

Mid-Paleocene palaeogeography of the Danish area

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At the Danian/Selandian transition the North Sea Basin experienced a marked change, from deposition of almost pure carbonate during the Upper Cretaceous and Danian to deposition of greensand, marl and clay during the Selandian. Erosional features at the Top Chalk surface and the occurrence of an overlying conglomerate (transgressive lag deposit) indicates that large parts of the Danish area were subaerially exposed at the Danian/Selandian transition, probably due to regional tectonic uplift. Tectonically induced inversion of fault trends in the Central Trough and the Sorgenfrei-Tornquist Zone and differential relative subsidence between the Ringkøbing-Fyn High and the Norwegian-Danish Basin strongly affected the distribution of the lower Selandian sediments. Three palaeogeographic maps are presented to illustrate the various stages of the early Selandian transgression in order to demonstrate the mid-Paleocene evolution of the Danish area.

Keywords: Paleocene, Palaeogeography, Denmark.

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The Paleocene deposits on- and offshore Denmark have been the subject of numerous studies over the last hundred years (onshore) and since commercial drilling started in the offshore region in the 1960s. The Danian/Selandian boundary is of interest because it marks one of the most profound changes in depositional environments recorded in the North Sea Basin, from Upper Cretaceous-Danian carbonate deposition to post-Danian deposition of siliciclastic sediments. Commercial interest is focused on the chalk fields of the Central Trough and on upper Paleocene channelized turbidite sandstones capped by hemipelagic marls and clays. However, the bulk of the published studies have so far concentrated either on the Chalk Group or on the overlying siliciclastic succession, and only few studies have attempted to correlate the on- and offshore areas. This dual bias has introduced an undesirable incoherence in the knowledge about the mid-Paleocene evolution of the Danish area. The objective of the present paper is therefore to incorporate information about the Top Chalk surface with the lithological evolution of the lowermost Selandian deposits on- and offshore Denmark in order to unravel the mid-Paleocene palaeogeographic development of the Danish area.

The study is based on analyses of petrophysical well logs, and high-resolution and conventional seis-

mic surveys, integrated with published outcrop- and well reports. Results from 3-D basin modelling (Gemmer et al. 2002, Nielsen 2002) were used to indicate distributions of marine and terrestrial environments in areas where no Paleocene sediments are preserved (i.e. north of the Sorgenfrei-Tornquist Zone).

The presented maps represent our best estimate of the mid-Paleocene development of the Danish area based on all available data. Obviously, details of the maps are subject to changes as more information becomes available, especially from exploration drilling in the eastern North Sea. Even so, we hope that the maps will help improve the understanding of events associated with the mid-Paleocene depositional turnover.

Geological setting

During the Mesozoic the epicontinental North Sea Basin suffered several major tectonic phases, which controlled the subsidence pattern of the basin (Ziegler 1990). To the northeast the North Sea Basin is bounded by the Sorgenfrei-Tornquist Zone, which has a long history of crustal deformation (Liboriussen et al. 1987, Michelsen & Nielsen 1993, Thybo 2000). The North

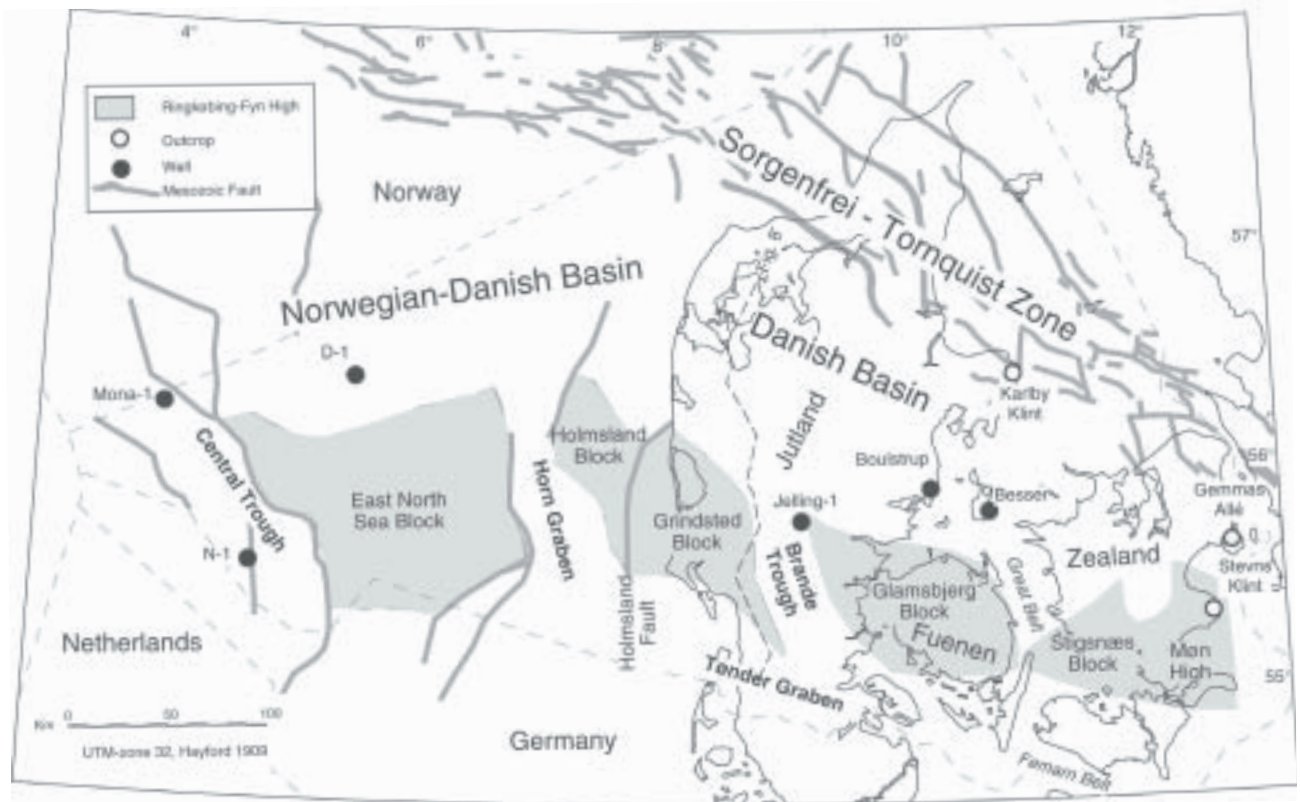


Fig. 1. Location map. The Mesozoic faults indicate the structural architecture of the area, with special emphasis on the Ringkøbing-Fyn High and the intersecting grabens and troughs. The location of Fig. 8 in western-central Jutland is indicated with a dashed line.

Sea Basin is dissected by the E-W striking Ringkøbing-Fyn High, which separates the Norwegian-Danish Basin and the North German Basin. The Ringkøbing-Fyn High is cut by a number of approximately N-S striking Mesozoic grabens and troughs (Fig. 1). During the Cenozoic, the centre of the North Sea Basin subsided to depths of more than 3 km while the margins suffered substantial erosion as a response to tectonic uplift and a long-term eustatic lowering (Ziegler 1990, Japsen 1998, Huuse 2002).

The Top Chalk surface is a major geological boundary in the North Sea area marking a major change in deposition from chalk and limestone below to siliciclastic sediments above the boundary (Fig. 2, Lieberkind et al. 1982, Kristoffersen & Bang 1982, Huuse 1999). The Danian limestone deposits are dominantly biogenic indicating that the supply of clastic sediments from the basin margins or from intra-basinal highs was almost absent, although a slightly increasing clay content towards the top of the

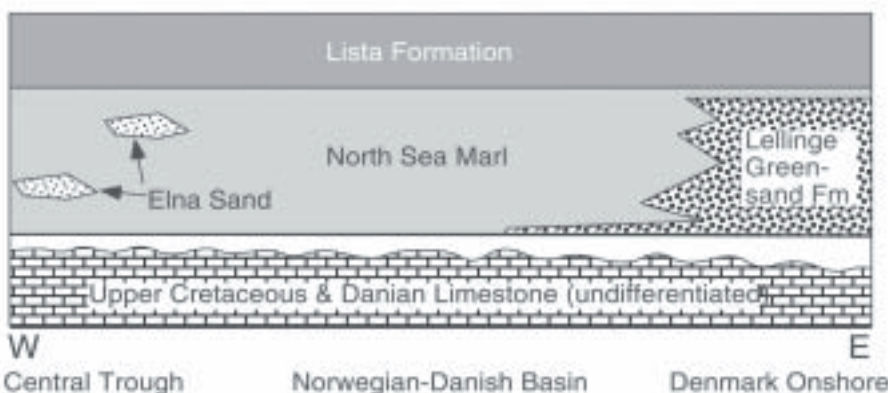


Fig. 2. Simplified lithostratigraphic scheme of the Upper Paleocene deposits on- and offshore Denmark.

