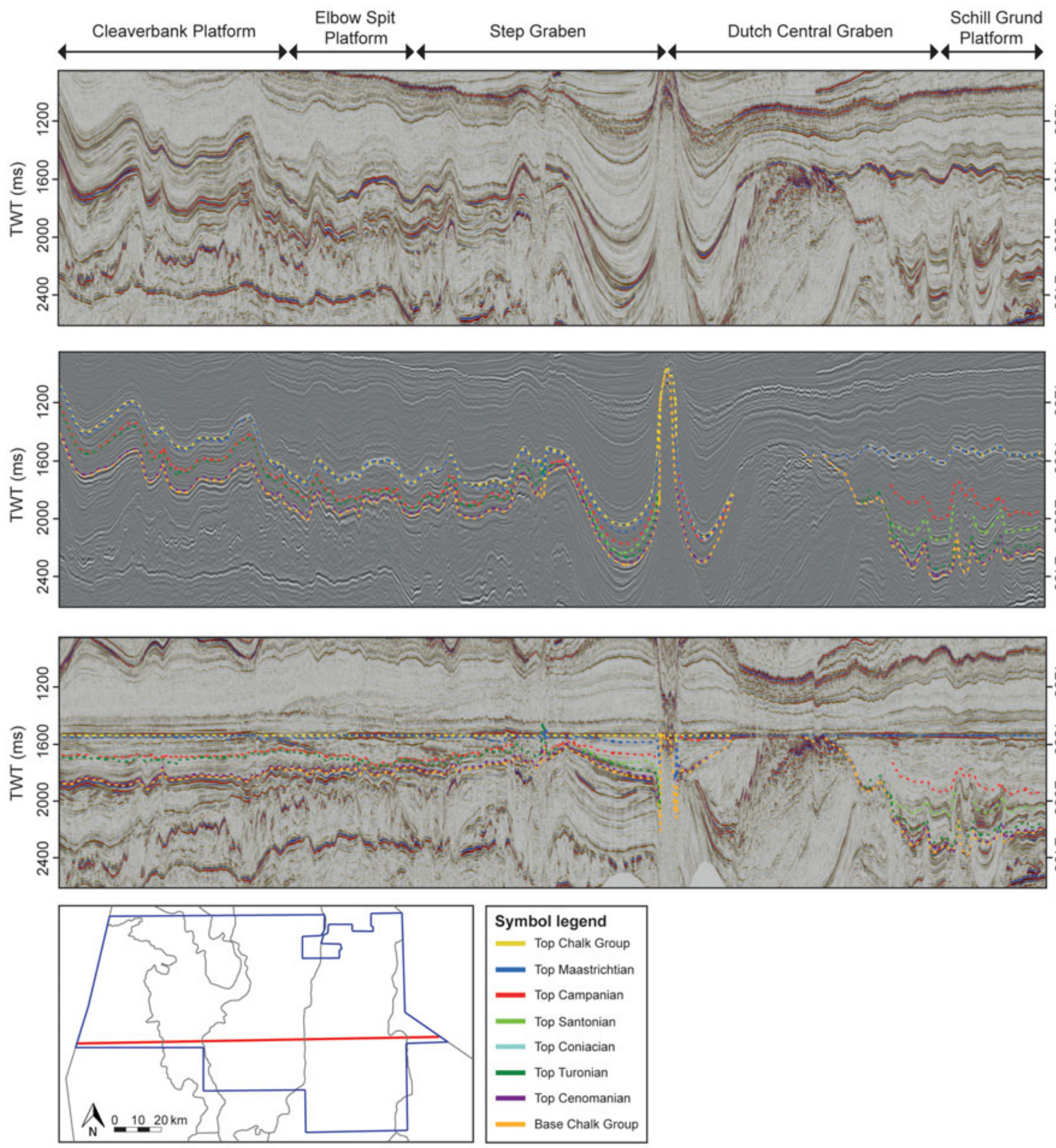

Figure 6. (Colour online) W–E seismic section through the middle part of the study area: without interpretations (above), with dotted lines as interpretations of the unit tops (middle) and flattened on the Top Chalk (below). The location of the section is indicated by the red line on the map. Where the interpretation of a unit is not presented, the unit is either absent or not possible to interpret due to a lack of biostratigraphic well control or due to barriers such as salt diapirs. The arrangement of the different structural elements and their seismic characteristics are visible, as well as the presence of salt structures and general interpretations of the seismic units.

Campanian. Uplift in the NW section (which is located in the study area) could have caused erosion. However, Campanian and post-Campanian deposits lie conformably on top of the Turonian, while onlap structures on the early Campanian are expected in case of early Campanian tilting.

Van Hoorn (1987) studied the structural evolution of the Sole Pit High in the British part of the Southern North Sea, located *c.* 50 km SW of the Cleaverbank Platform. Van Hoorn (1987) dated the first inversion in this area as intra-Turonian. This inversion led to thinning and onlap of Turonian–early Campanian deposits onto the Sole Pit High. A similar tectonic evolution could explain the missing Coniacian–Campanian on the Cleaverbank Platform. However, no onlap features on the Cleaverbank Platform were present in the study area. It is therefore concluded that the Cleaverbank Platform in the study area showed uniform uplift during Coniacian–Campanian times.

6.d. The Sub-Hercynian inversion phase

Clear reflection truncations were recognized below and within the Campanian (Step Graben and western Dutch Central Graben), and below and within the Maastrichtian (Elbow Spit Platform and eastern Dutch Central Graben). These unconformities indicate that the earlier tectonic stability ended during the

