Geological evolution of the Chalk Group in the northern Dutch North Sea

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Abstract

The Late Cretaceous to Early Tertiary chalk play in the Dutch North Sea area has received increased attention since many hydrocarbons fields were found in these sediments in the Norwegian and Danish North Sea. However, not much is known on the sedimentology and stratigraphy of the Chalk Group in the Dutch North Sea. A relatively new 3D seismic survey in the northern Dutch North Sea provided the opportunity to study the interior of the Chalk Group in detail.

An analysis of the tectono-sedimentary history of the Chalk Group in a northern Dutch North Sea area is performed, by integration of biostratigraphic well data and seismic data. Seven seismic units, based on the seven chronostratigraphic stages of the Late Cretaceous and Early Tertiary, are interpreted throughout the roughly five different structural elements of the study area. Reflection terminations have been identified and the tectonic evolution of the area was reconstructed, based on mostly onlap-structures and truncations. Periods of relative subsidence and erosional events can be distinguished.

The most important geological events that must have taken place during and after the deposition of the Chalk Group are described. The first period of chalk deposition was a phase of relative tectonic quiescence. However, the thickness map of the Turonian shows a SW-ward tilting, which has not been recognized before. Another exception to the regional subsidence is little or no deposition of Coniacian and Santonian sediments in the western part of the study area, which is likely due to subsidence of the eastern part during the Coniacian and Santonian. During the Campanian and Maastrichtian, a widespread inversion phase occurred in two pulses, visible as seismic truncations. It started in the Step Graben and western Dutch Central Graben at the end of the Campanian and the second pulse during the Maastrichtian affected the Elbow Spit Platform and eastern Dutch Central Graben. The uplift and subsequent erosion had a differential effect and was strongest in the Step Graben, where even the Turonian sequence was partly eroded. Subsequently, a period of regional subsidence resulted in the deposition of thick Maastrichtian sequences. The subsidence possibly continued during the Danian (early Tertiary) but this is uncertain since the Danian sequence is very thin in most of the study area as a result of a renewed uplift and erosion phase at the end of the Danian. This inversion phase ended the chalk deposition and from this time onward, siliciclastic sediments were deposited instead.

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1. Introduction

1.1 North Sea Chalk

During the Late Cretaceous and Early Tertiary (100-61 Ma) the Chalk Group accumulated in the North Sea Basin. After several rifting pulses during the Triassic and Jurassic, post-rift thermal relaxation occurred in the North Sea Basin, starting in the Cenomanian (early Late Cretaceous). Subsidence combined with an eustatic sea level rise caused a transgression in Northwest Europe. Large areas of land were flooded, which resulted in a reduction of erosional material input into the oceans. The warm seas with clear water resulted in the production of large amounts of coccoliths, which are calcareous nannoplankton. The skeletons of these organisms accumulated at the ocean floor, forming the Chalk Group sediments. The Alpine continental convergence at the end of the Danian (Early Tertiary) ended the phase of chalk deposition. As a result of the orogeny, the influx of erosional material into the oceans increased, leading to less clear water conditions. From this time onward, siliciclastic sediments were accumulated instead of chalk (Ziegler, 1990).

Outcrops of the same Chalk Group are present as white cliffs at the south coast of England, United Kingdom (figure 1). Other famous chalk outcrops are the cliffs in Normandy, northern France and the Stevns Klint, Denmark.

Figure 1 Beachy Head, chalk cliffs formed during the Late Cretaceous, near the town Eastbourne, United Kingdom (https://en.wikipedia.org/wiki/Beachy_Head)

1.2 Aim and outline of the study

The Chalk Group has been a subject of interest in Denmark and Norway for many years now, but in the Netherlands, detailed knowledge on the chalk is limited. Van der Molen (2004) published a thesis about the Chalk Group in the Dutch North Sea in which he discusses the sedimentary development as well as the seismic stratigraphy of the chalk. Also Saes (2013) and Huijgen (2014) did research on the chalk, respectively in the southern Dutch Central Graben and in the Step Graben and Dutch Central Graben. They analyzed seismic and biostratigraphic data to interpret intra-chalk stratigraphy and the tectonic history of the depositional system.

Many hydrocarbon fields that were discovered in the North Sea of Denmark and Norway are in chalk reservoirs. Therefore, it would be very interesting to investigate the behavior of the group in the Dutch North Sea as well. The aim of this research project is to increase the knowledge on intra-chalk sedimentology and stratigraphy in the northern Dutch North Sea. The more specific research question of the project is “To what extent are intra-chalk geological events recognizable in the different structural elements of the northern Dutch North Sea (Cleaver Bank Platform, Elbow Spit High and Platform, Step Graben, Central Graben and Schill Grund Platform)? What are the differences and similarities and how can we explain these in a geological context?”

This study was performed within the framework of a second-year MSc. thesis project which is a part of the Earth Sciences (specialization Solid Earth) programme at the VU University in Amsterdam (The Netherlands). The study was conducted at EBN in Utrecht. A seismic workstation and interpretation software were provided by EBN.

1.3 Study area

The study area is located in the northern part of the Dutch North Sea, see figure 2.

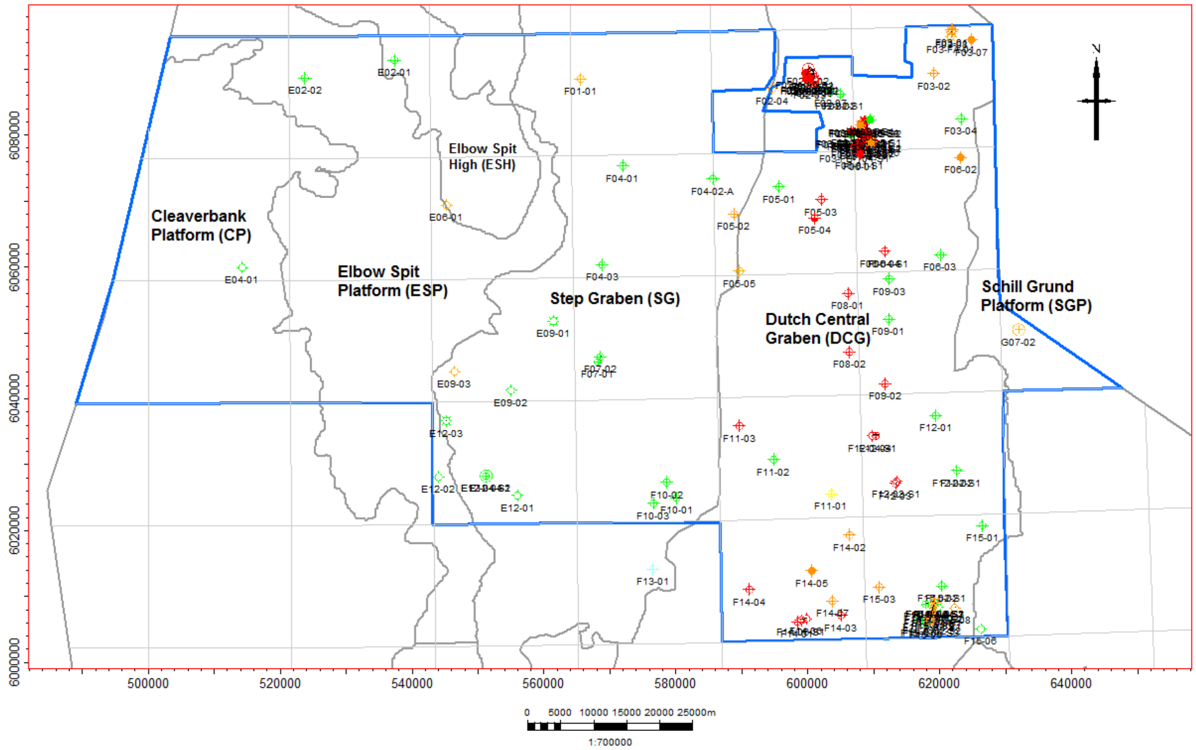


Figure 2 Map of the study area in the northern Dutch North Sea. The outline of the study area is indicated by the blue line. The names refer to the structural elements.

It covers parts of the D, E, F and G license blocks. The area contains parts of five structural elements that were created during Mesozoic times: Cleaver Bank Platform, Elbow Spit High and Platform, Step Graben, Central Graben and Schill Grund Platform. All of these structural elements are approximately north-south oriented.

2. Geological setting

2.1 Tectonic history

2.1.1 Introduction

The tectonic setting of the northern Dutch North Sea Basin consists of a range of sub-basins, platforms and highs that resulted from a series of tectonic phases from the Paleozoic to Tertiary. Figure 3 illustrates the structural elements that were present at the time when the deposition of chalk started, as interpreted by Kombrink *et al.* (2012). These highs, platforms and basins resulted from rifting pulses during the Triassic and Jurassic. The most important structural elements that are subject of this study are the Cleaver Bank Platform, Elbow Spit High and Platform, Step Graben, Dutch Central Graben and Schill Grund Platform. The tectonic events that created the structure of the northern Dutch North Sea Basin will be discussed in chronological order.

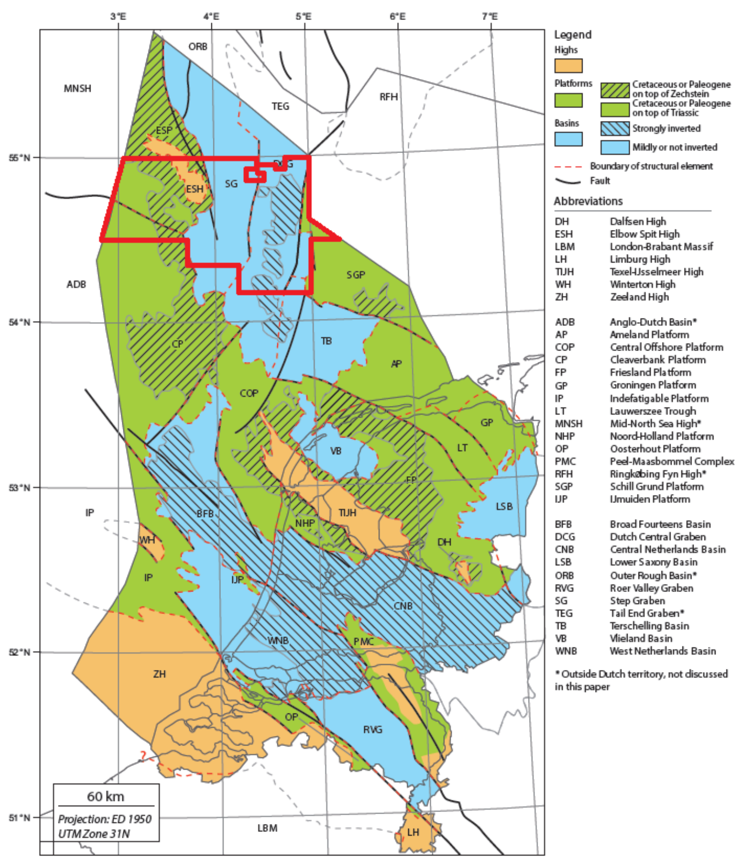


Figure 3 Late Jurassic - Early Cretaceous structural elements of the Netherlands (Kombrink et al., 2011). The study area is indicated within red lines.

2.1.2 Paleozoic

During the Hercynian orogenic cycle, that occurred in Devonian to early Permian times, fold belts developed in North America, northwest Africa and Europe (Ziegler, 1990). These fold belts formed the large mountain system, that resulted from the convergence of Gondwana and Laurussia. They were located at the centre of super-continent Pangea. The fold belt that was present in western and central Europe is called the Variscan fold belt and developed during Carboniferous times. It was a major E-W trending fold belt. At that time, the Netherlands was located in the northern foreland of these mountains (Kombrink, 2012).

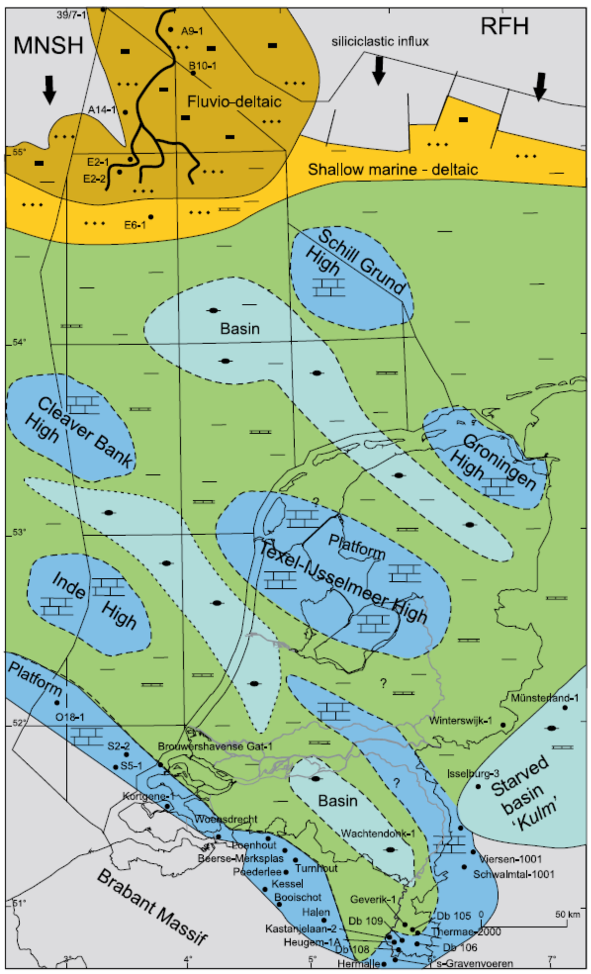


Figure 4 Paleogeographic sketch map of the Early Carboniferous (Geluk et al., 2007, after Bless et al., 1976; Lokhorst, 1998). Inferred carbonate platforms and intra-platform basins are shown. Wells shown reached the mapped interval. RFH: Ringkøbing-Fyn High; MNSH: Mid North Sea High.

Deltaic sediments moved southward from the Mid North Sea High (Geluk *et al.*, 2007) and accumulated in the northern offshore area during the early Carboniferous (figure 4). South from this deltaic environment, carbonate platforms were present. Among these were the Cleaverbank Platform and the Schill Grund Platform.

During the late Carboniferous, a regression increased the rates of siliciclastic sedimentation in the foreland basin. Fluvio-deltaic sediments and coals accumulated. During the Stephanian (latest Carboniferous) and Autunian (early Permian) stresses built up in the Variscan foreland and post-orogenic wrench faults became active (Ziegler, 1990). This caused the Variscan orogen to collapse and resulted in a major hiatus between the Carboniferous and Permian rocks in the Netherlands.

In Permian times, Rotliegend sediments accumulated in the Southern Permian Basin, a large sag basin that stretched from the United Kingdom to Poland. Fluvial and aeolian sandstones moved towards the north into a playa basin. Subsequently, marine evaporites were deposited (Zechstein Group).

2.1.3 Mesozoic and Early Tertiary

During the Late Triassic, Pangea started to break up. While the Southern Permian Basin was still subsiding, initial extensional faulting occurred in the Netherlands.

In middle Jurassic times, a thermal Central North Sea Dome developed (Mid-Kimmerian phase) (Herngreen and Wong, 2007). This dome caused extensive uplift and erosion in the North Sea. During the Late Kimmerian Phase, extensive rifting took place and the rift structures formed in the Dutch North Sea. The Dutch Central Graben is one of them. Post-rift thermal relaxation and eustatic sea level rise followed and the rift-basins were filled with Jurassic and Early Cretaceous sediments, overstepping the margins of the basins (Van der Molen, 2004). The transgression proceeded and at the end of the Early Cretaceous, large areas of land were flooded, which caused a reduction in the input of erosional material into the oceans (Ziegler, 1990). The warm and clear water seas contained sea levels that exceeded present levels with 100 to 300 metres. This resulted in the production of large amounts of calcareous nannoplankton (coccoliths). The skeletons of these organisms accumulated at the ocean floor, forming the Chalk Group sediments. The Chalk Group was deposited in the North Sea Basin during the Late Cretaceous and Early Tertiary (100-61 Ma).

Oceanic Anoxic Events (OAEs) are periods of large-scale organic carbon burial, as a result of anoxic conditions. One of these worldwide OAEs occurred at the Cenomanian to Turonian boundary, about 93.5 million years ago (Mort *et al.*, 2007; Turgeon and Ceaser, 2008). This episode is referred to as OAE2 and resulted in the deposition of the Plenus Marl Member. Turgeon and Creaser (2008) claim that OAE2 was triggered by a massive magmatic episode with for instance the emplacement of large igneous provinces or mid-ocean ridges.

While Mesozoic times were dominated by rifting phases, compressional phases occurred during the Cretaceous and Paleogene (Van der Molen, 2004). These phases were identified in 1987 by Van Wijhe (1987). De Jager (2007) studied the timing and intensity of the inversion phases, as illustrated in figure 5. During the deposition of the chalk, two important compressional phases occurred. The first phase is referred to as the 'Sub-Hercynian' phase, starting in the early Turonian and continuing to the early Maastrichtian. The second phase took place during the Danian (Early Tertiary) and is called the 'Laramide' pulse. Several Jurassic basins were inverted and locally the whole chalk succession was eroded, for example in parts of the Dutch Central Graben (Herngreen and Wong, 2007). The cause of these inversion phases is likely the compression in the Alpine foreland related to the Tethys closure and the opening of the North Atlantic Ocean (Ziegler, 1990).

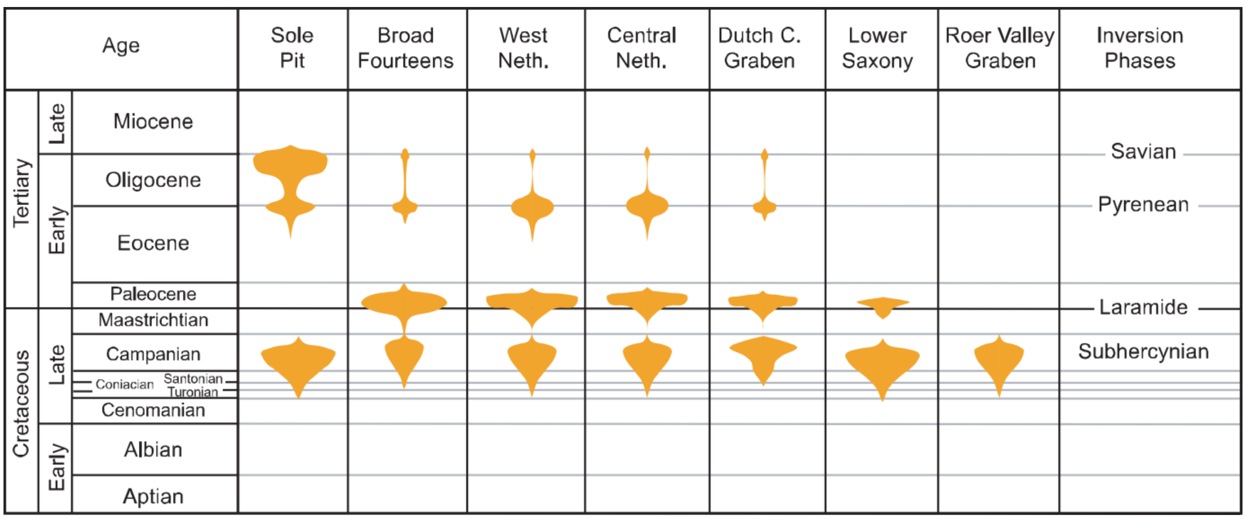


Figure 5 Timing and relative intensity of Alpine inversion in the North Sea (De Jager, 2007)

The Alpine continental convergence at the beginning of the Tertiary ended the phase of chalk deposition. As a result of the orogeny, the influx of erosional material into the oceans increased, leading to less clear water conditions. This initiated siliciclastic sediment accumulation instead of chalk (Ziegler, 1990).

2.2 Stratigraphy

2.2.1 Subdivisions

The Chalk Group generally has a very homogeneous lithology and is subdivided in the Netherlands in three stratigraphic formations: the Texel Formation (Cenomanian), the Ommelanden Formation (Turonian to Maastrichtian) and the Ekofisk Formation (Danian) (Van der Molen, 2004, after: Van Adrichem Boogaert and Kouwe, 1994). However, in the Danish and Norwegian part of the North Sea, a more detailed subdivision of the chalk is used. Here, the chalk is a very important reservoir for hydrocarbon production. In figure 6, the lithostratigraphic subdivisions of the Chalk Group in Norway and Denmark are visible.

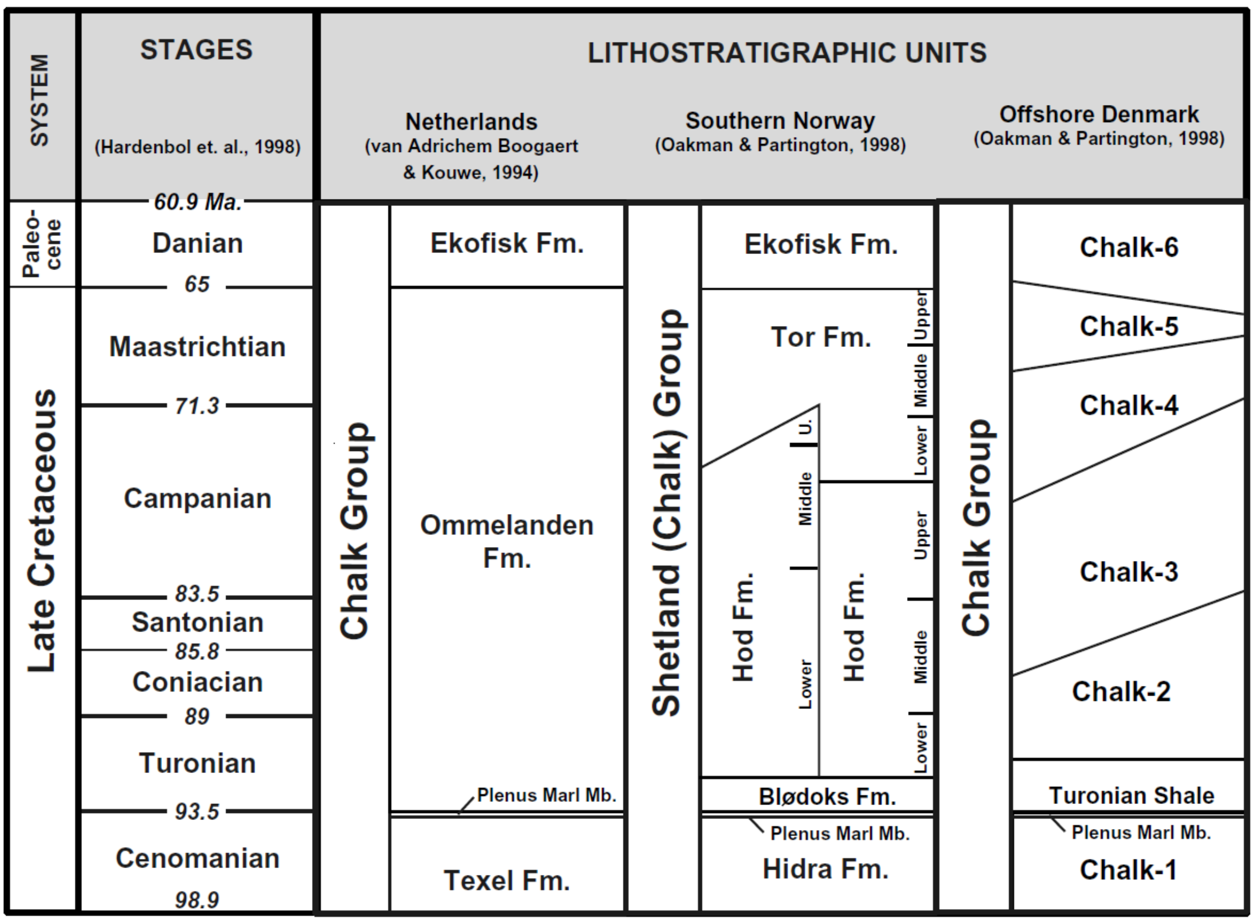


Figure 6 Lithostratigraphic subdivision of the Chalk Group in the Netherlands, Danish and Norwegian sectors of the North Sea (Van der Molen, 2004)

Recently, many 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. Many of these studies identified different units, mostly based on biostratigraphic and seismic data. A comparison of these studies is shown in figure 10. There are clearly many differences between the subdivisions. Generally, the only similarity could be that most subdivisions are in one way or the other based on the tops of the biostratigraphic units (Cenomanian to Danian).

Denmark

Esmerode *et al.* (2008) divided the Chalk Group of the southern Danish Central Graben into five seismic units (figure 7). They identified two extensive unconformities within the Turonian-Campanian sequence that were created by bottom currents and at some places modified by mass transport processes. Back *et al.* (2011) focused on the Danish Central Graben and proposed a subdivision that defined three interpretation levels. Larsen *et al.* (2014), divided the Late Cretacous Chalk Group in south-west Denmark into nine units, based on seismic facies analysis, seismic structural analysis and correlation to wireline-logs. The unconformity that is best recognizable on seismic in the Danish sector of the North Sea is possibly of intra-Campanian age (Megson and Tygesen, 2005) and most likely is comparable to the Late Campanian unconformity in the UK (Errat *et al.*, 1999). Kristensen *et al.* (1995) also used an interdisciplinary approach to produce a consistent biostratigraphic subdivision, in this case to identify reservoirs. This resulted in a new subdivision of the Maastrichtian in the Dan field with five biostratigraphic units and five (slightly different) main seismic units. Klinkby *et al.* (2005) identified four seismic horizons in the Danish Central Graben: Top Chalk Group, Intra Danian, Top Maastrichtian and near-Top Jurassic. The three units in between them are known as the Danian Porous, the Danian Tight and the Maastrichtian Porous.

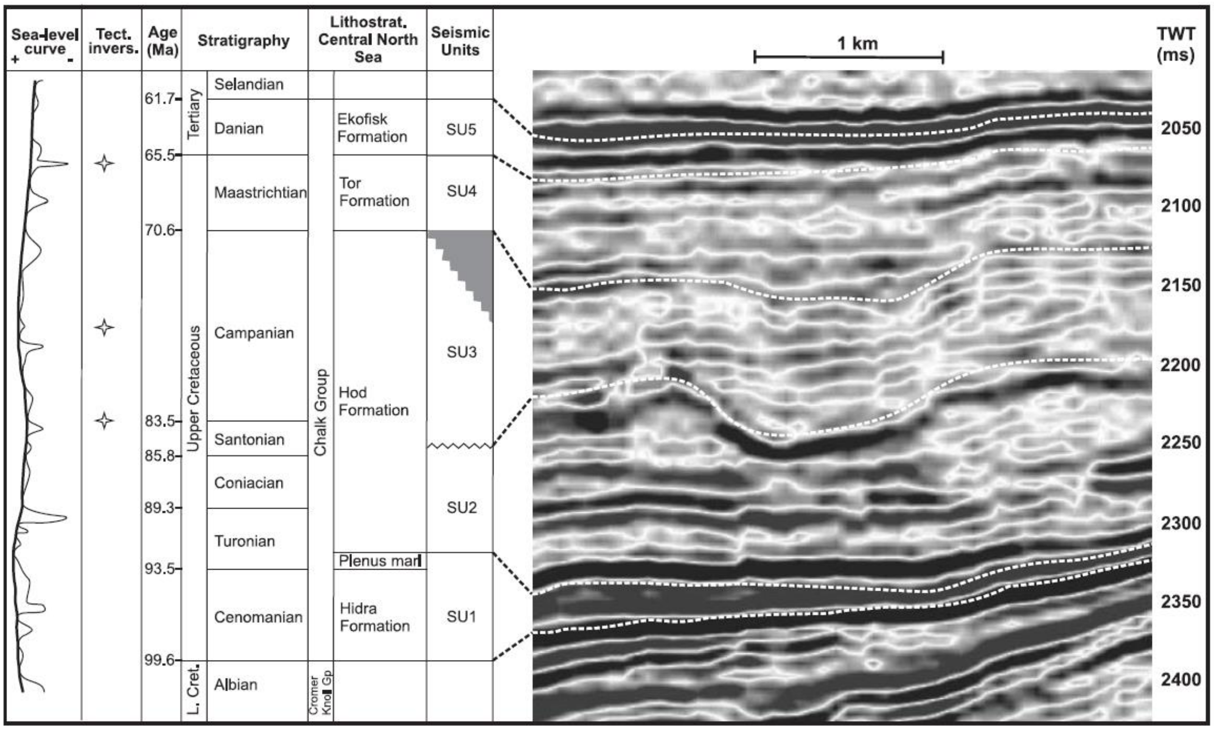


Figure 7 Upper Cretaceous lithostratigraphy and seismic units used by Esmerode et al., 2008

Norway

Bramwell *et al.* (1999) investigated the Chalk Group in the Greater Ekofisk area in Norway. The Shetland Group is the name for the Cenomanian to Danian siliciclastic deposits in the northern North Sea and is traditionally divided into five formations (Deegan and Scull, 1977): Ekofisk, Tor, Hod, Blod¢ks (same as Plenus Marl) and Hidra. Bramwell *et al.* (1999) recognized several unconformities within the Tor and Hod formations from seismic and biostratigraphic data. Gennaro *et al.* (2013) made an overview of the allo-, litho- and biostratigraphy of the Chalk Group in the southern Norwegian region of the North Sea, linked to seismic data (figure 8). They identified eight seismic horizons and hence seven stratigraphic sequences within the Chalk. They also identified three major tectonic phases. In addition, they correlated their data with the previous stratigraphic subdivisions made by Bramwell *et al.* (1999) and Bailey *et al.* (1999). Gennaro *et al.* (2013) identified a seismic horizon at the top part of the Campanian section. It is the top of the Magne Fm, named as such by Bailey *et al.* (1999), and also the top of the KU 3 (Upper Hod Fm), named by Bramwell *et al.* (1999). This horizon does not correlate well with boundaries from the biostratigraphic studies that were used by Bailey *et al.* (1999). The seismic horizon shows erosional truncation of underlying sediments and also onlap on ridges. Downlap also occurs and channel-like features are recognizable. Wireline logs show a change to lower gamma ray and sonic values above the unconformity. The Maastrichtian chalk contains less clay than the Campanian chalk. Another subdivision of the chalk was made by Fritsen (1999), on the North Sea Eldfisk field. He identified four unconformities: Lower Santonian, Lower Campanian, Middle Campanian and Lower to Middle Danian.

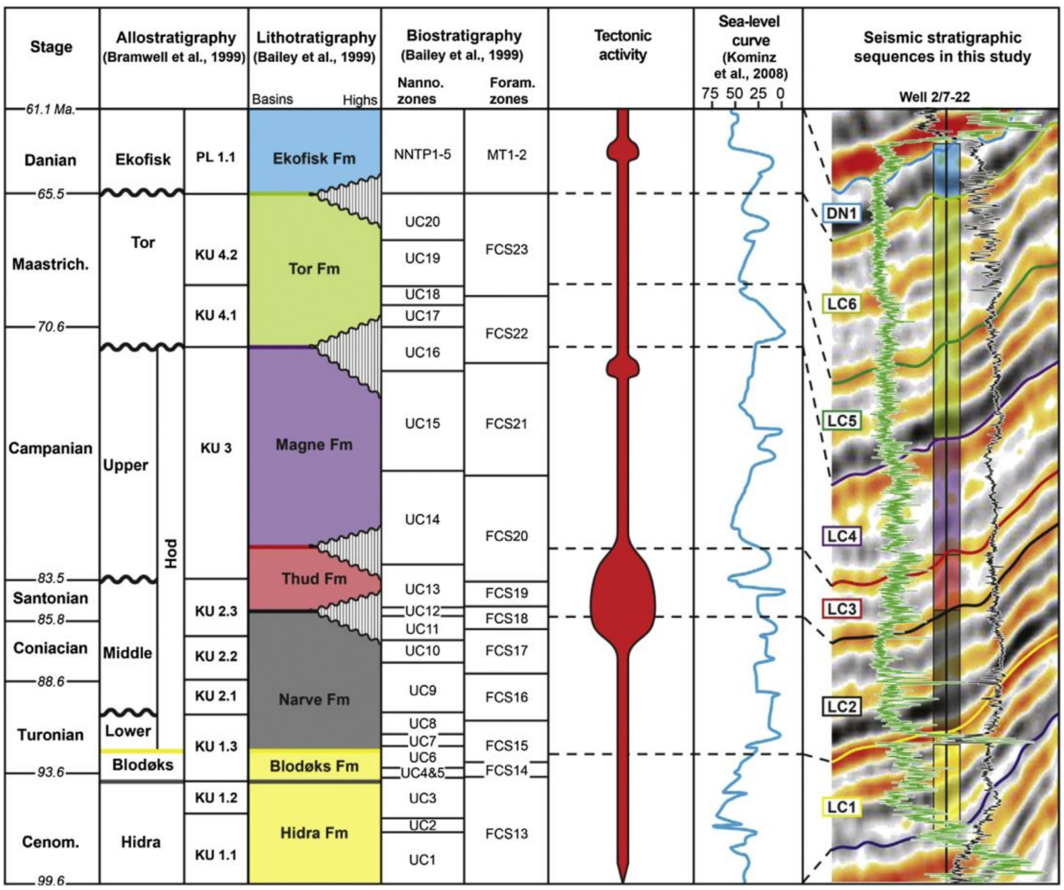


Figure 8 Allostratigraphic and lithostratigraphic subdivision of the Chalk Group in the southern Norwegian sector of the North Sea and the corresponding seismostratigraphic units (Gennaro et al., 2013)

The United Kingdom

Mortimore (2010) made a very detailed stratigraphic description and subdivision of the Late Cretaceous in England that was also based on biostratigraphic and wireline log data (figure 9). He also compared the stratigraphy to global sea level data and tectonic events. Mortimore (2010) did not use any seismic data in his study.

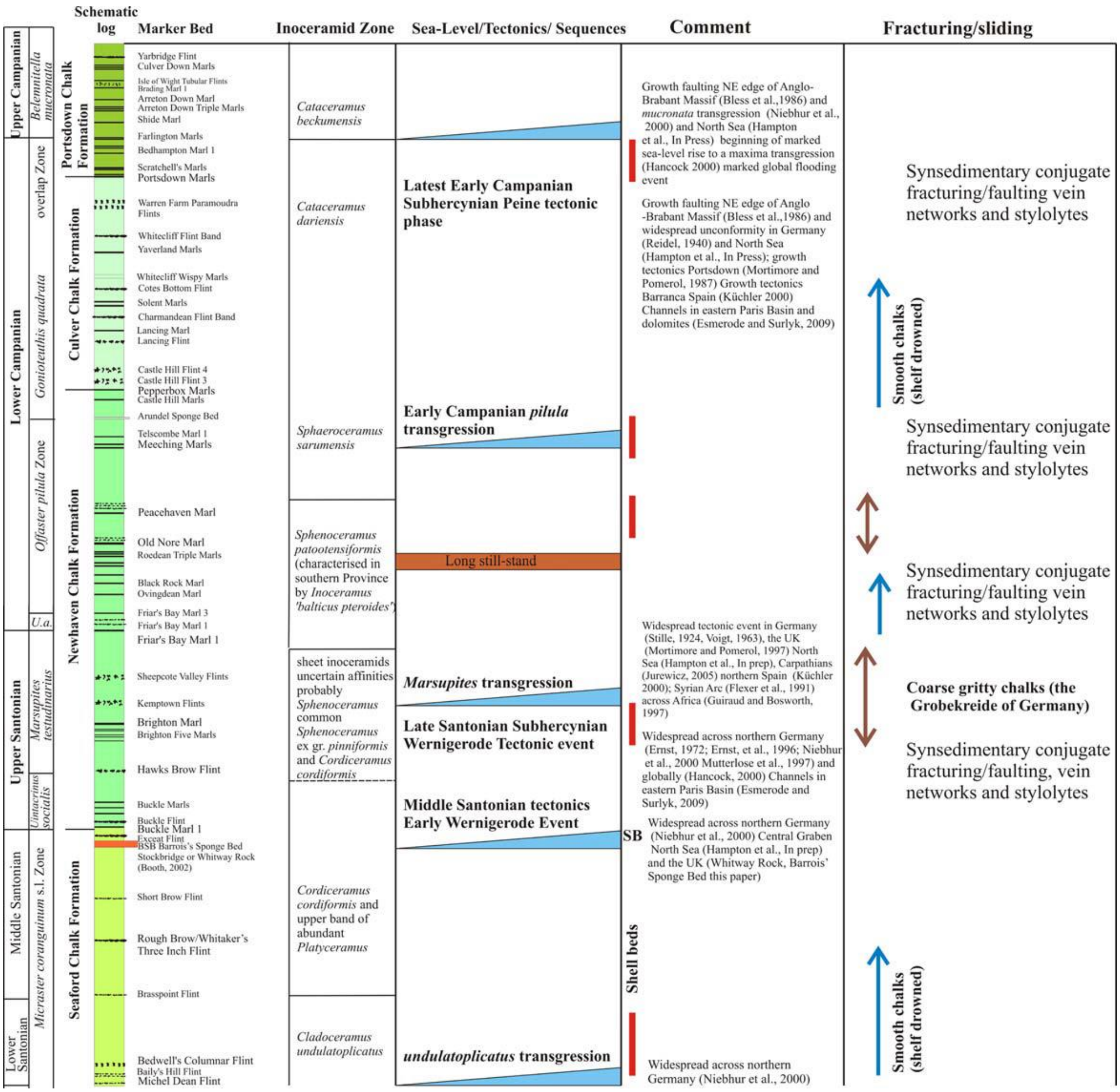


Figure 9 Integration of the English Southern Province White Chalk Subgroup stratigraphy with global sea level and tectonic events (Mortimore, 2010)

Integration

When comparing the subdivisions of the most important scientific publications on the North Sea Chalk Group, it becomes clear that there is no consensus on this subject. This is shown in the comparison provided in figure 10. It is quite clear that this table is dominated by distinct variations. However, similarities are present. The coincidence of unit boundaries between the various models seems to be mainly based on the chronostratigraphy. Most publications made use of the tops of the stages within the Late Cretaceous and Early Tertiary for their classification.