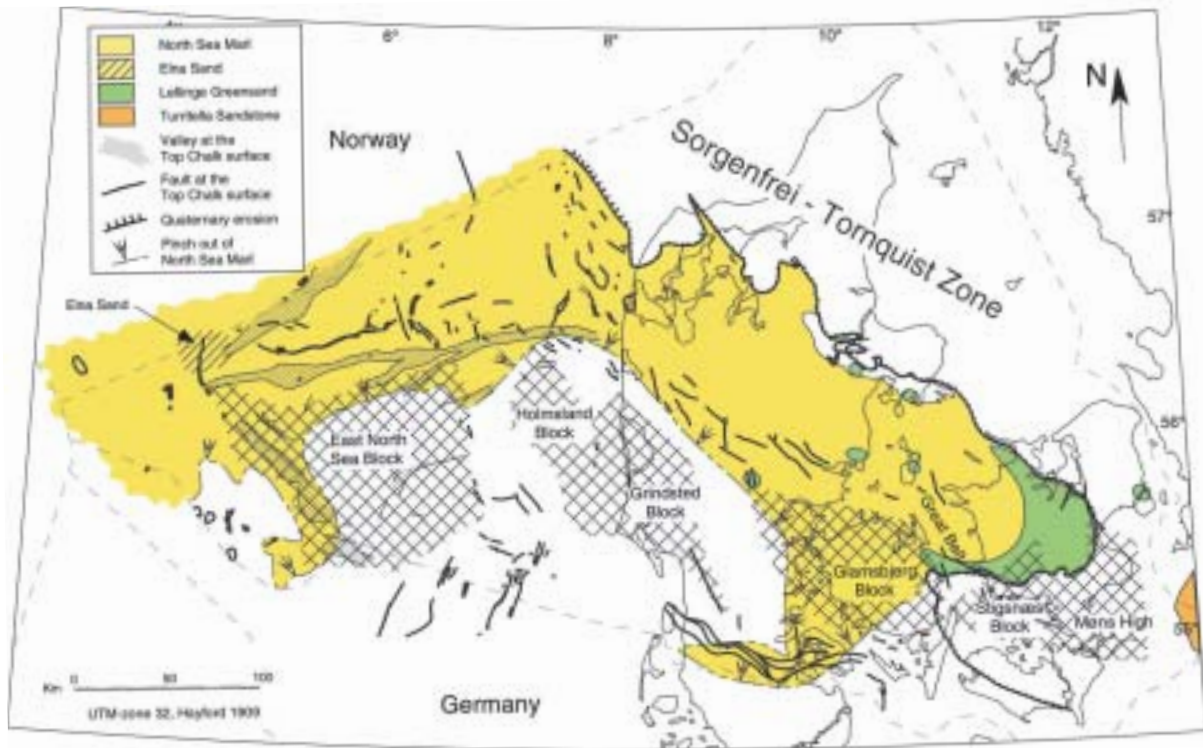


Fig. 3. Map showing the distribution of the North Sea Marl, interpreted distribution of the Lellinge Greensand, suggested distributions of the Turritella Sandstone and occurrence of the Elna Sand. The map is based on Gry (1935), Dinesen et al. (1977), Heilmann-Clausen et al. (1985), Thomsen & Heilmann-Clausen (1985), Nielsen & Japsen (1991), Heilmann-Clausen (1995), and this study.

Danian limestone heralds the large increase in siliciclastic input to the North Sea Basin, which took place at the Danian/Selandian transition (Thomsen 1995). Deposition of siliciclastic sediments supplied from the margins of the North Sea Basin prevailed during the remaining part of the Cenozoic (Kockel 1988, Ziegler 1990, Michelsen et al. 1995, 1998, Huuse 2002). The dominant source areas of the Cenozoic sediments changed between the eastern and the western margins during the Paleogene. During the Neogene and Quaternary the sediments were mainly supplied from the NE, E and SE (cf. Michelsen et al. 1998, Huuse 2002). The changes are reflected in the geometry of the deposited sequences and in the lithological variations of the sediments (Spjeldnæs 1975, Nielsen et al. 1986, Michelsen et al. 1995, 1998, Clausen 1998, Clausen et al. 1999, 2000, Huuse 2002). Tectonic changes affected parts of the North Sea Basin during the Cenozoic with marked structural inversion taking place during the Paleocene (Liboriusen et al. 1987, Vejrbæk & Andersen 1987, 2002, Clausen & Korstgård 1993, Korstgård et al. 1993, Danielsen et al. 1995). The inversion of the former extensional structures locally affected the depositional patterns. The timing and magnitude of uplift of the margins of the North Sea Basin is still under intense debate (cf.

Japsen 1998, Huuse 2002, Japsen & Chalmers 2000) and will not be dealt with here.

Danian and lower Selandian sediments

Danian limestone

The Danian limestone below the Top Chalk surface is referred to as the Chalk-6 unit in the Danish Central Trough area (Lieberkind et al. 1982), the Ekofisk Formation in the UK and Norwegian area (Deegan & Scull 1977, Isaksen & Tonstad 1989) and Danske Kalken in the Danish onshore area (Heilmann-Clausen 1995) (Fig. 2). The term Danian limestone is preferred here. Facies changes of the Danian limestone indicate variations in palaeobathymetry between the shallower Ringkøbing-Fyn High and the deeper Norwegian-Danish Basin (Thomsen 1995). During the late Cenozoic the Danian limestone was eroded in the easternmost parts thereby exposing limestone of Mastrichtian age (Thomsen 1995).

Lellinge Greensand

The Lellinge Greensand and the North Sea Marl were deposited on top of the Chalk Group. The Lellinge Greensand was deposited in shallow water depths under relatively high energy conditions as indicated by the presence of cross bedding, phosphate nodules and rolled fossils (Gry 1935, Heilmann-Clausen 1995, Claus Heilmann-Clausen, pers. com. 2000). It is interpreted to be a shallow marine facies deposited close to the palaeo-coastline. The *Turritella* Sandstone, which is a glauconitic sandstone containing the macrofossil *Turritella* in abundance, is believed to have been deposited very close to the palaeo-coastline (Andersen & Heilmann-Clausen 1984). Unfortunately, the *Turritella* Sandstone has never been found *in situ*, but its distribution, although affected by glacial drift may be used to indicate areas of proximal sedimentation. The North Sea Marl is an open marine sediment deposited well below wave base, and trace fossils indicate deeper water conditions in the western parts of the Danish area compared to the eastern part (Heilmann-Clausen 1995).

The Lellinge Greensand dominates in the eastern parts (Fig. 3) and isolated outcrops may be found east of the general truncation of the upper Paleocene sediments. Such localities include the Copenhagen Harbour (Gry 1935) and Gemmas Allé, Copenhagen (Stouge et al. 2000). Lellinge Greensand was deposited in the western part of the Great Belt area while North Sea Marl in the eastern part of the Great Belt area (Thomsen 1995). The Lellinge Greensand is encountered in the Jelling-1 well, and thin layers are reported from other wells and from outcrops in Jutland (Gry 1935, Thomsen & Heilmann-Clausen 1985, Laursen & Andersen 1997). Although the *Turritella* Sandstone is only encountered as glacial drift blocks, the shallow marine *Turritella* Sandstone is inferred to have been deposited east of the general truncation of the upper Paleocene deposits (Andersen & Heilmann-Clausen 1984).

Gry (1935) reported the occurrence of Lellinge Greensand along the northeastern erosional truncation of the upper Paleocene deposits in eastern Jutland. In this area the Lellinge Greensand is younger than the greensand deposited in central Zealand (Erik Thomsen pers. com. 2000). The Lellinge Greensand in the Jelling-1 well and in the western part of the Great Belt is located at the northern and eastern rims of the Glamsbjerg Block. The Lellinge Greensand observed at Bovlstrup and at Besser (Samsø) is located on a topographic high of the Top Chalk surface (Ter-Borch 1990, Clausen & Huuse 1999). Along deeper Mesozoic horizons this area constitutes a structurally controlled high (Japsen & Langtofte 1991). The distri-

bution of the Lellinge Greensand thus seems to reflect the structural architecture of the Danish onshore area and may suggest an overall structural control on the palaeobathymetry during the earliest Late Paleocene.