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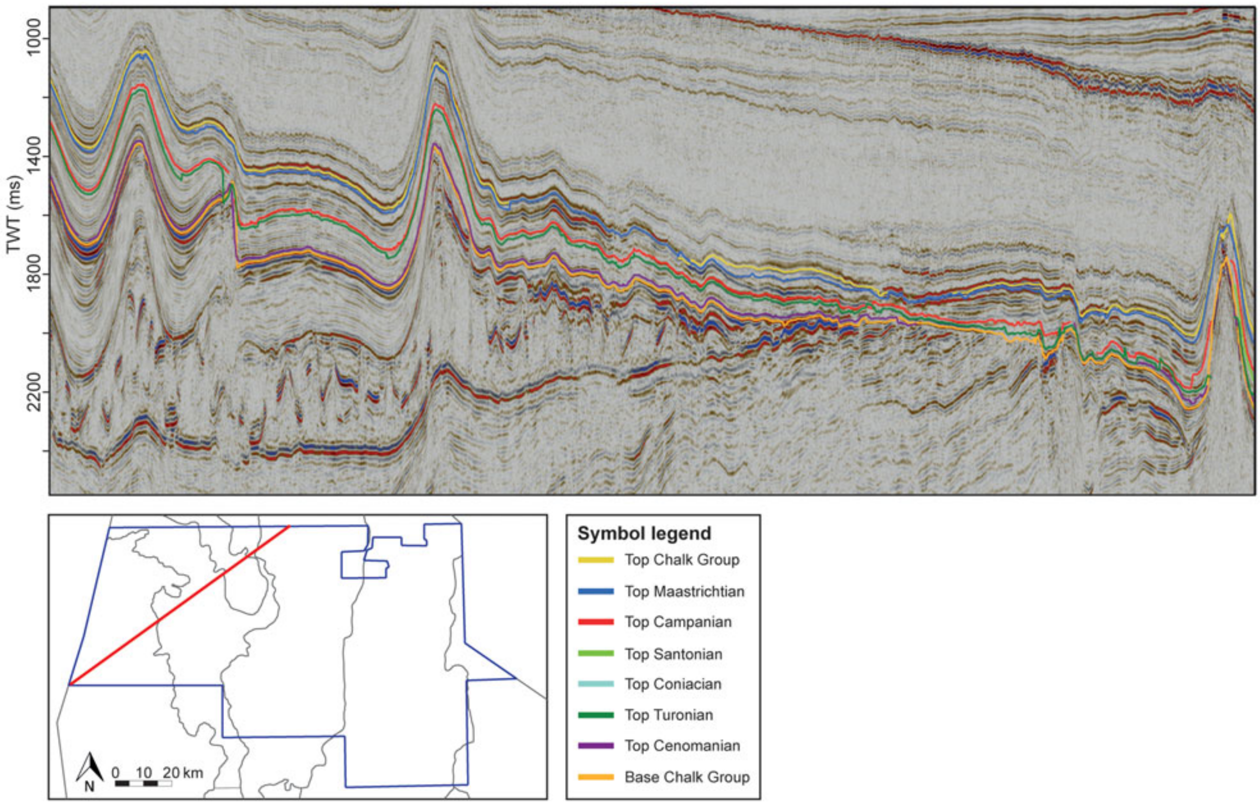

Figure 7. (Colour online) SW–NE section through the Cleaverbank Platform, the Elbow Spit Platform and Elbow Spit High and a small part of the Step Graben. The red line on the map indicates the location of the section in the study area. A salt wall is visible at the SW part of the section, at the Cleaverblank Platform, with Turonian reflections onlapping to this local high. Coniacian to Santonian deposits are absent on the Cleaverbank Platform and parts of the Elbow Spit Platform.

Campanian. A significant uplift and erosion phase occurred in two pulses during late Campanian and Maastrichtian times in most parts of the study area, except on the Cleaverbank Platform and the Schill Grund Platform, where no evidence of erosion was found. The uplift started at the end of the Campanian in the Step Graben (Fig. 8) and western Dutch Central Graben (Fig. 9). The uplift of the Elbow Spit Platform (Fig. 10) and eastern Dutch Central Graben (Fig. 11) occurred later, during the Maastrichtian.

Van der Molen (2004) discussed a large uplift and erosion phase in the same area and proposed that the Campanian/Maastrichtian uplift phase did not affect the Cleaverbank Platform and the Schill Grund Platform in the study area. He stated that most of the Dutch North Sea area was uplifted at the end of the Campanian and that uplift continued during the Maastrichtian in the Central Graben, Step Graben and Elbow Spit Platform. This only partly agrees with the interpretations of this study, since the eastern Dutch Central Graben and Elbow Spit Platform appeared to be affected during Maastrichtian times. However, in the western Dutch Central Graben, the erosional surface coincides clearly with the top of the Campanian, which indicates that uplift within that part of the basin did not continue into the Maastrichtian.

A widely recognizable regional unconformity in the southeastern part of the study area was identified by M. Huijgen (unpub. M.Sc. thesis, Vrije Universiteit, Amsterdam, 2014). It comprises parts of the Step Graben, Dutch Central Graben and Schill Grund Platform. Huijgen interpreted the erosive unconformity to be of late Campanian age, which slightly differs from the interpretation proposed in this study which is based on a more extensive analysis of the biostratigraphic data of a higher number of wells.

A large erosive unconformity of late Campanian age, similar to the one in the western Dutch Central Graben of the study area, was determined by M. Saes (unpub. M.Sc. thesis, Utrecht Univ., 2013) in the southern part of the Dutch Central Graben, *c.* 50 km south of the area of this study.

According to De Jager (2007), inversion in the Dutch Central Graben started at the onset of chalk deposition and peaked during the Late Campanian, creating post-Campanian onlapping unconformities. This means that uplift did not continue during the Maastrichtian, which contrasts with the results of this study supported by new and detailed seismic data.

A widespread erosional unconformity was not only recognized in the Dutch North Sea but also in Germany, Denmark, Norway and the United Kingdom. Anderskouv & Surlyk (2011) found evidence of

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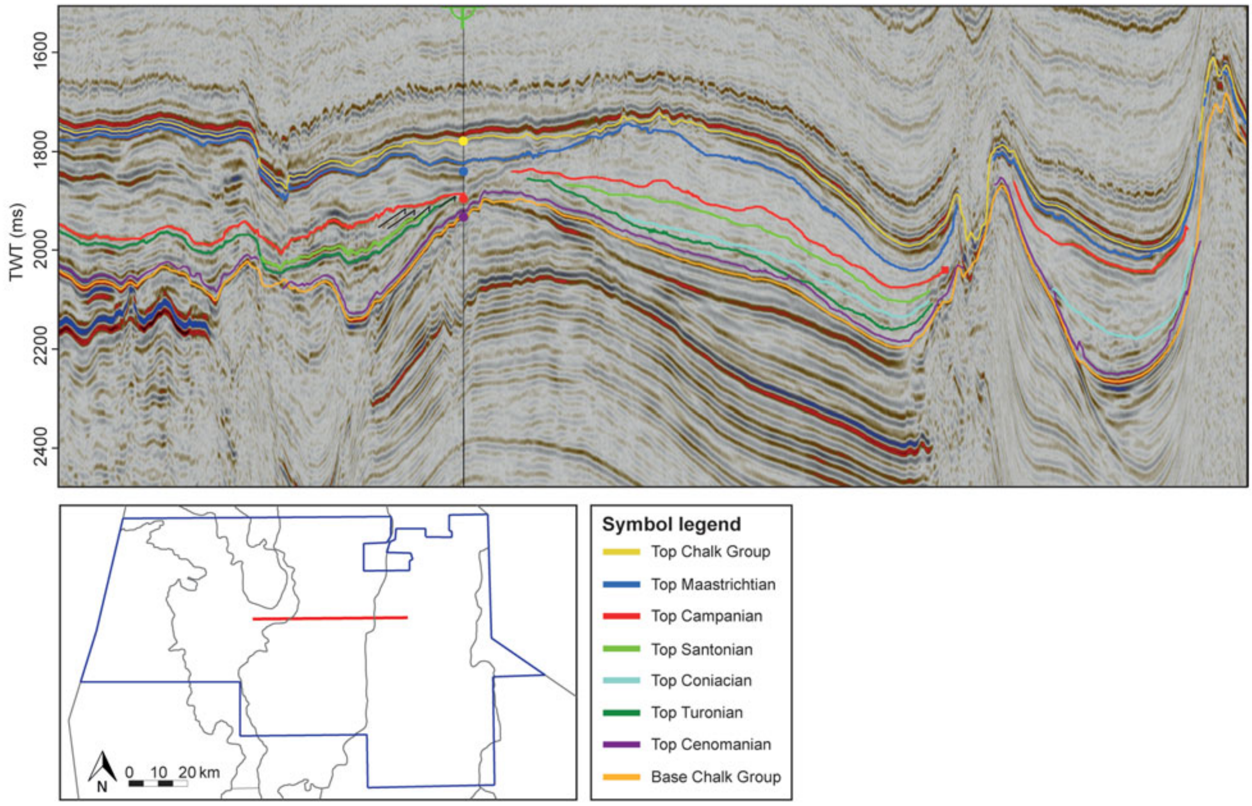