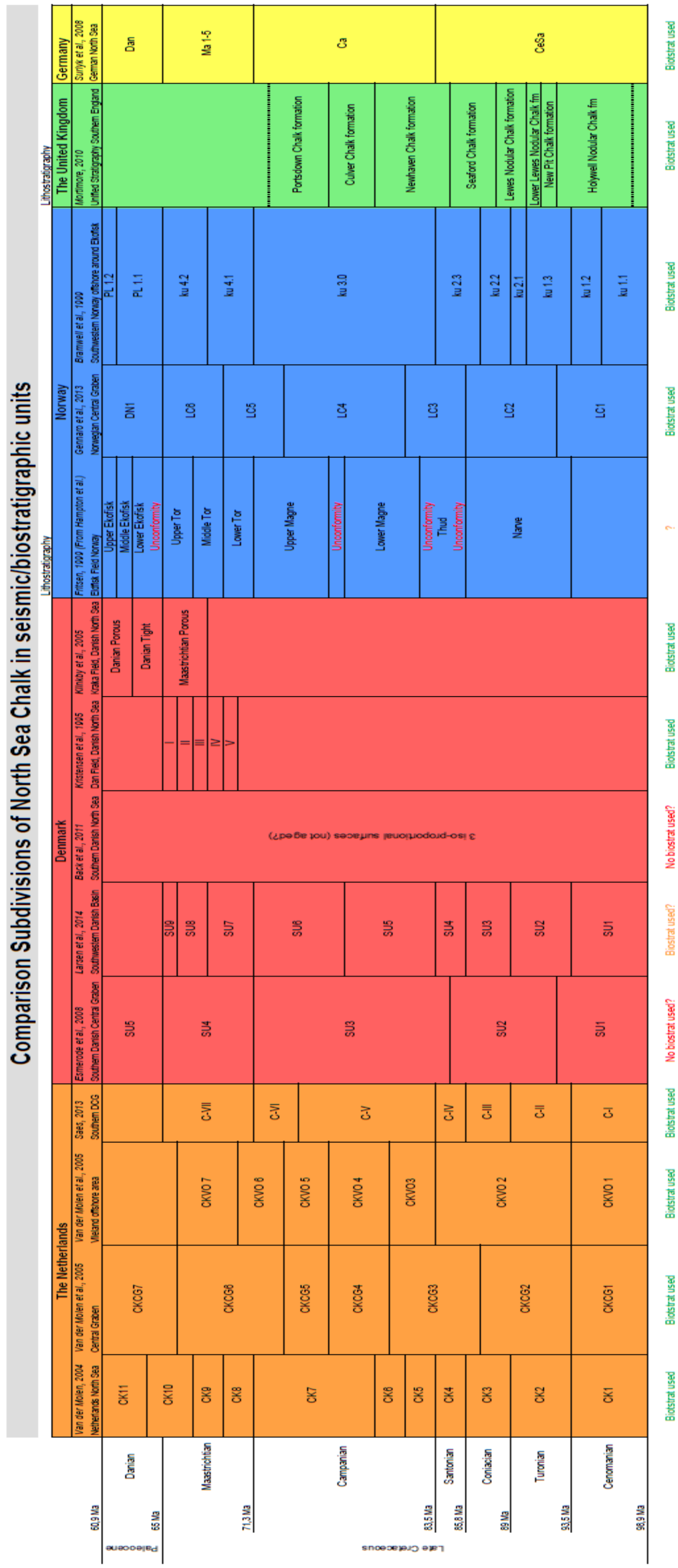


Figure 10 Comparison of the multiple subdivisions of the North Sea Chalk in The Netherlands, Denmark, Norway, The United Kingdom and Germany

2.2.2 Chalk composition

The Chalk Group in the North Sea is dominated by biomicrites that mainly consist of coccoliths, which are aggregates of shell-platelets produced by unicellular algae (coccolithophorids) that lived in an open-marine (pelagic) environment (Van der Molen, 2004), see figure 11. Coccoliths consist of calcite ($CaCO_3$) and are circa 0.5-20 micrometres in diameter. A mud of these calcareous nannofossils is the main component of the chalk, which is predominated by grains of clay to silt size (Fabricius, 2007). Various planktonic foraminifera are also present in the chalk. The chalk sediments have a very homogeneous appearance.

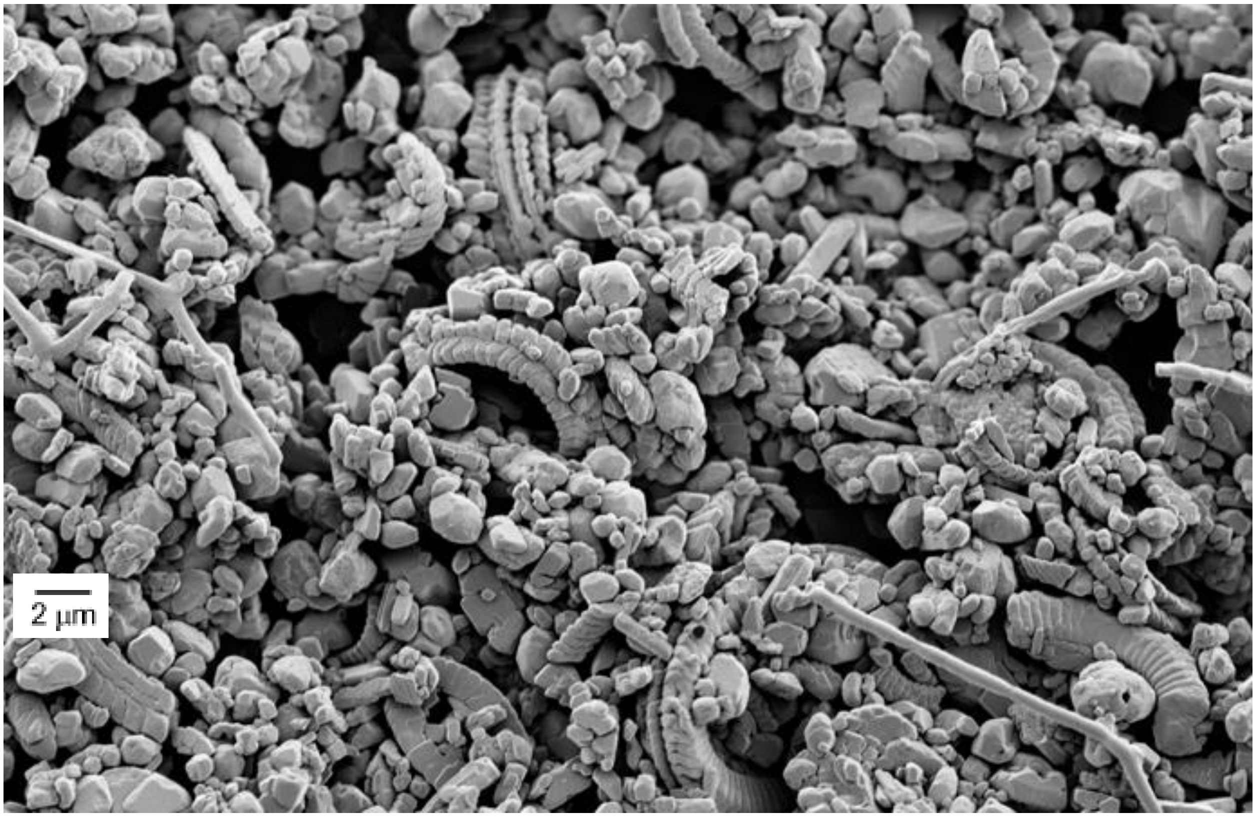


Figure 11 Scanning electron micrograph of Stevns chalk (Denmark) of Maastrichtian age, with partially and fully broken coccoliths (Fabricius, 2007)

Not only calcareous skeletal grains are present in the chalk. Also siliceous nannoplankton and microfossils occur, for instance diatomes, spicules and remains of sponges (Fabricius, 2007). The siliceous components originate from a terrestrial or coastal environment and could have been transported by wind, rivers, turbidites and even volcanic ash.

Layers of nodular chert are present in the chalk as well, also referred to as flint. These flint concretions consist of cryptocrystalline quartz crystals (Hancock, 1990; Zijlstra, 1995). Siliceous fossils contain opal-A, which turns into opal-CT when buried and these components have a high solubility and could thus equilibrate with pore water. This Si-rich water could eventually float into larger pores or fractures and precipitate there. Consequently, burial-diagenetic chert could form (Fabricius, 2007). Another way in which chert can be produced is via microbial action. Microbes could dissolve and reprecipitate opal and could also make pyrites and sulphates grow as concretions. Since the chert layers developed periodically, it is thought to be the result of orbital variations, the so-called Milankovitch astronomical cycles (Hart, 1987; Zijlstra, 1995). The production of chalk, the presence of bottom currents and the influx of terrigenous material vary periodically as a result of this cyclicity, causing changes in lithology such as the chert layers. Also the rhythmic bedding of the chalk itself as well as the presence of hardgrounds is related to this cyclicity. Hardgrounds are hardened patches (synsedimentary lithification surfaces) of chalk that result from the precipitation of new calcite crystals, caused by H_2S that oxidizes the aerobic zone of the seabed creating new carbonate ions that could combine with calcium (Scholle, 1974; Hancock, 1990; Zijlstra, 1994, 1995; Molenaar & Zijlstra, 1997). The H_2S was produced as a result of the activity of sulphite-reducing bacteria.

2.2.3 Chalk deposition

The Chalk Group has been deposited by multiple sedimentation mechanisms. The main way of sedimentation is classically thought to be the sinking and accumulation of coccoliths that came out of suspension, also referred to as a “pelagic rain” (Van der Molen, 2004; Fabricius, 2007) or “blanket deposit” (Masoumi *et al.*, 2014). Since the coccoliths were so small and light, many coccoliths reached the seabed as a part of a faecal pellet (Van der Molen, 2004). The larger components, for instance radiolarians, were able to sink to the seabed.

Coccolithophorids live in open-marine pelagic environments. During the Late Cretaceous, temperatures and sea levels were high. This is the reason why such vast amounts of chalk could have been deposited in a very large area (Van der Molen, 2004; Fabricius, 2007). Chalk deposition rates were in the order of 150 to 250 mm per thousand years (Tucker and Wright, 1990). There is still debate on the water depth at which chalk has been deposited. Ranges from hundred up to a thousand metres were proposed in the literature (Van der Molen, 2004). Kennedy (1987) mentions 300 to 600 metres as a widely quoted range. Zijlstra (1994; 1995) summarizes the outcomes of studies on this subject and states that there is no consensus. He comes up with arguments for a relatively deep depositional environment, based on the absence of benthic organisms that only live in the photic zone (Bromley, 1965) and the absence of aragonite (Hudson, 1967). On the other hand, he also refers to arguments for a very shallow depositional environment, mainly based on the presence of fossils of light-dependent organisms (Bromley, 1975, 1979; Bathurst, 1971). According to Håkansson *et al.* (1974) and Zijlstra (1995) the chalk was deposited in a relatively shallow epi-continental sea and this kind of sea has no present-day equivalents. According to all authors it is very unlikely that parts of the chalk sequence have been exposed above the sea level, since no evidence of this was found in the fossil record.

When coccolith-loaded pellets reached the seabed, they did not come out of suspension directly. The upper few millimetres constisted of a suspension of pellets in water. The uppermost part of the seabed that was solid and consisted of newly deposited coccoliths was intensely bioturbated. The majority of the animals lived in the ‘mixed zone’, see figure 12. Burrowing animals lived in the ‘transition zone’ as shown in figure 12. These burrowing animals reached a depth of circa one meter, according to Hancock (1990). Bioturbation removed most sedimentary structures and reduced the porosity of the sediments.

Recently, the general ideas on deposition mechanisms of the Chalk Group have been strongly revised. The classical theory of the settlement of calcareous ooze from suspension was reconsidered since multiple seismic discontinuities were observed within the chalk. Gravitational processes and oceanic currents are now believed to play a significant role in the deposition process of the chalk, as illustrated in figure 13. The sea floor is thought to have been very irregular and must have contained valleys, ridges, channels and even biogenic mounds. Multiple kinds of mass movements occurred, for instance slumps, turbidity currents and debris flows. Slopes occurred mainly as a result of inversion tectonics and salt movement. (Lykke-Andersen and Surlyk, 2004; Van der Molen, 2004; van der Molen *et al.*, 2005; Fabricius, 2007; Surlyk and Lykke-Andersen, 2007; Esmerode *et al.*, 2008; Surlyk *et al.* 2008; Back *et al.*, 2011).

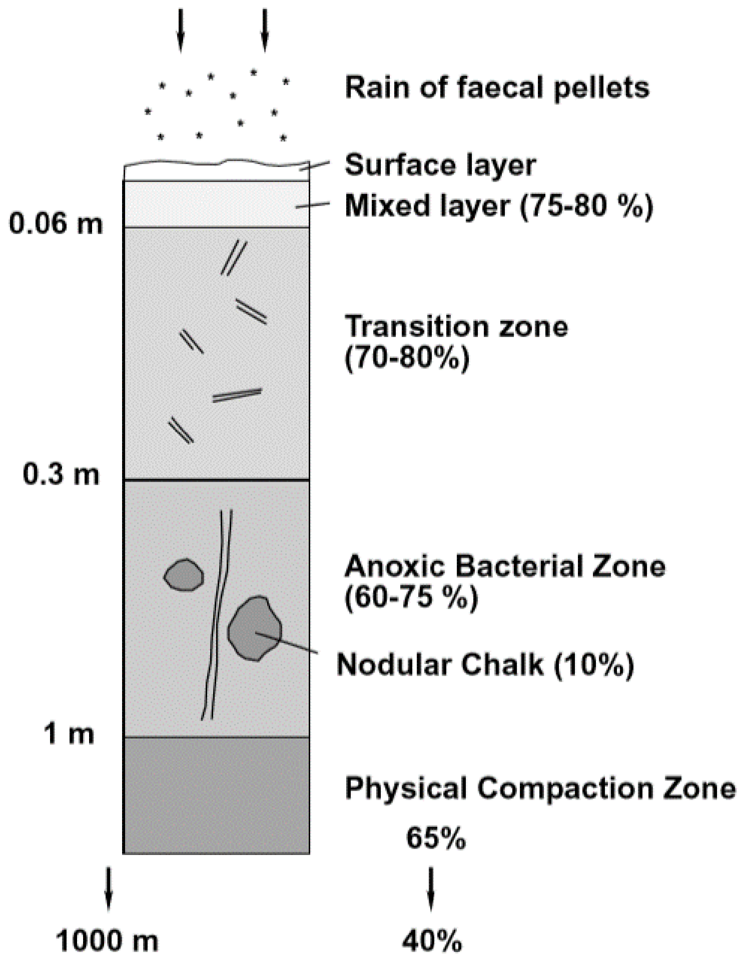


Figure 12 Typical layers in chalk at the time of accumulation, with approximate values for porosity (Hancock, 1990)

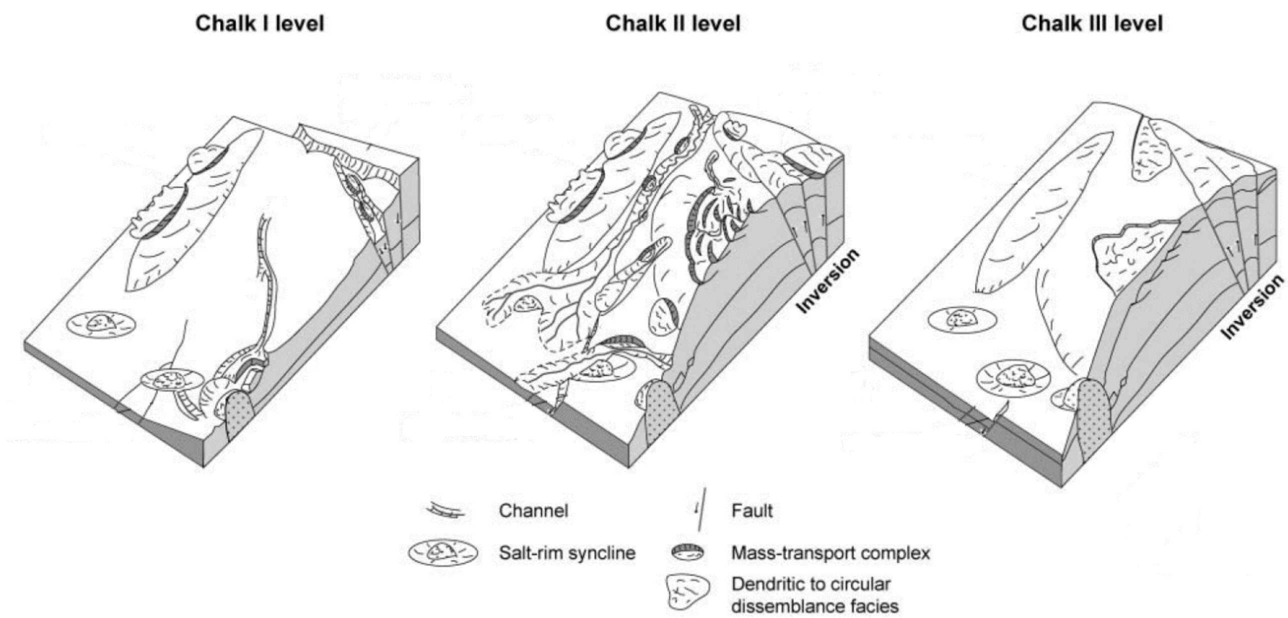


Figure 13 Schematic illustration of the sedimentary and redisposition processes that occurred during the chalk deposition (Back et al., 2011). Back et al. (2011) distinguished three different phases.

Thickness variations of chalk units could have been caused by three different processes. First, regional and local tectonic movements cause an increase (subsidence) or decrease (uplift) of accommodation space. Second, sedimentary and redeposition processes create thickness variations for instance by channel incision or slumping. The third possible explanation for thickness variations is the available supply of nutrients. A limited supply of nutrients causes a decrease in living coccolithophorids and thus a decreasing sedimentation rate of coccoliths at the sea floor. However, not much is known on this subject and whether this could have an effect on thickness variations at the scale of this study area. In addition, the coccoliths may be transported before accumulation and hence the availability of nutrients may cause thickness variations at other locations.

3. Methodology

3.1 Seismic reflection data

For this research, parts of two 3D seismic surveys were studied. The most important of these is the DEF-survey (2012), a survey of circa 150 by 80 kilometres, located in the D- and E- and F-blocks of the Dutch North Sea, see figure 14. Also a small part of the G-block is included. The spacing of the in-lines is 12 metres and 13 metres of the cross-lines. The DEF-survey consists of seismic from 0 to 10 seconds in two-way-time but only the data between approximately 1 and 3 seconds were used. Fugro acquired this DEF-survey in 2012. The second 3D seismic cube is called the Terracube Area 3 (2011) and covers the F- and G-blocks of the study area (figure 14). The part of this cube that was used for this study is about 100 by 70 kilometres large and partly overlaps the DEF-survey. The spacing for in-lines and cross-lines is 27 and 23 metres respectively. The Terracube Area 3 seismic cube stretches from 0 to 5 or 6 seconds two-way-time and again, the part between 1 and 3 seconds was used, roughly. The seismic surveys were loaded into the software Petrel by Schlumberger to visualize them. This is also the software that was used for the interpretation of the data. The SEG convention was used in all seismic data. An increase in acoustic impedance results in a negative response and a blue seismic loop. The average temporal resolution of the seismic data is circa 11 milliseconds (TWT), which results in a resolution of circa 16 to 20 metres. This is the minimal thickness that a unit needs to visualize the base and the top of this unit separately.

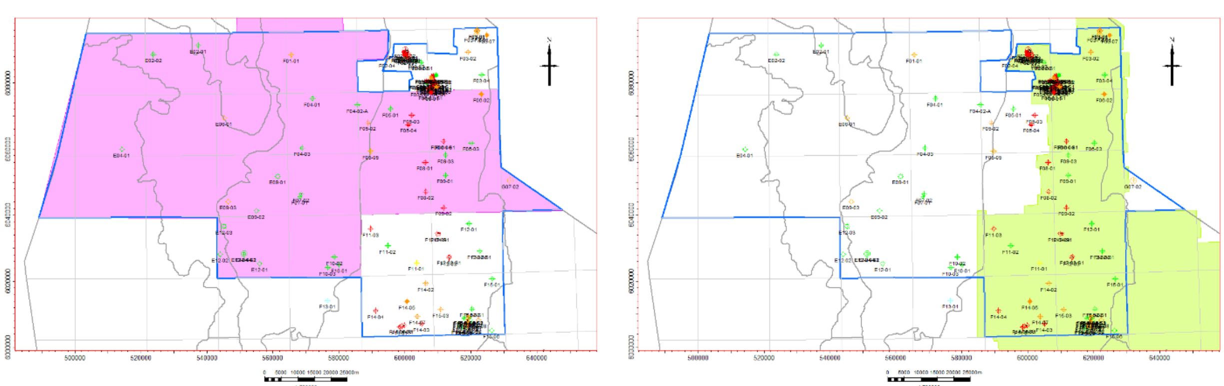


Figure 14 Locations and extent of the two seismic surveys: left the DEF-survey in pink and right the Terracube Area 3 survey in green. The outline of the study area is indicated in blue.

3.2 Well data

In the study area, 82 wells with at least some lithostratigraphic and/or biostratigraphic information on the Chalk Group are present. Also well logs were available for almost all of these wells. Two sources provided this information: the NLOG website with public information about wells that are at least five years old, and a report from Wintershall Noordzee (WINZ) with additional biostratigraphic information on 11 wells.

3.2.1 Well tops

All wells contain at least two lithostratigraphic tops. The lithostratigraphic tops are Top Chalk, Top Ekofisk formation, Top Ommelanden Formation, Top Plenus Marl Member, Top Texel Formation and Base Chalk (i.e. the top of the underlying formation at the location of the well). The depths of these formation tops were imported in Petrel to display the tops on the correct location on the seismic. An table with all used well tops is shown in the appendix.

Chronostratigraphic ‘tops’ were deduced from well reports on biostratigraphy. This information was mainly based on transitions of the occurrence of specific fossils. These reports were ‘translated’ into chronostratigraphic well tops. For multiple wells, exact depths of the transitions were absent, but ranges of depths are reported in between which the transition should take place. In these cases, the middle of such a range was used as the ‘top’ and a lower confidence level was assigned to it. Each biostratigraphic level contains three tops in Petrel, with three different confidence levels. One of these three confidence levels is applied to each top. Confidence level 1 indicates a top that is located no more than 10 metres higher or lower than the depth that is given to it. Tops with a confidence level of 2 or 3 could be 50 and 100 metres higher or lower, respectively. The biostratigraphic tops were displayed on the seismic in Petrel.

3.2.2 Well logs

Well logs were available for almost all wells in the study area. Only the density, gamma ray and sonic logs were used for this research. The sonic log was of high importance for the time-depth relations. 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 locations of these transitions. The digital well logs were imported in Petrel to tie the wells to the seismic.

3.2.3 Well-to-seismic tie

Specific time-depth relations are acquired to link the well tops to the seismic and, thus, to figure out which reflections coincide with the tops of the units (see section 3.3). For this study, mostly checkshot and Vertical Seismic Profile (VSP) data were used that were corrected by EBN. The top and the base of the Chalk Group could be recognized quite easily and could therefore be used as an indication for the correctness of the well-to-seismic tie. If a well did not contain any checkshot data, the sonic log was the most important source of time-depth information, but also the obvious top and base of the Chalk Group itself could be used to tie the wells to the seismic. The TWT and the depth of the top and the base of the chalk were read off from the seismic and the well tops. These two points were then fixed. In between, the relation between the TWT and the depth were determined by the sonic log.

3.3 Seismic interpretation

3.3.1 Paper

To become familiar with the large seismic cubes and the variety of geological elements (platform, step graben, central graben, etc.), the first interpretations were done on paper sections of a few large (50 to 75 km) west-east lines within the seismic surveys. After identification of reflection terminations, the boundaries between structural elements were determined and the most striking unconformities were marked.

3.3.2 Petrel

Subsequently, the seismic and well data were loaded in Petrel and detailed interpretations were performed. All interpretations were conducted using Petrel software.

The aim of the interpretation analysis was to identify the tops of the seven units, which are based on the chronostratigraphic stages of the Late Cretaceous and Early Tertiary, throughout the whole study area. The tops determined are the tops of the Cenomanian, Turonian, Coniacian, Santonian, Campanian, Maastrichtian and Danian. When the locations of these tops are known, the ages of tectonic events could be assigned. To achieve this, horizons were created for all tops of the units in Petrel. The interpretation of a particular unit started at the locations of wells that included the most reliable biostratigraphic information on the top of this unit. A specific seismic reflection was assigned to the top of the unit at these locations. Between these locations, the reflection was interpreted when reliable. The top and base of the chalk were already mapped in the study area by EBN and TNO.

To interpret a top of a unit on the seismic, 2D seeded autotracking was used on a few in-lines and cross-lines. Afterwards, the horizon of this top was autotracked in three dimensions, to fill up the gaps. A quality check was done after the 3D autotracking and errors were corrected using the eraser.

The following settings and techniques were used to produce a reliable and accurate interpretation.

- Different colour scales. Mostly the (default) seismic scale was used, which comprises red, white and blue colours. In addition, the greyscale was useful to visualize the locations of faults and unconformities.
- Different vertical exaggerations. For a clear visualization of the lateral extent of a reflection, the seismic was stretched in a vertical direction, by using a Z-scale of for example 15 to 20.
- Flattening of an under- or overlying surface was useful when picking a seismic reflection. Flattening of the Top Chalk emphasized the lateral extent of the underlying reflections.

3.3.3 Paleoscan

PaleoScan software was tested. It aims to compute geologic time models directly from the seismic information. Paleoscan can perform automatic sequence stratigraphy interpretation on a seismic cube, by making many seismic horizons. This was tested on the seismic cubes in the study area. The results produced were incorrect at many locations and very chaotic due to the vast amount of horizons the software generates. However, at some locations the results were useful as a check of the extent of a specific reflection.

3.3.4 Attributes

Specific characteristics of the seismic data itself provided information on the extent of the reflections. For instance, the effect of 'tuning' gives information on the vicinity of a reflection termination. If a seismic unit becomes thinner and eventually disappears, the amplitude of the seismic response will be clearly higher around the location where the unit is at its tuning thickness, as visible in figure 15.

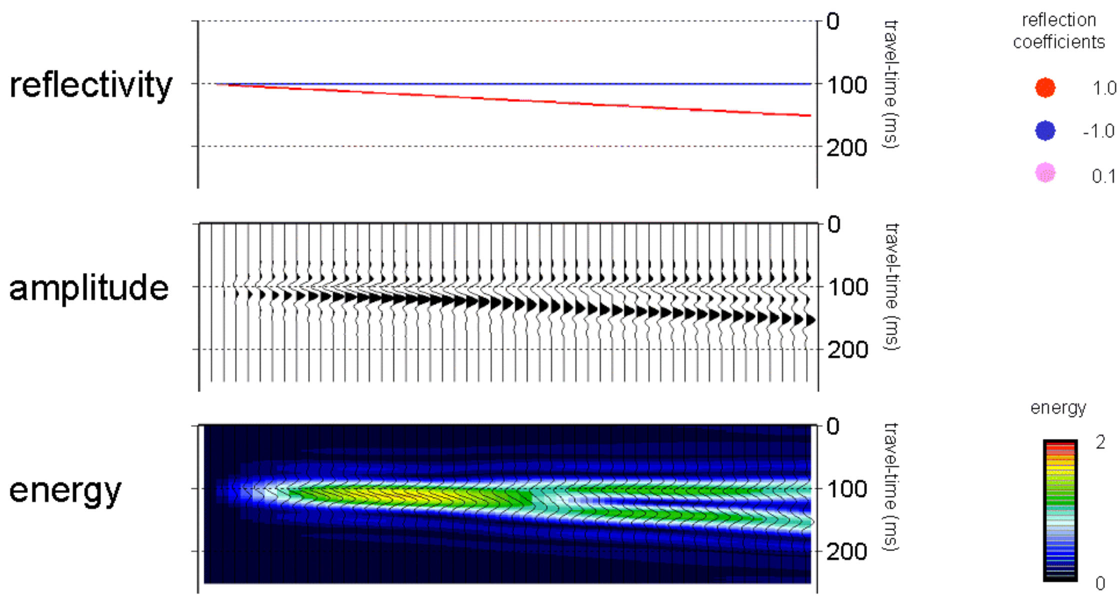


Figure 15 Schematic figure showing an example of the tuning effect. The reflectivity of a leftward thinning unit is shown, as well as the amplitude of the seismic signal and the energy. From: http://www.freeusp.org/RaceCarWebsite/TechTransfer/OnlineTraining/AVO_Tune/AVO_Tune.html

After interpreting the tops of the units, these horizons were checked using attribute extractions. Multiple attributes were extracted at the surfaces of the Top Chalk and Base Chalk, for instance Root Mean Square Amplitude and Average Negative Amplitude. Anomalies (clear edges or lines) on these attribute maps were compared to the seismic to understand if there could be a relation with a tuning layer. If so, the anomaly was used to define the boundaries of the interpreted horizons. Attribute anomalies could also visualize lithology changes.

Subsequently, the interpreted horizons were gridded into surfaces. With these surfaces, thickness maps of the seismic units were produced.

4. Results and interpretations

4.1 Description of the seismic units

In order to constrain the geological history of the chalk sequence in the study area, seven units were interpreted where possible. These units are based on the seven chronostratigraphic stages of the Late Cretaceous and Early Tertiary. The seismic character of the units is described in table 1 and a description of the seismic reflections, which form the tops of the units can be found in table 2. Maps of the areal extent of the units and the depth of the tops were made from the interpretations, as well as time-thickness maps. The thickness map of the entire Chalk Group sequence is shown in figure 31.

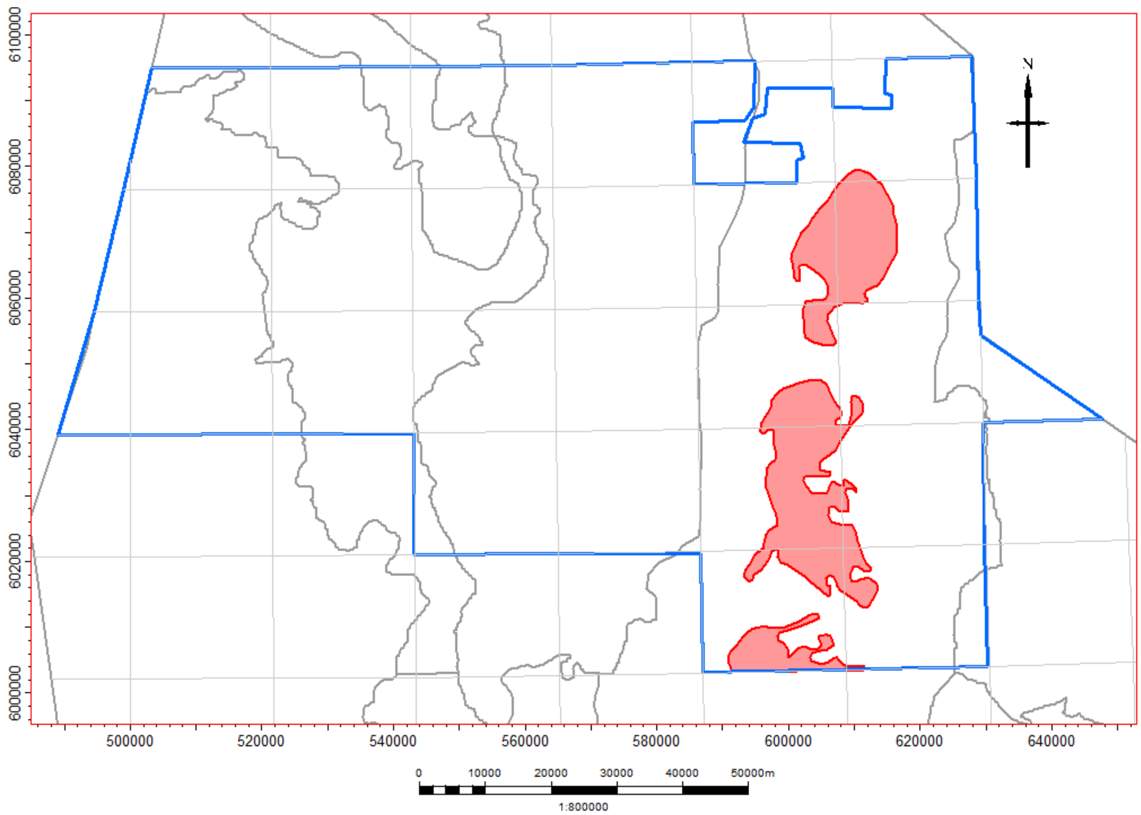


Figure 16 Map with the outline of the areas where the Chalk Group is absent (red areas). The blue line indicates the outline of the study area and the grey lines the boundaries of the structural elements.

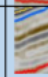
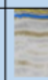
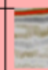
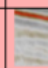
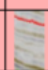
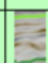
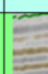
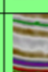
Stage	Nr	Location seismic facies	Reflection configuration	Reflection continuity	Reflection amplitude and frequency	Lateral relationships	Extent in the study area	Depth range	Image
7: DANIAN	(a)	CP, ESP/ESH, SG, DCG and SGP	Only 1 reflection thick, see description Top Danian for details	Very continuous	High amplitude	In SG merges into 2 and if not present, truncated by post-chalk deposits	Everywhere except from eastern CP, western ESP and ESH, small part of SG, large parts of DCG and on and around salt structures.	1000-2200 ms	
	(b)	Parts of SG and ESP	Maximum 3 reflections thick, parallel	Very continuous to not very continuous because of thin units	Low to medium amplitude	In west and east merges into (a)		1600-1900 ms	
6: MAASTRICHTIAN	(c)	western CP	Parallel, folded reflections	Very continuous	Medium amplitude	In east truncated by Top Chalk	Everywhere except from large parts of DCG and on and around salt structures.	1100-1700 ms	
	(d)	eastern ESP/ESH and SG	Reflections are not parallel at all, some onlap structures. Also bifurcations and merging of reflections (local thickening of units)	Alternation of continuous and non-continuous reflections	High amplitude	In west truncated by Top Chalk In east bounded by salt		1600-1900 ms	
	(e)	DCG and SGP	Upper part contains parallel reflections, lower part also truncated reflections in DCG but less visible because transparent	Alternation of continuous and non-continuous reflections	Low amplitude, transparent	In west bounded by salt In middle DCG truncated by Top Chalk		1500-2000 ms	
5: CAMPANIAN	(f)	CP and western ESP/ESH	Only 1 or 3 reflections thick, see description Top Campanian for details	Very continuous	Medium amplitude	In east merges into (g)	Everywhere except from parts of ESP, SG, middle part of DCG and on and around salt structures.	1200-1800 ms	
	(g)	eastern ESP/ESH and western SG	Not parallel, many onlap structures but also truncations	Non-continuous reflections	Alternation of low and high amplitude reflections	In west merges into (f) In east merges into (h)		1600-1800 ms	
	(h)	eastern SG and western DCG	Quite parallel reflections, but at some locations chaotic seismic response in lower part	Quite continuous, but lower part non-continuous	Low to medium amplitude	In west merges into (g) In east truncated by Top Chalk		1800-2300 ms	
	(i)	SGP	Parallel reflections, folded at many locations	Quite continuous, but also truncated reflections present	Medium amplitude	In west bounded by salt		1700-2100 ms	
4: SANTONIAN	(j)	Western SG and northwestern DCG	Only 1 reflection thick, see description Top Santonian for details	Quite continuous	Low amplitude	In west bounded by salt In east truncated by Campanian (h)	Not known as result of limited biostratigraphic information. Definitely present in parts of DCG and SGP	1800-2200 ms	
	(k)	Eastern SG, SGP and eastern DCG	Mostly parallel reflections, some onlap structures	Quite continuous	Medium to high amplitude, medium frequency	In west bounded by salt		1900-2100 ms	
3: CONIACIAN	(l)	eastern SG and western and southeastern DCG	Quite parallel reflections but also onlap structures at the edges Depth of Top Turonian at some locations not known so thickness not known	Not very continuous	Alternation of low and high amplitudes, medium to high frequency	In west onlap onto Turonian In middle disrupted by salt In east onlap onto pre-chalk deposits	Not known as result of limited biostratigraphic information. Definitely present in parts of DCG and SG	1800-2200 ms	
2: TURONIAN	(m)	CP	Parallel reflections	Very continuous	Medium to high amplitudes, high frequency	In west partly bounded by salt In east merges into (n)	Everywhere except from parts of ESH, CP, large parts of DCG and on and around salt structures.	1100-1700 ms	
	(n)	ESP/ESH, western SG	Mostly parallel but also onlap structures	Very continuous	High amplitudes, 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	Quite continuous	High amplitude, medium frequency	In west merges into (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 for details	Very continuous	Low to high amplitude	In between disrupted by salt tectonics In ESH onlap onto Base Chalk In middle part DCG onlap onto pre-chalk deposits	Everywhere except from ESH, middle part DCG and on and around salt structures.	1200-2200 ms	
	(q)	southeastern DCG	Parallel reflections	Quite continuous	Low to medium amplitude, medium to high frequency	In west bounded by salt		1700-2300 ms	

Table 1 Overview of the identified seismic sequences, shown in stratigraphic order, based on the biostratigraphic subdivision

Horizon	Extent of the horizon in the study area	Reflection phase	Reflection continuity	Reflection amplitude	Lateral relationships	Depth range
TOP DANIAN	Everywhere except from eastern CP, western ESP and 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	In SG merges into 2 and if not present, truncated by post-chalk deposits	1000-2200 ms
TOP MAASTRICHTIAN	Everywhere except from large parts of DCG and on and around salt structures.	Red (negative, trough)	Continuous	Low to very high amplitude (tuning effect)	In east truncated by Top Chalk	1100-1700 ms
TOP CAMPANIAN	Everywhere except from part of ESH, southern SG, middle part of DCG and on and around salt structures.	Red (negative, trough)	Not very continuous, especially in SG and ESP/ESH	Low to medium amplitude	In east merges into number 7	1200-1800 ms
TOP SANTONIAN	Not known as result of limited biostratigraphic information. Definitely present in parts of DCG and SGP	Red (negative, trough)	Not continuous	Low to medium amplitude	In west bounded by salt In DCG truncated by Campanian (number 8)	1800-2200 ms
TOP CONIACIAN	Not known as result of limited biostratigraphic information. Definitely present in parts of DCG and SG	Blue (positive, peak)	Not continuous	Low to medium amplitude	In west onlap onto Turonian In middle disrupted by salt	1800-2200 ms
TOP TURONIAN	Everywhere except from parts of ESP, large parts of DCG and on and around salt structures.	Blue (positive, peak)	Quite continuous	Mostly low, but up to high amplitude locally	In west partly bounded by salt In east merges into number 14	1100-1700 ms
TOP CENOMANIAN	Everywhere except from ESH, middle part DCG and on and around salt structures.	Blue (positive, peak)	Continuous	Varying from low to high amplitude	In between disrupted by salt tectonics In ESH onlap onto Base Chalk	1200-2200 ms
BASE CHALK	Everywhere in the study area	Red (negative, trough)	Very continuous	High to very high amplitude	Present everywhere in the study area	1300-2300 ms

Table 2 Description of the seismic reflections that represent the tops of the biostratigraphic units

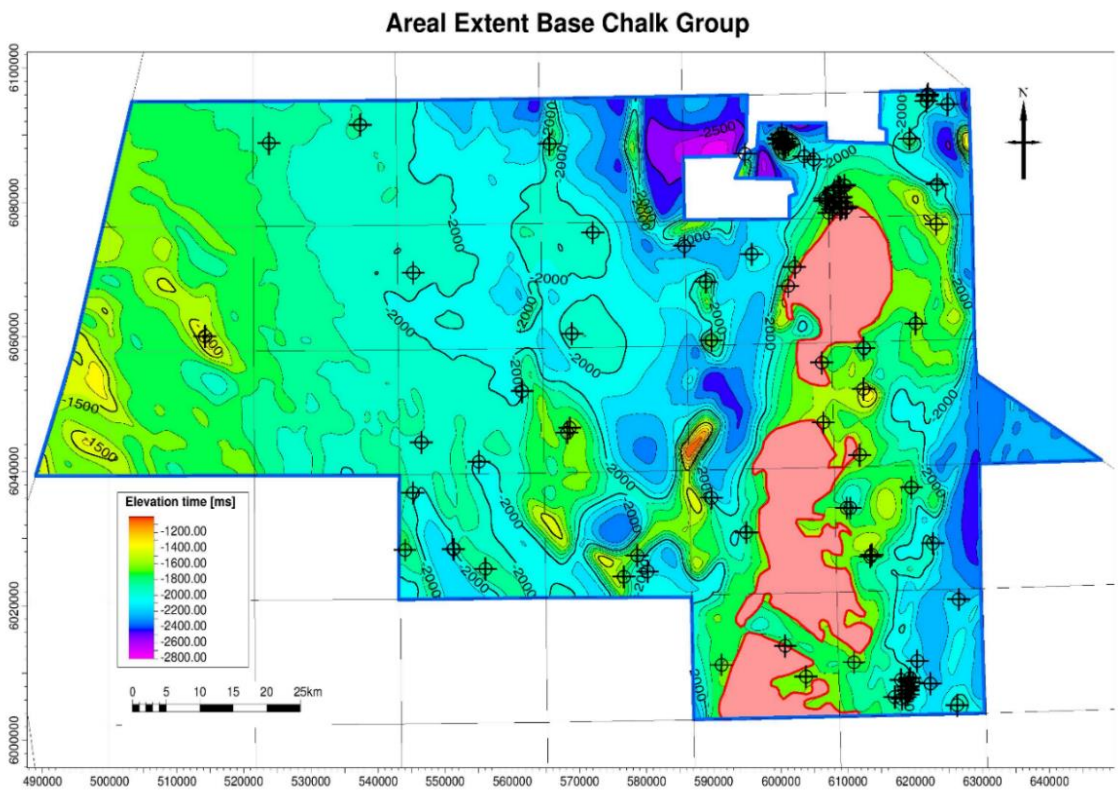


Figure 17 Areal extent of the Base Chalk horizon. The elevation of the Base Chalk is measured in two-way time (milliseconds). The blue line indicates the outline of the study area and the areas filled in red are the areas where the Chalk Group is absent. The shown wells contain information on the depth of this horizon. The same explanation of elements applies to the other figures in this report.