North Sea Marl

The North Sea Marl is widespread across the Danish area, but is absent on most of the Ringkøbing-Fyn High in the North Sea, in Jutland and south of Zealand. The North Sea Marl has a very distinct well-log pattern: a relatively smooth trend of increasing gamma-ray signature and decreasing velocities. Figure 4 shows a section of well logs from the western part of the Danish Central Trough to the eastern part of the Norwegian-Danish Basin. The North Sea Marl is subdivided into a lower and an upper unit separated by the key biomarker *Parasubbotina pseudobulloides* (first down hole occurrence). The general pattern is one of decreasing thickness towards the west with an increase in the westernmost part (Fig. 4, Kristoffersen & Bang 1982, Nielsen & Japsen 1991) The westernmost area has a log pattern, which differs significantly from that observed in the rest of the Danish area. The biomarker *P. pseudobulloides* indicates that the younger part of the North Sea Marl dominates in the westernmost part. The thickening of the North Sea Marl in the northeastern Danish North Sea (Skagerrak maximum) is also seen on high-resolution seismic sections (Fig. 5), where the marl can be seen to thin southwards before developing a local depocentre coinciding with the Ibenholt Valley.

Elna Sand

The Elna Sand occurs as discrete sand bodies in the North Sea Marl (Nielsen & Japsen 1991, Danielsen et al. 1995). The sand bodies are interpreted as turbidites originating from the northeast (Danielsen et al. 1995, Michelsen et al. 1995). The stratigraphic position and the lateral distribution of the individual sand bodies (Danielsen et al. 1995) indicate that the sands do not represent a classic lowstand fan deposit. The Elna Sand may be interpreted as due to gravitational collapse of sediments prograding from southern Norway into the Norwegian-Danish Basin (Danielsen et al. 1995). Gravitational collapse may have been facilitated by a high sediment input rate causing an oversteepening of the prograding front. Such collapses may have been triggered by storm-wave loading or by minor sea-level changes, but tectonic activity in the adjacent Sorgenfrei-Tornquist Zone may also have

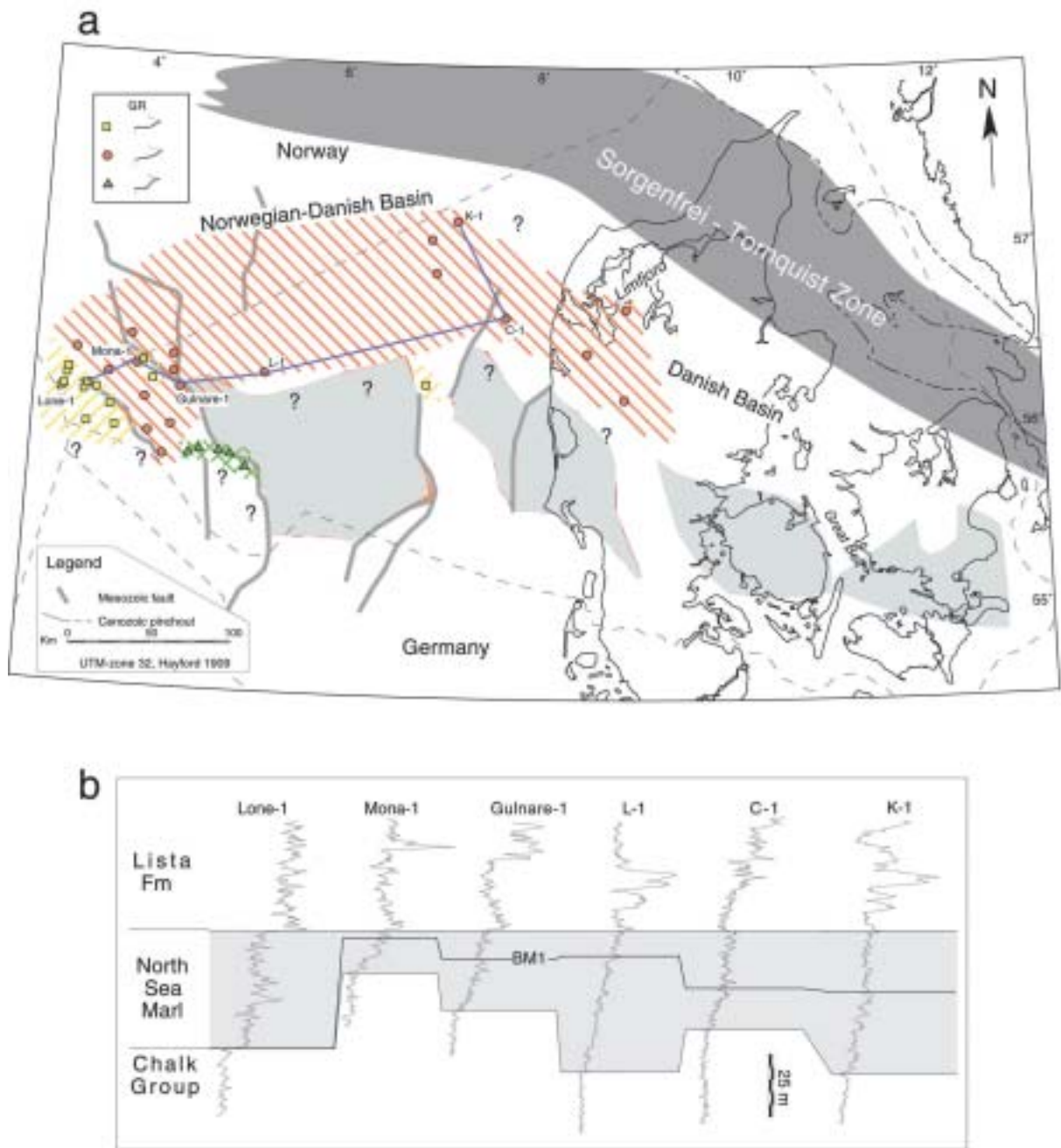


Fig. 4. (a) Map showing the lateral distribution of the different characteristic log patterns for the North Sea Marl. East of the Lindesnes Ridge-Inge High the pattern with abrupt increase at the base is restricted to structural highs, whereas the abrupt change at the base as well as at the top is restricted to the southern part of the Danish Central Trough, especially close to the Coffee Soil Fault. (b) The lateral variations in gamma-ray response across the Norwegian-Danish Basin. Note the position of the biomarker BM1 (*P. pseudobulloides*).

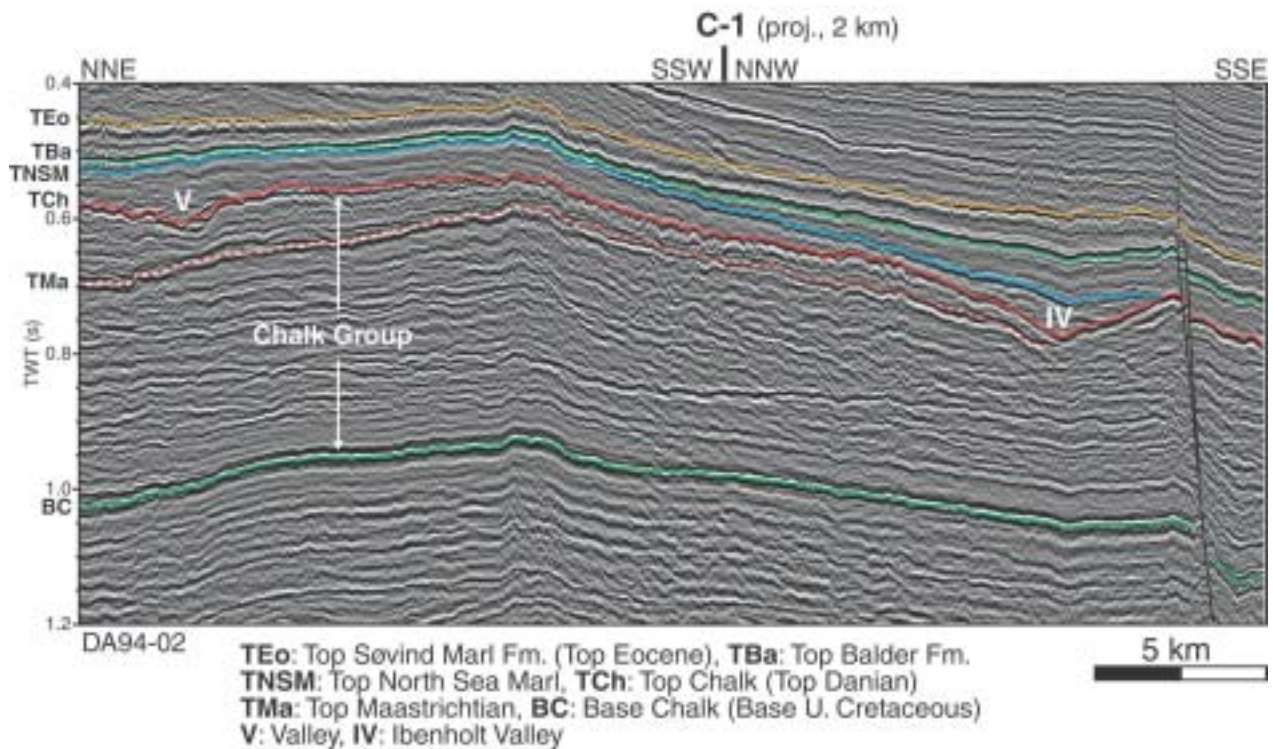


Fig. 5. Seismic section showing a local North Sea Marl depocentre in SW Skagerrak. Note the thinning of the North Sea Marl towards the south, interrupted by a local depocentre related to the Ibenholt Valley, before onlapping towards the south onto the Ringkøbing-Fyn High.