Figure 8. (Colour online) W–E section through the central part of the Step Graben with the interpreted units. The red line on the map indicates the location of the section in the study area. The visible well is F04-03. The black arrows show truncations below the top of the Campanian, which indicate that inversion occurred during the late Campanian.

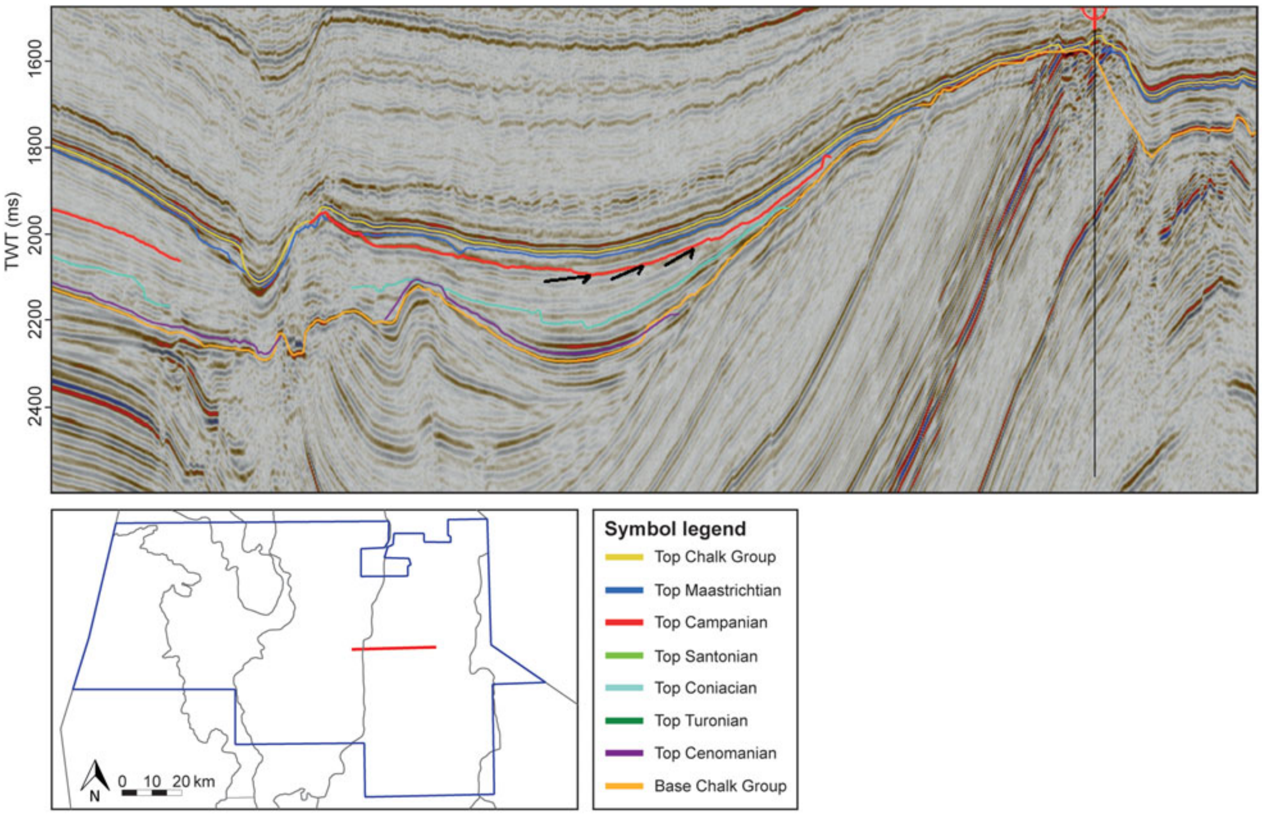

Figure 9. (Colour online) W–E section through the western Dutch Central Graben, with black arrows indicating reflection truncations that show the Campanian erosion due to inversion. The red line on the map indicates the location of the section in the study area.

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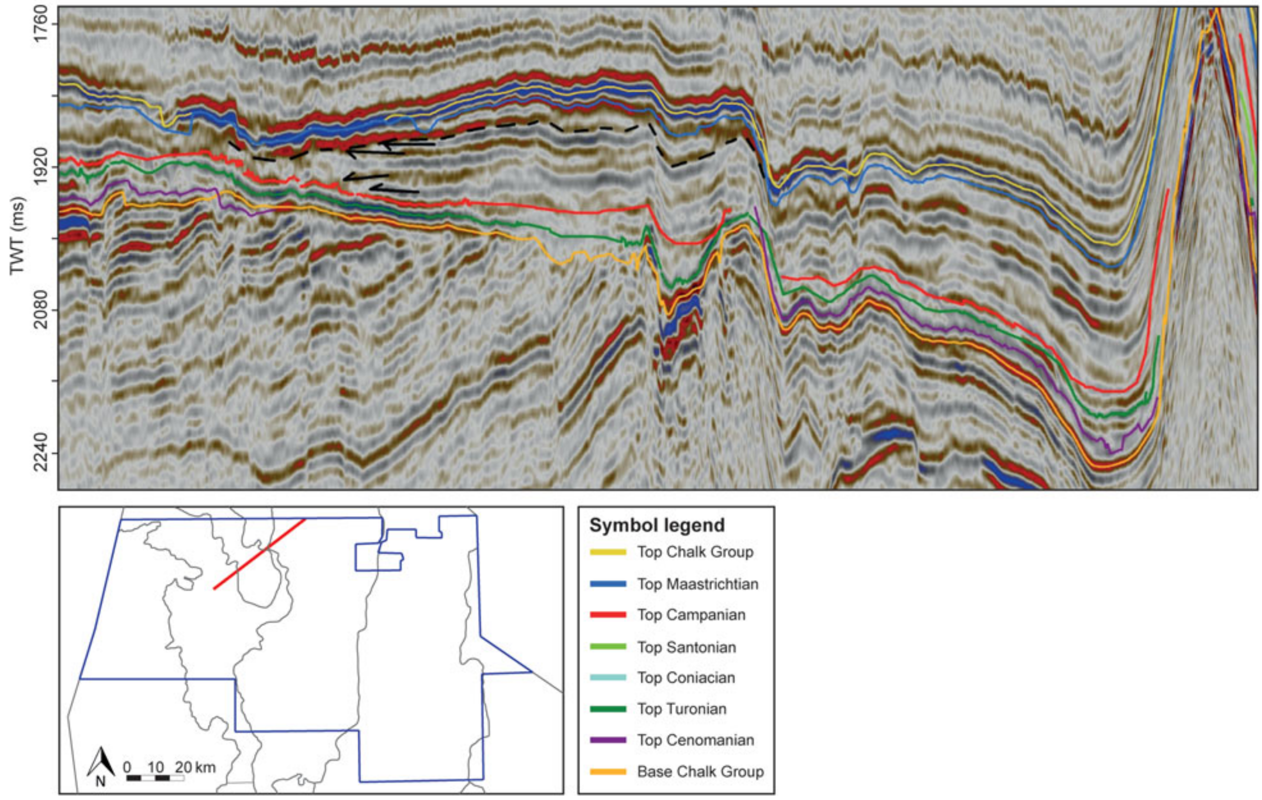