4.1.1 Unit 1: Cenomanian (Texel Formation)

The oldest unit of the Chalk Group represents the Cenomanian sequence, that is part of the Texel Formation. The age of this sequence ranges from 100.5 Ma to 93.9 Ma, according to the International Commission on Stratigraphy (Cohen *et al.*, 2013). The areal extent of the base and top of this sequence are outlined in figure 17 and 18, respectively. The Plenus Marl Member could be the upper part of the Cenomanian sequence (Jarvis *et al.*, 1988), although some authors assigned the Plenus Marl Member to the Early Turonian (Jefferies, 1963; Lieberkind *et al.*, 1982; Crittenden *et al.*, 1991). The Chalk Group is present everywhere in the study area, except for a few 'patches' in the Dutch Central Graben, where all units are absent (figure 16). The Cenomanian unit is absent in a part of the Elbow Spit Platform that coincides roughly with the Elbow Spit High, and in a large part of the Dutch Central Graben (figure 18). The Cenomanian shows onlap onto pre-chalk deposits here. The reflection of the Base Chalk is very continuous and of high amplitude (table 2). Unit 1 is generally very thin and comprises mostly of only one reflection (table 1 and figure 19). The southeastern Dutch Central Graben is an exception, where the thickness of the Cenomanian reaches a maximum of 5 reflections. The Top Cenomanian reflection could be classified as continuous and the amplitude varies throughout the study area from low to high.

4.1.2 Unit 2: Turonian (Ommelanden Formation)

The second unit represents the basal unit of the Ommelanden Formation and is of Turonian age, approximately 93.9 Ma to 89.8 Ma (Cohen *et al.*, 2013). Figure 20 shows the areal extent of unit 2. The Turonian sequence shows onlap onto pre-chalk deposits at a part of the Elbow Spit High and at the Dutch Central Graben. It is truncated by Late Campanian/Early Maastrichtian deposits in the middle of the Step Graben. The seismic reflections within unit 2 are mostly very continuous and amplitudes are medium to high (table 1). The Turonian unit is thickest in the southwestern part of the study area and becomes gradually thinner towards the northeast (figure 21), with an exception between the Elbow Spit Platform and the Step Graben. The Top Turonian reflection has medium amplitude in the largest part of the study area but could also be high, locally (table 2).

4.1.3 Unit 3: Coniacian (Ommelanden Formation)

Unit 3 comprises the Coniacian sequence, with an age from 89.8 Ma to 86.3 Ma (Cohen *et al.*, 2013). As shown in figure 22, which visualize the areal extent of unit 3, it is only present in a very limited part of the study area. However, this does not mean that unit 3 is not present in the rest of the study area. It means that the Top Coniacian could not be interpreted there. This is the result of a lack of well control on biostratigraphy and/or a less continuous or transparent seismic response, that obstructed continuation of the seismic reflection representing the Top Coniacian. However, it is known that the Coniacian is very thin or absent on the Cleaverbank Platform. This is deduced from interpretations of other units. The seismic character of unit 3 is an alternation of reflections with low and high amplitudes, that are generally not very continuous (table 1), the Top Coniacian included (table 2).

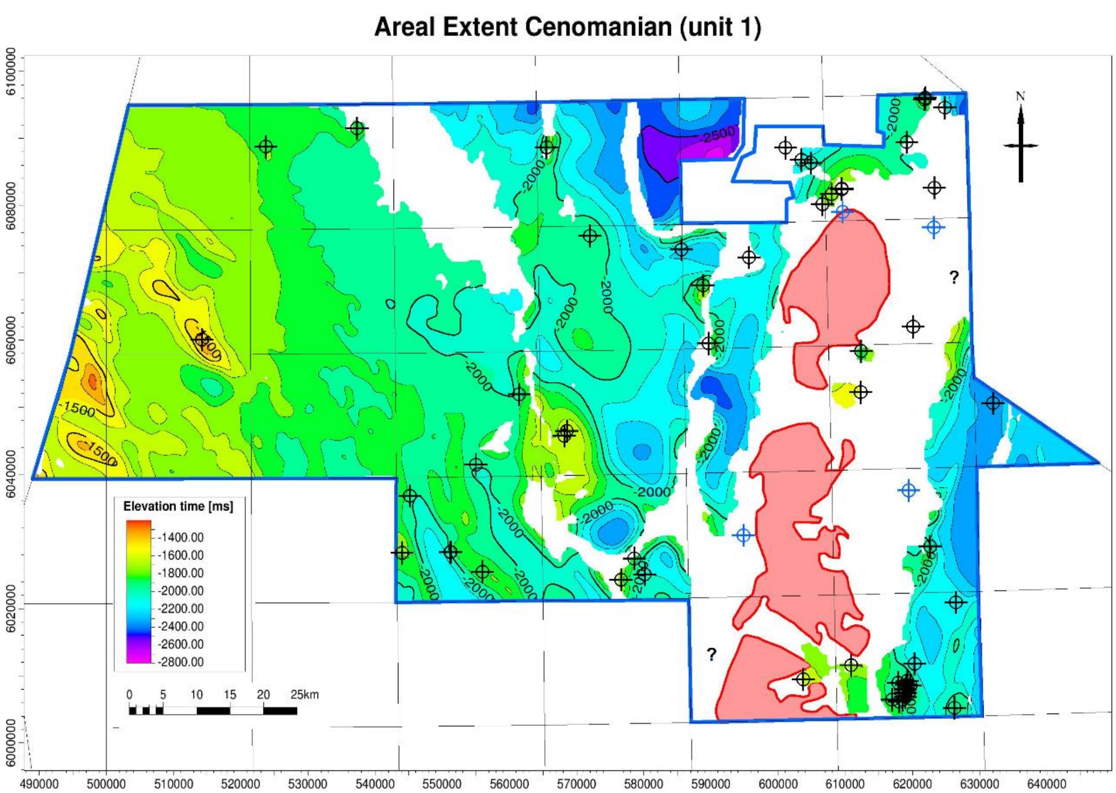


Figure 18 Areal extent of the Cenomanian unit. The elevation of the Top Cenomanian is measured in two-way time (milliseconds). Black coloured wells contain information on the presence and/or depth or thickness of the unit. Blue coloured wells indicate that the unit is present but the unit could not be interpreted on seismic because of a very small thickness or a low seismic quality (for instance a result of salt presence) or non-continuous seismic reflections. The blue line indicates the outline of the study area and the areas filled in red are the areas where the Chalk Group is absent. The question marks indicate some locations where no interpretation was possible due to a lack of information or limited seismic quality. The same explanation of elements applies to the other areal extent maps as well as the thickness maps in this report.

Thickness Cenomanian (unit 1)

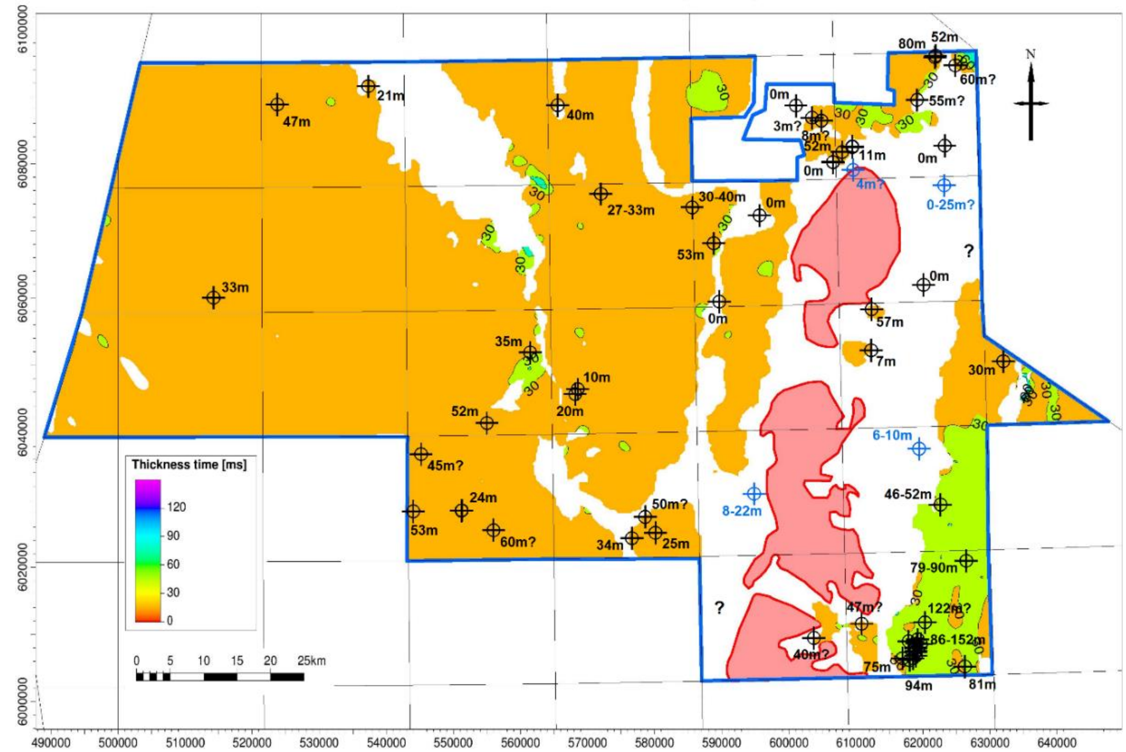


Figure 19 Thickness map of the Cenomanian unit in two-way time (milliseconds). Thicknesses derived from wells in metres are noted next to the well. This also applies to the other thickness maps in this report.

Areal Extent Turonian (unit 2)

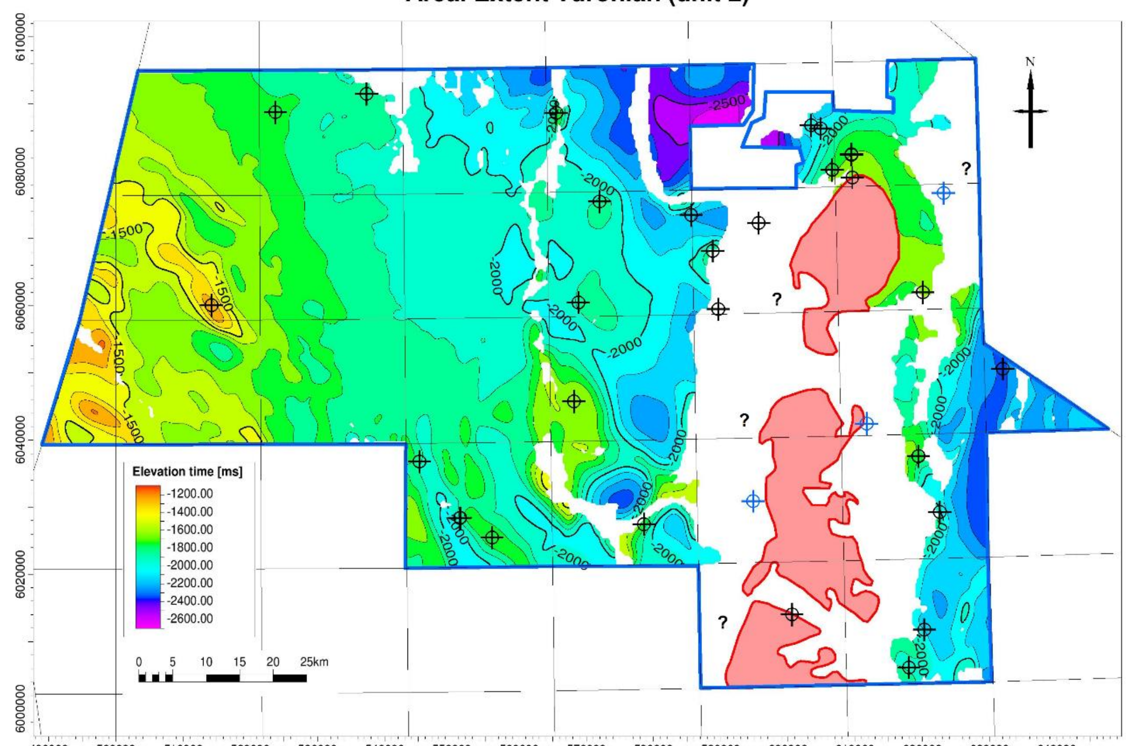


Figure 20 Areal extent of the Turonian unit with the elevation of the Top Turonian

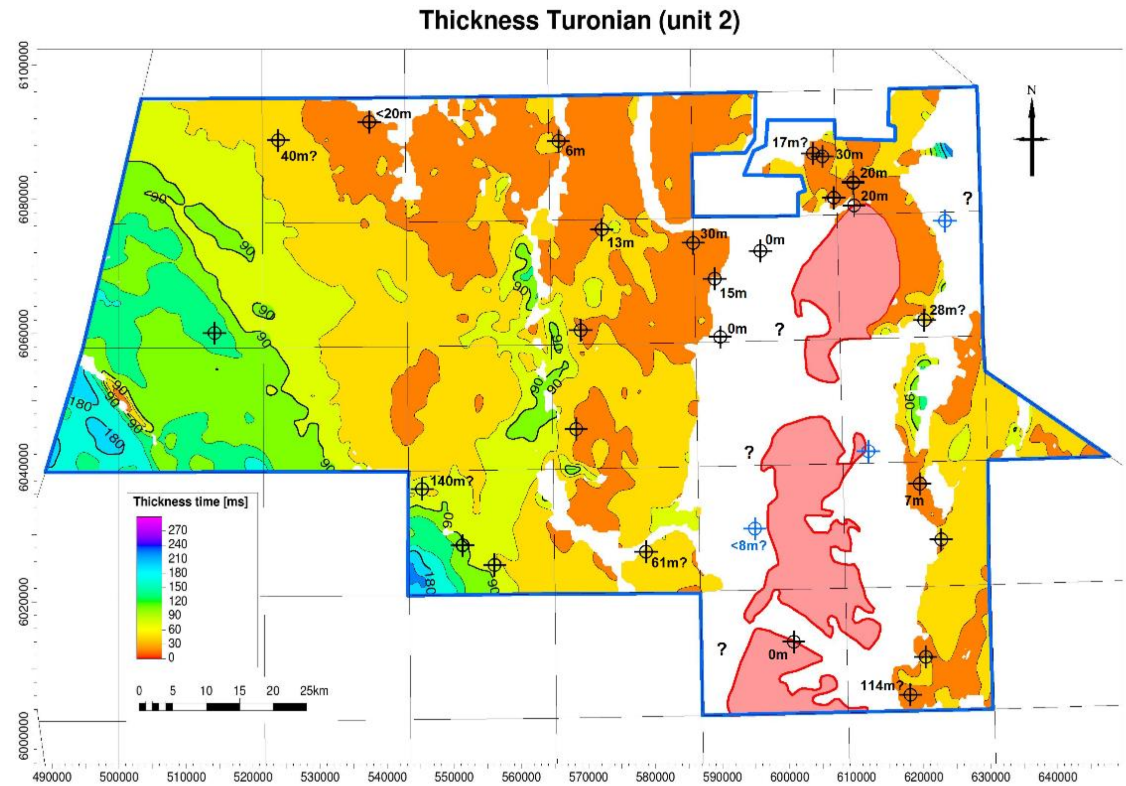


Figure 21 Thickness map of the Turonian unit in two-way time (milliseconds)

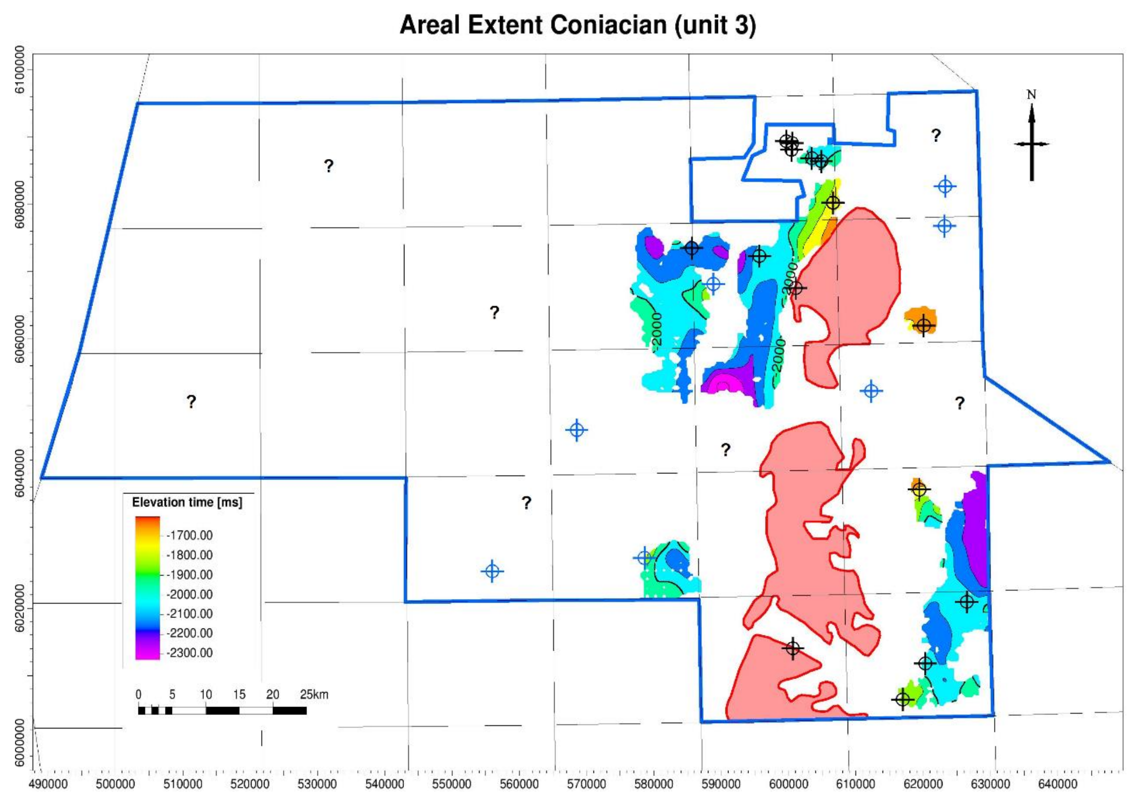


Figure 22 Areal extent of the Coniacian unit with the elevation of the Top Coniacian

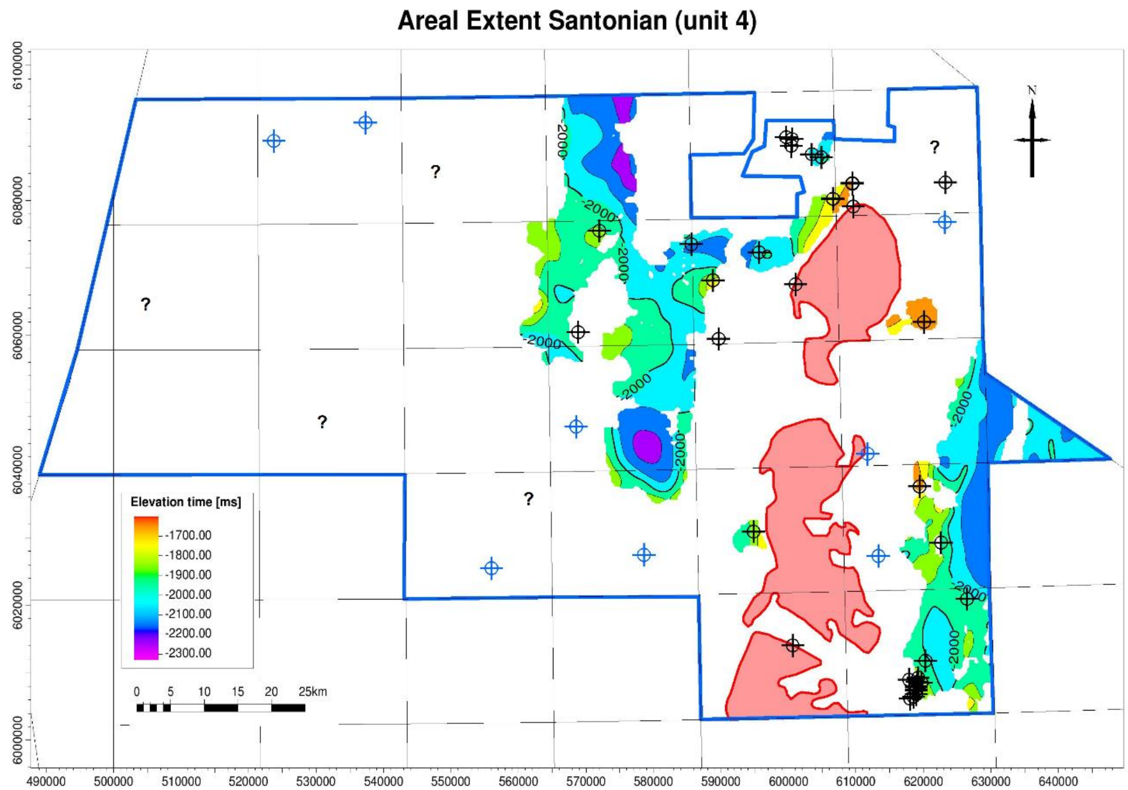


Figure 23 Areal extent of the Santonian unit with the elevation of the Top Santonian

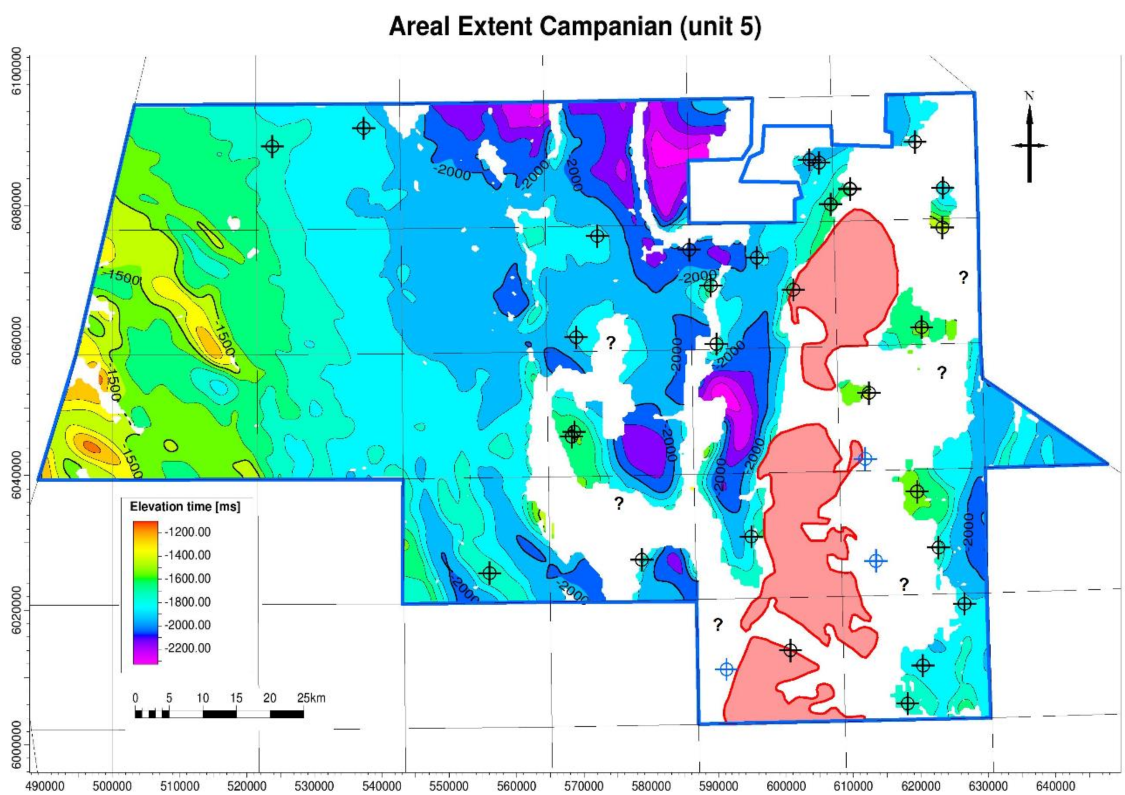


Figure 24 Areal extent of the Campanian unit with the elevation of the Top Campanian

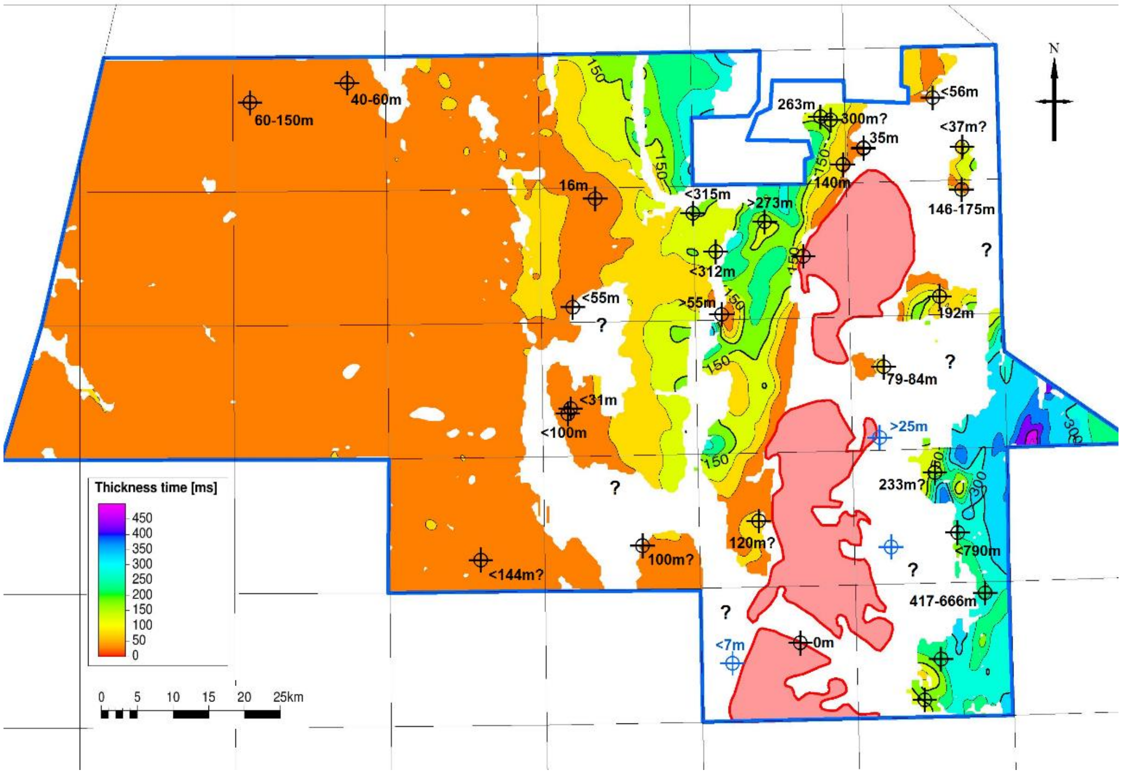


Figure 25 Thickness map of the Coniacian to Campanian units in two-way time (milliseconds)

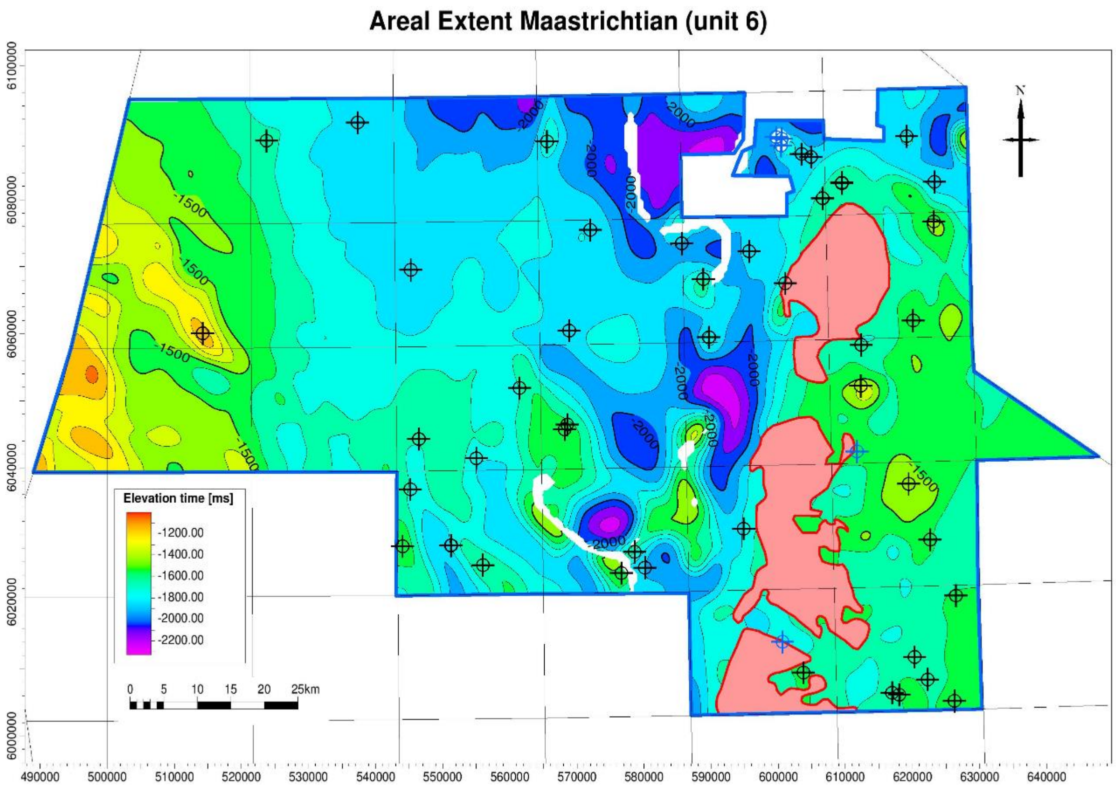


Figure 26 Areal extent of the Maastrichtian unit with the elevation of the Top Maastrichtian

Thickness Maastrichtian (unit 6)

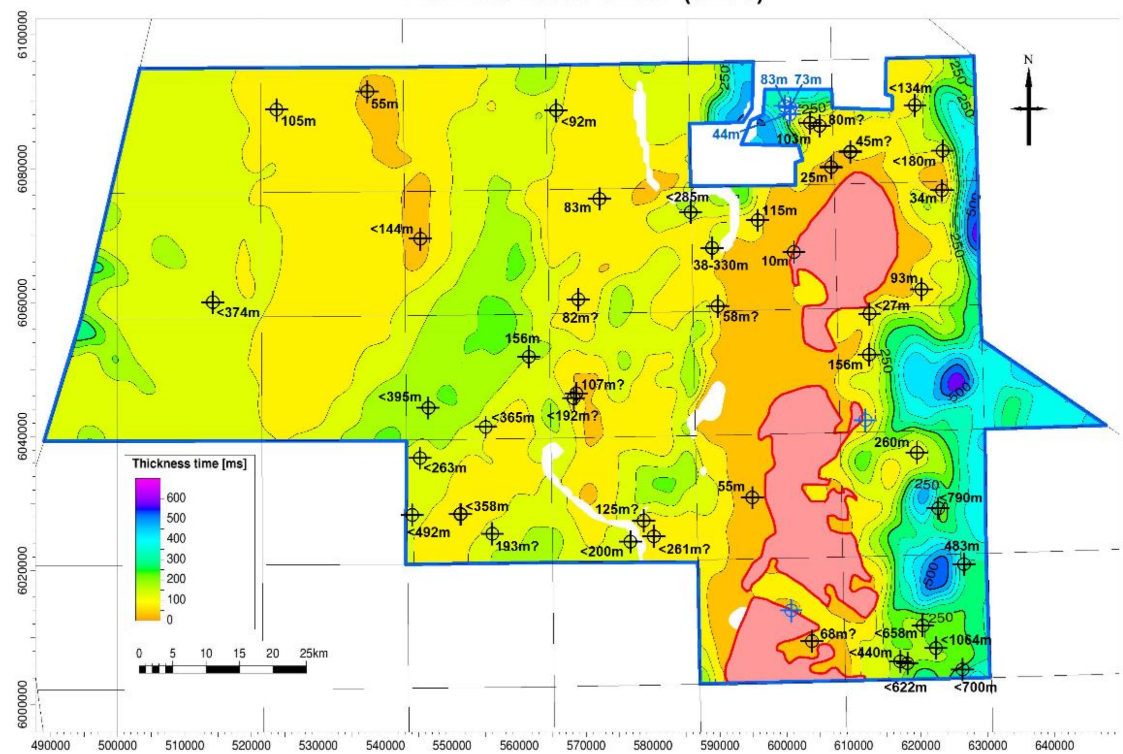


Figure 27 Thickness map of the Maastrichtian unit in two-way time (milliseconds)

Areal Extent Danian (unit 7)