had an effect on the stability of the slope. The sudden eustatic fall which took place during the later stages of North Sea Marl deposition (cf. Fig. 6, Haq et al. 1988, Michelsen et al. 1998), could be one such triggering mechanism, although the timing and magnitude of events on the Haq et al. curve is still under debate. In the light of the debate about the amount and timing of uplift of southern Norway (cf. Japsen 1998, Clausen et al. 2000, Huuse 2002) it is interesting

to note that the Elna Sand and the upper Paleocene build outs further to the northeast indicate a significant sediment input from the northeast during the late Paleocene, thus indicating that southern Norway experienced significant erosion in the earliest Paleogene.

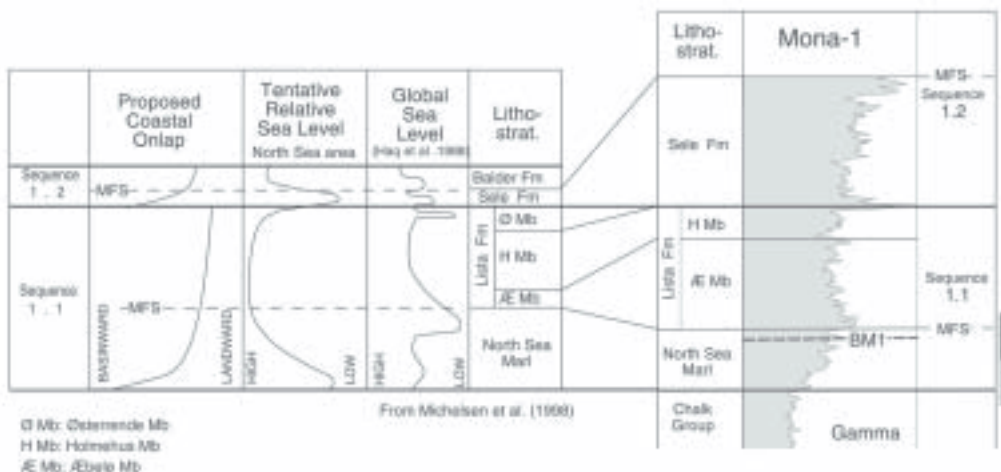


Fig. 6. Sequence stratigraphic subdivision, a proposed coastal onlap curve, tentative relative sea level from the North Sea area (based on on-shore and offshore observations), and lithostratigraphic subdivision of the upper Paleocene succession from Michelsen et al. (1998). This is correlated with the Mona-1 well. Biomarker BM1 (*P. pseudobulloides*). See text for further discussion.

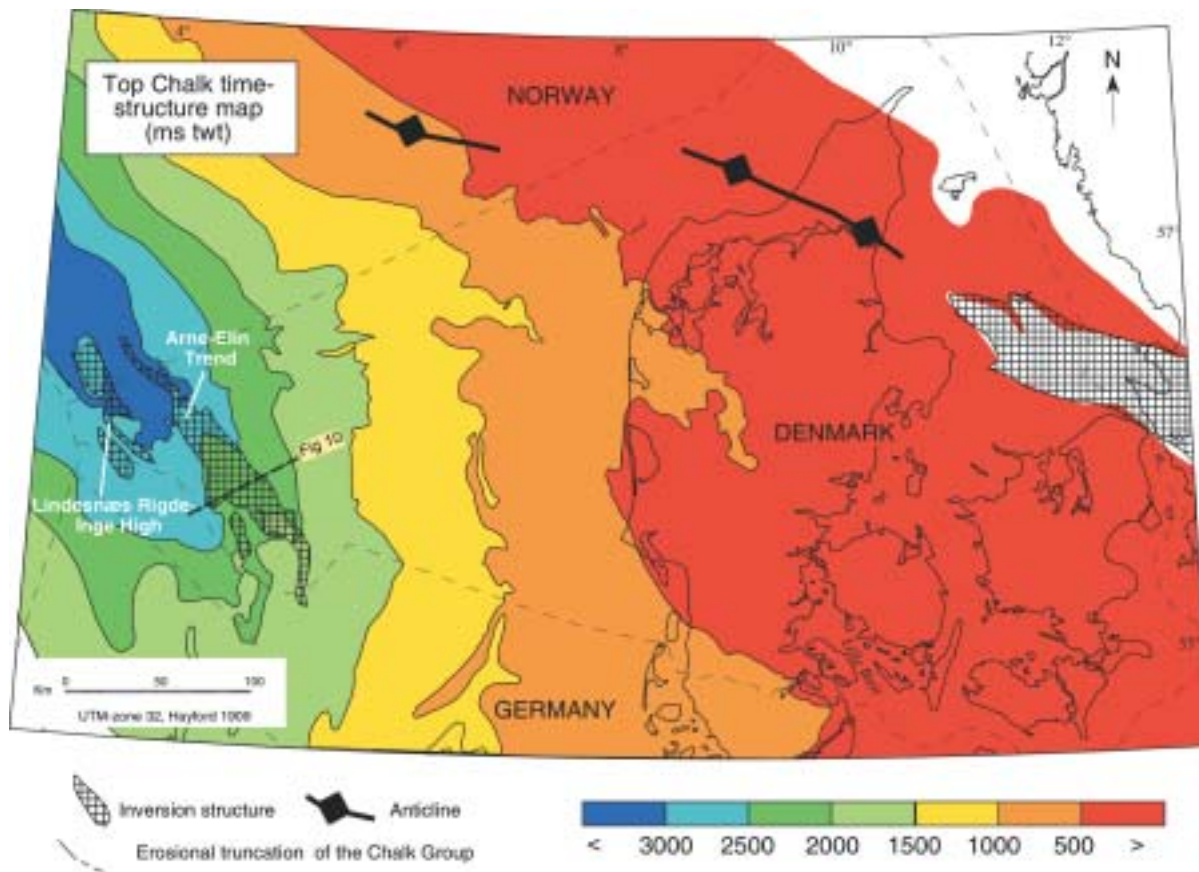


Fig. 7. The general topography of the Top Chalk surface superimposed by the outline of areas, which became inverted during the late Cretaceous-Paleocene. Based on Day et al. (1981), Ziegler (1990), Clausen & Huuse (1999) and Vejbæk & Andersen (2000).

The Top Chalk surface Structural features

At present the Top Chalk surface has a pronounced regional dip towards the west, reflecting the relative subsidence centred above the Mesozoic Central Trough and relative uplift of the basin margins taking place during the Cenozoic (Fig. 7) (Japsen 1998). The Paleocene inversion took place broadly in the southern part of the Central Trough, along the Arne-Elin Trend and at the Lindesnes Ridge-Inge High in the northern part of the Danish Central Trough (Fig. 7). Differential subsidence across the major graben-bounding fault also took place in the northern part of the Central Trough area. The complicated subsidence pattern of the Central Trough is interpreted to be due to dextral shearing of the Central Trough, which introduced transpression and transtension along different fault trends depending on their orientations (Vejbæk & Andersen 1987, 2002, Clausen & Korstgård 1993, Clausen et al. 1996, Clausen & Huuse 1999). The Ringkøbing-Fyn High is a diffuse high at the Top Chalk surface outlined by trends of normal faults

detaching along the Top Zechstein (Huuse 1999). The topography of the Top Chalk surface (Fig. 7) indicates the outline of the Sorgenfrei-Tornquist Zone. Salt structures (pillows, diapirs and associated rim synclines) are conspicuous in areas where mobile Zechstein salt is present, especially in the Norwegian-Danish Basin, and in the southern Central Trough (Clausen & Huuse 1999, Huuse 1999).