Figure 10. (Colour online) Zoom-in on the SW–NE section of Figure 7 through the Elbow Spit Platform and Elbow Spit High. Reflection terminations are illustrated with black arrows and indicate Maastrichtian onlap and truncations, of which the latter is evidence of erosion due to Maastrichtian inversion. The red line on the map indicates the location of the section in the study area.

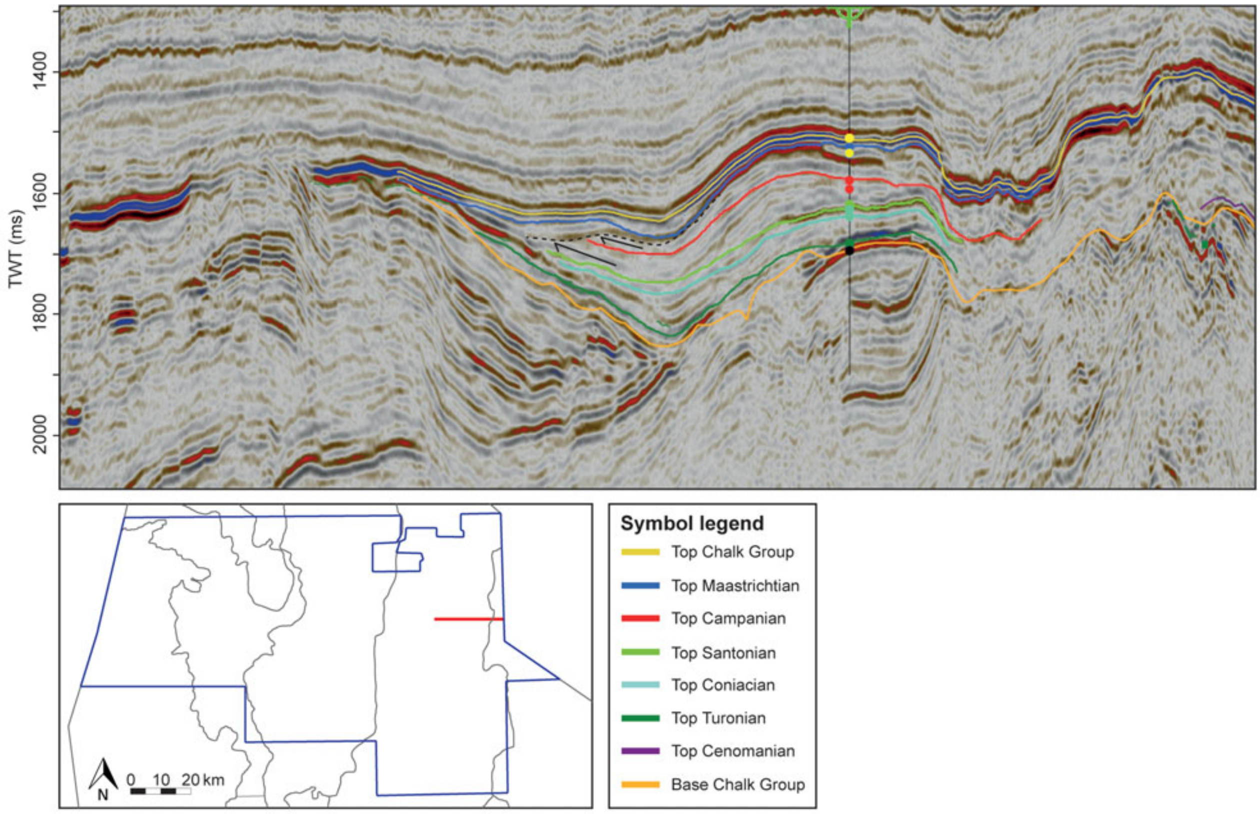

Figure 11. (Colour online) W–E section through the eastern Dutch Central Graben. The visible well is F06-03. The black arrows illustrate reflection truncations that indicate erosion due to uplift of the Maastrichtian inversion phase. The red line on the map indicates the location of the section in the study area.