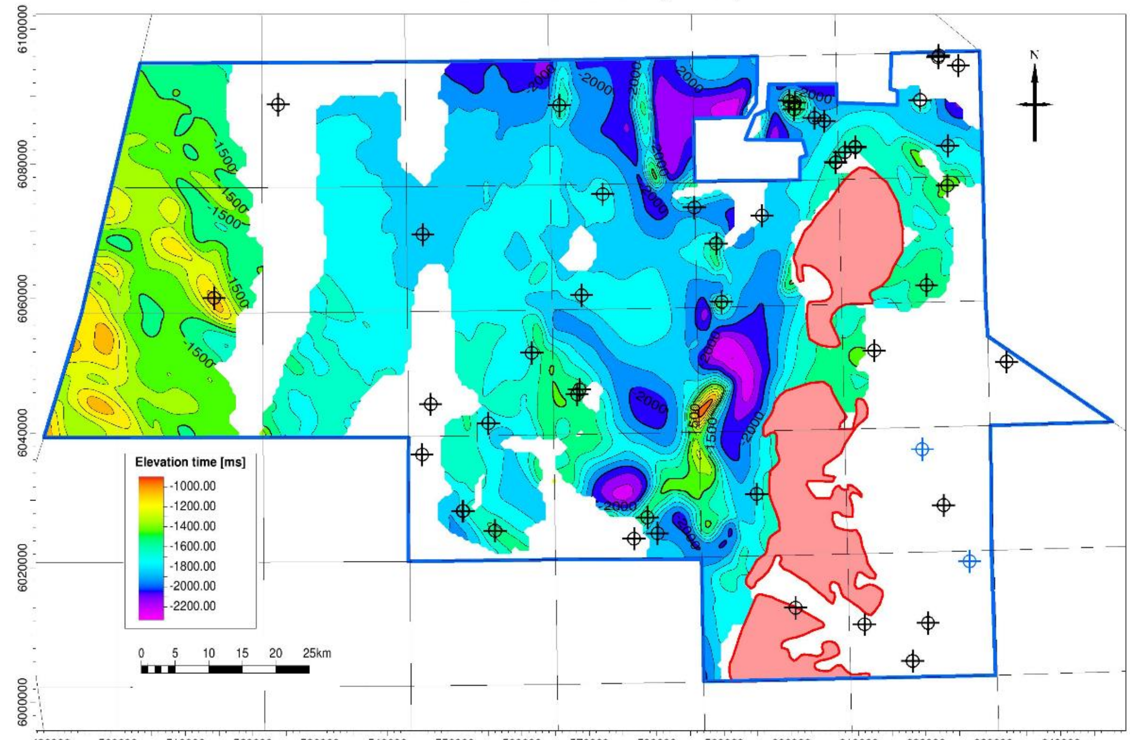


Figure 28 Areal extent of the Danian unit with the elevation of the Top Danian

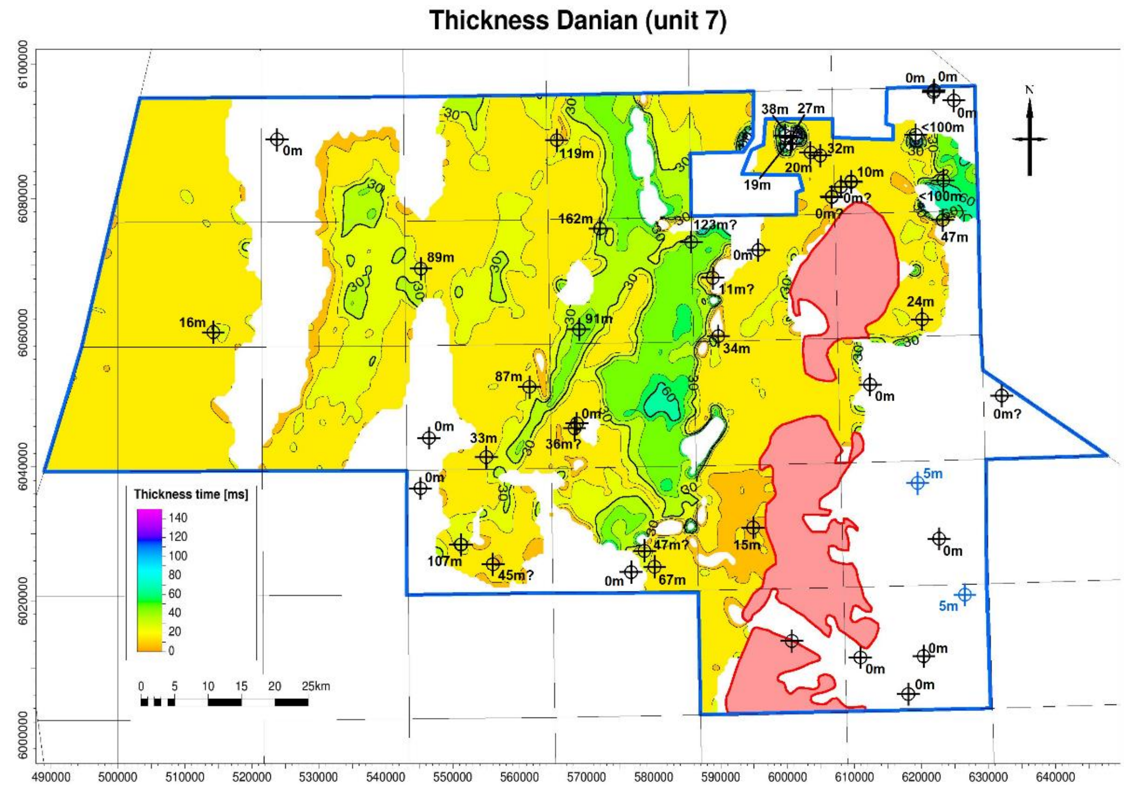


Figure 29 Thickness map of the Danian unit in two-way time (milliseconds)

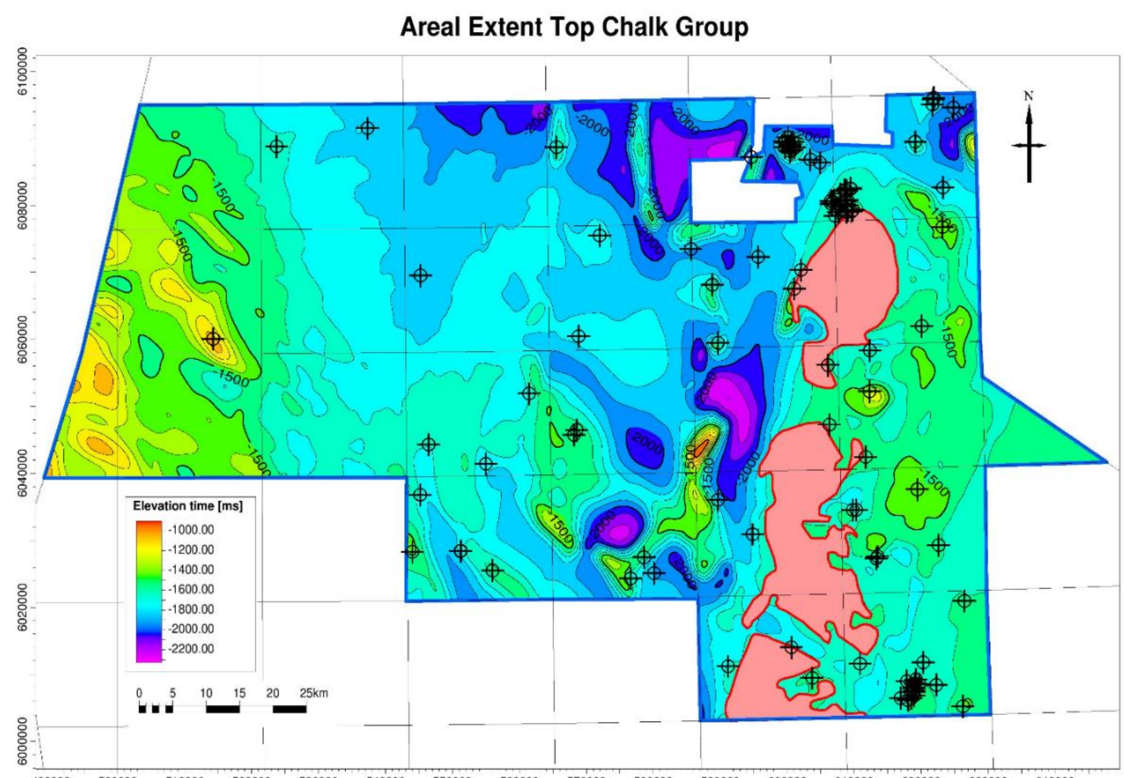


Figure 30 Areal extent of the Top Chalk horizon, elevation measured in two-way time (milliseconds)

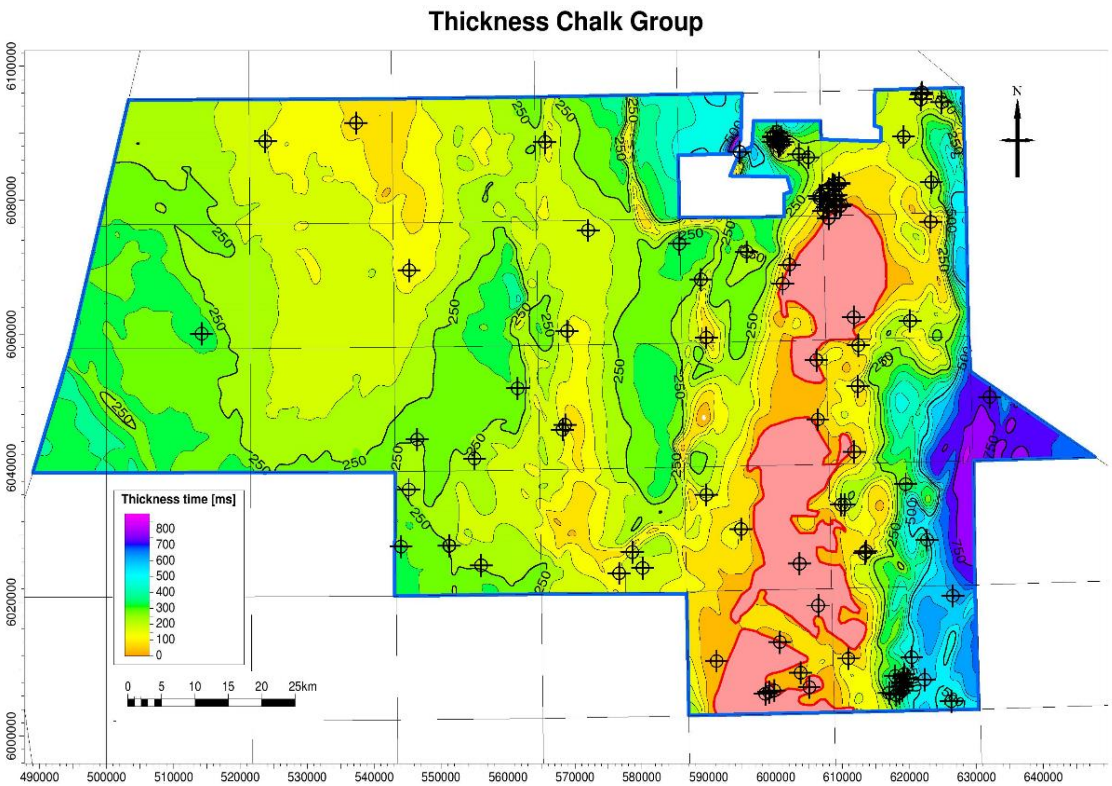


Figure 31 Thickness map of the complete Chalk Group in two-way time (milliseconds)

4.1.4 Unit 4: Santonian (Ommelanden Formation)

With an age of 86.3 Ma to 83.6 Ma (Cohen *et al.*, 2013), unit 4 comprises the Santonian sequence. Similar to unit 3, the areal extent of the Top Santonian is very limited (figure 23). This is again a result of a limited seismic response, in combination with a lack of biostratigraphic well control. The seismic character of unit 4 is quite similar to unit 3, with varying amplitudes, mostly low (tables 1 and 2). However, the continuity of the reflections is generally somewhat higher than those of unit 3.

4.1.5 Unit 5: Campanian (Ommelanden Formation)

Unit 5 coincides with the Campanian sequence that was deposited between 83.6 Ma and 72.1 Ma (Cohen *et al.*, 2013). In contrast to units 3 and 4, the Campanian unit does cover a large part of the study area (figure 24). The gaps in figure 24 illustrate the locations where it was not deposited or eroded. In this case, the top of the unit is absent in parts of the Step Graben and a large part of the Dutch Central Graben. Campanian seismic reflections are mostly of low or medium amplitudes, although some higher amplitude reflections occur in the eastern Elbow Spit Platform and Elbow Spit High and in the western Step Graben (tables 1 and 2). In these parts, reflections are not continuous, while in the rest of the study area, reflections of unit 5 are quite continuous. The thickness of the combination of units 3, 4 and 5 is shown in figure 25. It is clearly very thin in the western part of the study area and thicker in the eastern Step Graben and the Dutch Central Graben.

4.1.6 Unit 6: Maastrichtian (Ommelanden Formation)

Unit 6 is the youngest unit of the Ommelanden Formation. It is of Maastrichtian age, hence from 72.1 Ma to 66.0 Ma in age (Cohen *et al.*, 2013). Figure 26 displays the distribution of unit 6. Except from the parts of the Dutch Central Graben where the Chalk Group is absent, the Maastrichtian sequence is present in the entire study area. It extends further in the Dutch Central Graben than all other units. Seismic reflections of unit 6 contain the whole range of amplitudes, from low to high (table 1). The continuity of these reflections alternates from high to low. This continuity variation is probably the result of the fact that the Maastrichtian is a relatively thick sequence in a large part of the study area as well as a result of sedimentary or redeposition structures like slumps and channels. The Maastrichtian unit is the thickest unit and is thickest on the Schill Grund Platform and the eastern Dutch Central Graben. The top of the Maastrichtian is continuous and the amplitude varies from low to very high. These very high amplitudes are the result of the tuning effect, explained in section 3.3.

4.1.7 Unit 7: Danian (Ekofisk Formation)

Unit 7 is of Danian age (Early Tertiary), from 66.0 Ma to 61.6 Ma (Cohen *et al.*, 2013). The top coincides with the top of the Chalk Group if present (figure 30). The Top Danian is present everywhere in the study area, except from the chalkless parts in the Dutch Central Graben and the locations where also the Top Maastrichtian was removed by erosion (figure 28). The Danian consists of only 1 reflection, with parts of the Elbow Spit Platform, the Step Graben and the northeastern Dutch Central Graben as exceptions (figure 29). At these locations, the Danian unit is thicker and amplitudes are low to medium. In the rest of the study area, the reflection has a high amplitude and is very continuous.

4.2 Overview interpretations

The tops of seven chronostratigraphic units were interpreted throughout the study area where a reliable interpretation was possible. The interpretations are described and illustrated in section 4.3 for each structural element. To give an overview of the interpretations in the whole study area, figure 32 and 33 show two west-east lines through the different structural elements. The upper section of both figures is the general seismic section with a seismic (default) colour scheme (red, blue and white). The middle section has a greyscale colour scheme and shows the interpretations of the unit-tops as dotted lines. The lower section is the same section with a flattened Top Chalk, and a seismic (default) colour scheme.

When the top of a seismic unit is not displayed here, it was not interpreted at this specific location. This could either mean that it was not present at the locations, or that is could not be interpreted because of a lack of biostratigraphic well control of low seismic quality that obstructed the interpretation from other regions. It is expected that not all units are present throughout the whole study area as a result of erosion or non-deposition.

A striking feature is the large salt wall between the Step Graben and Dutch Central Graben. The chalk is locally absent on top of this salt wall. The Chalk Group is also absent in the central part of the Dutch Central Graben, as visible in the two sections. The variable thickness of the chalk is also remarkable. In the western part of the study area, the thickness is quite uniform (circa 300 to 400 ms TWT), except the very thin sequence on the Elbow Spit High. In the eastern part, the chalk is much thicker on the Schill Grund Platform and parts of the Dutch Central Graben (up to 750 ms TWT).

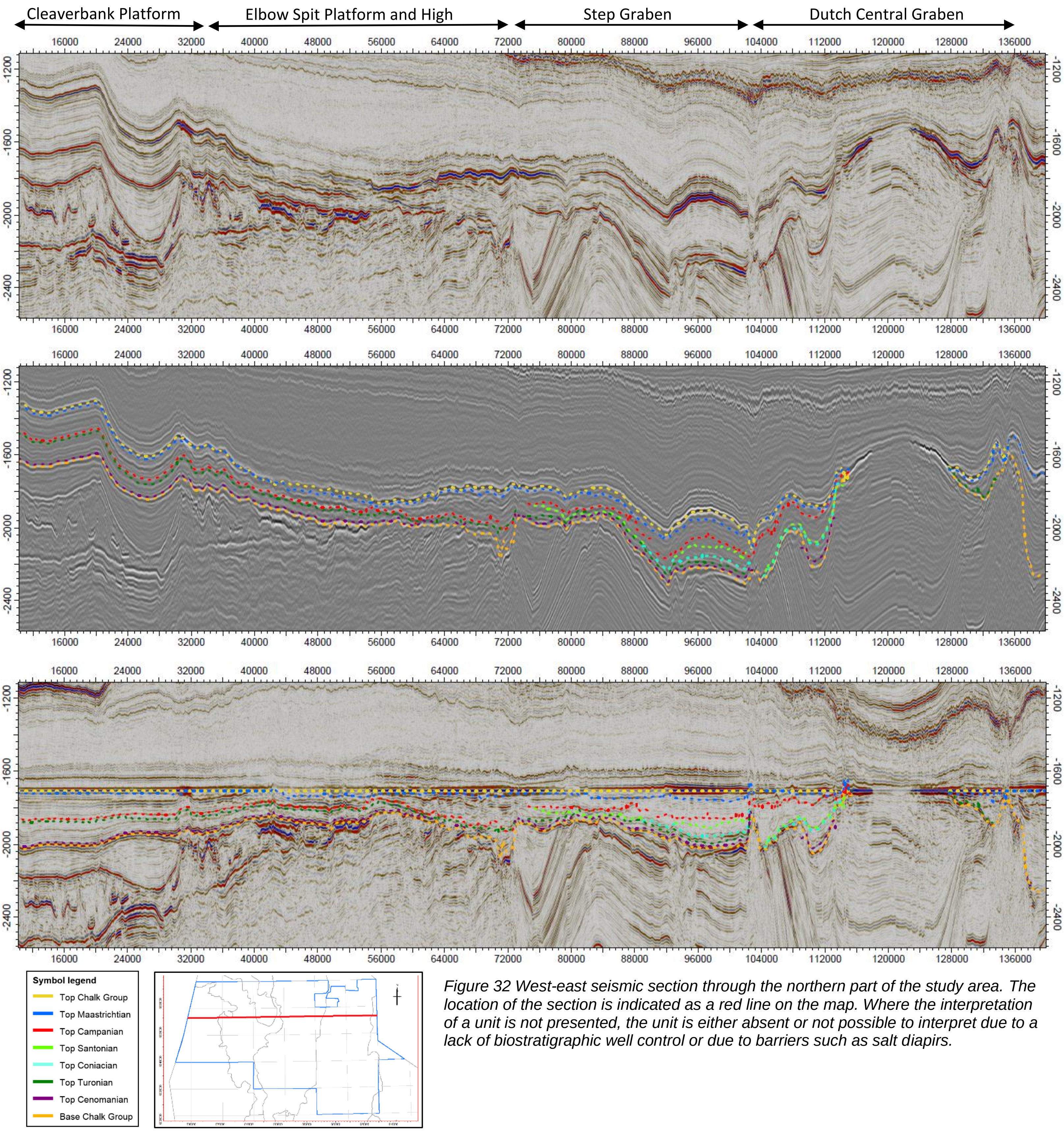


Figure 32 West-east seismic section through the northern part of the study area. The location of the section is indicated as a red line on the map. Where the interpretation of a unit is not presented, the unit is either absent or not possible to interpret due to a lack of biostratigraphic well control or due to barriers such as salt diapirs.

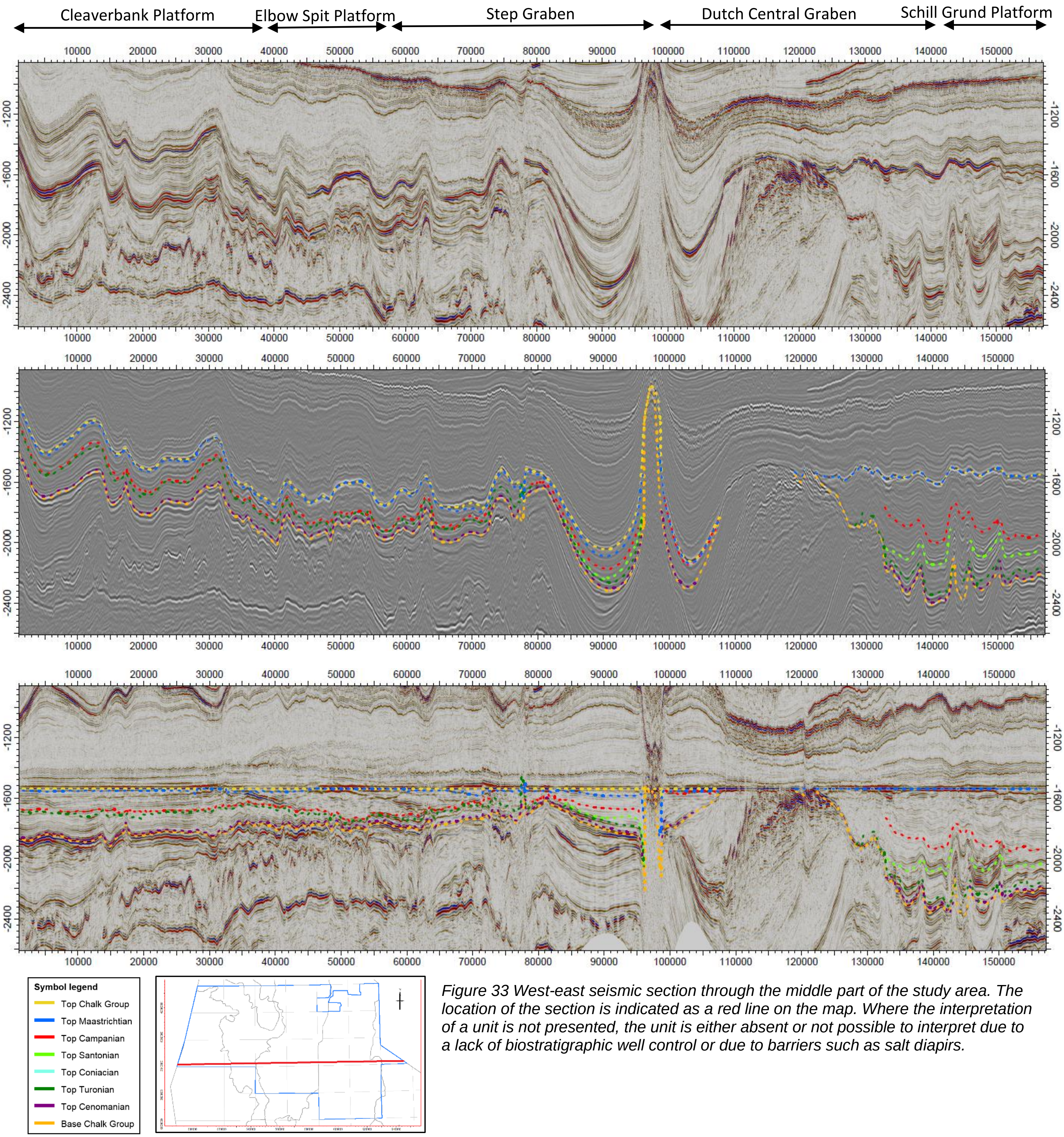


Figure 33 West-east seismic section through the middle part of the study area. The location of the section is indicated as a red line on the map. Where the interpretation of a unit is not presented, the unit is either absent or not possible to interpret due to a lack of biostratigraphic well control or due to barriers such as salt diapirs.

4.3 Results and interpretations per structural element

There are large differences between the structural elements, not only in seismic character, but also in the amount and timing of disconformities, like onlap-structures and truncations. These features could be of great importance to determine the geological history of the Chalk Group in the study area. In the following section, the structural elements are described in terms of sequence stratigraphy. At the end of each section, an interpretation of the geological history of the specific area is presented.

4.3.1 Cleaverbank Platform (CP)

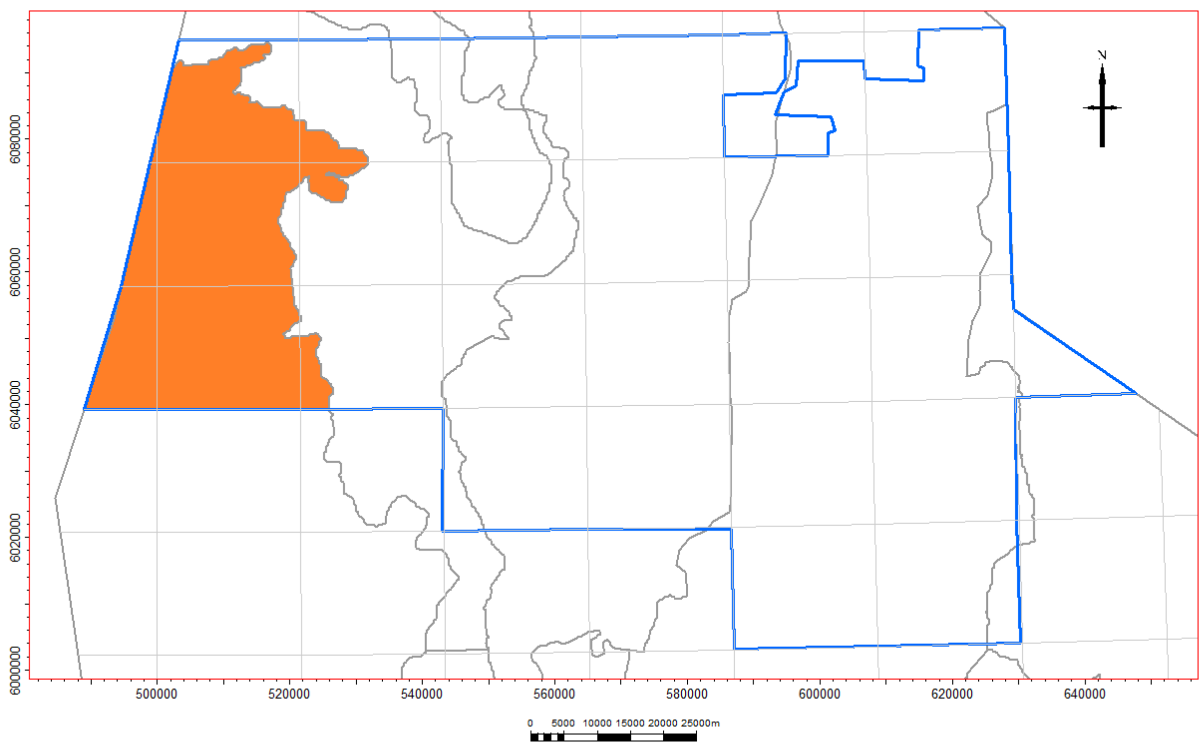


Figure 34 Location of the Cleaverbank Platform, indicated in orange

The Cleaverbank Platform is located in the most western part of the study area (figure 34). In figure 35, a general overview of the Cleaverbank Platform is shown in a west-east section. The western and central part of the platform were folded as a result of salt movement after the deposition of the chalk and contain very continuous reflections. The thickness of the chalk increases towards the southwest, as shown in figure 31. When going northeastward, the chalk becomes thinner and reflections terminate.

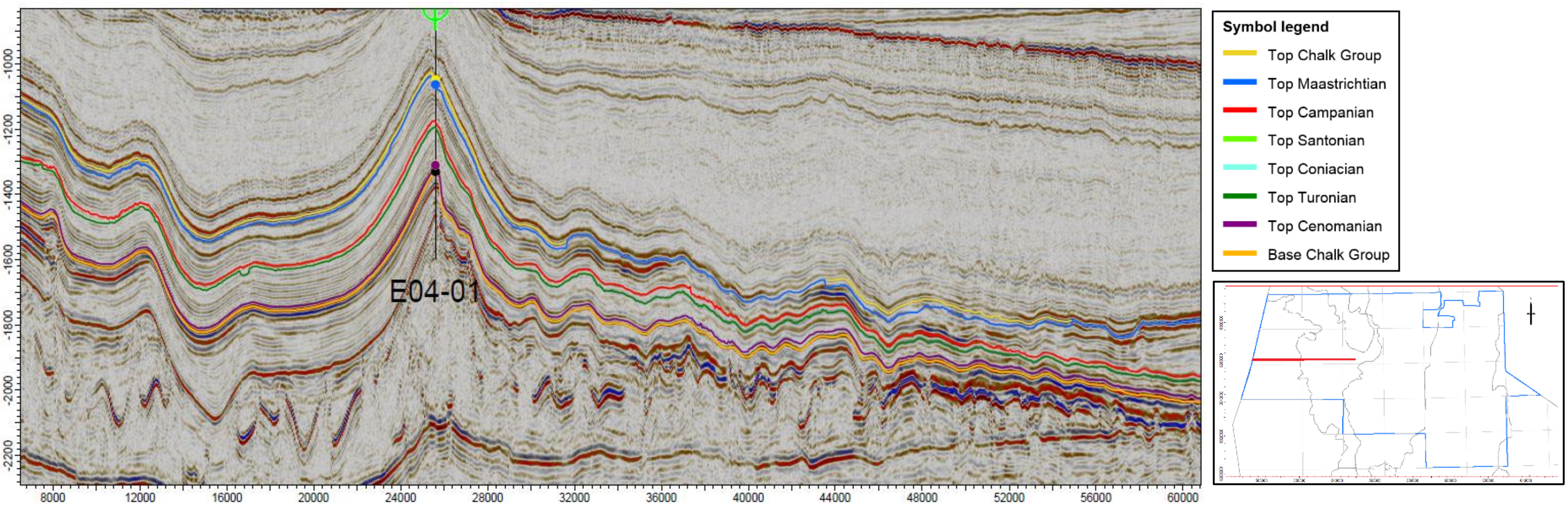


Figure 35 West-east section through the Cleaverbank Platform and Elbow Spit Platform. The red line on the map indicates the location of the section in the study area.

Starting from the onset of chalk deposition, Cenomanian deposits are present almost everywhere on the Cleaverbank Platform, also in the thinnest chalk part (figure 18). The Cenomanian lies conformably on pre-chalk deposits. The Top Cenomanian is very continuous and parallel to the base of the chalk. The Cenomanian unit is relatively thin on the Cleaverbank Platform (figure 19).

While the thickness of Cenomanian deposits is very homogeneous in the Cleaverbank Platform, the Turonian deposits show large differences in thickness (figure 21). The Turonian sequence is thickest in the southwest of the study area. The ultimate southwestern corner is almost bounded by a salt wall. In the section of figure 36, this salt wall is shown. The lower part of the Turonian contains parallel reflections and shows a uniform thickness. However, the upper part is onlapping towards the salt. Also the Campanian and earliest Maastrichtian were influenced by the local uplift due to salt activity. Overlying Late Maastrichtian deposits are parallel to the top of the chalk and have a uniform thickness.

The top of the Campanian is present almost directly above the Top Turonian on the Cleaverbank Platform (figure 35 and 36). This means that Coniacian and Santonian are very thin or absent, and maybe also a part of the Campanian is missing.

On top of the Campanian, the Maastrichtian was deposited in vast amounts on the Cleaverbank Platform. Danian deposits are very thin and on the eastern Cleaverbank Platform even absent (figure 28). In figure 37, it is visible that not only the Danian, but also a few reflections of the Maastrichtian unit are truncated by post-chalk deposits.

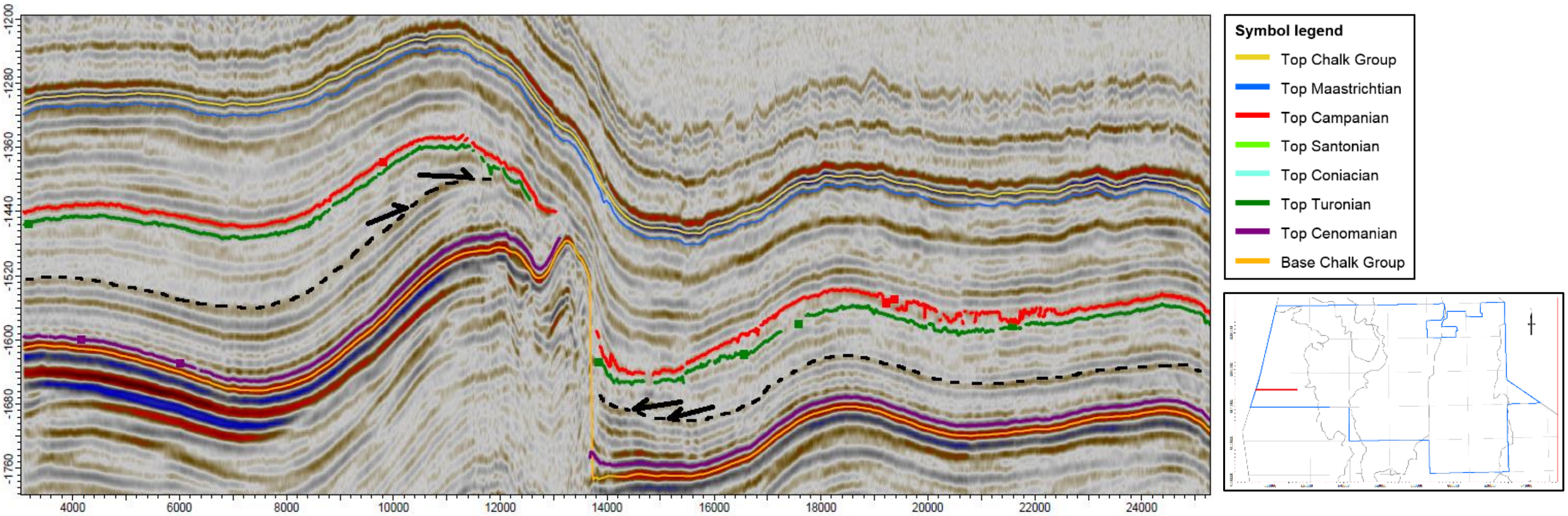


Figure 36 West-east section through the western part of the Cleaverbank Platform, showing a salt wall in the middle of the section.

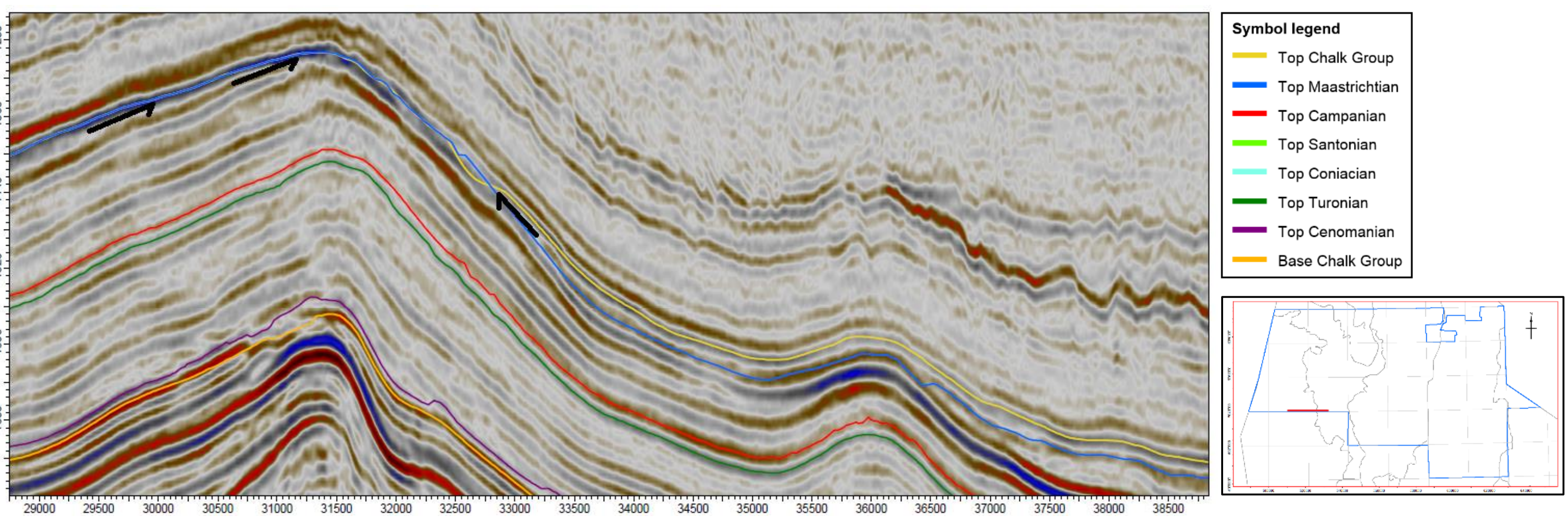


Figure 37 West-east section in the southeastern part of the Cleaverbank Platform. The red line on the map indicates the location of the section in the study area.

Interpretation geological history Cleaverbank Platform

1. The Cenomanian was deposited everywhere, with a uniform thickness and continuous reflections. Thus, at the onset of chalk deposition, there was no or almost no sea floor topography on the Cleaverbank Platform.

2. During the Turonian, the southwestern part of the Cleaverbank Platform subsided with respect to the northeastern part. The platform seems to be tilted towards the southwest at this time. This resulted in a very thick Turonian sequence in the southwest, and thinner in the northeast. In addition, salt activity started in the southwest during the Late Turonian, creating onlap-structures onto this local high. The salt wall was growing until the earliest Maastrichtian.

3. Coniacian to Late Campanian sediments are very thin or absent on the Cleaverbank Platform. There are two possible explanations for this. The first is that during Coniacian to Campanian times, the Cleaverbank Platform was high with respect to the eastern part of the study area and that no or very little deposition took place as a result of this elevation. The second option is that the Cleaverbank Platform was uplifted during the Late Campanian. In this case, Coniacian, Santonian and Early to Mid Campanian sediments were removed by erosion as a result of the uplift. The first option is more likely because no erosional surfaces or angular unconformities have been observed that could be evidence for an uplift phase. The Campanian seems to lie conformably on top of the Turonian.

4. During latest Campanian, Maastrichtian and Danian times, the whole Cleaverbank Platform subsided, or the sea level rose. Thick Maastrichtian sediments and Danian sediments were deposited, probably everywhere.

5. The Danian and Late Maastrichtian are not present in the eastern part of the Cleaverbank Platform. The Danian reflection and upper reflections of the Maastrichtian are truncated by post-chalk deposits. This suggests that the absence of the Danian and Late Maastrichtian is a result of erosion and not a result of non-deposition. Therefore, at the end of the Danian, a new uplift phase occurred. This

erosional phase has removed locally Danian deposits and the upper part of the Maastrichtian.