Erosional features

Erosional features at Top Chalk have a variety of expressions: basin margin erosion, valley and local channel erosion, local erosion associated with small-scale depressions at the top of salt structures (Fig. 8).

Regional erosion occurred at the margins of the North Sea Basin during the late Cenozoic. Erosion at the Top Chalk surface onshore Denmark can be subdivided into a mid-Paleocene and a late Cenozoic phase. The late Cenozoic erosional phase is illustrated by the Base Quaternary sub-crop map of Sorgenfrei (Sorgenfrei & Buch 1964: fig. 13) and by Figure 8. The

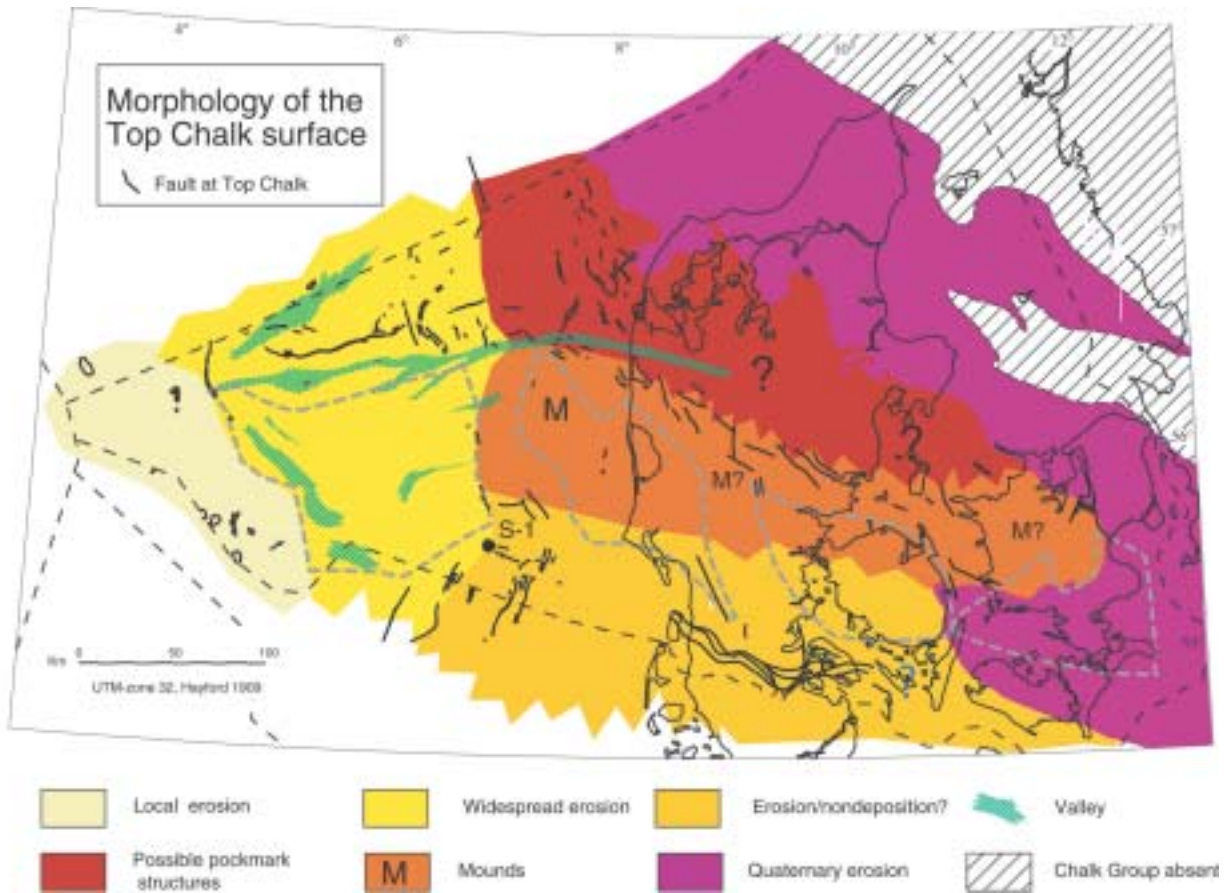


Fig. 8. Distribution of erosional features at the Top Chalk surface (see text for further explanation).

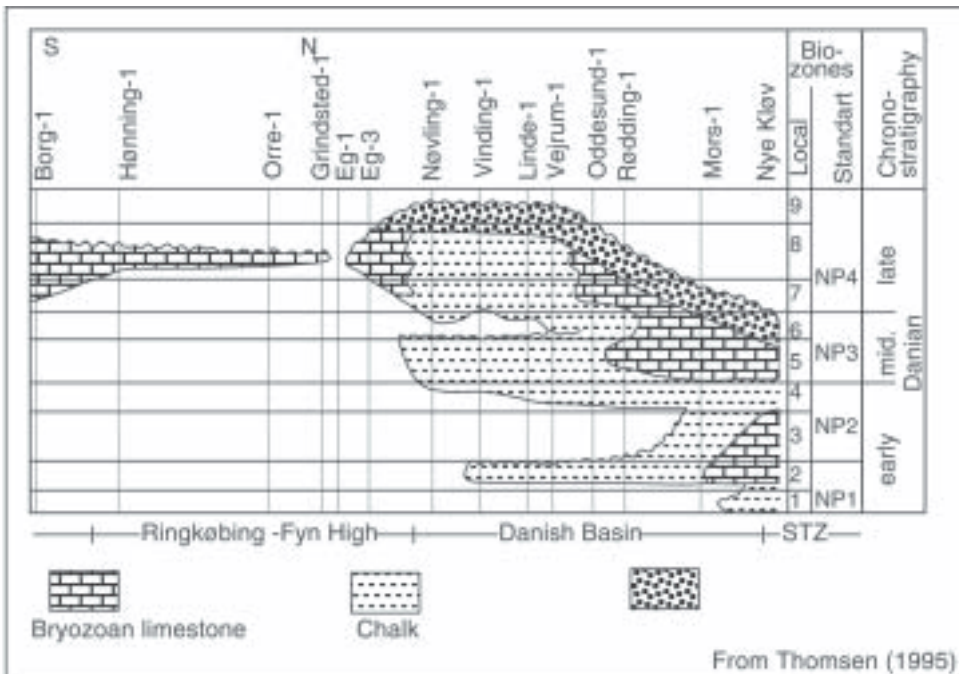


Fig. 9. The evolution of the Danian limestone across the Ringkøbing-Fyn High onshore Denmark (from Thomsen 1995). For location of the section see Fig. 1. See text for further explanation.

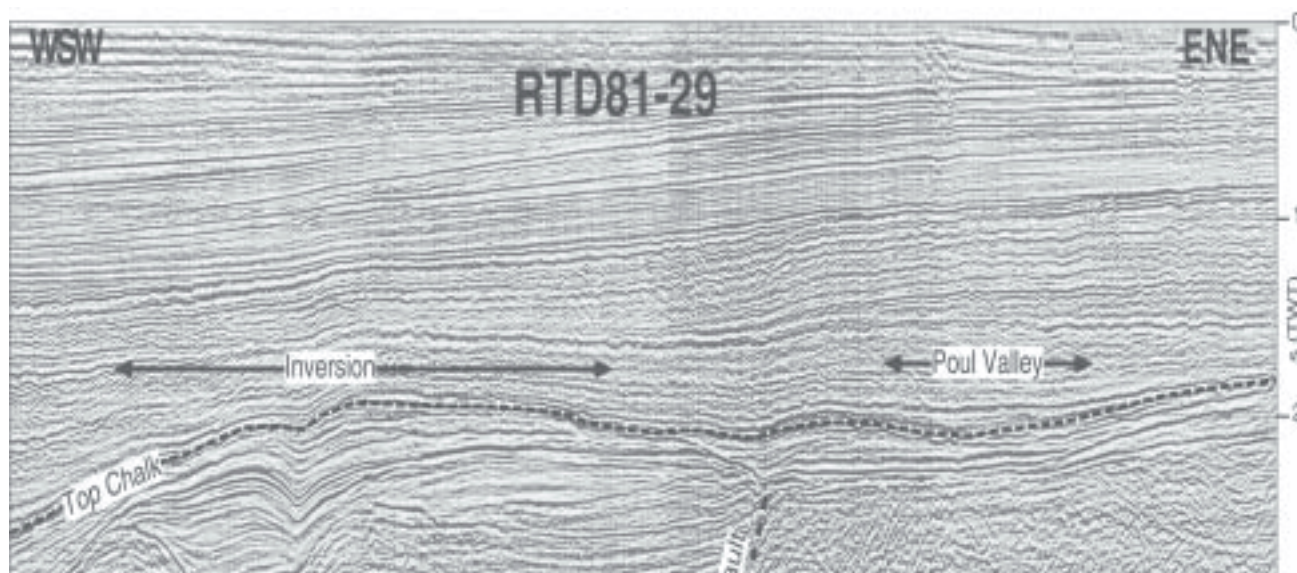


Fig. 10. Seismic section across the southern Danish Central Trough. The Poul Valley is eroded into the Chalk Group east of the inverted Central Trough area. See text for further explanation.

mid-Paleocene basin margin erosion is not evident from seismic sections but is reflected by variations in the age of the top of the Chalk Group as determined by biostratigraphy (Fig. 9) and by the amount and character of reworked sediments observed in the Upper Paleocene deposits. In the onshore area the most intense mid-Paleocene erosion took place along the basin margin and at the Ringkøbing-Fyn High (Thomsen 1995).