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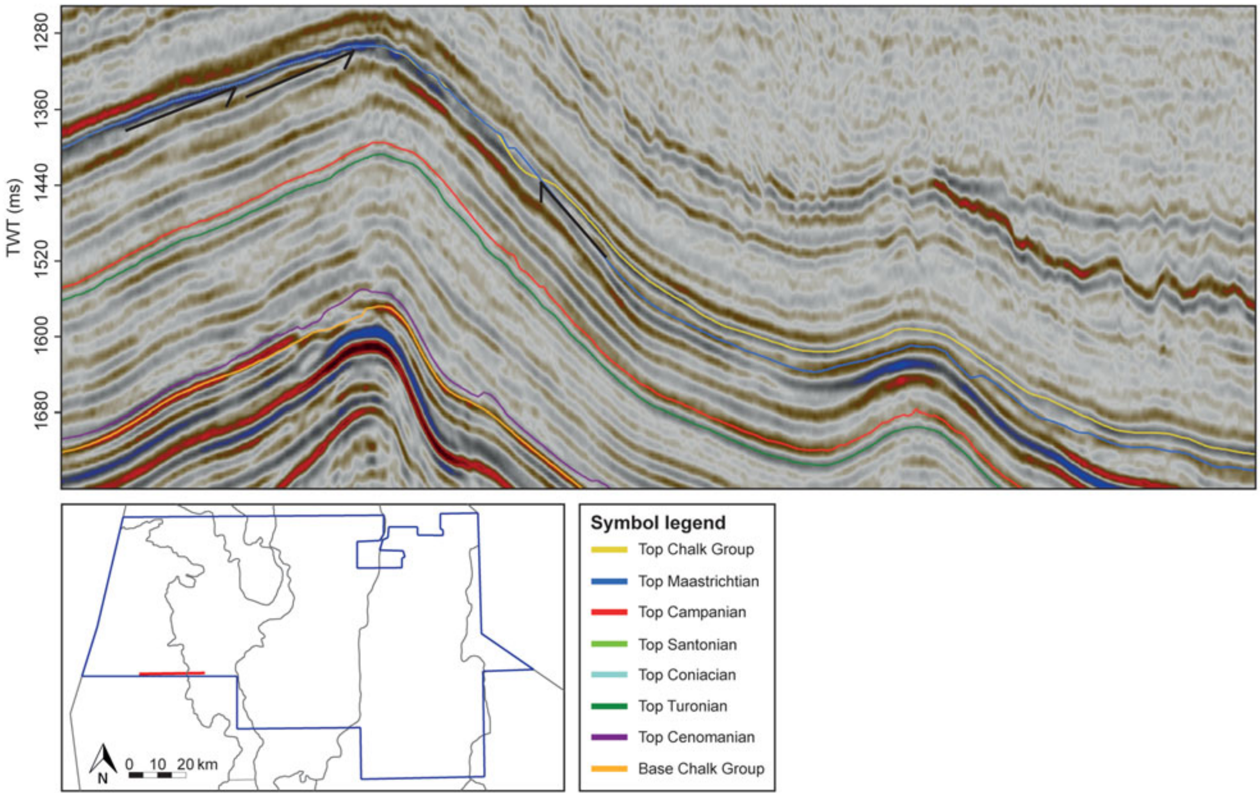

Figure 12. (Colour online) W–E section in the SE part of the Cleaverbank Platform. The black arrows illustrate reflection truncations that indicate erosion due to uplift of the Danian inversion phase. The red line on the map indicates the location of the section in the study area.

erosion near the Campanian–Maastrichtian boundary in the Danish North Sea and explained it by an inversion pulse or a significant sea-level drop. Vejbæk & Andersen (2002) stated that continuous inversion took place and identified three different Sub-Hercynian phases of increased intensity: latest Santonian, mid Campanian and late Maastrichtian. The latter two roughly coincide with the two inversion pulses found in the Dutch northern North Sea of this study.

In the Chalk Group in the Norwegian North Sea three different phases were identified: a pre-inversion phase, a syn-inversion phase and a post-inversion phase (Gennaro *et al.* 2013). The inversion initiated in the Norwegian Central Graben during the latest Coniacian-to-earliest Santonian and ended at the end of the Campanian. The inversion culminated during the Santonian. The Sub-Hercynian inversion phase thus ended earlier in the Norwegian North Sea than in the Dutch and Danian North Sea, where Maastrichtian inversion occurred.

Evidence of local inversion was also found in the German sector of the North Sea. A major phase of inversion during the Santonian and Campanian affected especially the eastern part of the German Central Graben (Kockel, 1995; Arfai *et al.* 2014). Surlyk, Jensen & Engkilde (2008) studied the Chalk Group of the Schillgrund High and discussed that the Cenomanian to Campanian deposits were tilted towards the SW at the Campanian–Maastrichtian boundary, overlain by onlapping deposits. No evidence for such tilting was found in the present study area.

6.e. The Laramide inversion phase

Reflection truncations are also visible in the upper part of the Chalk Group below the Palaeogene clastics (Fig. 12). Danian and even upper Maastrichtian reflections are truncated at the Top Chalk on parts of the Cleaverbank Platform and Elbow Spit Platform. These truncations indicate that uplift and erosion occurred at the end of the Danian in almost the entire study area. This inversion phase is referred to as the Laramide phase (Van der Molen, 2004; De Jager, 2007). As stated, the Danian sequence is very thin, mostly only one reflection (which is *c.*16–20 m), except for some anomalies on the Elbow Spit Platform and in the Step Graben. It is not possible to constrain the initial thickness of the Danian from the available data and thus it is unknown how much of the Danian sequence was removed by the Late Danian uplift and erosion phase in this area. On the Cleaverbank Platform and on the Elbow Spit Platform, the Danian inversion took place along a N–S axis and removed Danian and Late Maastrichtian deposits. Danian deposits are also absent in the SE part of the study area (Fig. 3). It is uncertain whether this is a result of the Laramide inversion and erosion, or a result of non-deposition. No evidence of erosion was found.

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Van der Molen (2004) argued that the Laramide phase affected the Dutch Central Graben more than the Elbow Spit High and the Cleaverbank Platform, based on the abundance of reworked chalk found in seismic data. This may be in agreement with this study because the Danian is absent in a large part of the Dutch Central Graben. However, the cause of this absence is uncertain. Van der Molen *et al.* (2005) stated that the Laramide inversion phase led to the complete removal of the Chalk Group in parts of the Dutch Central Graben, but they did not show clear seismic reflection truncations that support this strong Danian inversion phase.

6.f. Comparison of the inversion phases

According to De Jager (2007), the Laramide inversion in the Dutch Central Graben was stronger than the Sub-Hercynian phase, because of the deep truncation of older deposits below the Palaeogene. Based on the data of this study, it is not easy to compare these events, for two reasons. Firstly, the original thickness of the Danian deposits in the study area is unknown, although the sequence most likely was relatively thin. Biostratigraphic data of the well A12-01, located 50 km north of the study area (Fig. 1), show a Danian thickness of *c.* 60 m (NLOG). In this well, the lower Palaeocene chalk is conformably overlain by upper Palaeocene deposits, so the Danian sequence was not affected by inversion. Secondly, the Sub-Hercynian phase did not have the same timing in the western and eastern Dutch Central Graben. However, the Sub-Hercynian phase is known to have eroded at least Santonian to Campanian deposits in the west and Campanian to lower Maastrichtian deposits in the east (Figs 9 and 11). It is unlikely that the Santonian to Campanian sequence or the Campanian to lower Maastrichtian sequence (removed by the Sub-Hercynian inversion) was originally thinner than the upper Maastrichtian to Danian sequence (removed by the Laramide inversion). This idea is based on the periods of deposition time that these eroded sequences cover, which is *c.* 14–15 million years for the Sub-Hercynian phase and 7–8 million years for the Laramide phase (Cohen *et al.* 2013). When assuming similar deposition rates, the Sub-Hercynian inversion must have had a stronger impact. However, this hypothesis is not confirmed by the thicknesses of the units on the Schill Grund Platform, where no evidence was found for a Sub-Hercynian inversion phase and deposition could thus have been continuous. In the latter area the Danian is absent while the Maastrichtian sequence is extremely thick and even thicker than the Santonian and Campanian sequence together. Therefore, it is likely that on the Schill Grund Platform the original Maastrichtian–Danian sequence was thicker than the original Santonian–Campanian sequence and thus the Laramide phase was stronger than the Sub-Hercynian phase. On the other hand, the thicknesses or deposition rates on the Schill Grund Platform could be different from the other structural elements, so it is uncertain if the Schill Grund Platform is a good analogue for the entire area. In addition, the thicknesses of the Maastrichtian sequence may be strongly influenced by an irregular sea floor morphology during deposition and by redeposition processes.