4.3.2 Elbow Spit Platform and High (ESP & ESH)

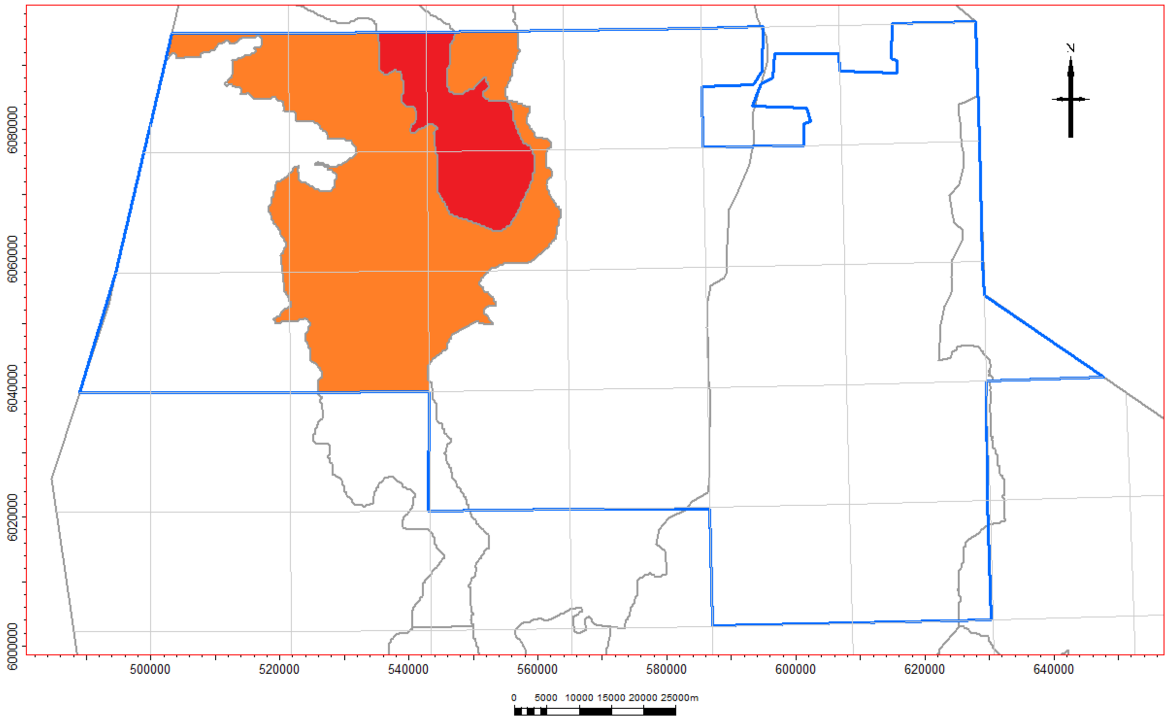


Figure 38 Location of the Elbow Spit Platform, indicated in orange, and the Elbow Spit High, indicated in red

The Elbow Spit Platform is located east of the Cleaverbank Platform and stretches from the northern to the southern boundary of the study area (figure 38). In the northeastern part of the platform, the Elbow Spit High is present. On the western side of the Elbow Spit Platform, the chalk sequence is thinner than on the Cleaverbank Platform and it is thinnest at the Elbow Spit High (figure 31). Towards the east, the thickness increases again.

Seismic reflections are not parallel as on the Cleaverbank Platform but are dominated by terminations, like truncations and onlap-structures. Figure 39 shows a west-east section through the Elbow Spit Platform.

Cenomanian deposits are present in the western part of the Elbow Spit Platform, but are absent in the northeast, approximately at the location of the Elbow Spit High (figure 18). In the section in the north of the Elbow Spit Platform (figure 40), the top of the Cenomanian shows onlap onto the pre-chalk deposits consisting here of pre-Zechstein deposits. The oldest Turonian reflections show this onlap as well. As visible on the areal extent map of the top of the Turonian (figure 20), the Turonian sequence is absent on parts of the Elbow Spit High, but extends much further on it than the Cenomanian deposits.

In the west-east section of figure 39 and 40, you can also see that the Coniacian to Campanian sequence is very thin on the Elbow Spit Platform and High: mostly one single reflection. This is similar to the Cleaverbank Platform. However, the same sequence is thicker in the Step Graben. This is also clearly visible on the thickness map of the Coniacian to Campanian sequence (figure 25).

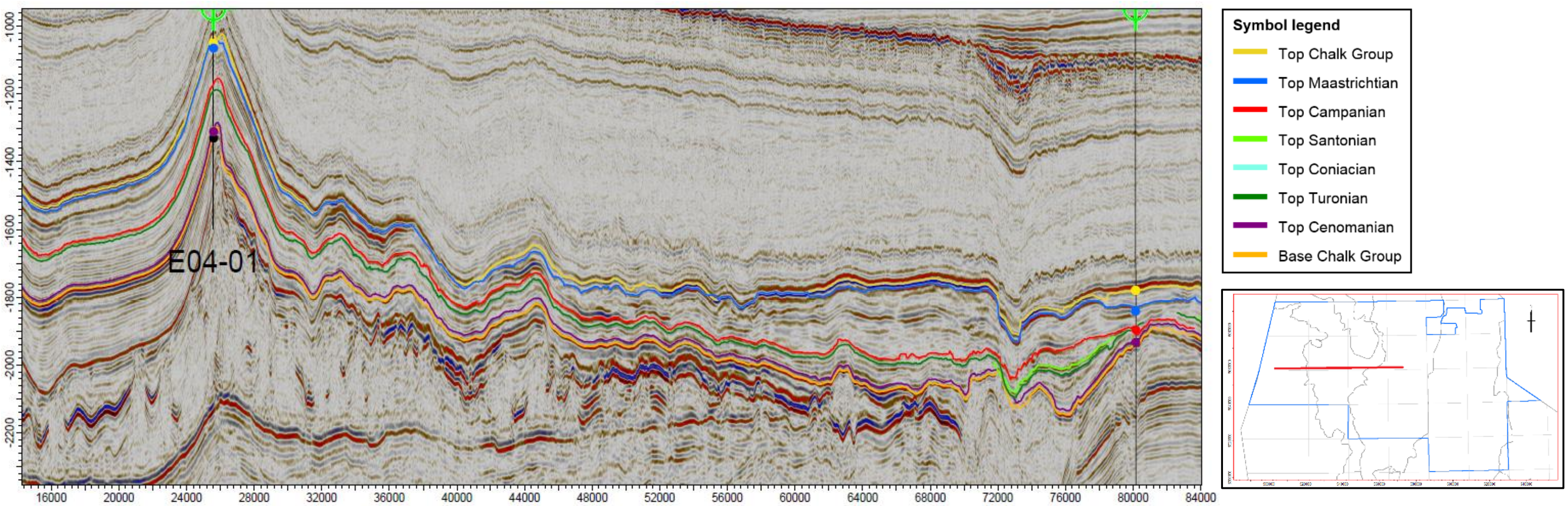


Figure 40 West-east section through the Elbow Spit Platform. The red line on the map indicates the location of the section in the study area.

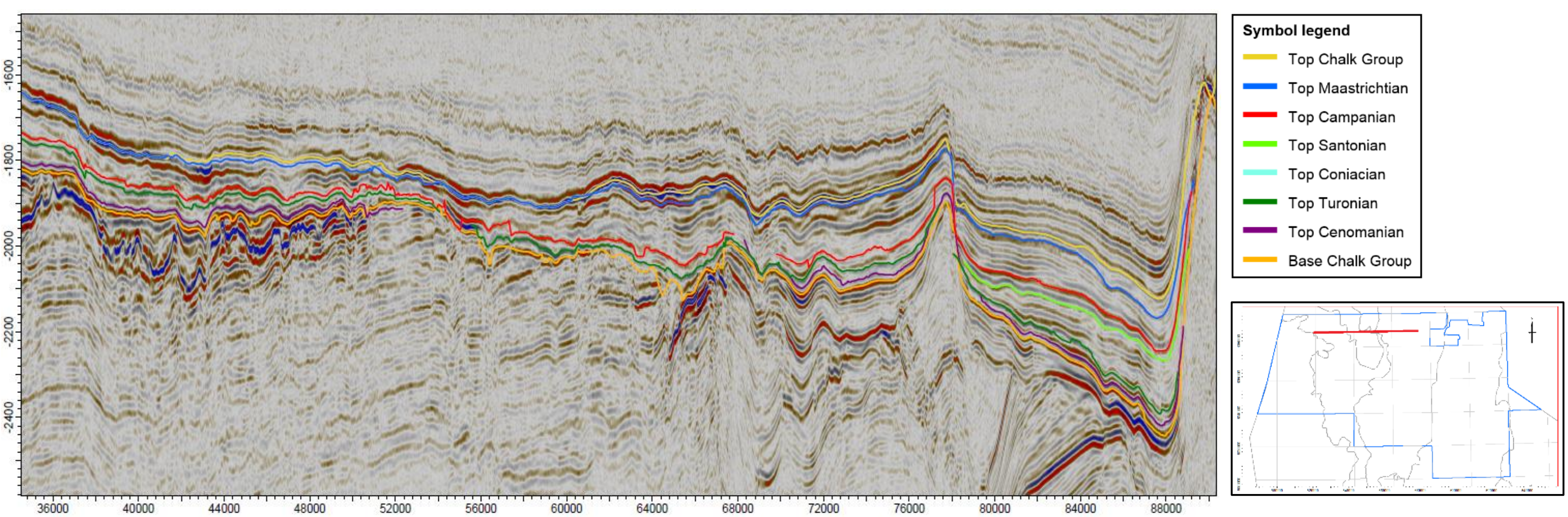


Figure 39 West-east section through the northern part of the Elbow Spit Platform and Elbow Spit High. The red line on the map indicates the location of the section in the study area.

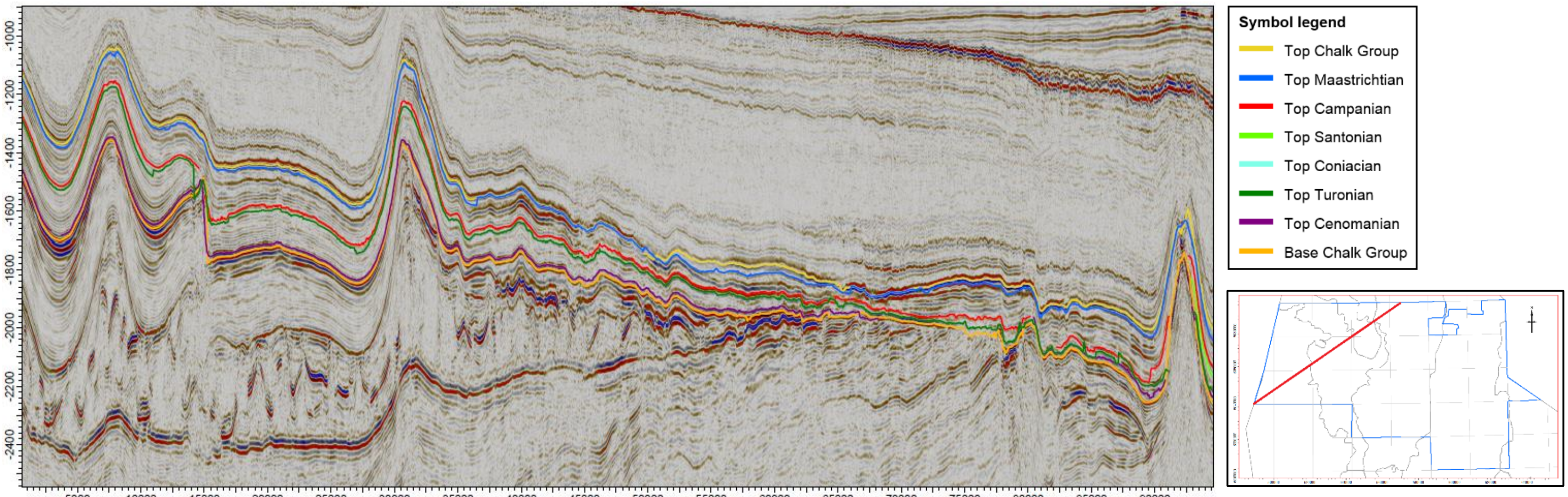


Figure 42 Southwest-northeast section through the Cleaverbank Platform, the Elbow Spit Platform and Elbow Spit High and a small part of the Step Graben. The red line on the map indicates the location of the section in the study area.

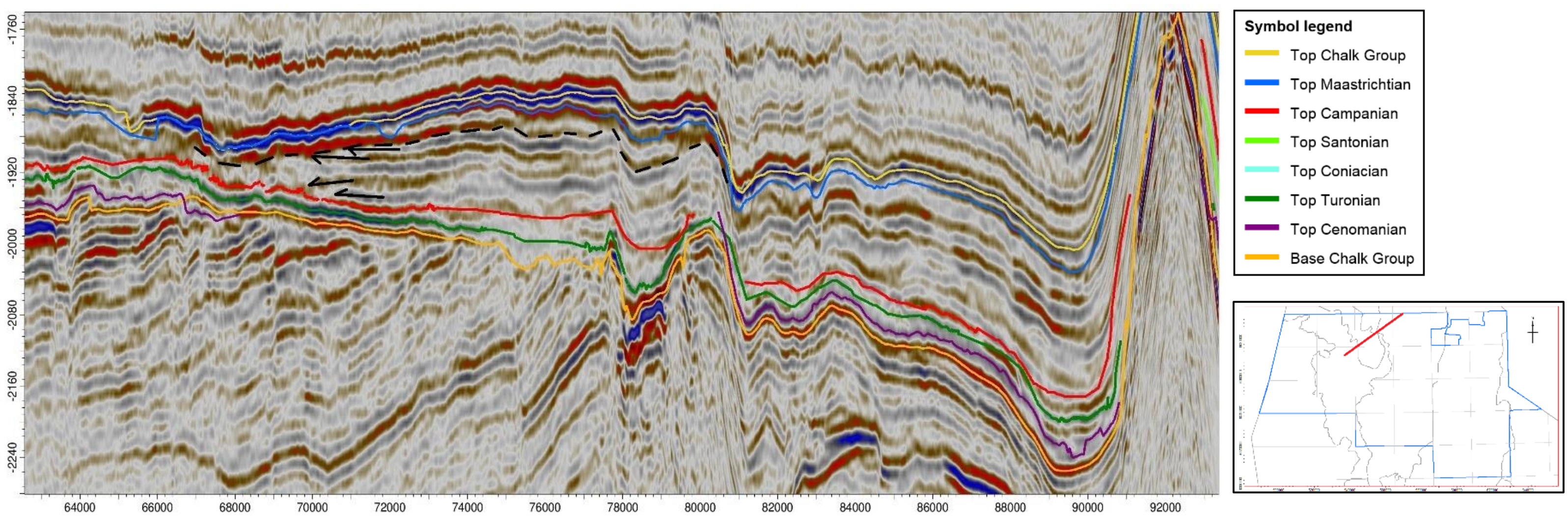


Figure 41 Zoom-in on the southwest-northeast section of figure 41 through the Elbow Spit Platform and Elbow Spit High. The red line on the map indicates the location of the section in the study area.

In the sections of figures 39 up to 41, a thicker chalk sequence is present east of the Elbow Spit High. Only the Maastrichtian unit causes this increase in thickness. The seismic response is not very clear here, since reflections are not continuous and have a relatively low amplitude. However, onlap-structures towards the west are visible in the Maastrichtian sequence (figure 42).

An erosional surface of Maastrichtian age is visible in figure 42. Older Maastrichtian reflections are truncated by a younger Maastrichtian reflection. This phenomenon is recognizable at both sides of the Elbow Spit High in the section of figure 43 which is flattened on the top of the chalk.

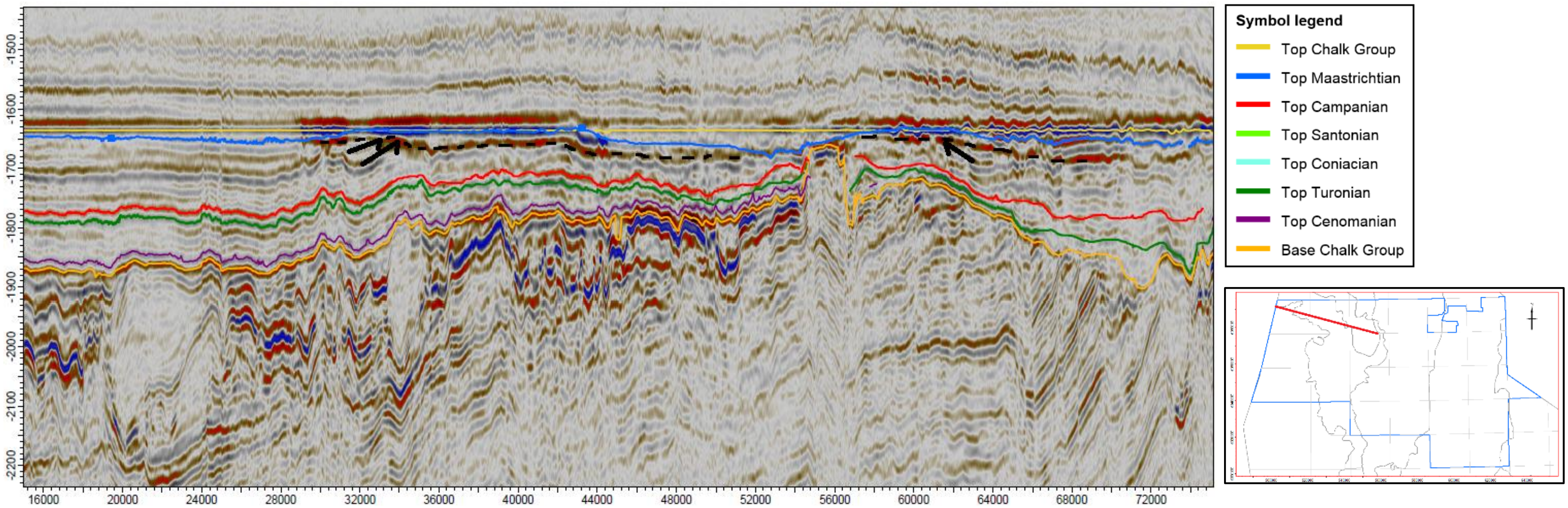


Figure 43 Northwest-southeast section through the Elbow Spit Platform and Elbow Spit High. The section is flattened on the Top Chalk.

The upper part of the Maastrichtian is not present everywhere on the Elbow Spit Platform. It is absent in the western and northern part. The upper part of the Maastrichtian is truncated by the post-chalk sequence (figure 44), similar to the situation on the eastern Cleaverbank Platform. At the locations where the upper part of the Maastrichtian is absent, also the whole Danian sequence is absent.

The Danian sequence is thicker in a north-south trending “valley” of circa ten kilometres wide. This is visible in the centre of figure 43 and on the thickness map (figure 29).

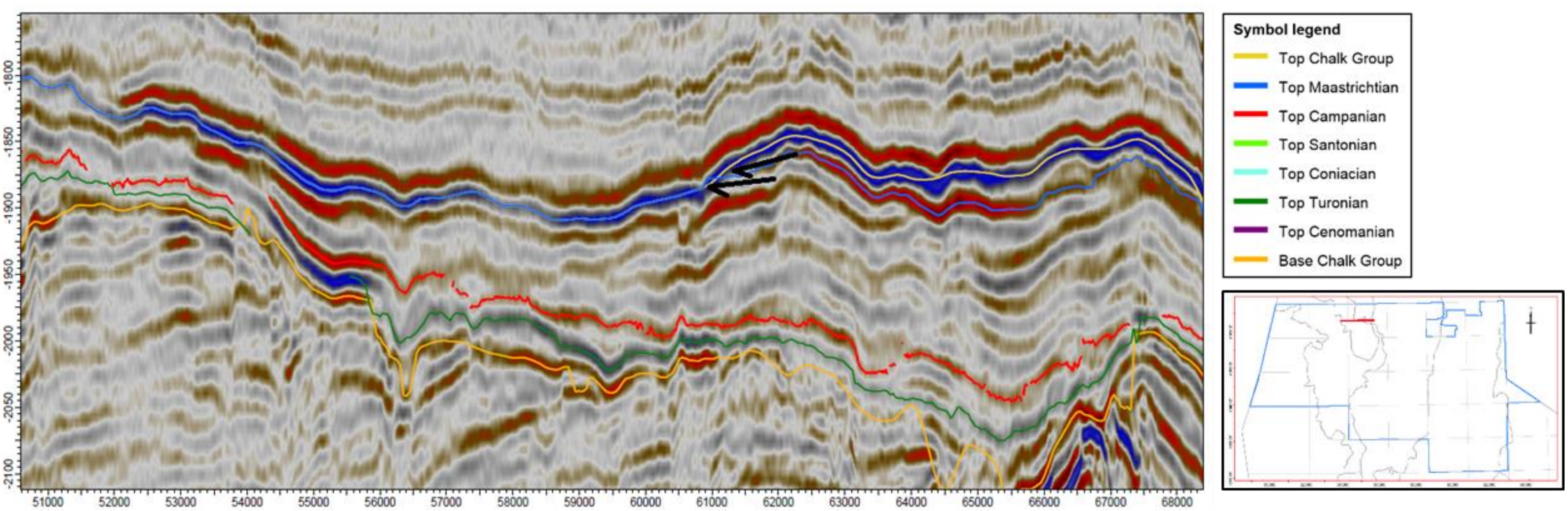


Figure 44 West-east section through the Elbow Spit High and the eastern part of the Elbow Spit Platform

Interpretation geological history Elbow Spit Platform

The geological evolution of the Elbow Spit Platform and High is illustrated in figure 45.

1. The Elbow Spit High was present at the onset of chalk deposition in the northeast of the Elbow Spit Platform. Cenomanian deposits show onlap onto this high. On the rest of the platform, the Cenomanian was deposited with a uniform thickness.

2. The Elbow Spit High was much smaller during Turonian times, since the Turonian was deposited (partly) on top of it. Subsidence must have taken place at the Elbow Spit High, because it is not plausible that the Turonian overstepping is the result of Cenomanian deposits that had filled up the flanks of the high, since these deposits are relatively thin and don’t show thickness variations. The Turonian deposits overstepping the high could also be explained by a sea level rise.

3. During the Coniacian, Santonian and Campanian, subsidence took place east of the Elbow Spit Platform and this resulted in a thicker Coniacian to Campanian sequence in the Step Graben. Very slow or no deposition took place on the Elbow Spit Platform. The subsidence in the Step Graben may be caused by salt movement because a salt wall is present between the Elbow Spit Platform and the Step Graben.

4. Subsidence took place during the Early Maastrichtian, relatively strong on the eastern side. The stronger subsidence in the east may be caused by salt movement. The subsiding area resulted in a relatively thick Maastrichtian sequence that shows onlap onto the Campanian sequence but also had overstepped the Elbow Spit High.

5. Later during the Maastrichtian, uplift and erosion took place on the Elbow Spit Platform and High, resulting in reflection truncations. Older Maastrichtian deposits were removed.

6. After the Maastrichtian erosive event, the rest of Maastrichtian and Danian deposits were accumulated on the entire Elbow Spit Platform and High.

7. At the end of the Danian, a new erosional phase occurred in the western and northern part of the Elbow Spit Platform, that eroded not only Danian deposits but locally also part of the Maastrichtian. A thicker remaining Danian sequence is present in a north-south trending part of the platform. This could be the result of a differential effect of the Late Danian inversion phase or it could have been a thicker Danian sequence because of the presence of a valley or channel. However, no evidence of incision was found.

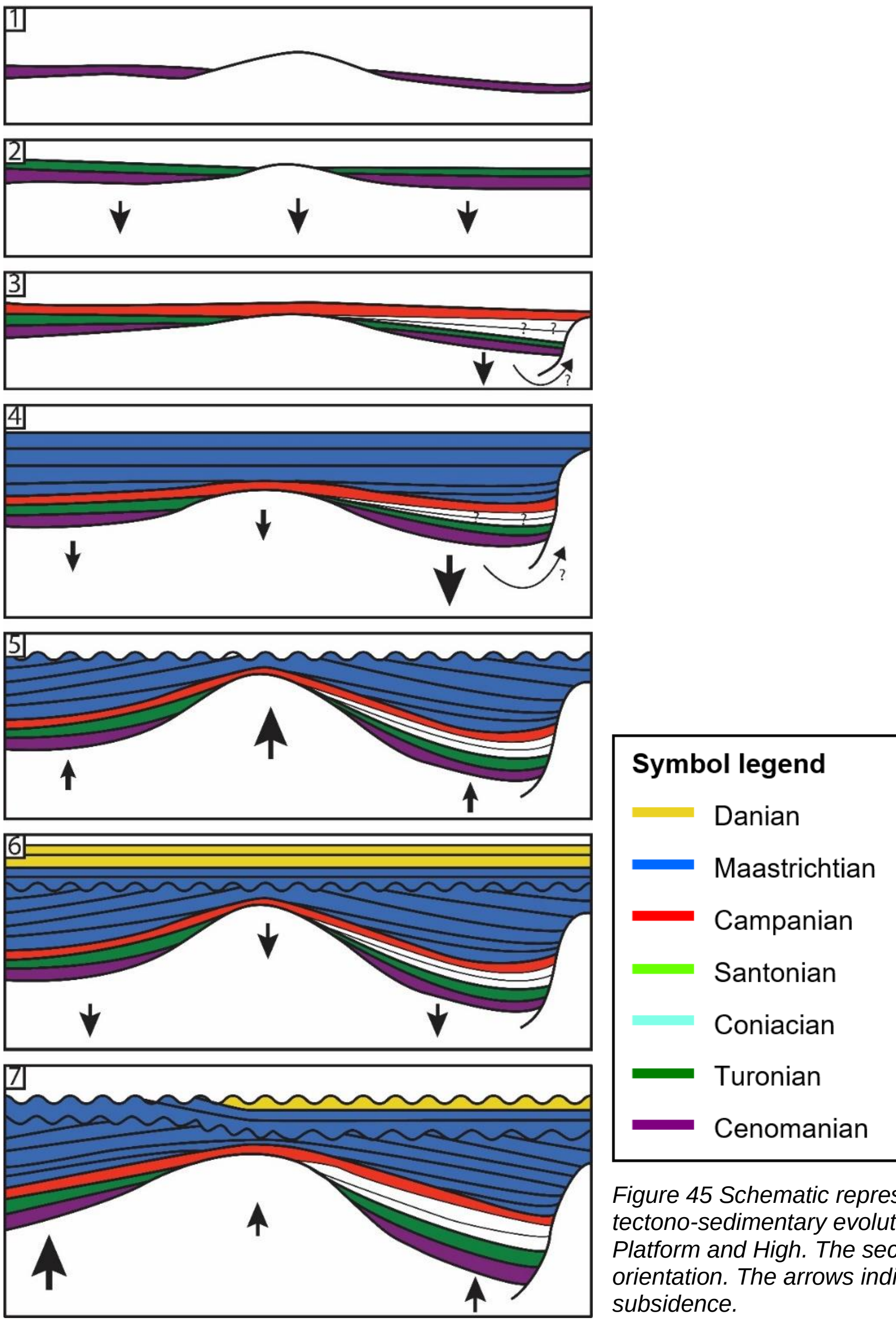


Figure 45 Schematic representation of the interpreted tectono-sedimentary evolution of the Elbow Spit Platform and High. The sections have a west-east orientation. The arrows indicate relative uplift and subsidence.

4.3.3 Step Graben (SG)

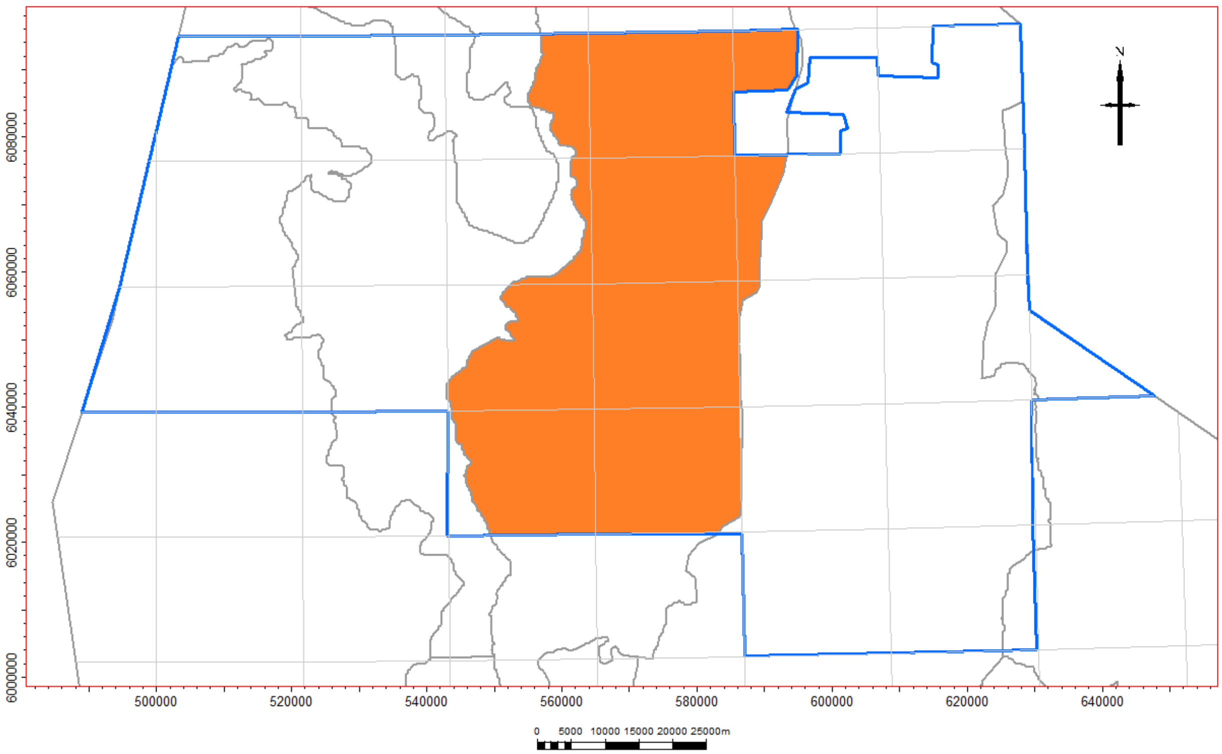


Figure 46 Location of the Step Graben, indicated in orange

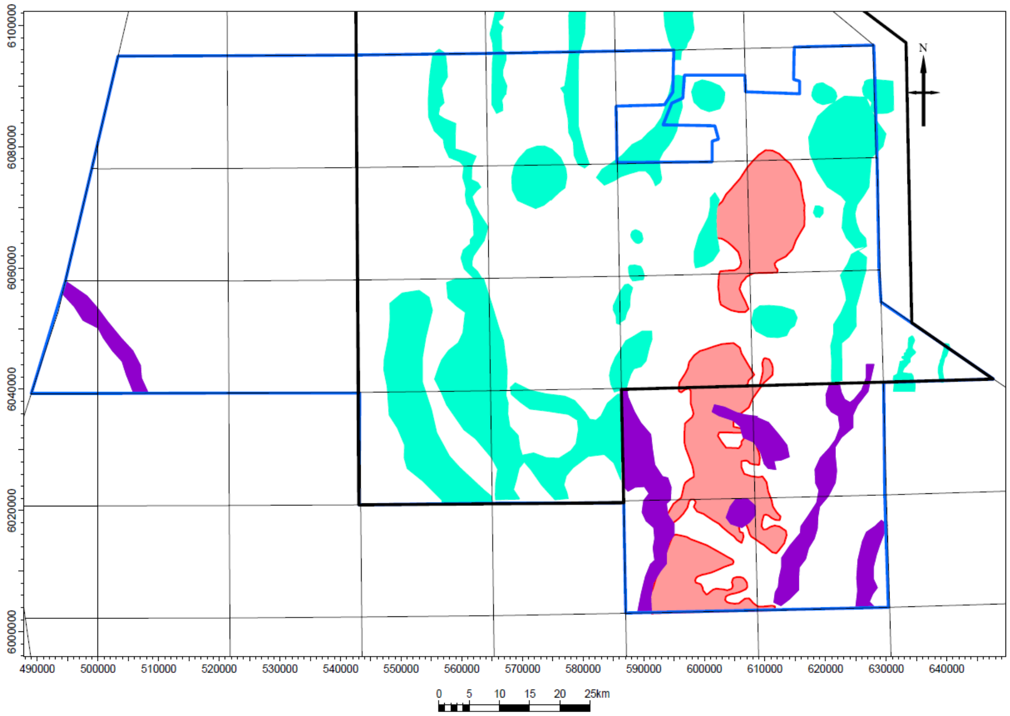


Figure 47 Outlines of the salt structures in turquoise, identified by Van Winden (2015) and in purple identified for this study. The area that was taken into account by Van Winden (2015) is indicated by the black line. The Chalk Group is absent in the red areas.

The Step Graben is located in the central part of the study area, east from the Elbow Spit Platform (figure 46). It stretches from the northern to the southern boundary of the study area and is separated from the Elbow Spit Platform by salt walls and faults. It is bounded in the east by normal faults and salt walls or diapirs that are related to the faults. The deposits of the Step Graben were greatly affected by halokinesis. Figure 47 shows the outlines of the salt walls and diapirs as identified by Van Winden (2015) and this study.

On the west-east section in the central part of the Step Graben (figure 48), many terminations and thickness variations are visible.

Cenomanian deposits are present almost everywhere in the Step Graben (figure 18). Exceptions are the locations of salt diapirs and walls, where the Cenomanian is absent. The thickness of the Cenomanian is quite homogeneous and consists of only one seismic reflection (figure 19 and 48).

Turonian deposits thicken towards the west of the Step Graben and towards the southwest, as visible in figure 21. Well E12-03, in the southwestern part of the Step Graben, indicates a Turonian thickness of approximately 140 metres, while only circa 30 metres of Turonian deposits are present in the northeast (well F04-02-A). However, Turonian deposits are absent in the central part of the Step Graben, see the areal extent of the Turonian (figure 20) and the section of figure 47.

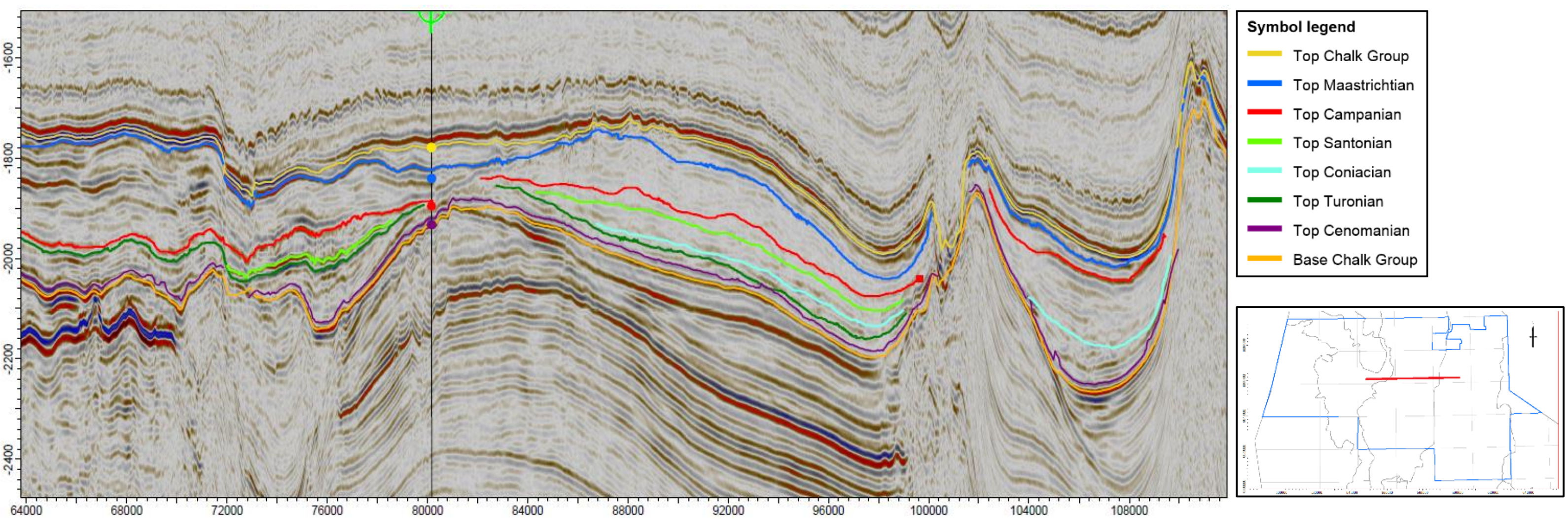


Figure 48 West-east section through the central part of the Step Graben. The red line on the map indicates the location of the section in the study area. The well that is visible is well F04-03.

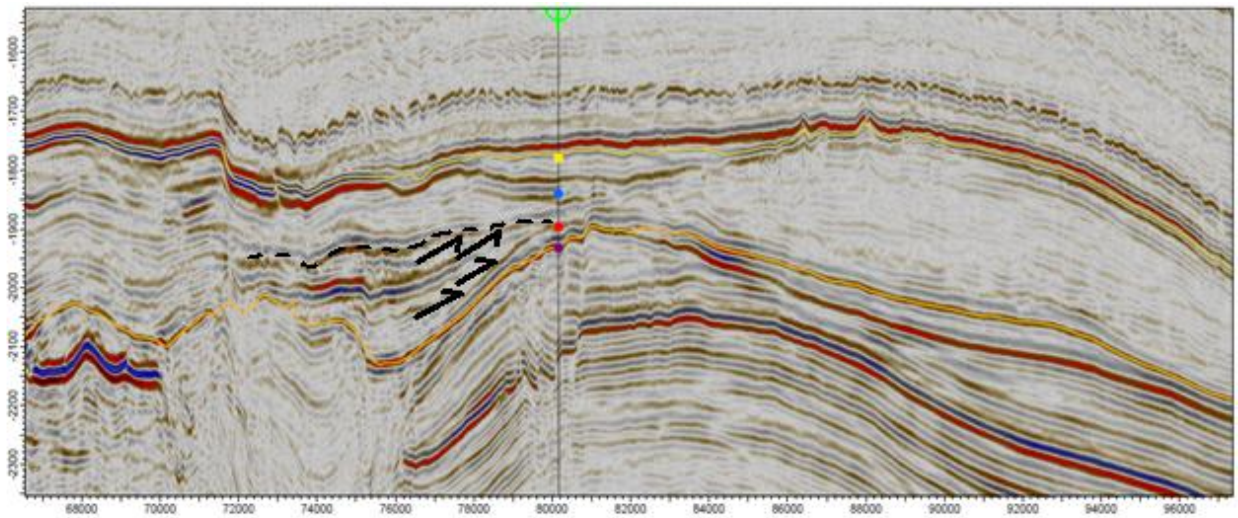


Figure 49 Zoom-in on the section of figure 47, without the interpretation of the units. The arrows indicate onlap-structures and truncations and the dotted line the erosional surface.