In the eastern North Sea area a large number of minor channels have been observed between Danian mound structures situated on the eastern part of the Ringkøbing-Fyn High. Similar mounds are absent west of the Horn Graben area where the Top Chalk surface has an abraded appearance (Huuse 1999). Mounds within the Danian limestone have been reported from the Ringkøbing-Fyn High onshore Denmark and can be observed in the coastal cliffs of Stevns and Karlby Klint (Surlyk 1997). The mounded character of the Danian limestone thus seems to extend from Zealand across the Danish mainland and inner waters to the Horn Graben as indicated in Figure 8. The mounds observed onshore are bryozoan mounds, which form larger mound complexes comparable in size to the mounds observed offshore. It is thus possible that the offshore mounds may represent bryozoan mound complexes (cf. Huuse 1999), although some of the mounds could also have been produced by post-depositional soft-sediment deformation.

In the eastern part of the Norwegian-Danish Basin a large number of up to 5–10 m deep and 100–300 m wide depressions in the Top Chalk surface are ob-

served on high-resolution seismic sections (Huuse 1999: fig. 13). The depressions are overlain by the lowermost Upper Paleocene North Sea Marl and have previously been suggested to be karst structures, although alternative explanations such as pockmarks is more probable (especially after inspection of 3-D seismic surveys). A major implication of the interpretation of the depressions as karst structures is that the Top Chalk surface must have been subaerially exposed far into the present North Sea area during the mid Paleocene. However, recent studies indicate that the sediments both above and below the Top Chalk surface are marine indicating more than 200 meters of water-depth in the western and central parts of the Norwegian Danish Basin (Rasmussen, pers. com.)

A number of valleys in the Chalk Group are mapped in the Danish area (Fig. 8). The major valleys terminate at the eastern boundary of the Danish Central Trough. The most consistent and coherent pattern is observed offshore where the seismic grid is much denser than onshore. There is, however, also seismic indication of an eastward extension of the Ibenholt Valley into a structurally controlled depression, which follows the northern flank of the Ringkøbing-Fyn High towards the southeast. The position of the Ibenholt Valley coincides with a change in the facies of the underlying limestone between the mounded (bryozoan?) and abraded limestone on the Ringkøbing-Fyn High and pelagic chalks deposited in the Norwegian-Danish Basin. This suggests that the position of the Ibenholt Valley could have been influenced by facies changes in the underlying Chalk

Group. However, the facies changes of the limestone were most likely controlled by the regional structural setting and it is likely that the Ringkøbing-Fyn High, the D-1 structure and other salt structures could have influenced the position of the valley by creating a regional low just north of the Ringkøbing-Fyn High. The Poul Valley, which is a major valley located just east of the Central Trough, and the presence of less prominent and less coherent valleys west of the Poul Valley at the inversion anticline in the southern Danish Central Trough indicate a complex interaction between inversion, erosion and sedimentation in the southern Central Trough (Fig. 10, Clausen 2000). In the easternmost part the fill of the Ibenholt Valley has a prograded character which is interpreted to indicate a relatively coarse-grained facies of the otherwise fine-grained upper Paleocene sediments possibly analogous with the Lellinge Greensand onshore Denmark (Clausen & Huuse 1999, Huuse 1999).

In the area of the East North Sea Block several scattered channels and shallow valleys have been observed giving the Top Chalk surface an abraded appearance (Fig. 8). Both Danian and Selandian deposits are absent in the S-1 well located in the southern part of the Ringkøbing-Fyn High. This seems to indicate that widespread low-relief erosion took place on the East North Sea Block and south of the Ringkøbing-Fyn High in the North Sea area. In the eastern Danish North Sea, onlap of upper Paleocene and lower Eocene deposits towards the south indicates that the area south of the Ringkøbing-Fyn High was at or above wave base during most of the early Cenozoic.

The North Sea Marl is observed in several wells in the Tønder Graben and in the Fuenen area and it is unclear whether erosion of the Chalk Group also took place in these areas.

Sea-level changes

The North Sea Marl and its equivalents correspond to the lower part of Sequence 1.1 defined in the central and eastern North Sea Basin by Michelsen et al. (1995, 1998). The erosion observed at the Top Chalk surface and the transgressive lag conglomerate at the base of the North Sea Marl (and its equivalents) indicate that a significant sea-level drop occurred at the Danian/Selandian transition. A relative high on the gamma-ray log, which is interpreted to indicate the maximum flooding surface, marks the top of the North Sea Marl (Fig. 6, Michelsen et al. 1998). This means that the North Sea Marl and its equivalents were deposited during a sea-level rise following the

abrupt sea-level drop, which occurred at the end of the Danian. The global sea-level curve compiled by Haq et al. (1988) shows a significant and sudden drop in sea-level during deposition of the North Sea Marl, a drop which so far has not been observed in the Danish area, possibly due to the distal setting of the preserved deposits. Conversely, the regional drop in sea-level at the Danian/Selandian transition is not noted in the Haq et al. curve, possibly indicating that the sea-level drop in the North Sea could be due to regional tectonic uplift.

Palaeogeography

The mid-Paleocene evolution of the Danish area is depicted by three palaeogeographic maps, which are discussed in the following. The maps reflect subsequent stages of the transgression following the abrupt sea-level drop at the Danian/Selandian transition: at the time of maximum regression, during the transgression and at maximum transgression. The intention of these maps is to improve the understanding of the mid-Paleocene development of the eastern North Sea Basin, a subject that is of major concern to both explorationists and geologists working in the area. Note that the maps represent our current state of knowledge and are subject to changes as more data become available, especially from exploration drilling in the eastern North Sea.

Maximum regression (Fig. 11)

The distribution and character of the erosion at the Top Chalk surface as indicated in Figure 8 and the presence of a transgressive lag conglomerate in the onshore area Gry (1935) indicates that the surface was exposed to erosion in the eastern part of the Danish area. The tectonic evolution of the Central Trough, as described by Clausen & Korstgård (1993) and Danielson et al. (1995), resulted in non-deposition of sediments in the southern Central Trough, which consequently is interpreted to have been a shallow marine area, albeit not necessarily subaerially exposed. A basal conglomerate overlying the Chalk Group is observed in the N-1 well in the southern Central Trough (Figs 1, 12), indicating that the area was exposed to wave erosion at the Danian/Selandian transition. A basal conglomerate is found in many outcrops in the onshore area (Gry 1935), but similar deposits have not been reported from wells in the eastern Danish North Sea, perhaps due to the absence of cores from these