M. Saes (unpub. M.Sc. thesis, Utrecht Univ., 2013) concluded that in the southernmost part of the Dutch Central Graben the intensity of the Laramide phase was smaller than that of the Sub-Hercynian phase. This contradicts the conclusions from Van der Molen (2004) and also the outcome of this study, when assuming that the absence of the Danian is a result of erosion.

The results show that the Laramide phase had the lowest impact on the Step Graben, where the Sub-Hercynian phase was possibly strongest compared to the rest of the study area. The late Campanian Sub-Hercynian inversion phase eroded not only the Campanian and Santonian, but also the Coniacian and parts of the Turonian. The Danian sequence is relatively thick in the Step Graben, indicating a limited effect of the Laramide phase. Based on these observations, it is likely that the Sub-Hercynian phase was stronger than the Laramide phase in the Step Graben.

On the Elbow Spit Platform, the Laramide phase removed the entire Danian sequence along two N–S inversion axes and locally also a part of the Maastrichtian (Figs 3, 7 and 10). The Sub-Hercynian phase eroded a lower Maastrichtian sequence, preserving older sequences (Fig. 10). It is not known how much of the Maastrichtian was eroded. Therefore, it is not possible to evaluate which inversion phase had a larger influence on the Elbow Spit Platform.

The Cleaverbank Platform and Schill Grund Platform contain no evidence of a Sub-Hercynian erosive event in the study area and likely have been inverted only at the end of the Danian (Figs 6 and 7).

Deckers & Van der Voet (2018) identified a distinction between the structural styles of the Sub-Hercynian and Laramide inversion phases in the southern North Sea, which is supported by the results from this study. They showed that the Sub-Hercynian phase was characterized by strong uplift and erosion, which is also visible in the Step Graben, Elbow Spit Platform and Dutch Central Graben (Figs 8–11) while the Laramide phase caused only mild domal uplift, as visible on the Cleaverbank Platform (Fig. 12).

7. Discussion of sedimentary and redeposition features

Besides thickness variations as a result of tectonic events, smaller-scale seismic discontinuities are present which are interpreted to result from either bottom currents or gravity-related resedimentation processes.

7.a. Incision features

The incision features described in Section 5 (Fig. 13) were interpreted to result from bottom currents of

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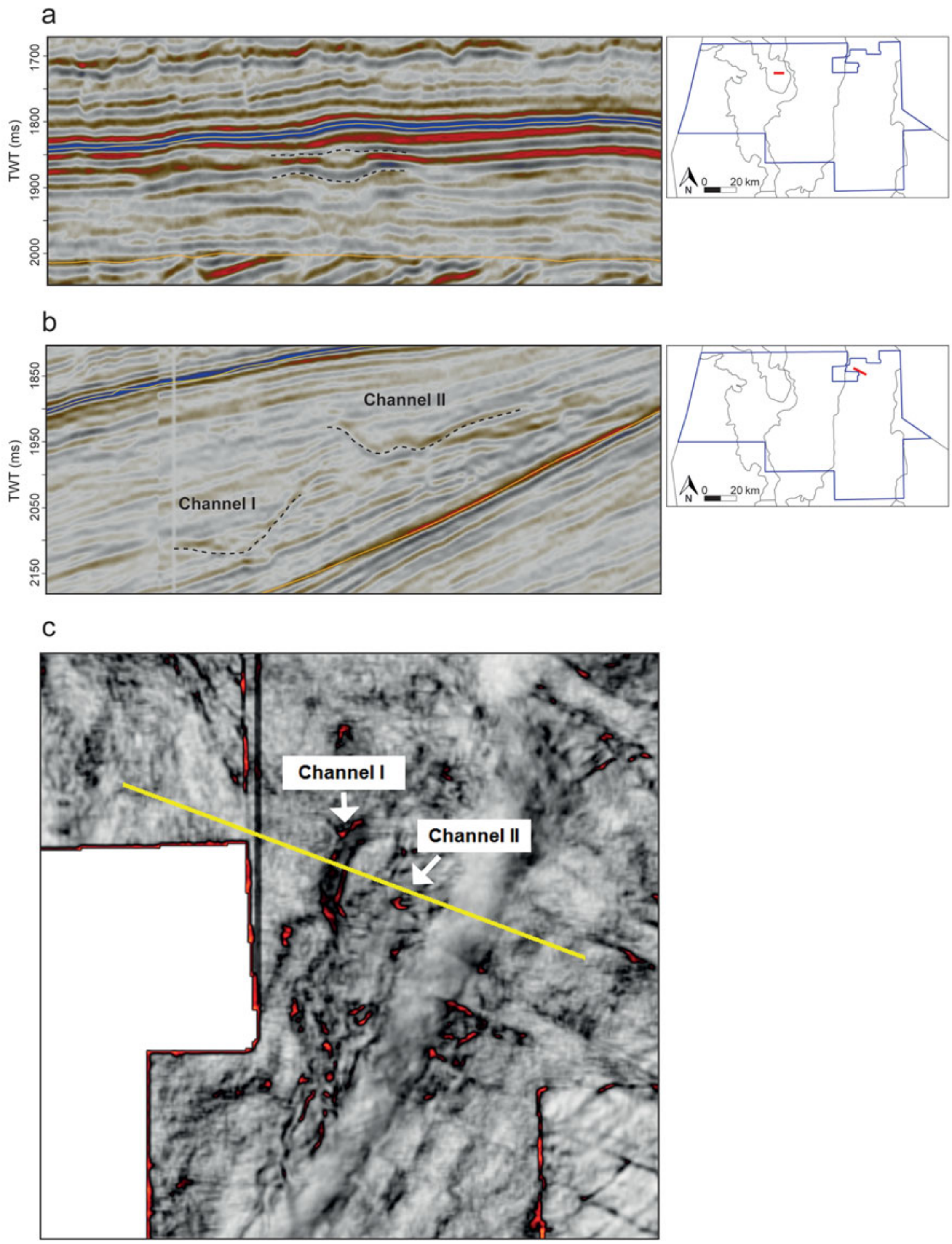

Figure 13. (Colour online) Incision features interpreted as channels. (a) Relatively small-scale channel at the Elbow Spit High, (b) larger-scale channels in the NW part of the Dutch Central Graben, (c) variance attribute map of the NW Dutch Central Graben, showing the same two channels as indicated in (b).

different scales. Evidence of channels of 300 m up to 1200 m wide was mainly found in the Dutch Central Graben. The channels are oriented parallel to the slope and hence may represent contour current features (e.g. Faugères *et al*. 1999).