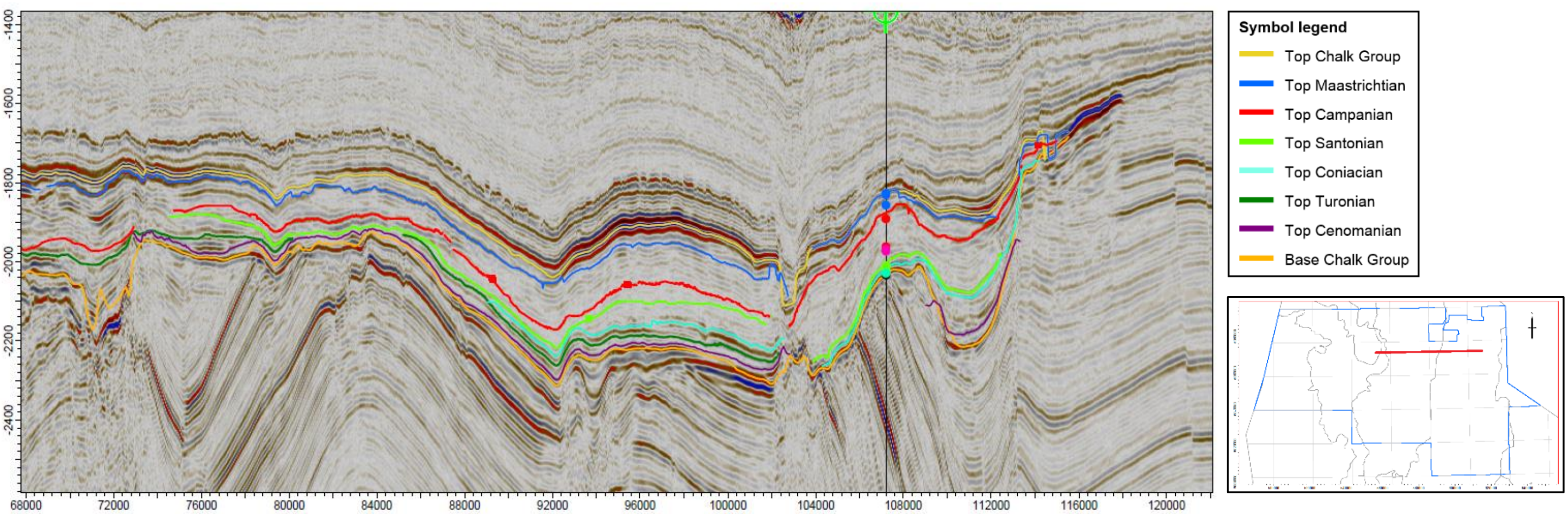


Figure 50 West-east section the northern part of the Step Graben.

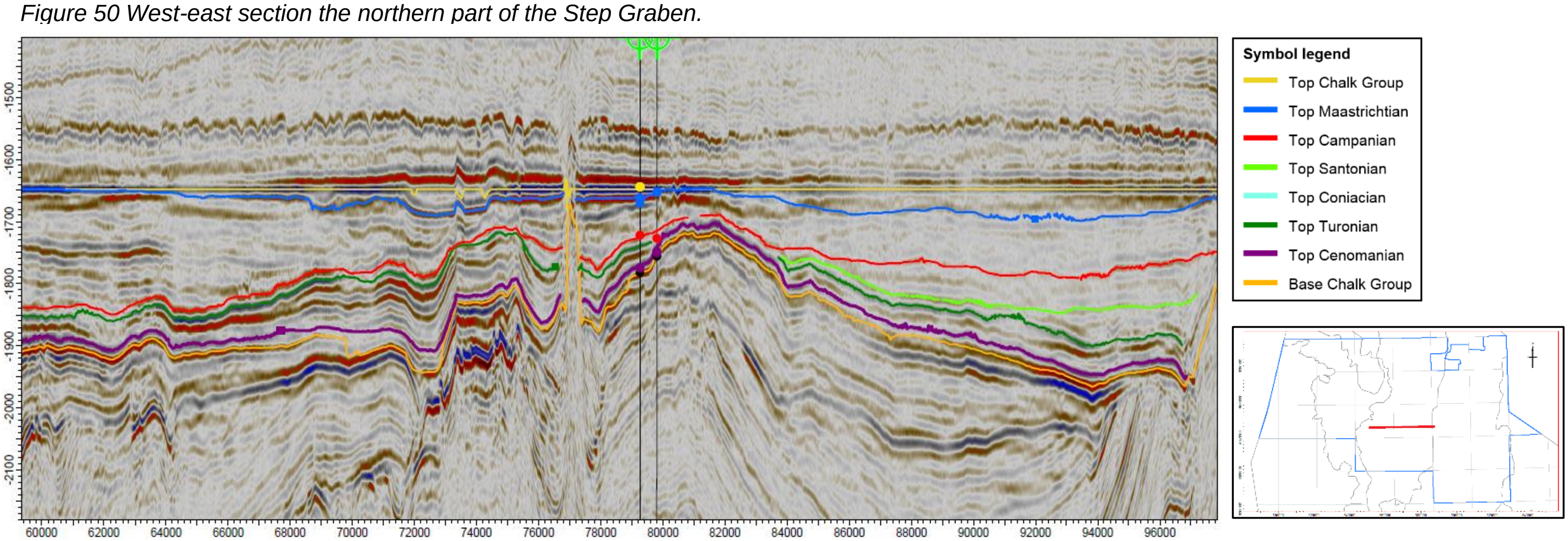


Figure 51 West-east section through the southern part of the Step Graben and Dutch Central Graben. The section is flattened on the Top Chalk.

In the middle of the section in figure 47, approximately Turonian to Campanian units are absent. On the western side, onlap-structures within the Turonian sequence onto probably early Turonian deposits are present. At some point, reflections are not onlapping anymore but are truncated by overlying deposits. The erosional surface approximately coincides with the top of the Campanian, since older reflections stop at this level. The top of the Turonian seems to be truncated by this surface as well. This kind of truncations was not found in the northern and southern part of the Step Graben (figure 50 and 51). In the south, deposits up to Santonian age show onlap onto the Cenomanian on the high and the Campanian oversteps it. In the north, Turonian and Coniacian deposits show onlap and the Santonian oversteps the high.

The top of the Coniacian is present in the eastern part of the section in figure 48 but the continuation of the reflection is unclear due to transparent and slightly chaotic seismic response. Whether the Coniacian sequence is present at the western side of the 'high' is not known. The Santonian sequence is interpreted on both sides of the high in figure 48, onlapping onto the Turonian deposits. However, in the southwestern part of the Step Graben an interpretation of the Santonian was not possible (figure 51) and the Santonian unit is probably absent here. The Campanian lies almost directly on top of the Turonian.

What we do know is that a Campanian sequence is present on both sides and at many locations also in the central part of the Step Graben. In the middle part of the Step Graben, it is not very clear if the Campanian is present on top of the high or not (figure 24 and 48). Different from the situation on the Elbow Spit High, it is clear that there is an erosional surface that coincides with the Top Campanian on the western part of the Step Graben.

The Maastrichtian represents a quite thick sequence on the western and eastern part of the section of figure 48. It is much thinner in the central part, see also the thickness map of the Maastrichtian of figure 27. At the sides, the reflections within the Maastrichtian sequence seem to show onlap onto the former 'high' in the middle. Only the upper part of the Maastrichtian oversteps this high.

A Danian sequence is present almost everywhere in the Step Graben. The Step Graben is the location in the study area (together with a few locations on the ESP) where the Danian sequence is relatively thick, see figure 29. It is thickest in the eastern Step Graben.

In addition, there is a strip of about 2 to 10 kilometres wide, stretching from north to south to southwest along the central part of the Step Graben, where the Danian thickness shows a clear anomaly with respect to the rest of the study area. Well F04-03 is located in the middle of this strip and contains a Danian sequence of approximately 90 metres thick. The RMS amplitude map of the Top Chalk shows the anomalies as well and the locations of the thicker Danian sequence coincide almost exactly with the RMS amplitude anomalies (figure 52).

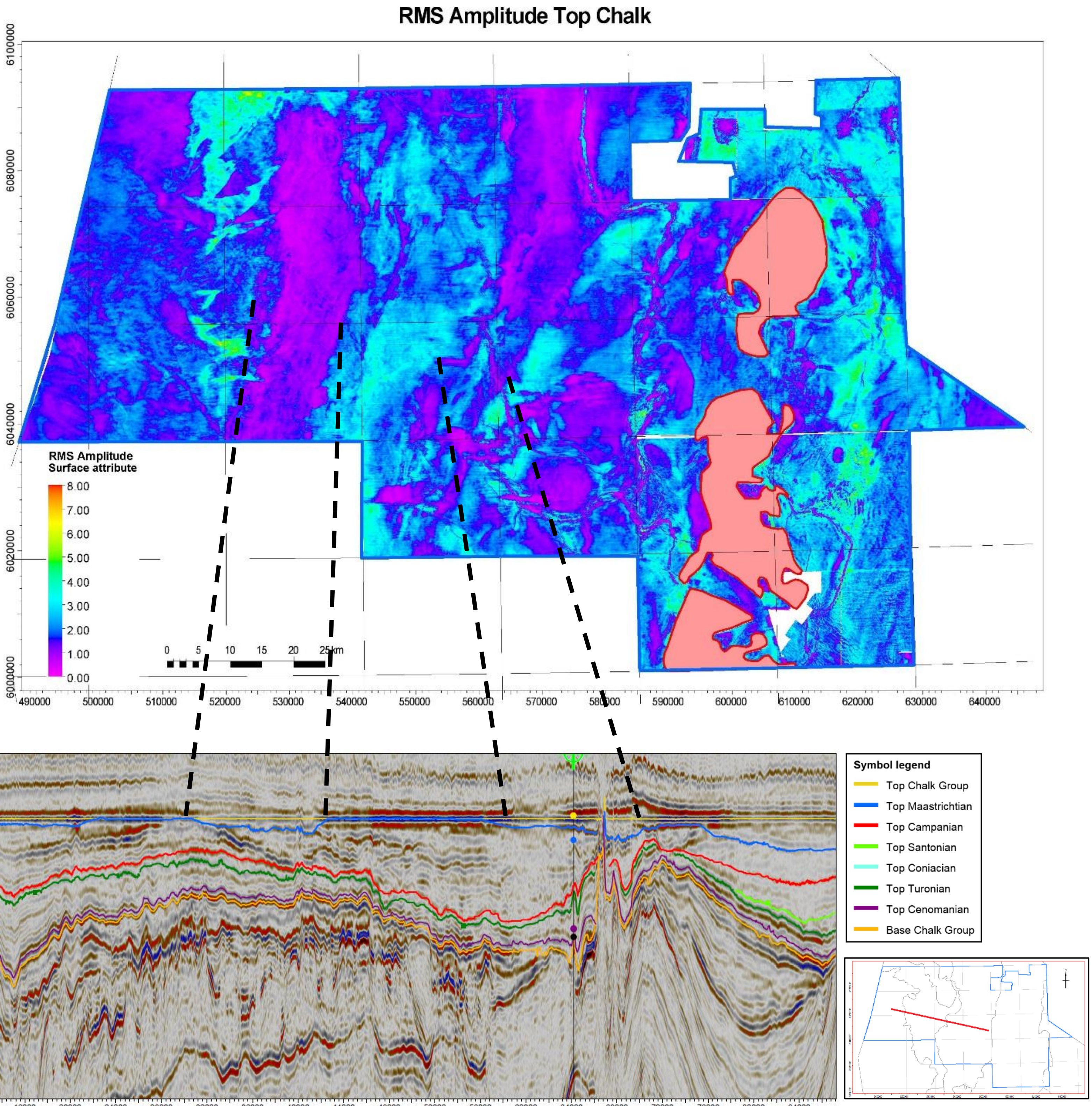


Figure 52 RMS Amplitude attribute on the Top Chalk (above) and a northwest-southeast section through the Elbow Spit Platform and Step Graben, flattened on the Top Chalk (below). The areas with a thicker Danian sequence are visible in both figures.

Interpretation geological history Step Graben

The geological evolution of the central part of the Step Graben is illustrated in figure 52, because this part contains the most complex geological history.

1. From the onset of chalk deposition, the Cenomanian was deposited with a quite homogeneous thickness throughout the Step Graben. A limited sea floor topography was present at this time. The Cenomanian is very thin, similar to the rest of the study area.

2. During the Turonian, subsidence took place in the western Step Graben with respect to the eastern part. During these times, accommodation space was created in the west and Turonian deposits are thicker here than in the eastern part of the Step Graben. The 'high' in the centre of the Step Graben must have grown during the Turonian, since the Turonian deposits show onlap onto the Cenomanian on this high in the northern and southern part of the Step Graben. Turonian deposits may have overstepped the high in the centre of the Step Graben, since the top of the Turonian is truncated by the Campanian at this location.

3. Coniacian to Campanian deposits show onlap onto the Turonian or did overstep the local high in the Step Graben. Coniacian sediments were deposited at least at a part of the eastern Step Graben. It is unlikely that a Coniacian sequence was deposited on the western part of the Step Graben because the Santonian lies almost directly on top of the Turonian at this location. The Santonian was deposited on both sides of the local high, onlapping towards this high and overstepping it in the north. Because Coniacian to Campanian deposits are onlapping onto the Turonian in the central part of the Step Graben, renewed uplift of the high must have occurred after the Turonian, or subsidence at the sides. The onlap-structures could also be explained by a sea level drop.

4. During the Late Campanian, uplift took place again in the central part of the Step Graben (trending north-south) and erosion created truncations. Erosion must have happened at least down to the Turonian, since the Turonian was locally truncated by the Late Campanian. At the end of the erosion, the sea floor must have been

flat. No evidence for this uplift phase was found in the northern and southern part of the Step Graben.

5. Subsequently, the Maastrichtian was deposited. From the Early Maastrichtian onwards, new uplift occurred in the central part of the Step Graben and/or subsidence took place at the sides. Sediment accumulation took place at the sides, onlapping onto the ridge in the middle. The subsidence in both the western and eastern part may be caused by salt withdrawal (rim syncline), since salt structures area present at both sides of the Step Graben. The idea that a central high was present again during the Maastrichtian as a result of renewed uplift could be an explanation for the thinner Maastrichtian sequence in the central part.

6. However, this relatively thin Maastrichtian in the central part may have been strengthened by another process. The Danian sequence is, unlike the Maastrichtian, relatively thick in the central part of the Step Graben (figure 52). This anomaly may be the result of a 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 *et al.* (2008) identified a very similar feature on the German Schillgrund High and also interpreted this as a deep channel (figures 54 and 55). The channel is interpreted to be of the same age as the feature in the Step Graben. Another possible explanation of the Danian anomaly could be that a chalk mound was present (Anderskouv *et al.*, 2007). The depositional environment of the Danian was described as “a well oxygenated carbonate shelf” with “strong open marine influences”, based on the biostratigraphy of well F04-03. Chalk mounds of this size were never identified on seismic.

7. At the end of the Danian, renewed uplift took place and parts of the Danian sequence were removed. A differential influence of this Late Danian inversion phase is the third possible explanation for the Danian anomaly. However, no evidence was found for a cause of this differential uplift.

8. After the deposition of the Chalk Group, the Step Graben was affected by fault movements and ongoing salt tectonics.

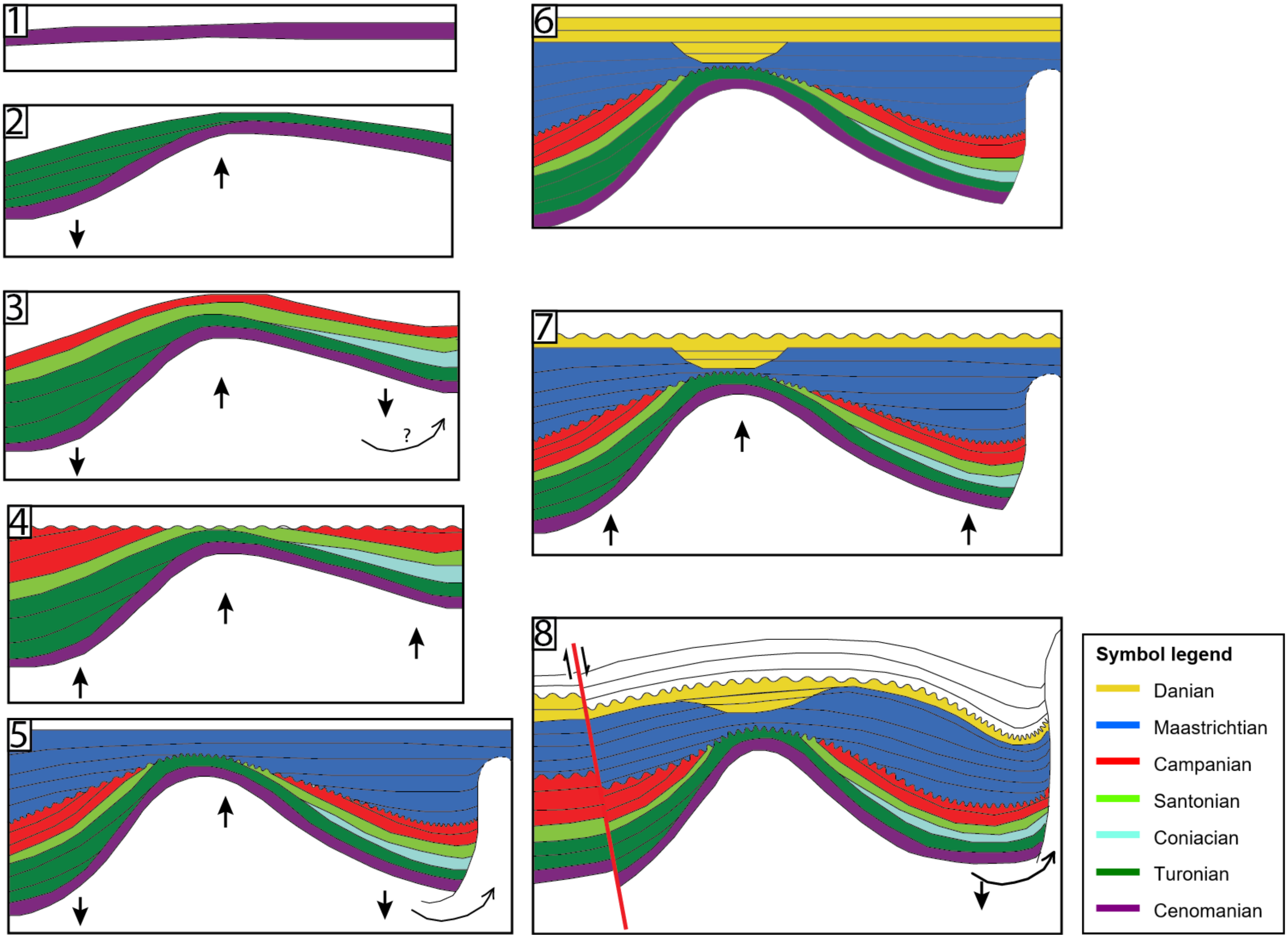


Figure 53 Schematic representation of the interpreted tectono-sedimentary evolution of the central part of the Step Graben. The sections have a west-east orientation and are based on the section of figure 47. The arrows indicate relative uplift and subsidence.

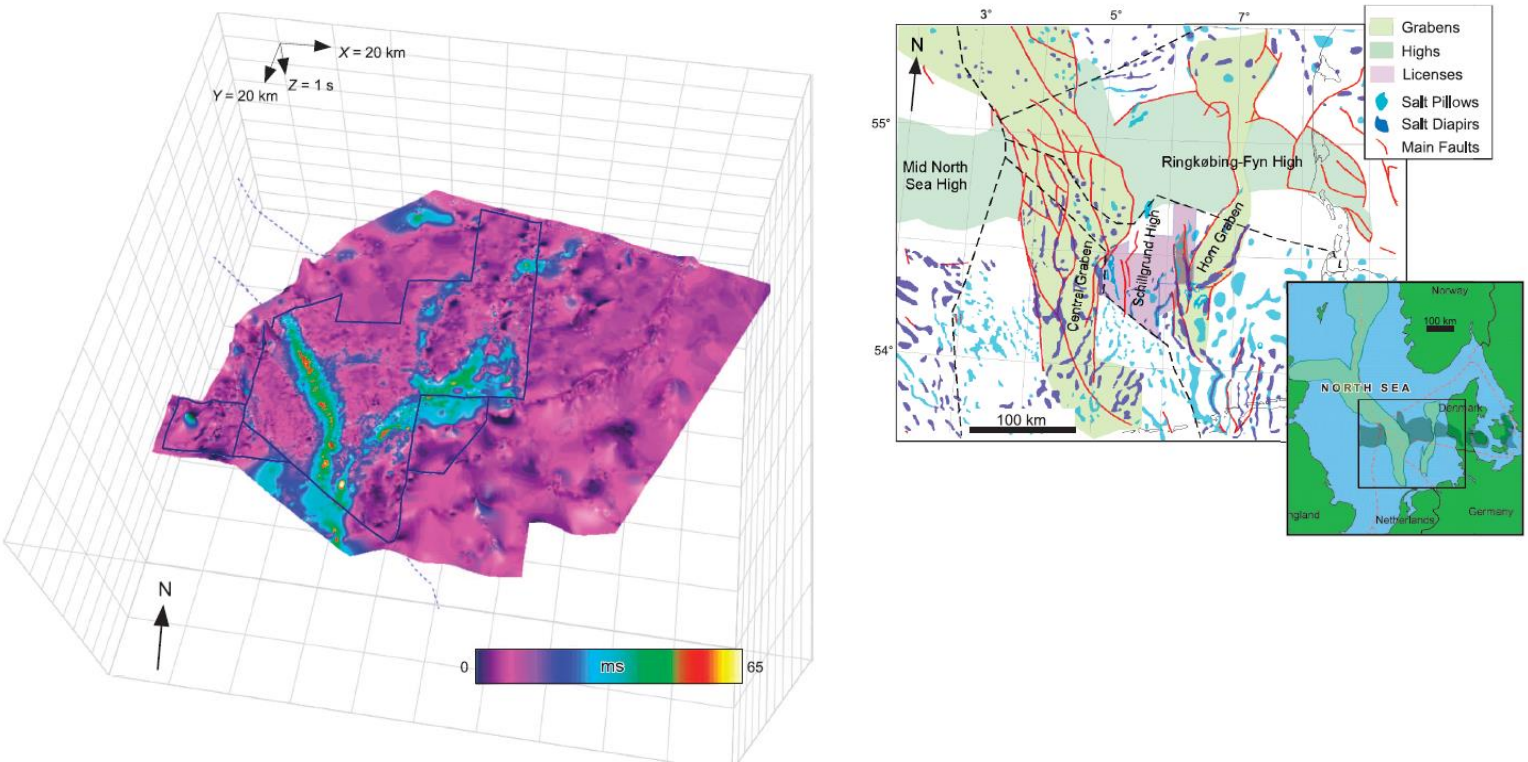
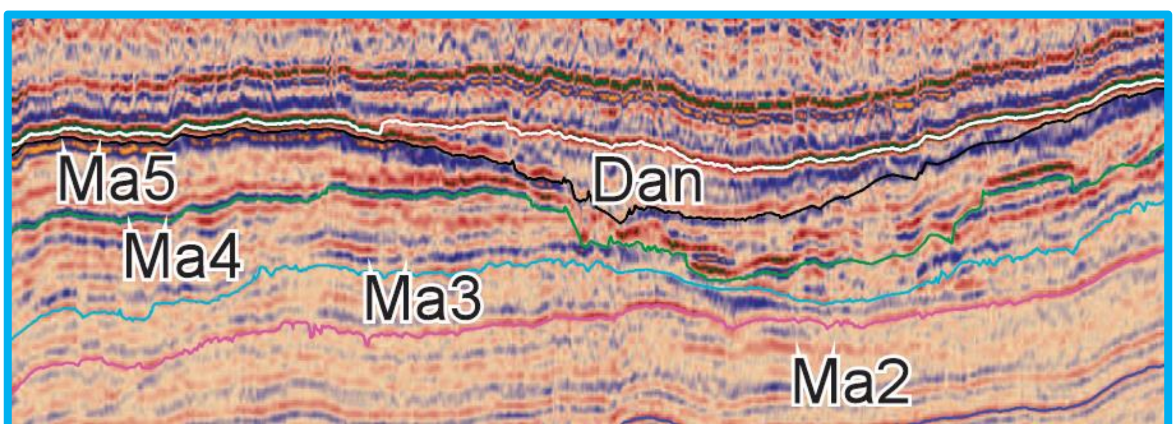


Figure 54 Left: time isochore map of the Danian Ekofisk Formation, clearly outlining the branching channel system cut into the top Maastrichtian (Surlyk et al., 2008). The study area of Surlyk et al. (2008) is framed by blue lines. The same study area is indicated as the purple area on the map (right).



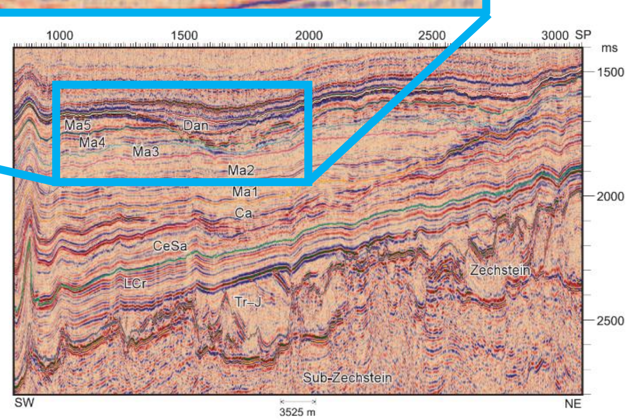


Figure 55 Southwest-northeast seismic section through the German Schillgrund High (Surlyk et al., 2008). The Maastrichtian unit is subdivided into different packages (named as Ma1, Ma2, etc.). The Danian unit is indicated by the abbreviation 'Dan'. The shape of the Danian looks very similar to the interpreted Danian channel in this study.

4.3.4 Dutch Central Graben (DCG)

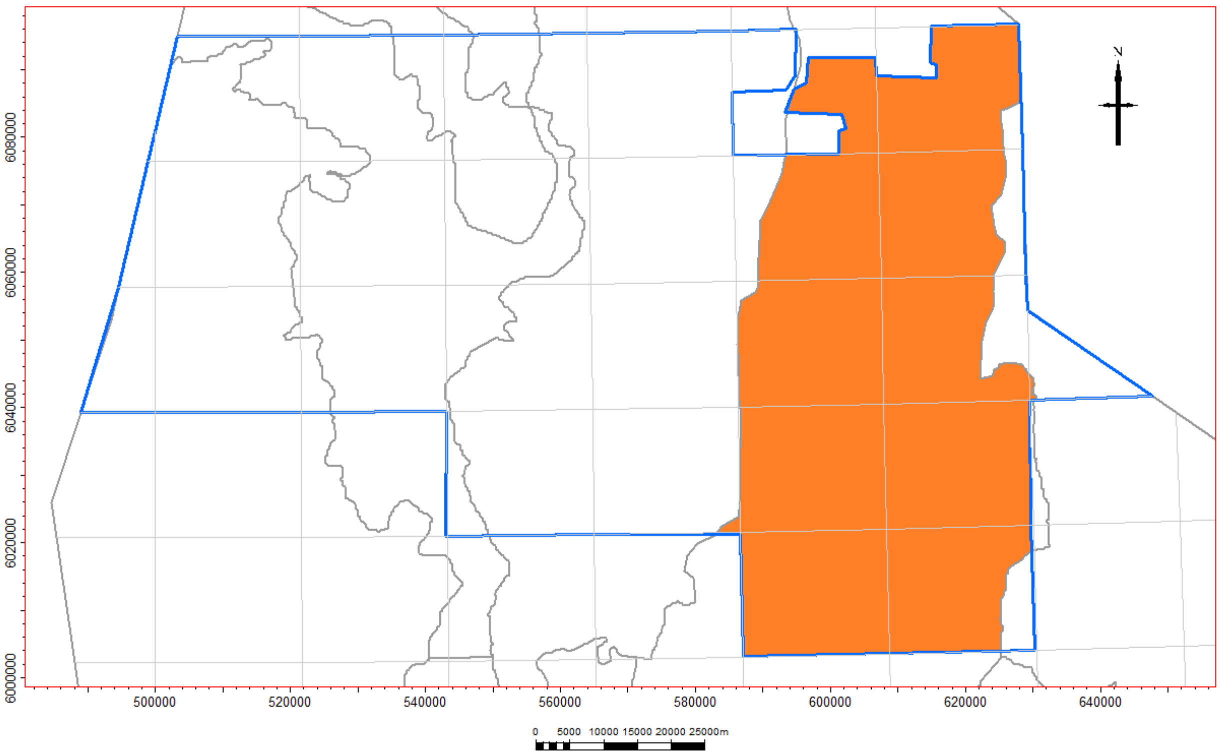


Figure 56 Location of the Dutch Central Graben, indicated in orange

The Dutch Central Graben is located in the eastern part of the study area (figure 56) and is the southern limb of the larger North Sea Central Graben, situated north of the Netherlands offshore area (figure 57).

In large parts of the Dutch Central Graben, the Chalk Group is very thin or not present at all (figure 31). On the other hand, the chalk is very thick in the southeastern part of the Dutch Central Graben, near the Schill Grund Platform. The interpretation in the Dutch Central Graben is difficult as a result of sedimentary and redeposition structures which made the seismic response more chaotic.

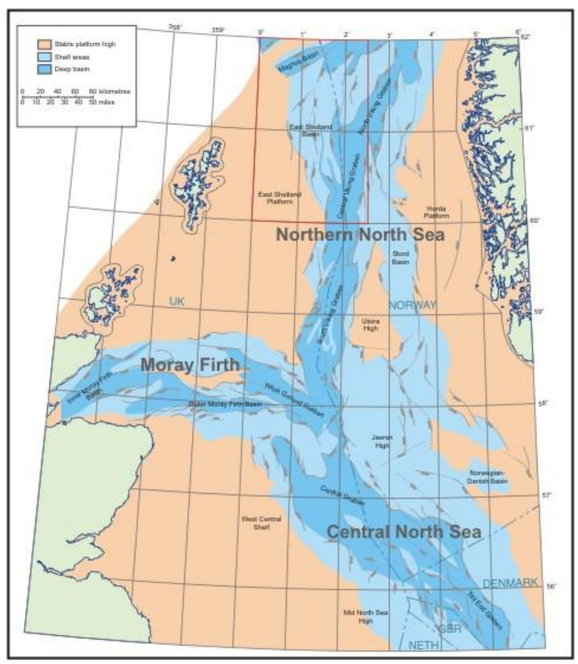


Figure 57 Location of the North Sea Grabens, north of the Netherlands offshore area. The Dutch Central Graben is an extension of the Central Graben in this figure. After Fraser et al. (2003)

Because of clear differences in seismic structures between the western part and the eastern part of the Dutch Central Graben, these are described separately.

Figure 58, 59 and 60 are sections through the western part of the Dutch Central Graben and shows that Cenomanian deposits are onlapping onto a large local high of pre-chalk deposits, see also the extent of the Cenomanian in figure 18. The Turonian could not be interpreted at these locations due to a lack of well control. Cenomanian to Coniacian are generally onlapping progressively higher onto the local high.

Figure 59 and 60 clearly show that pre-Campanian deposits are truncated by the top of the Campanian. At least the Campanian (and Santonian if present) were eroded. It is not very clear if the Coniacian is also truncated by the Campanian or not.

Maastrichtian deposits are thin in the western Dutch Central Graben, when comparing it to the rest of the study area (figure 27). Also The Danian sequence is very thin in the western part of the Dutch Central Graben and mostly consists of only one seismic reflection, like in most of the study area. It is absent at the locations where the Top Maastrichtian is also absent.

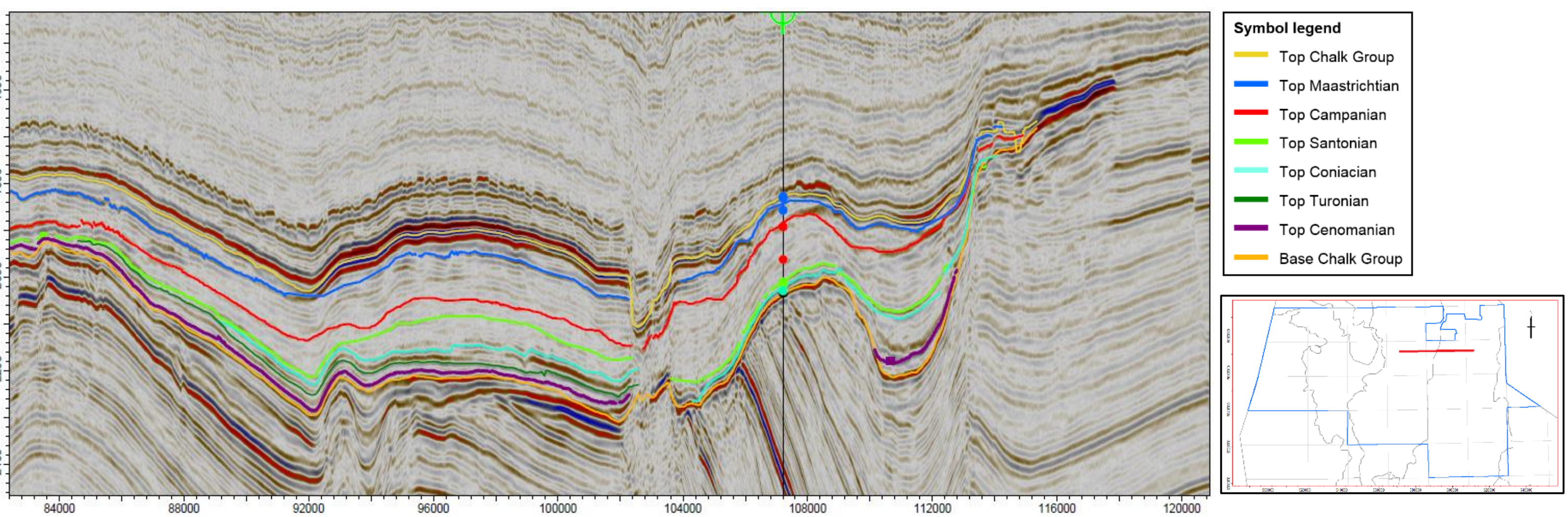


Figure 58 West-east section through the eastern Step Graben and western Dutch Central Graben. The visible well is F04-02-A.