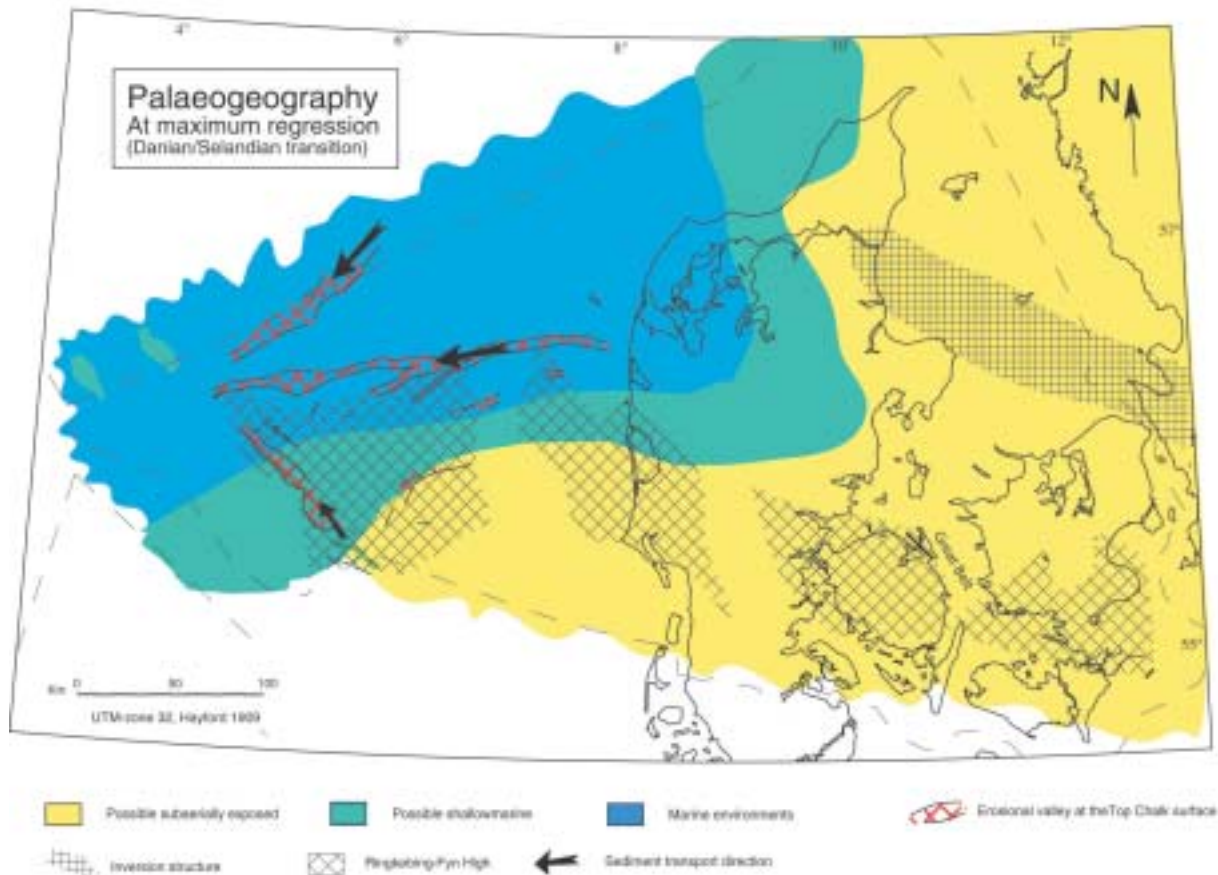


Fig. 11. Palaeogeography of the Danish North Sea area at time of maximum regression at the Danian/Selandian transition (base North Sea Marl). See text for discussion.

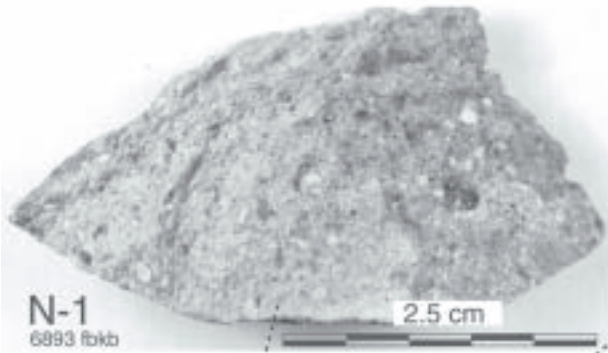
wells. The erosion observed on the Ringkøbing-Fyn High (Thomsen 1995) and on seismic sections indicate that large parts of the eastern North Sea Basin was subject to erosion at the Danian/Selandian transition (Clausen & Huuse 1999, Huuse 1999). The northern part of the Danish Central Trough is interpreted to have been below base level except at major topographic highs such as the Lindesnæs Rigde-Inge High, the Arne-Elin Trend and the D-1 structure in the western Norwegian-Danish Basin introduced by salt- and inversion tectonics. The complex distribution of areas which suffered erosion, areas indicating deep marine deposition and areas clearly showing transgression (i.e. areas which were subjected to at least shallow marine erosion) and their relations to inversion zones, salt structures, underlying structures and the basin margin suggests that a relative low sea level combined with tectonically generated topography controlled the distribution of marine environments, shallow marine environments and areas above sea level. The complexity of the system makes it hard to determine a precise location of the palaeo coast-

line, however, Figure 11 is a qualified guess of the environment distributions when the relative sea-level was at its lowest in the North Sea area.

During transgression (Fig. 13)

Figure 13 shows the possible distribution of marine and terrestrial environments during the transgression, which followed the mid-Paleocene sea-level lowstand. A thin layer of Lellinge Greensand and a conglomerate of phosphorite nodules and rolled fossils is often observed at the Top Chalk surface in Jutland (Heilmann-Clausen 1995) while more than 100 m of Lellinge Greensand is observed at Zealand (Gry 1935, Dinesen et al. 1977). The distribution of the Lellinge Greensand is also indicated in Figure 3. The accumulation of more than 100 m of Lellinge Greensand (Gry 1935), which is a shallow-marine sediment, indicate that accommodation space was generated continuously during sedimentation in the Zealand area. Lellinge Greensand is absent in the inverted part of

Basal conglomerate
Central Graben



Basal conglomerate
(Lellinge Greensand)
Copenhagen

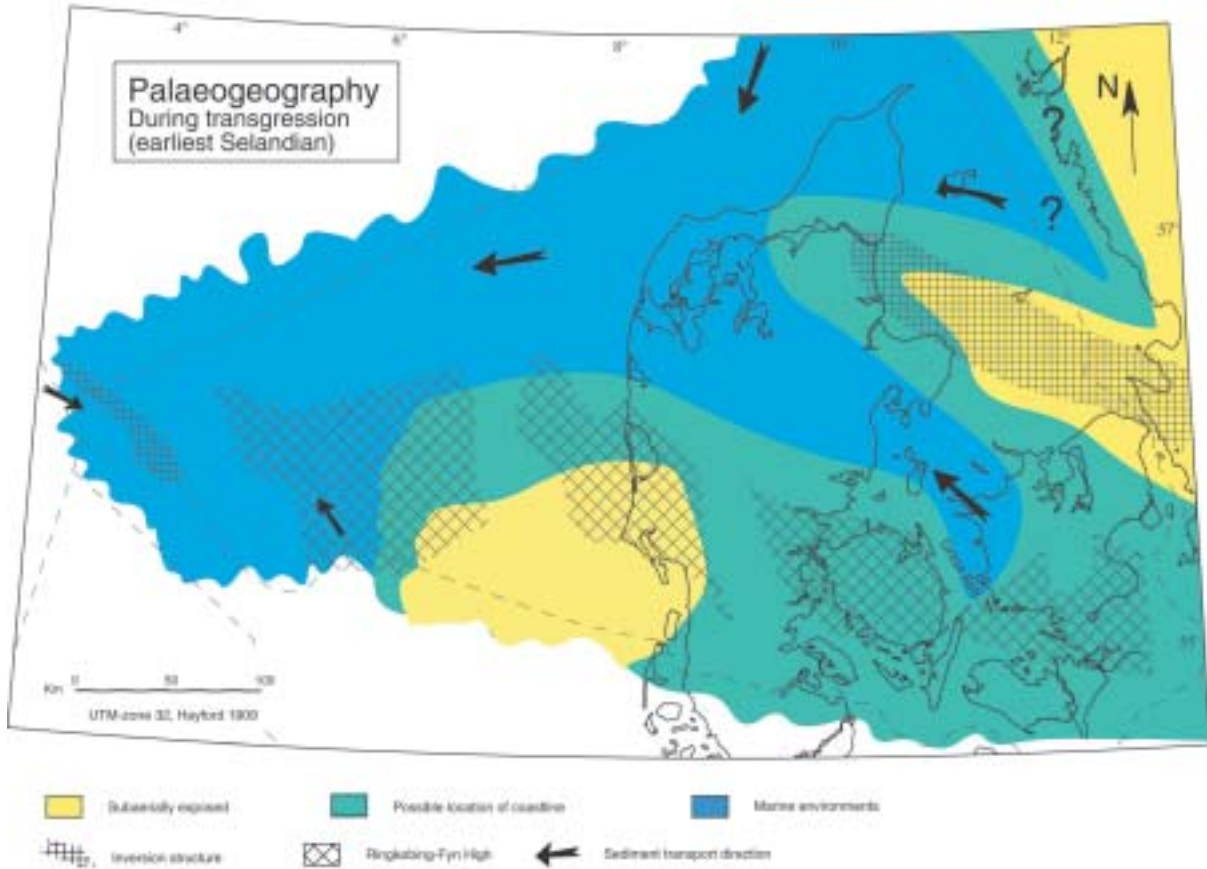
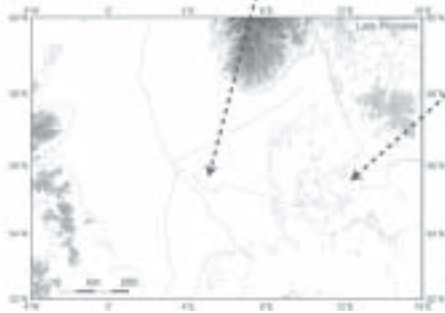
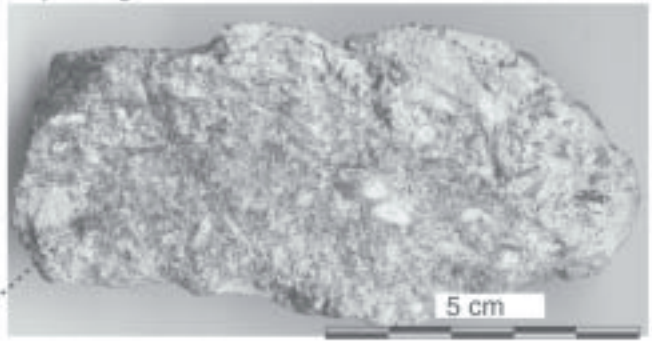