A series of studies were published during the last two decades on the sedimentary and redeposition features present within the Chalk Group in the North Sea (above-mentioned references and Evans & Hopson, 2000; Evans *et al.* 2003; Lykke-Andersen & Surlyk, 2004; Surlyk, Damholt & Bjerager, 2006; Anderskouv, Damholt & Surlyk, 2007; Esmerode, Lykke-Andersen & Surlyk, 2007; Surlyk & Lykke-Andersen, 2007; Esmerode, Lykke-Andersen & Surlyk, 2008; Surlyk,

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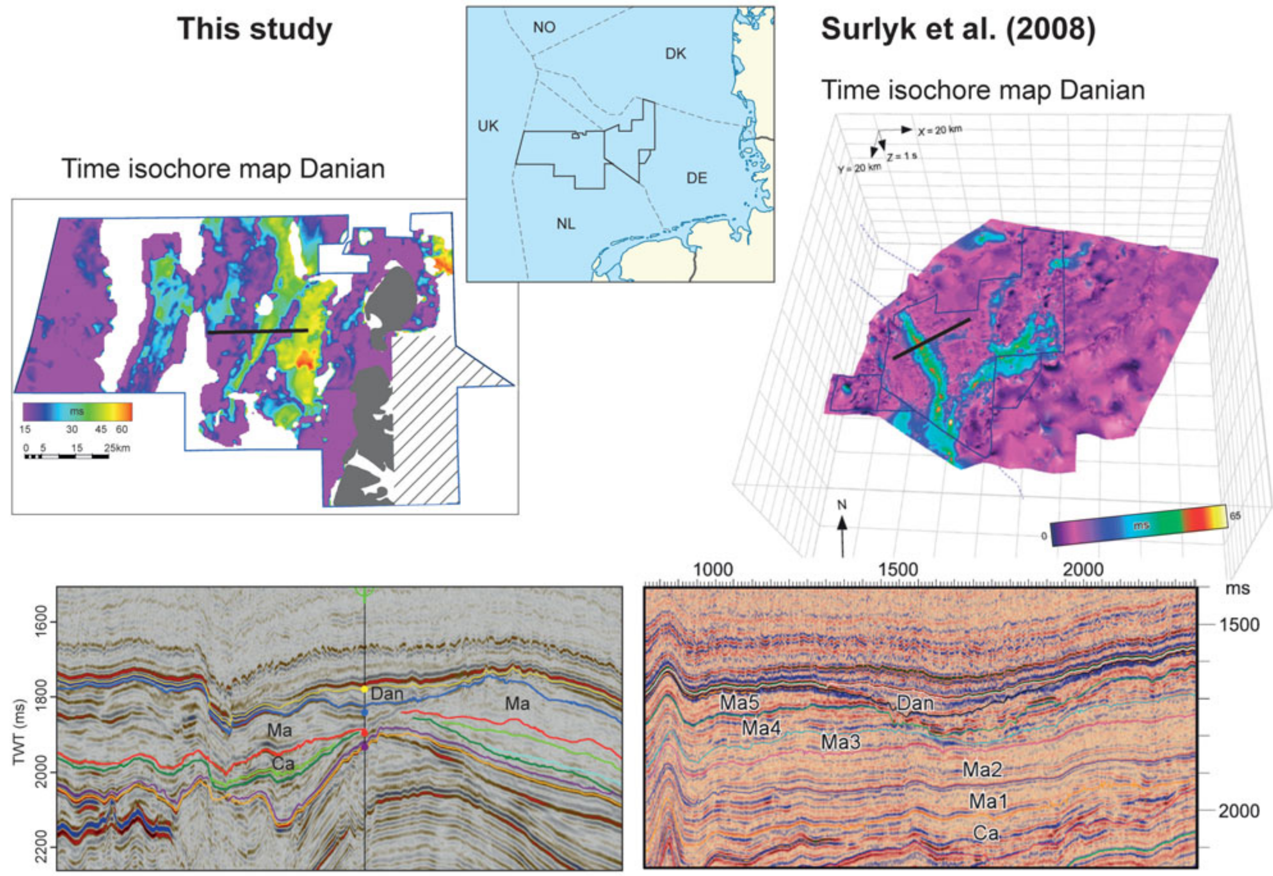

Figure 14. (Colour online) Comparison of the Danian channel found in this study (left) and the Danian channel identified by Surlyk, Jensen & Engkilde (2008) in the German Schill Grund High (right). Both study areas are indicated on the map. The time isochore maps of the Danian Ekofisk Formation show anomalies that are visible in the seismic sections below as deep Danian channels that cut into the top of the Maastrichtian. The black lines show the locations of the seismic sections, and the grey areas on the left map indicate the absence of the Chalk Group. The grey striped areas indicate where no reliable Danian thicknesses could be interpreted and the Danian is absent in the white areas. Abbreviations: Dan = Danian, Ma = Maastrichtian, Ca = Campanian.

Jensen & Engkilde, 2008; Back *et al.* 2011; Gennaro & Wonham, 2014; Masoumi *et al.* 2014; Gale *et al.* 2015; Arfai *et al.* 2016).

Syn-sedimentary channel features were first imaged in seismic data within the chalk of southern England, by Evans & Hopson (2000) and Evans *et al.* (2003). These channels are oriented parallel to the bathymetric contours. Lykke-Andersen & Surlyk (2004) described a major contour current system in the Danish Basin with channels up to 20 km wide. Evidence of contour-parallel bottom currents with contourite deposits and a very irregular sea floor topography was also found in seismic data from eastern Denmark (Surlyk & Lykke-Andersen, 2007) and the Danish Central Graben (Esmerode, Lykke-Andersen & Surlyk, 2008). Back *et al.* (2011) discussed multiple channel incisions on seismics in the southern Danish North Sea. However, these were mainly slope-perpendicular and interpreted as gravity-driven. The previously described contourite deposits caused by contour currents in the Danish and British North Sea largely resemble the incision features found in this study which are up to kilometre-scale, sinuous and slope-parallel (Fig. 13).

The anomaly of the Danian thickness in the Step Graben (Fig. 14) may be the result of a large channel incision during the Danian. In parts of the Step Graben, this idea of incision is supported by angular unconformities. This evidence is absent in other parts, which makes the interpretation of a channel not very certain. On the other hand, Surlyk, Jensen & Engkilde (2008) identified a very similar feature on the German Schillgrund High and also interpreted this as a deep channel, up to 15 km wide and 200 m deep (Fig. 14). The channel is interpreted to be of the same age as the feature in the Step Graben.