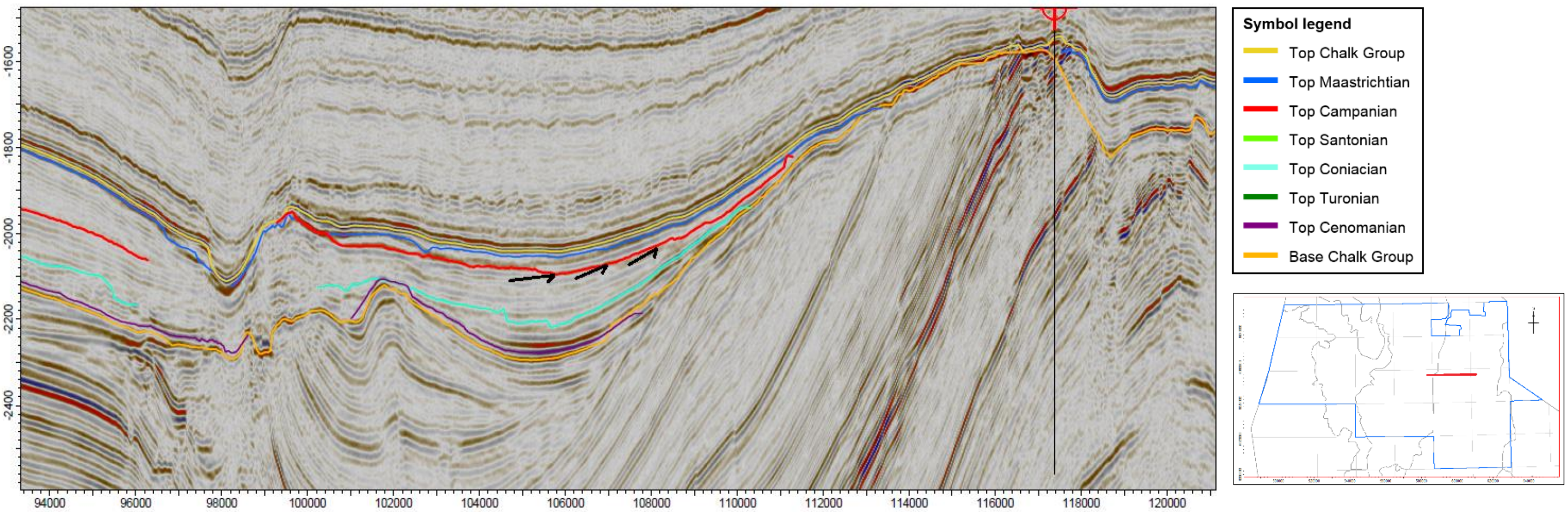


Figure 59 West-east section through the western Dutch Central Graben

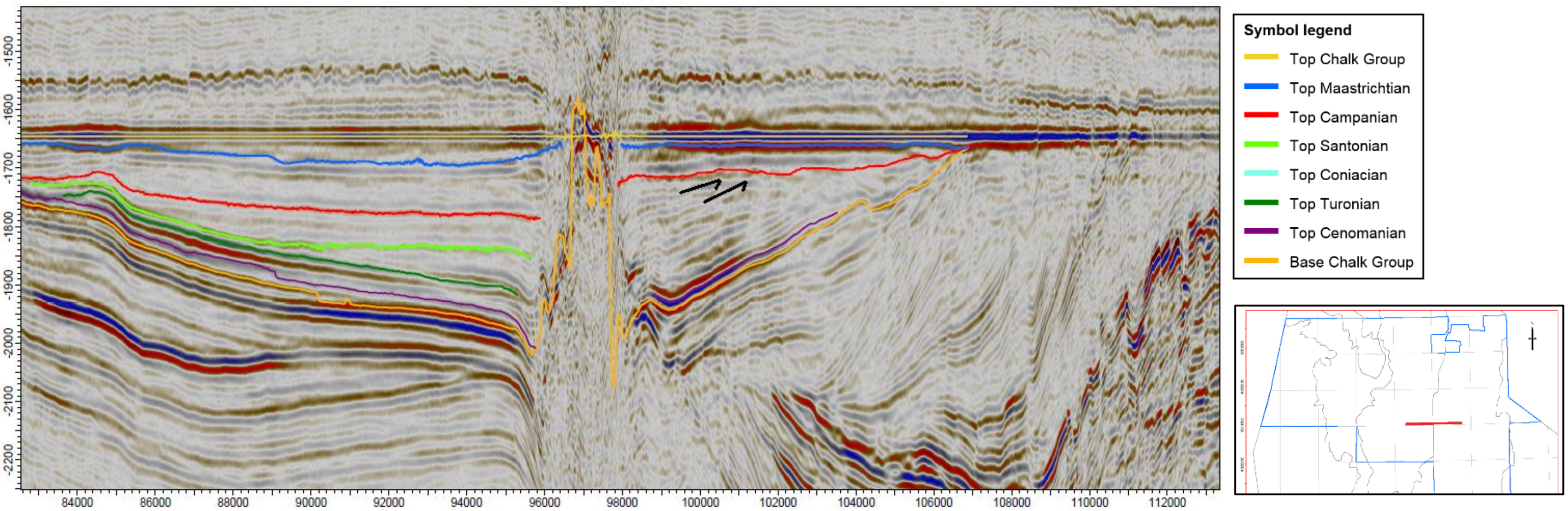


Figure 60 West-east section through the western Dutch Central Graben

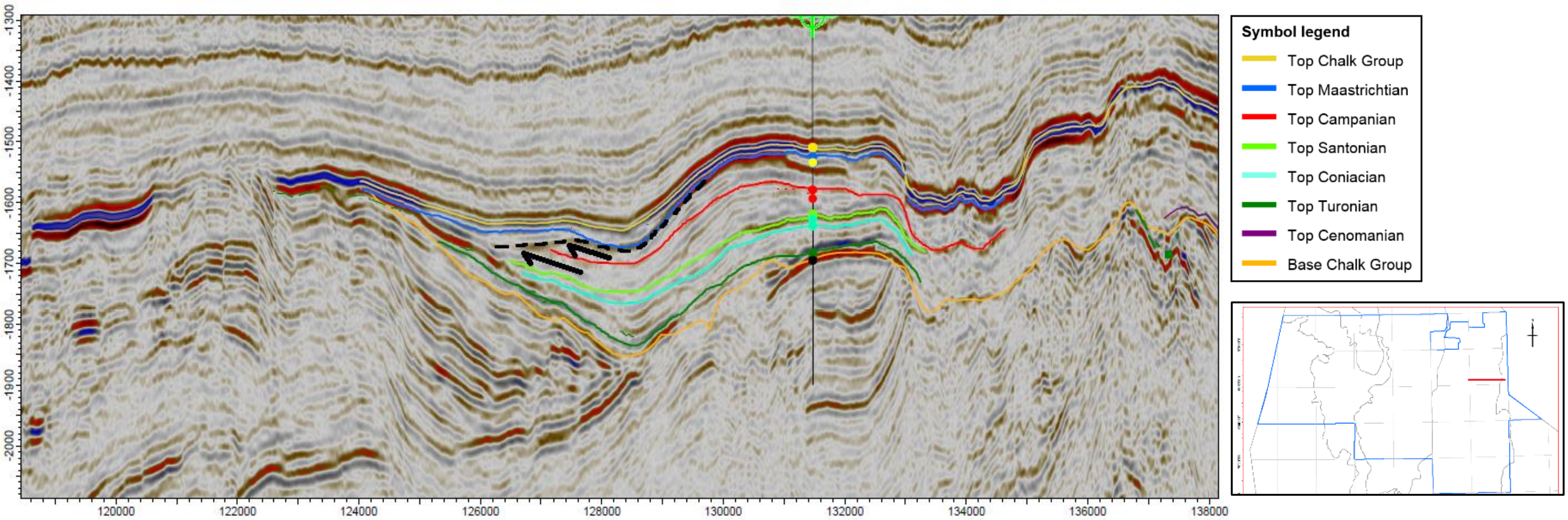


Figure 59 West-east section through the eastern Dutch Central Graben. The visible well is F06-03.

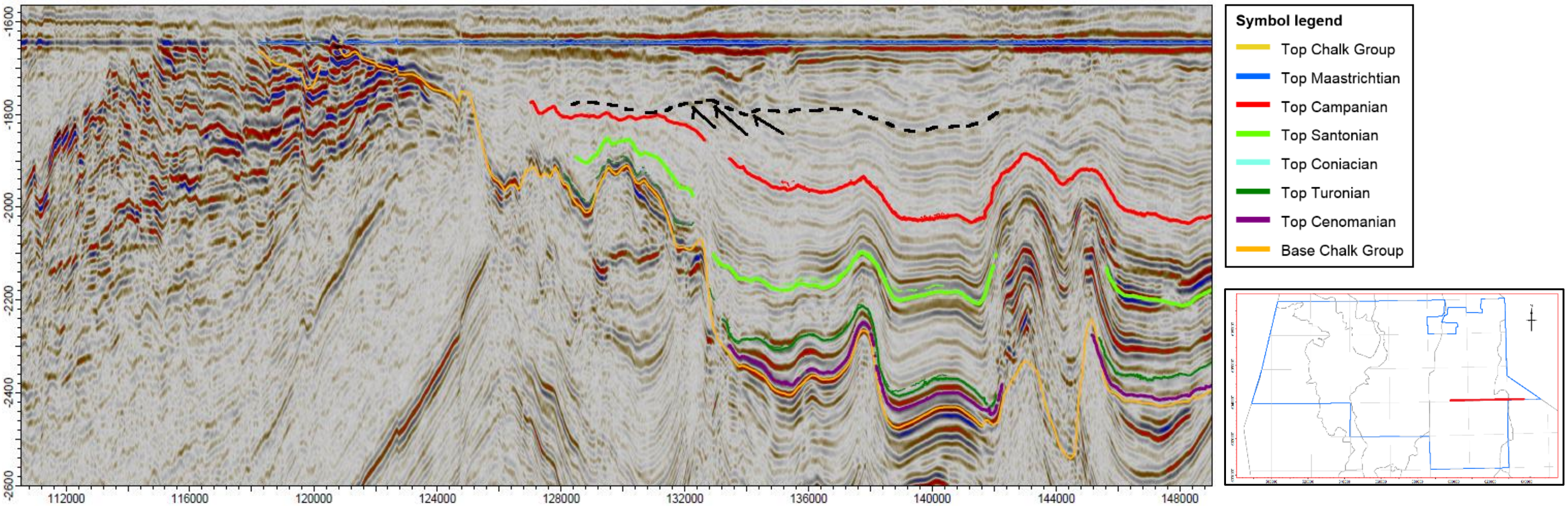


Figure 62 West-east section through the eastern Dutch Central Graben

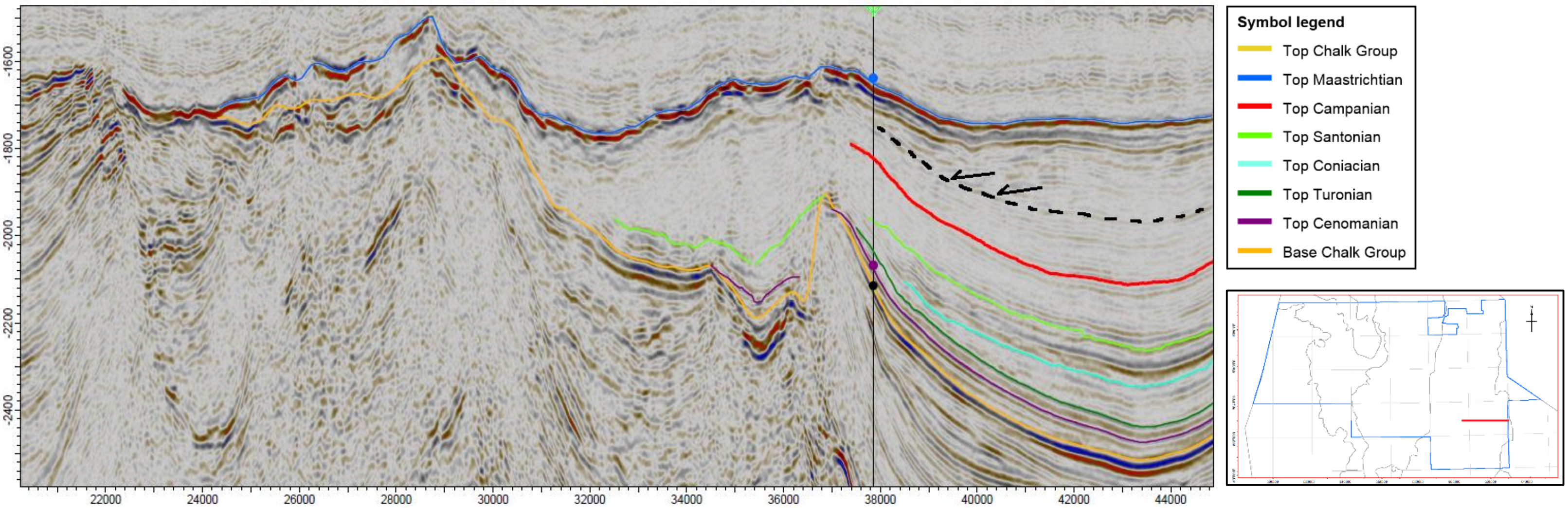


Figure 61 West-east section through the southwestern Dutch Central Graben

Figures 61, 62 and 63 are sections through the eastern part of the DCG. On the western parts of these sections, the chalk is absent.

The Cenomanian sequence is very thin in the northeast. The top of the Cenomanian is located 4 metres above the base of the chalk in well F06-03, which is much less than the resolution of the seismic (figure 61). That is the reason why it is not interpreted as a reflection in this area. However, in the southeastern part of the Dutch Central Graben, the Cenomanian is thicker than in the rest of the study area (figure 19). Well F15-01, located in the southeastern Dutch Central Graben, indicates a Cenomanian thickness of 75 to 90 metres.

Although the seismic quality is low in the area near the chalkless parts of the Dutch Central Graben, it is visible that the Cenomanian to Campanian sequence is onlapping onto the local high in the middle of the graben. The Turonian is generally onlapping higher onto the local high than Coniacian and Santonian deposits.

What is remarkable in this section, is that the top of the Campanian seems to be truncated by the Maastrichtian (figure 61), while in the western part, the Top Campanian itself is an erosional surface. Both figure 61 and 62 show a clear erosional unconformity of Maastrichtian age. Older Maastrichtian deposits as well as Campanian deposits are truncated.

The Maastrichtian sequence is very thick in the southeast. Besides the erosional surface with truncations, you can also see a sequence boundary with deposits onlapping to this surface (figure 62).

Interpretation geological history Dutch Central Graben

The geological evolution of the Dutch Central Graben is illustrated in figure 62.

1. A local high with a north-south ridge shape was present at the onset of chalk deposition in the centre of the Dutch Central Graben. Cenomanian was deposited around this local high, onlapping onto the pre-chalk deposits. The Cenomanian is almost absent at the northeastern part of the ridge. This flank was probably higher than the western part during the Cenomanian. The Cenomanian was thickest in the southeast, so some sea floor topography was present during the Cenomanian.
2. The Turonian sequence also shows onlap onto the local high on the eastern flank. The Turonian could not be interpreted on the western flank. In the western part, Coniacian is onlapping higher onto the ridge than older strata, which means that there was probably no or not much uplift during the Coniacian, or that the sedimentation rates exceeded the uplift. It could also be explained by a sea level rise. However, in the eastern part, the Turonian deposits are onlapping high onto the ridge, and Coniacian and Santonian lower. So, it is clear that at a certain moment during the Coniacian or Santonian, subsidence of the eastern flank or uplift of the ridge occurred. This subsidence may be caused by salt withdrawal

during the growth of salt structures, which are present both at the western and eastern boundary of the DCG.

3. In the west, Santonian and/or Campanian deposits were eroded during an inversion phase of Late Campanian age. Truncations are clearly visible. In the east, the Campanian and Early Maastrichtian are truncated by the Mid Maastrichtian. There are two possible explanations for this:
    - The Campanian erosive event that took place in the western part of the DCG also occurred in the eastern part, but is not visible on seismic. Analysing the Campanian sequence in the east in detail it shows that truncations could be present, but the data are not detailed enough to identify an erosional surface. After deposition of the Campanian and (at least) Early Maastrichtian, a second inversion phase occurred. That is the reason why the Top Campanian and also Early Maastrichtian were truncated.
    - The Campanian erosive event that took place in the western part of the DCG did not occur here in the eastern part but occurred later during Maastrichtian times. Campanian deposits were onlapping onto the high in the west, just like Turonian and Santonian deposits. Uplift took place during the Maastrichtian and a part of the Campanian was removed. This is the reason for the truncation of the Top Campanian.

    The second option is most plausible. Two separated pulses of uplift and erosion in the Campanian and Maastrichtian were not recognized anywhere else in the study area. Besides, it is likely that it represents the same event but the timing is not similar which could be due to a low accuracy of the data or the interpretation.

4. Maastrichtian deposits are relatively thin in the western Dutch Central Graben. A reason for this could be that the sea floor topography was already high at the end of the Campanian inversion phase and deposition was restricted. In the eastern Dutch Central Graben, the Maastrichtian is very thick. Strong subsidence of the eastern flank and/or uplift of the local high must have occurred during the Maastrichtian. This subsidence could have been caused by salt movement.

5. Danian deposits are generally thin in the entire Dutch Central Graben. This could be the result of a Late Danian inversion phase, although no truncations are found. Therefore it is also possible that deposition rates were low during the Danian.

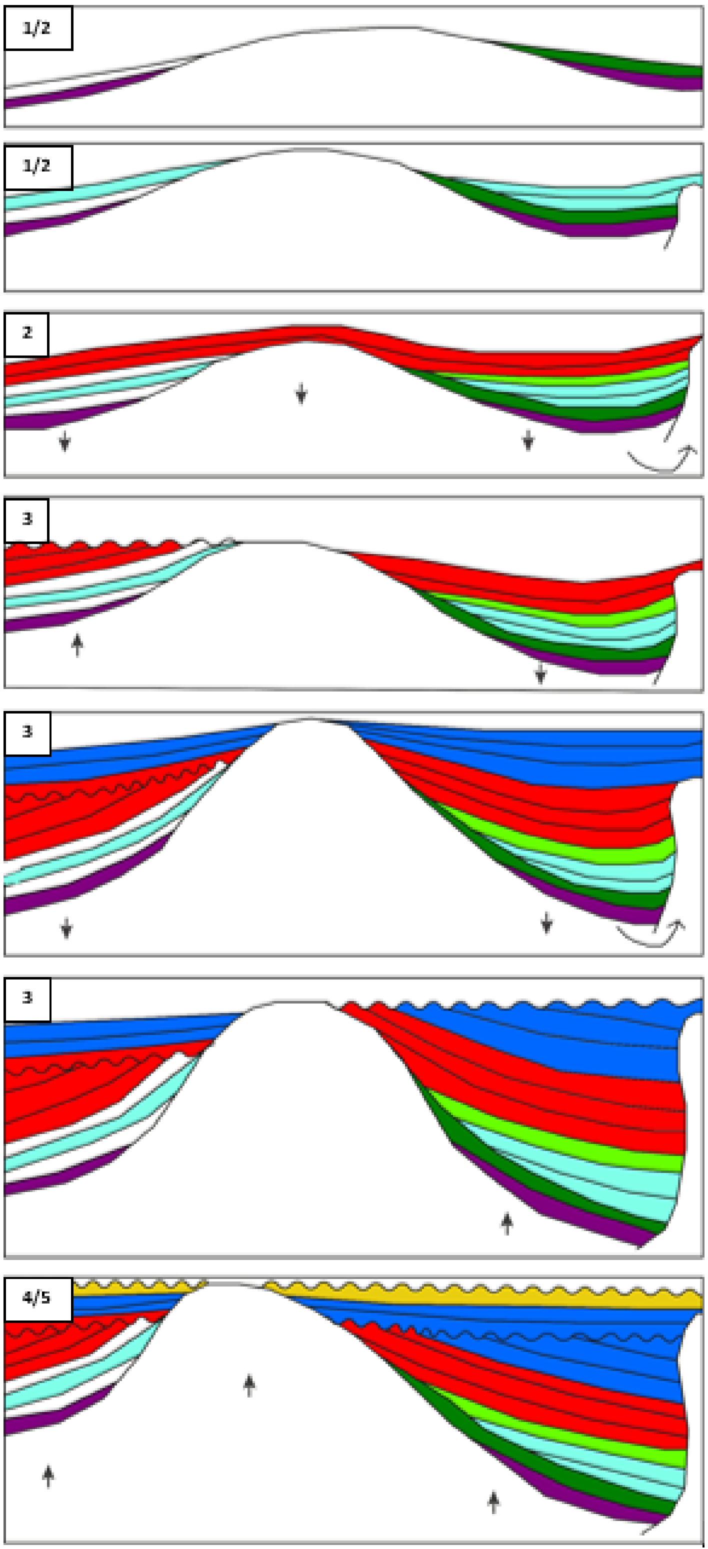


Figure 62 Schematic representation of the interpreted tectono-sedimentary evolution of the Dutch Central Graben. The sections have a west-east orientation. The arrows indicate relative uplift and subsidence.

4.3.5 Schill Grund Platform (SGP)

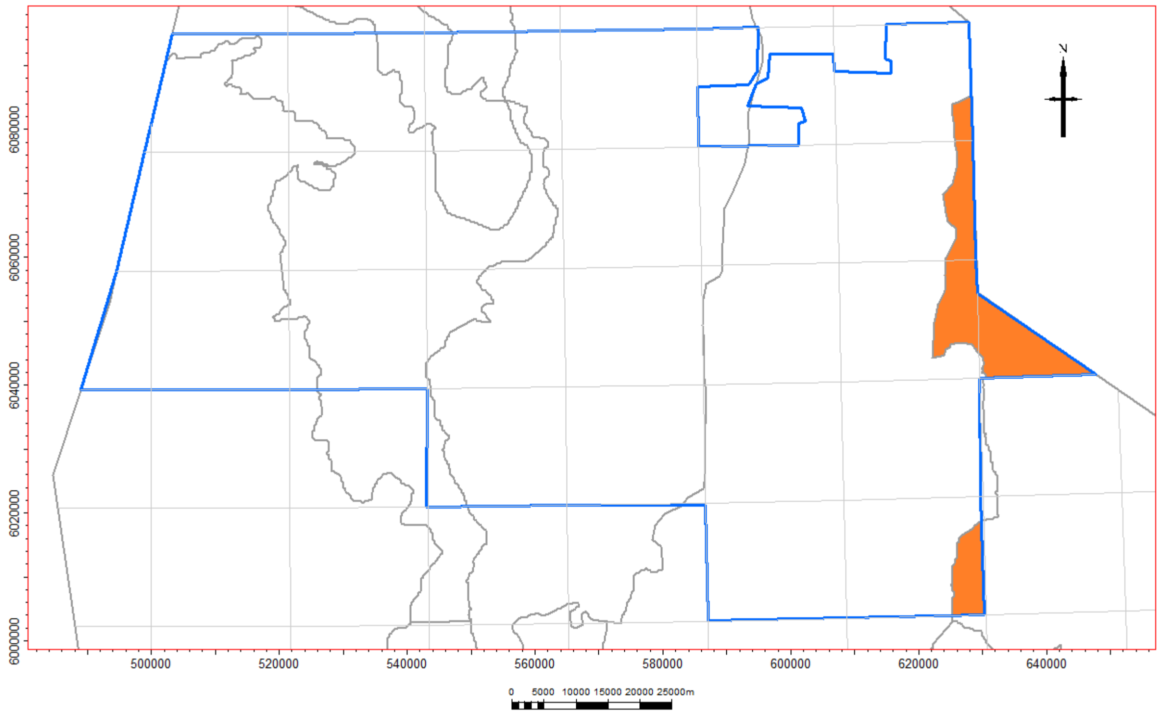


Figure 63 Location of the Schill Grund Platform, indicated in orange

The Schill Grund Platform is located at the easternmost part of the study area (figure 63). When looking at the thickness map of the Chalk Group in figure 31, it is very clear that the Schill Grund Platform contains by far the thickest chalk sequence, together with the southeastern Dutch Central Graben. In the northern part, the Schill Grund Platform is adjacent to the part of the Dutch Central Graben where the chalk is very thin or absent. Thus, the thickness variations within the Schill Grund Platform are very large. The platform is separated from the Dutch Central Graben by large normal faults and salt walls.

In figures 64 and 65, west-east sections through the Schill Grund Platform are shown with a thickening chalk sequence towards the east. The section of figure 65 is flattened on the Top Chalk.

The Cenomanian on the Schill Grund Platform is equally thick as in most of the rest of the study area. It is very thin, only 1 or a few reflections. However, in the southern part it is about 50 metres thicker, like in the southeastern Dutch Central Graben (figure 19). The Turonian is a little thicker than the Cenomanian (two or four reflections instead of one) and shows onlap onto pre-chalk deposits in the west. The top of the Coniacian could not be interpreted here due to a lack of biostratigraphic information.

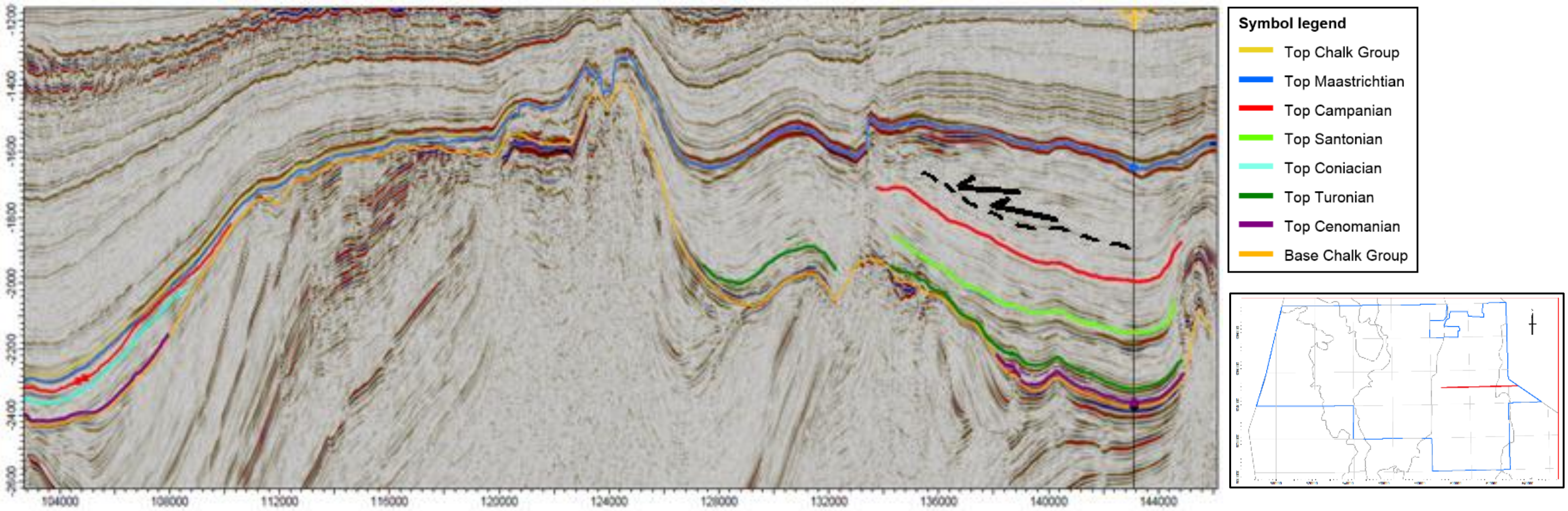


Figure 64 West-east section through the Dutch Central Graben and Schill Grund Platform

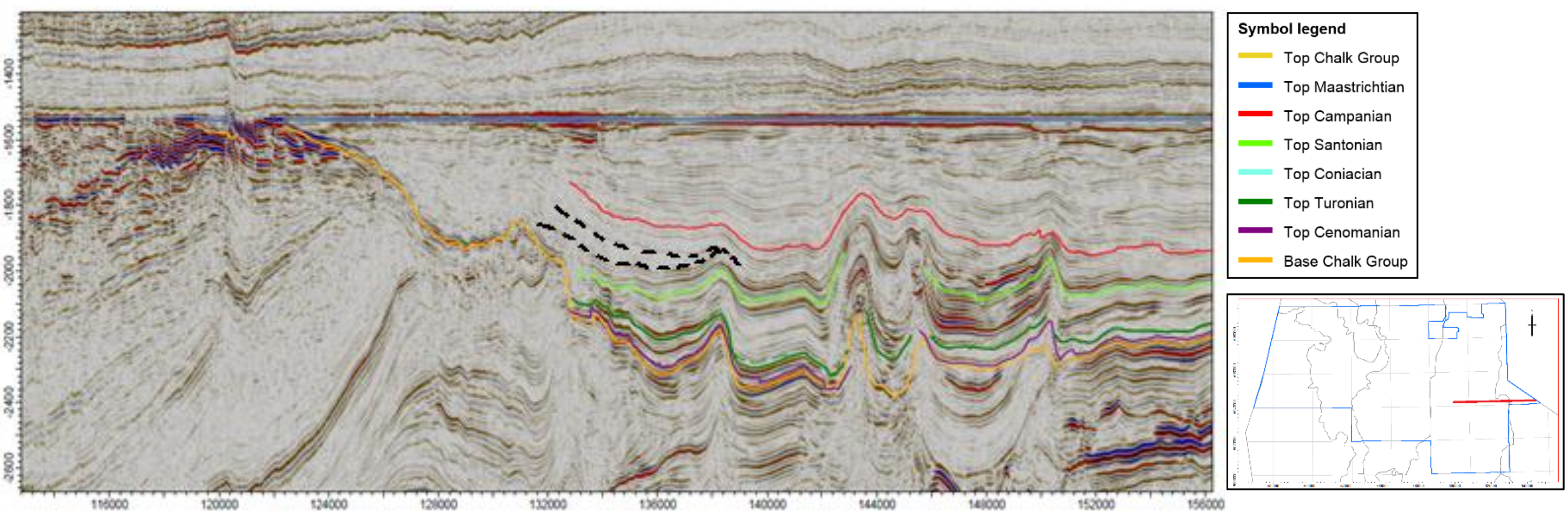


Figure 65 West-east section through the eastern Dutch Central Graben and the Schill Grund Platform

The Top Santonian was interpreted and it is very clear that the Coniacian-Santonian sequence is much thicker here than in the rest of the study area. Within this westward thinning sequence, reflections are not only parallel but show reflection terminations. The Coniacian-Santonian sequence seems to be characterized by onlap-structures towards the west onto the Turonian, although it is not very well visible.

What is very remarkable in the section of figure 65, is that a wedge is present in the middle of the Campanian sequence, thickening towards the west.

In the lower part of the Maastrichtian sequence, reflections are parallel and continuous, but in the Late Maastrichtian they become more chaotic. Similar to the southeastern Dutch Central Graben, a sequence boundary is present in the Maastrichtian with younger Maastrichtian reflections onlapping onto this boundary (figure 64). The Maastrichtian sequence is extremely thick here with respect to the rest of the study area.

Danian deposits are absent on the Schill Grund Platform.

Interpretation geological history Schill Grund Platform

1. While in the rest of the study area the Cenomanian is of almost equal thickness, the Cenomanian sequence is much thicker in the southern part of the Schill Grund Platform and the southeast of the Dutch Central Graben. This means that some sea floor topography was present at these times, or that subsidence took place during the Cenomanian at this position.
2. The Turonian was deposited on top of the Cenomanian and shows onlap onto the pre-chalk deposits towards the west. This could be explained by subsidence of the whole area or a sea level rise.
3. The same story applies to the Coniacian-Santonian sequence, that is thickening towards the east and onlapping towards the west onto the Turonian.
4. During the Early Campanian, (relative) subsidence must have taken place in the west of the Schill Grund Platform, since reflections in a wedge show onlap towards the east. This local subsidence could have been caused by the activity of the salt wall east of this wedge, creating a rim-syncline next to it. The rest of the Campanian is lying conformably on top of the wedge.
5. The Schill Grund Platform kept subsiding during the Maastrichtian, since also this unit is very thick with respect to the rest of the study area. The onlap of young Maastrichtian sediments onto older could be explained by local subsidence or a sea level drop. In contrast to the thick Maastrichtian, the Danian sequence is absent here. This could be caused by non-deposition or erosion. It is not likely that deposition had stopped after the deposition of the very thick Maastrichtian sequence. The Danian sequence is most likely to be removed by a new uplift phase at the end of the Danian, although no evidence for erosion was found in this area.

4.4 Integrated interpretation geological history

Many differences exist between the structural elements and a comparison of the results and interpretations is required to constrain a geological history for the entire study area. An integrated interpretation of the geological history of the whole study area is described in the following section. Figure 66 shows the thickness maps of five time-units.

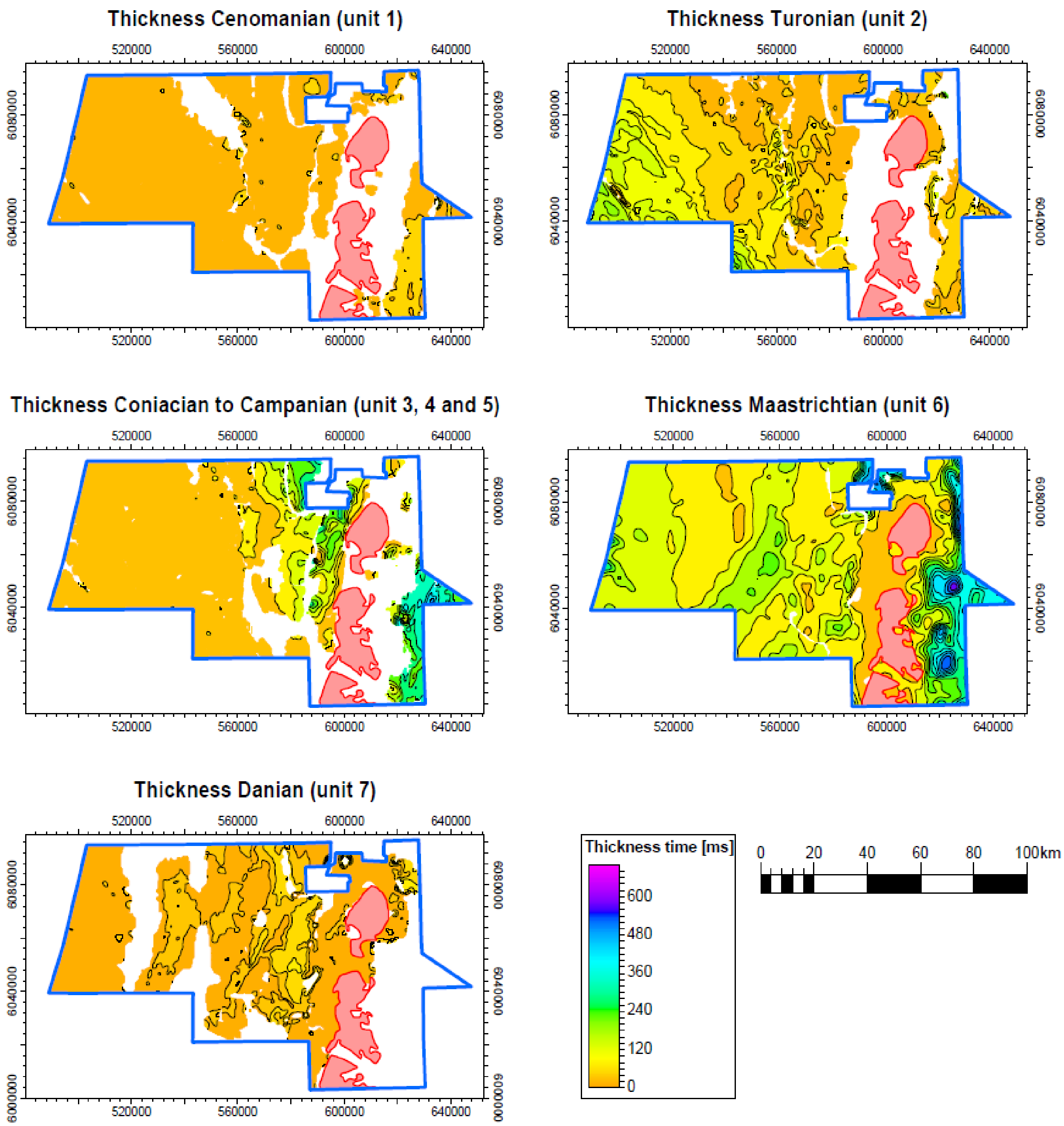


Figure 66 Thickness maps of five (combinations of) units, measured in two-way-time (milliseconds). No thickness maps were created for the separate Coniacian unit and Santonian unit because the areal extent of these units is very limited.

4.4.1 Cenomanian

In general, Cenomanian deposits are very homogeneously thin and parallel. The sea floor must have been generally flat. However, a small basin was present in the southeastern Dutch Central Graben and Schill Grund Platform, where approximately 75 to 90 metres of Cenomanian were deposited. Two 'highs' were present at the onset of chalk deposition, e.g. the Elbow Spit High and a second high at the location of the Dutch Central Graben, as a north-south ridge. At these locations, no deposition took place and Cenomanian deposits show onlap onto pre-chalk deposits.

4.4.2 Turonian

During the Turonian, the sea floor was not flat anymore. The southwestern part of the study area subsided with respect to the northeast, creating accommodation space for a thick Turonian sequence on the Cleaverbank Platform and the Elbow Spit Platform. Well E12-03 indicates a Turonian thickness of approximately 140 metres and it is even thicker in the most southwest part of the Step Graben. Turonian deposits are absent at a small part of the Elbow Spit High, but extend much further on it than Cenomanian deposits. Thus, subsidence must have taken place at the Elbow Spit High as well. Also on a small north-south strip in the central part of the Step Graben, a gap of Turonian deposits exists. However, this absence is the result of a later (Campanian) erosion phase instead of non-deposition.

4.4.3 Coniacian and Santonian

The Coniacian and Santonian could only be interpreted in a small part of the eastern study area because of a limited number of wells with biostratigraphic information on these levels. However, conclusions on the Coniacian and Santonian units could be drawn as well, based on interpretations of the other units. Coniacian and Santonian deposits are extremely thin or absent in the western part of the study area. Because of the very parallel and continuous character of the seismic reflections in this area, it is plausible that no or very slow deposition took place here during the Coniacian and Santonian. This could only be explained by relative uplift of the whole western part of the study area. This tectonic setting differs significantly from the Turonian setting, in which the southwest was subsiding instead of rising. In the Dutch Central Graben, Coniacian and Santonian deposits show onlap onto the local high that was still present at these times in the centre of the Dutch Central Graben. During the Coniacian or Santonian, subsidence of the eastern flank of the Dutch Central Graben took place or uplift of the local high itself. This is based on the observation that from this time onward, deposits show onlap onto underlying strata instead of overstepping the underlying deposits.

Similar to the Turonian sequence, also Coniacian and Santonian units are absent in the north-south strip in the middle of the Step Graben. This is again a result of erosion during a later (Campanian) phase.

4.4.4 Campanian

The Campanian is very thin in the western part of the study area and comprises one single seismic reflection. Similar to the Coniacian and Santonian, the fact that Campanian deposits are thin here is probably the result of no or low deposition rates until Late Campanian instead of erosion, since reflections are very parallel and continuous showing no evidence of erosion. Campanian deposits thicken towards the central and eastern part of the study area, which indicates that relative subsidence must have occurred here. However, Campanian deposits are absent in the central part of the Dutch Central Graben, just like all other units.

In the Step Graben and western Dutch Central Graben, an erosional surface is recognizable that is interpreted as Late Campanian. This erosional surface created truncations: older deposits were eroded. In the western part of the Dutch Central Graben, Santonian and/or Campanian deposits are clearly truncated by the top of the Campanian. In the eastern part of the Dutch Central Graben, the uplift phase is clearly younger than Campanian, since the Top Campanian was truncated itself by Maastrichtian deposits. Also the Elbow Spit Platform was affected by an inversion pulse that occurred later than Campanian. On the Cleaverbank Platform and Schill Grund Platform no evidence of an erosional phase was observed. On the Cleaverbank Platform, the (Late) Campanian lies conformably on top of the Turonian. On the Schill Grund Platform, constant subsidence took place during the Campanian and deposits are very thick with respect to the rest of the study area.

How much of the underlying deposits were removed by the Campanian erosional phase is not always easily recognizable. In the central part of the Step Graben, even the Top Turonian was removed. At the western part of the Dutch Central Graben, at least Campanian and Santonian deposits were eroded, and possibly also the top of the Coniacian.

4.4.5 Maastrichtian

During the Maastrichtian, relatively thick sequences of chalk were deposited in the whole study area. The remaining deposits are thickest on the Schill Grund Platform and southeastern Dutch Central Graben, where subsidence must have been strong. Also the Cleaverbank Platform and the southwestern and eastern part of the Step Graben contain vast amounts of Maastrichtian deposits. Thus, after the very slow or no deposition on the Cleaverbank Platform during Coniacian to Campanian times, renewed subsidence created accommodation space for Maastrichtian deposits. In the middle part of the Step Graben, where Turonian to Campanian deposits were eroded at the end of the Campanian, Maastrichtian deposits are thin. This could be the result of the Campanian erosional phase that uplifted the Step Graben high and thus limited accommodation space. The thin Maastrichtian section at this location could also be explained by Danian channel incision. Maastrichtian deposits are only absent in parts of the Dutch Central Graben where no chalk is present at all. The Maastrichtian deposits mainly show onlap here onto the high.