7.b. Distorted reflection features

The described complexes of chaotic and distorted reflections are interpreted as slope failure features caused by gravity-induced processes. Indications for mass transport deposits (MTDs) are visible in many parts of the Dutch Central Graben. These deposits mostly include slumps that transport slope material downhill and show a detachment surface. Two examples of such slumps are illustrated in Figure 15. The

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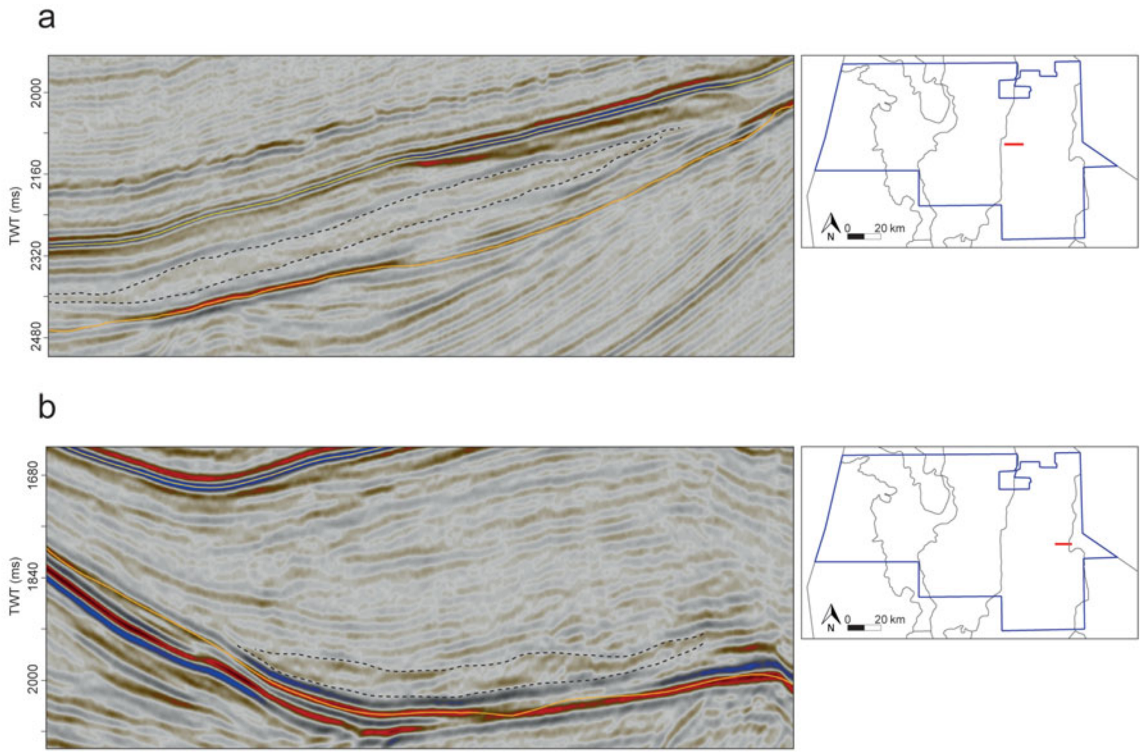

Figure 15. (Colour online) W–E seismic sections through the western (a) and eastern (b) Dutch Central Graben, showing chaotic and distorted reflection complexes, interpreted as slumps.

slumps that were found in the study area are up to seven km in length along the axis of displacement.

Especially in the Dutch Central Graben, relatively steep slopes must have been present during the deposition of the Chalk Group due to inversion. Multiple kinds of mass movement were recognized in the chalk in many areas of the North Sea, from both seismic data and drill cores (Kennedy, 1980, 1987*a*, *b*; Evans *et al.* 2003; Lykke-Andersen & Surlyk, 2004; Van der Molen *et al.* 2005; Surlyk, Jensen & Engkilde, 2008; Anderskouv & Surlyk, 2011; Back *et al.* 2011).

Esmerode, Lykke-Andersen & Surlyk (2008) discussed the link between bottom currents and slope failure and stated that the current activity caused erosion, which caused slope instability and triggered slumping. Such slumping as a result of channel margin collapse has also been described from Late Cretaceous chalk outcrops in S England by Gale *et al.* (2015).

Most sedimentary and redeposition features in the study area were found in the Dutch Central Graben. This may be a result of the strong inversion that took place in this area and the sea floor topography that already existed at the onset of chalk deposition, as interpreted based on onlapping Cenomanian reflections (Fig. 9). Steep slopes may have been present in the Dutch Central Graben during almost the entire Late Cretaceous and Early Palaeogene, partly due to salt movement. As a result, the chalk was exposed to syn-sedimentary processes such as contour-parallel bottom current activity and downslope mass movements. Hence, internal disconformities and pinchouts are features that frequently occur within these chalk deposits.

8. Conclusions

The development of the Chalk Group in the northern Dutch North Sea was reconstructed by interpreting seven chronostratigraphic units based on the integration of 3D seismic data and biostratigraphic well data. The chalk evolution is influenced by multiple processes, generally subdivided into tectonic and sedimentation processes or redeposition events.

- The first period of chalk deposition was a phase of relative tectonic quiescence and lasted from the Cenomanian to approximately the Campanian. Evidence of two exceptions to this tranquillity was found. First, southwestward tilting took place during the Turonian and created accommodation space in the SW. Next, little or no deposition of Coniacian and Santonian sediments occurred on the Cleaverbank Platform, while subsidence continued in the Step Graben and western Dutch Central Graben.
- Widespread inversion and erosion affected the Chalk Group showing two pulses during the Late Campanian and Maastrichtian (Sub-Hercynian phase). The timing of the uplift differs between the structural elements in the study area, starting in the western Dutch Central Graben and Step Graben during the Late Campanian, and ending in the Elbow Spit

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Platform and eastern Dutch Central Graben during the Maastrichtian. The second Maastrichtian pulse was never reported before in this area.

- After the Campanian/Maastrichtian inversion phase, subsidence took place and Late Maastrichtian and Danian sediments were deposited. At the end of the Danian, renewed uplift occurred and parts of the Danian sequence were eroded, leading to very thin Danian deposits in the study area. The inversion was strongest in two N–S strips of the Elbow Spit Platform and Cleaverbank Platform, where the entire Danian sequence was removed as well as parts of the Maastrichtian sequence.
- Halokinesis caused subsidence at a smaller scale influencing the chalk deposition, especially in the Step Graben and Dutch Central Graben where a series of salt diapirs and walls are present.
- Evidence of channel incisions was found in the study area at different scales. A prominent Danian thickness increase through the centre of the Step Graben was interpreted as a large channel. In addition, evidence of slope failure was found in the form of slumps or slides. These observations indicate that the chalk sea in the study area was obviously far from quiet and flat, and chalk reworking occurred at a large scale.

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