As mentioned above, a second uplift and erosion pulse occurred during the Maastrichtian, which affected the Elbow Spit Platform and the eastern Dutch Central Graben. Early Maastrichtian deposits were eroded by this event, which indicates it happened later during the Maastrichtian. In the eastern Dutch Central Graben, even Campanian deposits were eroded by the Maastrichtian inversion.

The upper part of the Maastrichtian is absent in two north-south stretching strips on the Elbow Spit Platform and Cleaverbank Platform. In these areas, the upper part of the Maastrichtian is truncated by post-chalk deposits. Danian deposits are also absent at these locations. It is probably the result of a Late Danian inversion phase.

4.4.6 Danian

During the Danian, the general subsidence that occurred during the Maastrichtian proceeded. Danian deposits are present in most parts of the study area, except from the north-south oriented strips on the Cleaverbank Platform and Elbow Spit Platform, a part of the southern Step Graben and the southeastern part of the study area. It is thickest in the eastern part of the Step Graben. Other positive anomalies exist on the Elbow Spit Platform and in the Step Graben. Those thicker Danian sequences could be explained by Danian channel incision, or by a differential effect of the Late Danian erosional phase.The most striking anomaly is a north-south-southwest strip in the central part of the Step Graben, approximately at the same location as the inversion axis of the Campanian uplift here. Well F04-03, in the middle of this strip, indicates a Danian thickness of circa 90 metres. This anomaly is interpreted as a large channel because of some angular unconformities that could indicate incision and because of a striking similarity with a Danian channel system in the German North Sea.

Danian deposits are absent in the same areas as where the top of the Maastrichtian was truncated: the north-south strips in the Elbow Spit Platform and Cleaverbank Platform. The absence of the entire Danian sequence here indicates that an uplift and erosion phase must have occurred at the end of the Danian (mentioned earlier). Danian deposits are also absent in the southeastern part of the study area and in the patches of the Dutch Central Graben that lack the entire chalk sequence. In this area, it is not very clear whether this absence must be explained by erosion or by non-deposition as a result of the topography of the high. However, no truncations or other evidence of erosion was found.

4.5 Sedimentary and redeposition features

Besides thickness variations as a result of tectonic events, also smaller scale structures are present which represent sedimentary and redeposition processes. These structures are described in the section below, divided into bottom current features and slope failure structures.

4.5.1 Bottom currents

Channel-like features are recognized in the study area at different scales. Relatively small channels, which are still larger than the seismic resolution, are about 300 metres wide and are present in the Dutch Central Graben as well as on the Elbow Spit High (figure 67). Larger channels were found mainly in the Dutch Central Graben, for instance in the F2 block (figure 68). The variance attribute map of figure 69 also visualizes these channels, which are oriented parallel to the contours of the slope and are up to 1200 metres wide. The channels are V-shaped or W-shaped and show meandering. Channels seem to be mostly present in Maastrichtian and Danian sequences but also older structures were recognized.

In the southwestern part of the Step Graben, inverted 'mini-basins' are visible on seismic (figure 70). These could have been former large channels. The lower mini-basin is probably of Campanian age and was inverted by salt tectonics. The larger mini-basin on top of it (Maastrichtian) was also inverted by the movement of the salt.

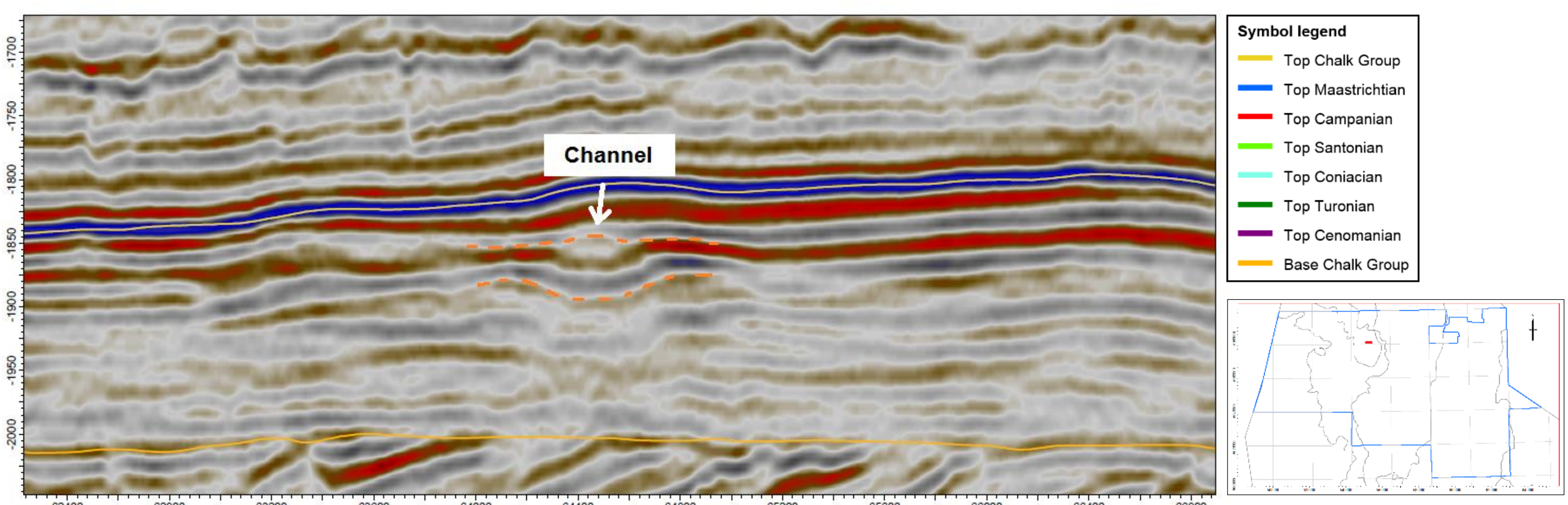


Figure 67 West-east section through the Elbow Spit High. The bottom and top of the channel structure is indicated by the orange dotted lines. The location of the section is indicated on the map by the red line.

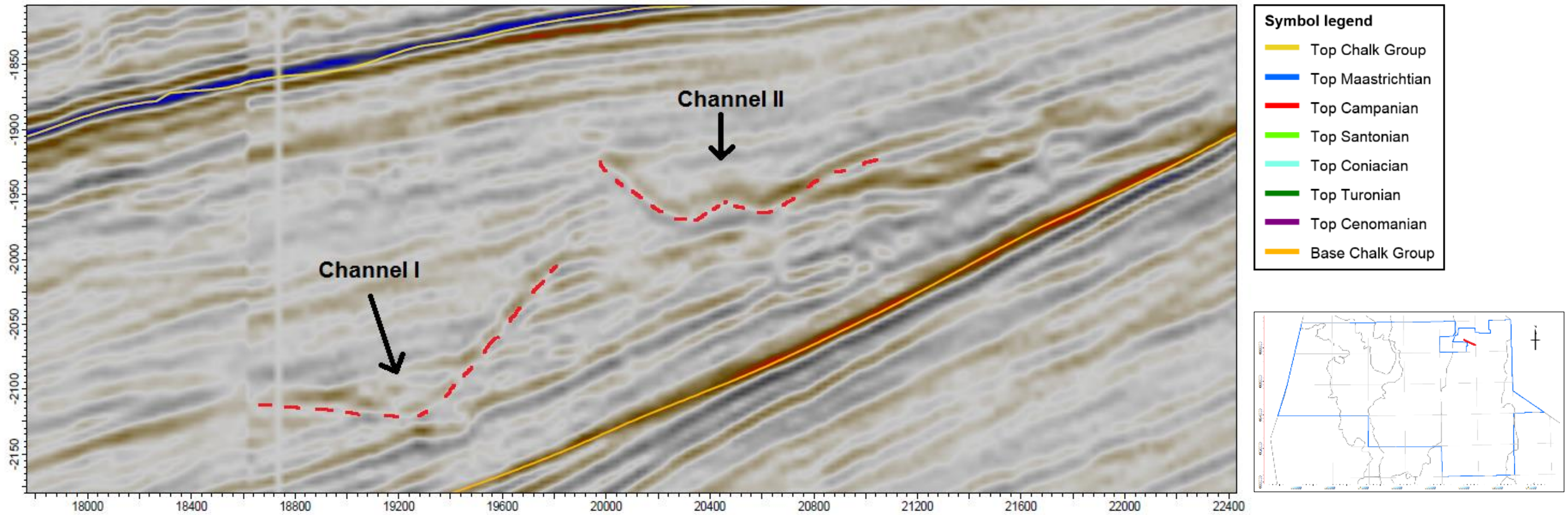


Figure 68 Northwest-southeast section in the northeastern part of the Dutch Central Graben. The bottoms of two channels are indicated by the red dotted lines. The location of the section is indicated on the map by the red line.

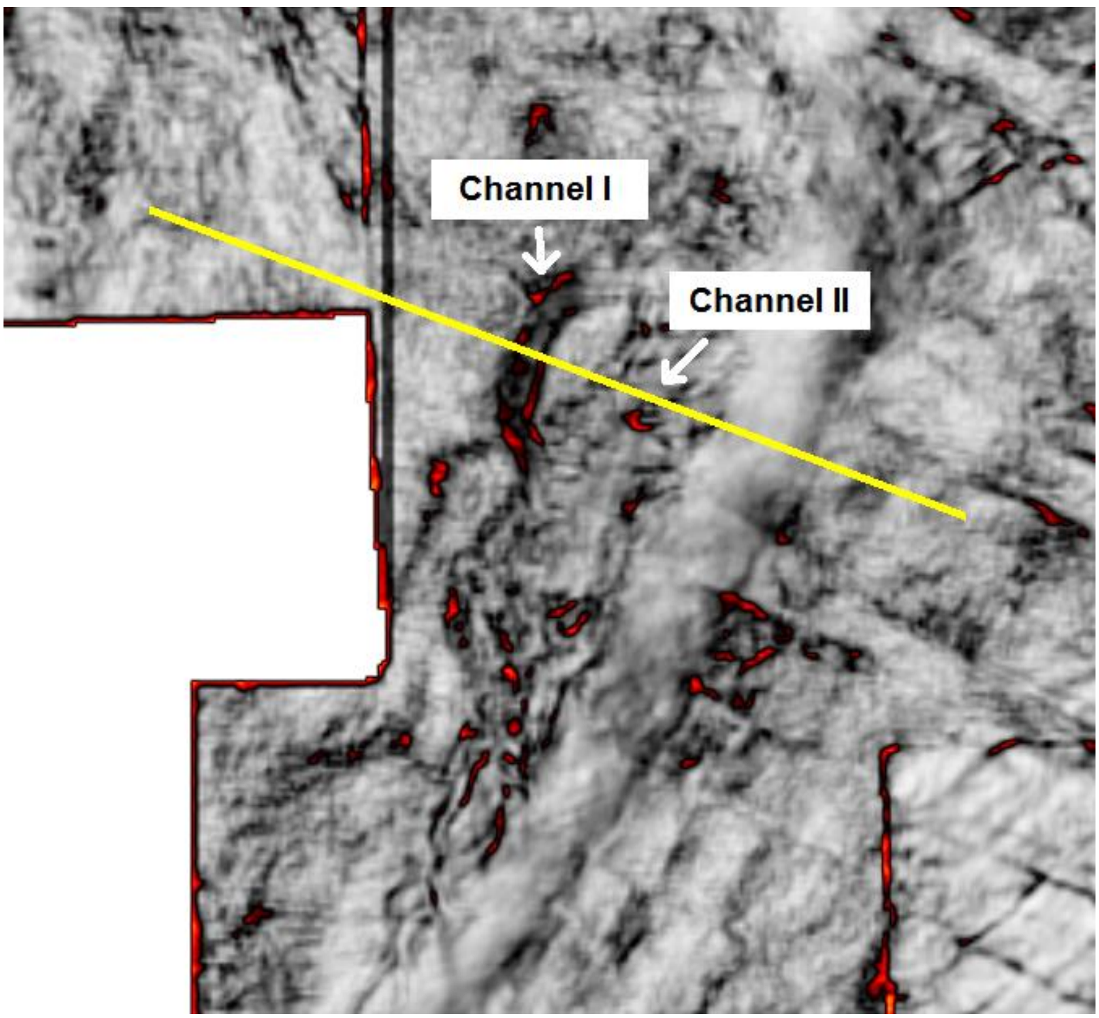


Figure 69 Variance map of the area around the section of figure 71 in the northwest Dutch Central Graben. The yellow line indicates the location of the section of figure 71 and the same channels are marked as well.

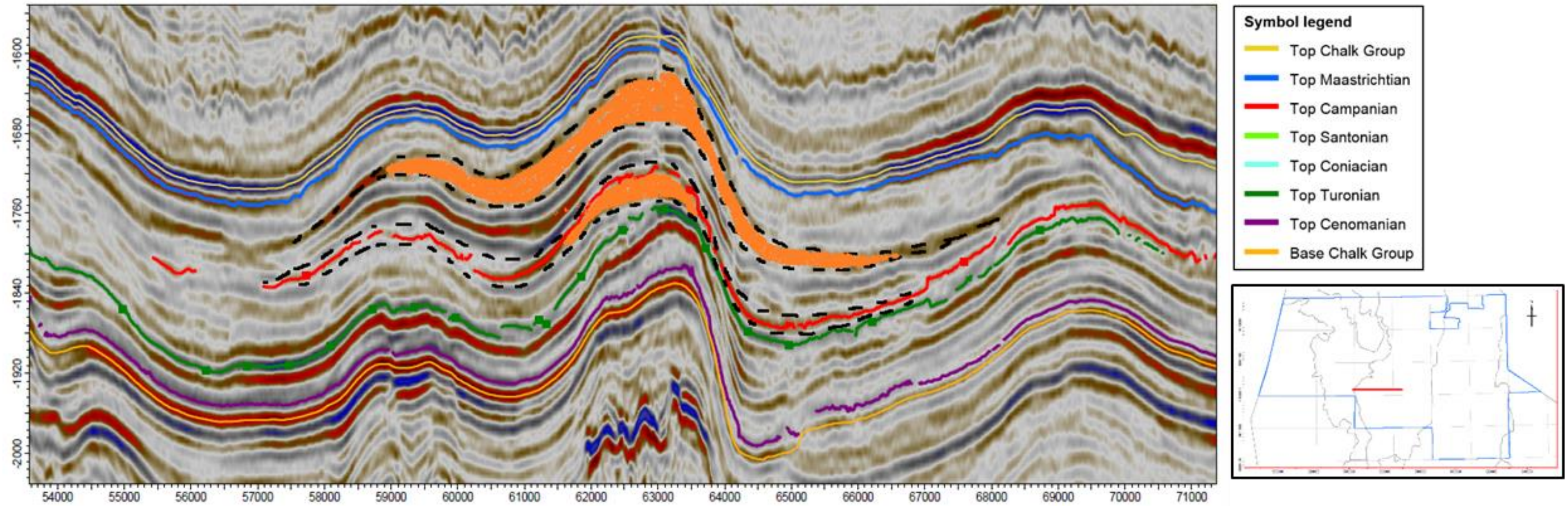


Figure 70 West-east section through the southwestern Step Graben. The orange indicates the infill of 'mini-basins'. The red line on the map indicates the location of the section in the study area.

4.5.2 Slope failure

Especially in the Dutch Central Graben, relatively steep slopes must have been present during chalk deposition because of inversion. Indications for slope failure are visible on seismic in many parts of the Dutch Central Graben. This mostly includes slumps, which replaced slope material downhill, sliding over a detachment surface. Two examples of such slumps are illustrated in figure 71 and 72. The slumps that were found in the study area are up to seven kilometres in length along the axis of displacement.

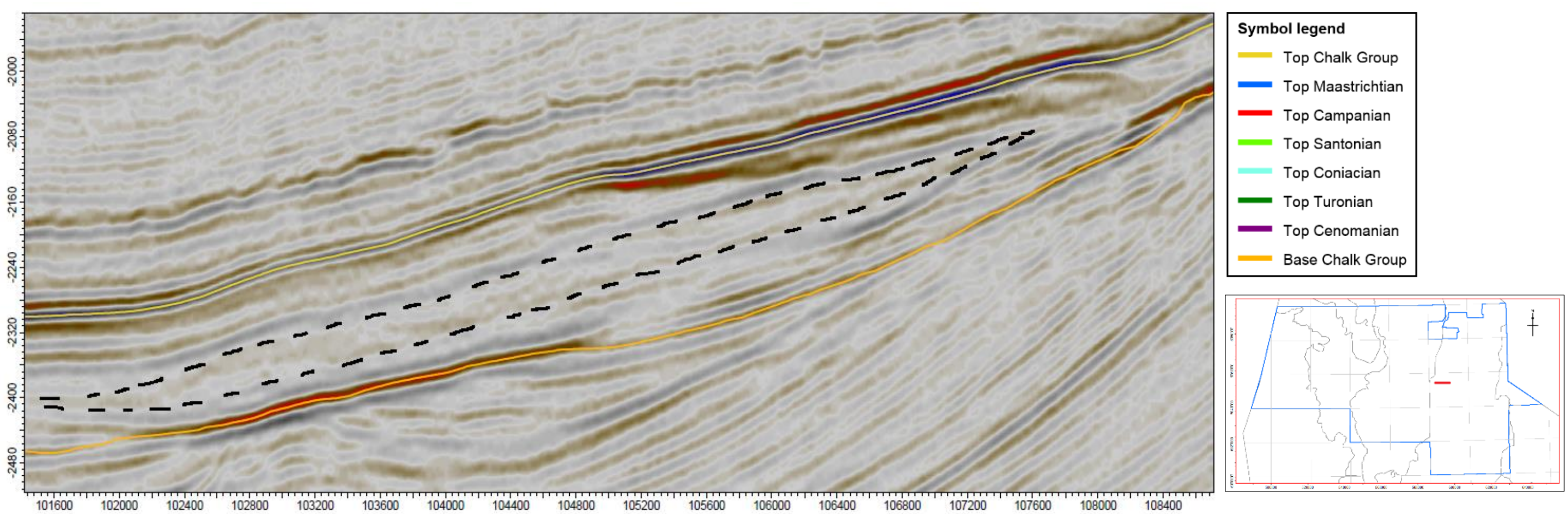


Figure 71 West-east section through the western Dutch Central Graben. The bottom and top of the slump or slide is indicated by the dotted lines.

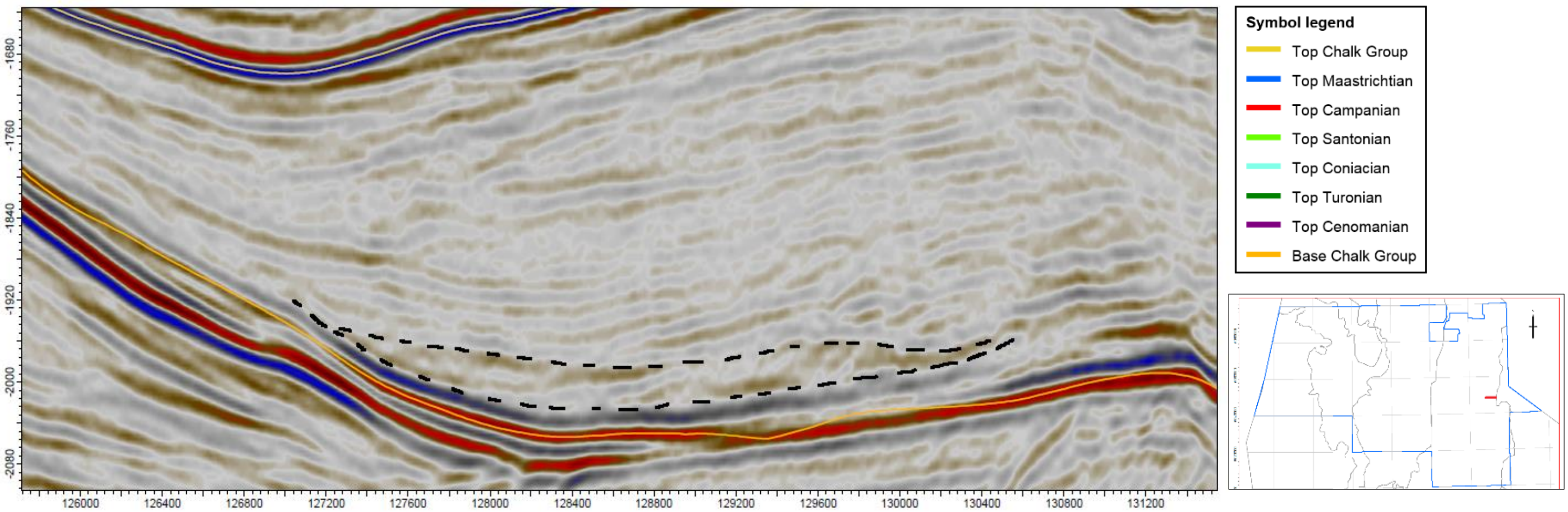


Figure 72 West-east section through the eastern Dutch Central Graben. The bottom and top of the slump or slide is indicated by the dotted lines.

5. Discussion

5.1 Tectono-sedimentary history of the North Sea Chalk Group

5.1.1 Turonian tilting

The thickness map of the Turonian in the study area shows that either subsidence must have occurred in the southwest, or that southwestward tilting took place. Van der Molen (2004) did not discuss this tilting or subsidence process but discusses a sea level rise during the Turonian, which could explain the thick Turonian sequence in the western part of the study area but does not explain the thickness differences. No other studies on this subject in or around this area were published.

5.1.2 Coniacian-Santonian uplift of the Cleaverbank Platform

The seismic character of the Cleaverbank Platform in the study area differs greatly from the other structural elements. Very continuous and parallel reflections indicate a period of tectonic quiescence and deposition on a subsiding platform. However, Coniacian and Santonian deposits are absent here and the only plausible explanation is relative tectonic uplift of the Cleaverbank Platform from Coniacian time onwards, causing non-deposition on the platform. The relative uplift of the platform could be caused by subsidence of the eastern part of the study area. Uplift during the Campanian is not likely to be the cause of the absence of the units, since no evidence for erosion was found in the seismic.

Van der Molen (2004) also discussed the tectonic history of the Cleaverbank Platform in the Dutch North Sea and he states that at least the southern Cleaverbank Platform (K-quadrant) subsided rapidly during Coniacian to Campanian times and that the entire Cleaverbank Platform was tilted SSE-wards during the early Campanian. So the NNW part (that is located in the study area) was relatively uplifted. This tilting could be an explanation for the absence of (parts of) the Coniacian to Campanian sequence, since uplift could have eroded this and no deposition took place during the early Campanian as a result of the tilting. However, no evidence of this tilting was found in the study area. Campanian and post-Campanian deposits lie conformably on top of the Turonian, while onlap-structures on the early Campanian would have been present in case of early

Campanian tilting. These onlap-structures are visible about 30 kilometres south of the study area, though (Terracube Area 2 seismic survey).

Van Hoorn (1987) studied the structural evolution of the Sole Pit High in the United Kingdom part of the Southern North Sea. This Sole Pit High is located about 50 kilometres southwest of the Cleaverbank Platform. Van Hoorn (1987) dates 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, onlap is not present on the Cleaverbank Platform in the study area, as mentioned before.

To conclude, the Cleaverbank Platform present in the study area must have been uplifted during Coniacian-Campanian times. Southward tilting, as proposed by Van der Molen (2004) and thus relative uplift in the northern part (this study) could be the cause of this. However, Van der Molen (2004) dated this tilting as early Campanian. No studies on Coniacian and Santonian non-deposition in this area were published so far.

5.1.3 The Sub-Hercynian inversion phase

In general, the oldest sequence of chalk deposition was a phase of relative tectonic quiescence and subsidence. This tectonic stability ended during the Campanian. A large uplift and erosion phase occurred in two pulses during Late Campanian and Maastrichtian times in a large part of the study area. The Cleaverbank Platform and Schill Grund Platform are exceptions, no evidence of erosion was found here. The uplift started at the end of the Campanian in the western Dutch Central Graben and Step Graben. The uplift of the Elbow Spit Platform and eastern Dutch Central Graben was later, during the Maastrichtian.

Van der Molen (2004) also recognized a large uplift and erosion phase in the same area. His interpretation coincides with the idea that this Campanian/Maastrichtian uplift phase did not affect the Cleaverbank Platform and the Schill Grund Platform in the area of this study. Van der Molen (2004) states that approximately the whole Dutch North Sea area was uplifted at the end of the Campanian and that uplift continued in the Dutch Central Graben, Step Graben and Elbow Spit Platform. This is partly in agreement with the interpretations of this study, since the western Dutch Central Graben and Step Graben appeared to be affected during Maastrichtian times. However, the erosional surface coincides clearly with the top of the Campanian in the western Dutch Central Graben, which indicates that uplift did not continue here into the Maastrichtian. This is in contrast with the interpretation of Van der Molen (2004).

Huijgen (2014) identified a widely recognizable regional unconformity in his study area. This area is located in the southeastern part of the area of this study and comprises of parts of the Step Graben, Dutch Central Graben and Schill Grund Platform. He interpreted the erosive unconformity to be of Late Campanian age, which is slightly different from the interpretation in this study.

Saes (2013) studied the southern part of the Dutch Central Graben, about 50 kilometres south from the area of this study. He also recognized a large erosive unconformity and interpreted it to be of Late Campanian age as well.

Inversion in the Dutch Central Graben was studied by De Jager (2007). He states that inversion 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.

A widespread erosional unconformity was recognized not only in the Dutch North Sea but also in Germany, Denmark, Norway and the United Kingdom. Anderskouv and Surlyk (2011) found evidence for 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 and Andersen (2002) state that continuous inversion took place and identified three different Sub-Hercynian phases of increased intensity: latest Santonian, mid Campanian and late Maastrichtian.

The Chalk Group in the Norwegian North Sea was studied by Gennaro *et al.* (2013). They identified three different phases: a pre-inversion phase, a syn-inversion phase and a post-inversion phase. The inversion initiated in the Norwegian Central Graben during latest Coniacian-to-earliest Santonian and ended at the end of the Campanian. The inversion culminated during the Santonian.

Not much is known on the German sector of the North Sea. However, Surlyk *et al.* (2008) studied the Chalk Group of the Schillgrund High in this area and discovered that the Cenomanian to Campanian deposits were tilted towards the southwest at the Campanian-Maastrichtian boundary, overlain by onlapping deposits.

5.1.4 The Laramide inversion phase

As mentioned, uplift and erosion occurred at the end of the Danian in almost the entire study area. This phase is referred to as the Laramide phase. The Danian sequence is very thin, except for some anomalies on the Elbow Spit Platform and in the Step Graben. It is not possible to constrain the former thickness of the Danian from the available data. This is the reason why it is unknown how much of the Danian sequence was removed by the Late Danian uplift and erosion phase.

On the Cleaverbank Platform and on the Elbow Spit Platform, Danian inversion took place along a north-south axis an removed Danian and Late Maastrichtian deposits. Danian deposits are absent in the southeastern part of the study area. It is not certain whether this is a result of the Laramide inversion and erosion, or a result of non-deposition. No evidence of erosion was found. Van der Molen (2007) argues that the Laramide phase had a larger impact on the Dutch Central Graben than on the Elbow Spit High and the Cleaverbank Platform. 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.

5.1.5 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. Based on the data of this study, it is not easy to compare these events because the original thickness of the Danian deposits is unknown and because the Sub-Hercynian phase did not occur at the same time 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 Early Maastrichtian to Campanian deposits in the east. It is not likely that the Santonian to Campanian sequence or the Campanian to Early Maastrichtian sequence, removed by the Sub-Hercynian inversion, was originally thinner than the Late Maastrichtian to Danian sequence, removed by the Laramide inversion. This idea is based on the periods of time that these eroded sequences cover, which is about 15 million yeas for the Sub-Hercynian phase and 8 million years for the Laramide phase. When assuming similar deposition rates, the Sub-Hercynian inversion must have had a larger impact. This hypothesis was not confirmed by the thicknesses of the units on the Schill Grund Platform, where no evidence was found for a Sub-Hercynian inversion phase. In this area, the Danian is absent. However, the Maastrichtian sequence is extremely thick and is even thicker than the Santonian and Campanian sequence together. Therefore, it is likely that 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 are possibly different from the other structural elements, so it is uncertain if the Schill Grund Platform is a good analogue. In addition, the thicknesses of the Maastrichtian sequence may be strongly influenced by an irregular sea floor morphology during deposition and by redeposition processes.

Saes (2013) studied the southernmost part of the Dutch Central Graben and concluded that the intensity of the Laramide phase was smaller than the Sub-Hercynian phase. This contradicts the conclusions from Van der Molen (2004) and also the outcome of this study, when assuming the absence of the Danian is a result of erosion. However, this study was done in an area more north from the area of Saes (2013).

The Laramide phase probabaly 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 inversion phase eroded not only the Campanian and Santonian, but also the Coniacian and the top of the Turonian. This makes it a sequence that covers circa 18 million years. The Danian sequence is relatively thick here, which could be an indication for a small 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 north-south inversion axes and locally a part of the Maastrichtian. The Sub-Hercynian phase eroded an Early Maastrichtian sequence, older sequences are preserved. It is not known how much of the Maastrichtian was eroded. Therefore, it is impossible to draw a conclusion on 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.

5.2 Sedimentary and redeposition features

Many studies on sedimentary structures and redeposition features within the Chalk Group were published recently. In the study area, mainly channels and slump or slide features were found on seismic. Only small angles are necessary for the chalk to move as a slump or slide because of the small grainsize, which is mostly clay to silt size in the chalk sediments. Kenter (1990) states that 'grainy, non-cohesive, mud-free sediments build steeper slopes than muddy, cohesive, sediments'.

Syn-sedimentary channel features were first imaged within the Chalk of southern England, by Evans and Hopson (2000) and Evans *et al.* (2003). The channels found in this study are oriented parallel to the bathymetric contours. Evidence of contour-parallel bottom currents and a very irregular sea floor topography was found in seismic data from eastern Denmark, by Surlyk and Lykke-Andersen (2007). This phenomenon was even earlier recognized in the chalk of the Danish Basin by Lykke-Andersen and Surlyk (2004). They found a major contour current system in the Danish Basin with even larger channels, which are up to 20 kilometres wide. As mentioned before, Surlyk *et al.* (2008) also identified deep slope-parallel channels in the German part of the North Sea, up to 15 kilometres wide and 200 metres deep. Back *et al.* (2011) found multiple channel incisions on seismic in the southern Danish North Sea. These channels look similar to those found in this study.

Down-slope mass-transport evidence was found in the form of slumps or slides in the study area. Multiple kinds of mass movement were recognized in the chalk in many areas of the North Sea (Evans *et al.*, 2003; Lykke-Andersen and Surlyk, 2004; Surlyk *et al.*, 2008; Back *et al.*, 2011).

Esmerode *et al.* (2008) found a relation between bottom currents and slope failure. They state that the current activity caused erosion, which caused slope instability and triggered slumping.

Most sedimentary and redeposition structures 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. Steep slopes may have been present in the Dutch Central Graben during almost the entire Late Cretaceous and Early Tertiary, partly due to salt movement. As a result, the chalk was exposed to syn-sedimentary processes like contour-parallel bottom current activity and down-slope mass movements. To better understand the processes it is necessary to determine the timing of the salt structures relative to the chalk deposition.

5.3 Limitations and recommendations

Some limitations and uncertainties of the data and interpretations are discussed below. Finally, alternative methods are recommended and suggestions for further research are explained.

The seismic interpretation

The largest uncertainty is the interpretation of the data, of course. Since the continuation and amplitude of the seismic reflections were not always ideal for interpretation, another person's interpretation is likely to be at least a little different from the one presented in this report.

Biostratigraphic well tops

The interpretations of the tops of the units are based on the biostratigraphic well tops and the seismic. However, very few tops are specified at a certain depth. Most well tops actually cover a range of possible depths. Confidence levels were applied. These uncertainties were taken into account when interpreting the seismic. Altogether, more precise biostratigraphic well tops could make the interpretation a lot more detailed and accurate. The biostratigraphic well top picks should be combined with other well data, for instance well logs, and seismic to determine more precise units within the chalk.

The seismic resolution

If the seismic resolution had been better, the interpretation would probably be easier or at least more detailed. This would be specifically of importance for the thin units of which the top and base are not always recognizable because of the resolution that exceeds the thickness of the unit itself. Besides, more reflection terminations would be visible when more specific layers would be shown because of a higher resolution. When more onlap-structures or truncations are visible it is easier to recognize erosional surfaces, for instance.

The amount of wells

The wells that were used in this study are not evenly spread over the study area. On the Cleaverbank Platform and the Elbow Spit Platform in the western part of the study area, very few wells are present. All possible public information was taken into account when making the interpretation. However, the tectono-stratigraphic evolution of the Cleaverbank Platform that resulted from this study is not in agreement with other publications. This could possibly be a result of the limited amount of information based on the limited number of wells available in the study area.

Recommendations

In order to verify the conclusions on the tectono-sedimentary history of the Cleaverbank Platform, a suggestion is to gain more biostratigraphic information in this area from old or new wells and to extend the area towards the south. Southward, reflections are not as parallel and continuous as in the study area and an interpretation based on timing could be useful here to construct the geological history in more detail. In addition, it could be very useful to extend the interpretation into the North Sea of the United Kingdom since a large number of wells are present in that area. More information on the biostratigraphy of the Cleaverbank Platform could be possibly found there.

Another recommendation is to make a similar general interpretation of units based on biostratigraphy in the rest of the Dutch North Sea. This could give us an insight in the general tectonic and stratigraphic history of the entire North Sea of the Netherlands.

Moreover, the integration of biostratigraphic information and interpretations with Germany, Denmark, Norway and the United Kingdom is even more important. Agreement on a set of litho- and/or biostratigraphic units could enable us to construct the geologic history of the whole chalk sequence in the North Sea.

In addition, a detailed study on the geomorphological aspects of the Chalk Group would be very interesting and useful. Sedimentary and redeposition processes are known to have affected the chalk by a large extent. This resulted in thickness variations and a more chaotic seismic response. Therefore, these kind of features need to be mapped and described to determine the geological events that affected the Chalk Group. The same applies to the timing of salt activity relative to the chalk deposition, which needs to be determined to better understand the sedimentary and redeposition processes. Smit *et al.* (2014) are currently performing a detailed study on the seismic morphology of the chalk deposits in the Danish North Sea, using 3D seismic, well log and biostratigraphic data. They also documented mass waste complexes in three dimensions. Another interesting aspect of the depositional environment of the Chalk Group is the water depth in which it was deposited. Since there is not much agreement on this topic, it could be interesting to re-evaluate the available information of the wells.

Gaining more knowledge on the tectonic and sedimentary history of the multiple structural elements of the Dutch North Sea could be helpful to the search for hydrocarbons. It could for instance enlighten facies differences, possible seal levels, reservoir properties etcetera which are of great importance for the petroleum industry. The chalk play gets more and more attention these days because of recent discoveries and the amount and size of Scandinavian hydrocarbon fields in the Chalk Group.

6. Conclusions

- The development of the Chalk Group in the northern Dutch North Sea was reconstructed based on the interpretation of seven chronostratigraphic units by the integration of biostratigraphic well data and seismic data. The evolution of the chalk was influenced by multiple processes, generally subdivided into tectonic and sedimentary or redeposition processes.
- The first period of chalk deposition was a phase of relative tectonic quiescence and lasted from Cenomanian to approximately Campanian times. Evidence of two exceptions to this tranquillity were found. Firstly, a southwestward tilting took place during the Turonian and created accommodation space in the southwest, leading to thick Turonian deposits on the Cleaverbank Platform. Secondly, relative uplift or very low sedimentation rates must have occurred during the Coniacian and Santonian on the Cleaverbank platform since Coniacian and Santonian deposits are very thin or even absent there. No evidence of erosion was found.
- The earliest most important tectonic event that affected the Chalk Group took place in two pulses during the Late Campanian and Maastrichtian. Widespread uplift and erosion influenced almost the entire study area. The Cleaverbank Platform and Schill Grund Platform are exceptions. This inversion phase was probably strongest in the Step Graben, where deposits down to the Turonian were eroded. The timing of the uplift seems to differ between the structural elements in the study area, starting in the western part of the Dutch Central Graben and Step Graben (Late Campanian) and ending on the Elbow Spit Platform and in the Dutch Central Graben (Maastrichtian). This inversion phase is generally referred to as the Sub-Hercynian phase.
- 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. Also Maastrichtian deposits were eroded locally. The inversion was strongest in two north-south strips of the

Elbow Spit Platform and Cleaverbank Platform, where the entire Danian sequence was removed and also parts of the Maastrichtian sequence. The absence of a Danian sequence in the southeastern part of the study area could either be caused by erosion or non-deposition.

- During the deposition of the Chalk Group, subsidence also occurred at a smaller scale. This is mainly the result of salt tectonics. Salt diapirs and walls are present in the study area, most of them in the Step Graben and Dutch Central Graben. During the growth of these salt structures, salt was withdrawn underneath 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. The halokinesis also resulted in erosion of the chalk on top of the salt diapirs.
- Not only tectonic events have caused thickness variations of the chalk units. During the deposition of the Chalk Group, the topography of the sea floor was very irregular. Multiple kinds of bottom currents and slope failure processes are known to have occurred. Evidence of channel incisions was found in the study area at different scales. A remarkable positive anomaly in the Danian thickness through the centre of the Step Graben was interpreted as a large channel and is 2 to 10 kilometres wide and approximately 80 kilometres long. Well F04-03 indicates a channel thickness of circa 90 metres. Also evidence of slope failure was found in the form of slumps or slides, up to seven kilometers in length along the axis of displacement. Based on these observations, the conclusion can be drawn that the chalk sea was far from quiet and flat and reworking of the autochthonous chalk occurred at a large scale.

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Appendix

Well tops

A spreadsheet with all wells and their lithostratigraphic and biostratigraphic tops and present units is included as a digital file.