Fig. 13. Palaeogeography of the Danish North Sea area during the transgression and deposition of the North Sea Marl in the early Selandian. See text for discussion.

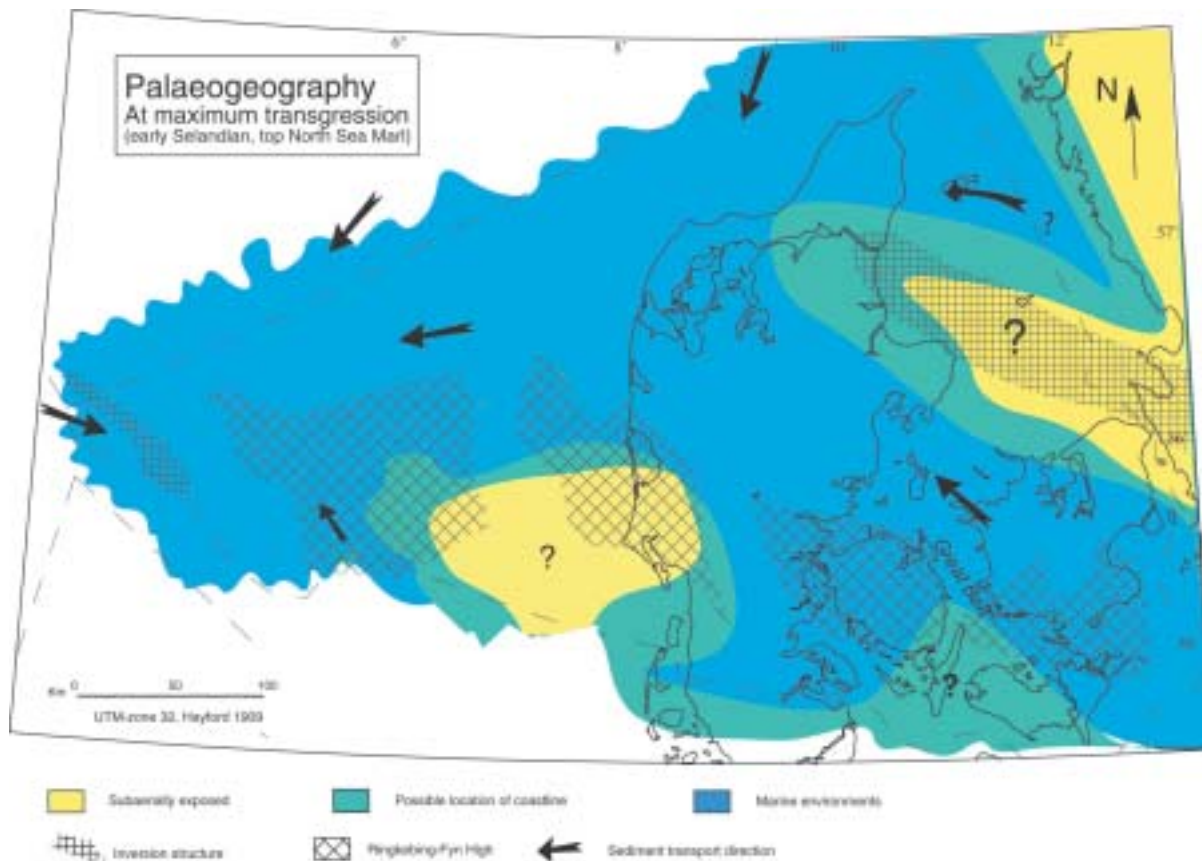


Fig. 14. Palaeogeography of the Danish North Sea area at the time of maximum transgression in the early Selandian (top North Sea Marl). The palaeogeography suggested in the northeastern most area is based on basin modelling and not geological observations. See text for discussion.

the Sorgenfrei-Tornquist Zone and at the eastern part of the Ringkøbing-Fyn High. Given an overall rise in sea level during deposition (cf. Fig. 6), the absence of Lellinge Greensand in areas adjacent to Zealand is most likely due to variations in the local tectonic subsidence/uplift patterns.

Seismic interpretations indicate that the sediments contained in the Skagerrak depocentre only includes North Sea Marl supplied from the north or northeast (Fig. 5). There are no indications of increased subsidence in this area and the development of the depocentre thus seems to be controlled mainly by the proximity to an area of erosion of the Chalk Group coinciding with the inverted Sorgenfrei-Tornquist Zone.

During the earliest Late Paleocene sediment starvation prevailed in the main part of the southern Danish Central Trough (Kristoffersen & Bang 1982, Nielsen & Japsen 1991). This was probably due to the occurrence of active inversion tectonics as indicated by Figure 10. The L-1 well located in the Ibenholt Valley indicates that at least the westernmost parts of the Ibenholt Valley was filled with the oldest part of

the North Sea Marl, since this constitutes the bulk of the marl interval. There are no direct indications of the age of the fill of the Poul Valley but it is likely that it is coeval with the fill of the Ibenholt Valley since the top of the marl covers both structures in a similar fashion. However, the Poul Valley may have been located at a topographically higher level compared to the Ibenholt Valley and thus it may have been filled slightly later than the Ibenholt Valley. Seismic sections across the eastern part of the Ibenholt Valley show a prograded pattern indicating that the easternmost parts of the valley may have been filled by high energy proximal sediments. We speculate that the valleys were filled more or less contemporaneously during the early stage of the marine transgression following the short period of subaerial exposure at the Danian/Selandian transition.

The inverted Lindesnes Ridge-Inge High (Vejbæk & Andersen 1987, 2000, Clausen et al. 1996) seems to separate the westernmost part of the Danish Central Trough from the bulk of the Danish area, and only minor amounts of sediment were deposited in the western part during the early stages of the transgres-

sion. Thus it seems probable that a submarine barrier may have hindered the transport of sediment from the east into the area and thus prevented deposition of the lower part of the North Sea Marl in the western part of the Danish Central Trough. The westward decreasing thickness of the upper part as indicated in Figure 3 also indicates that the source area in general moved further from the Central Trough area. Alternatively, it is possible that the distribution system was unable to carry the sediment so far to the west from an easterly source. Knox & Holloway (1992) show that the sediments of the coeval Maureen Formation in the eastern parts of the UK Central Trough were supplied from the Shetland area to the NNW. The local depocentre in the western Danish Central Trough is thus interpreted to be a result of input dominantly from the NNW, as the inverted Lindesnes Ridge-Inge High hindered input from the east. The position of the key biomarker (*G. pseudobulloides*) in the wells indicates that the sediments from the west arrived relatively late in the western part of the Danish Central Trough.

Maximum transgression (Fig. 14)

The distribution of marine and terrestrial environments at the time of maximum transgression indicated in Figure 14 is based on the present occurrence of North Sea Marl in large parts of the area in combination with observations of more local character: 1) the occurrence of relatively young Lellinge Greensand in eastern Jutland (Thomsen pers. com. 2000), 2) the hiatus at the base of the Lellinge Greensand observed at Gemmas Allé (Stouge et al. 2000), 3) continuous sedimentation in the Great Belt area (Thomsen 1995). These observations indicate that the transgression proceeded eastwards and that marine environments probably persisted far to the east. In the Femarn Belt south of Denmark neither Lellinge Greensand nor North Sea Marl is observed (Hansen 1996). We therefore suggest that the area south of the Ringkøbing-Fyn High at Zealand was an area of non-deposition during the early Late Paleocene, although any lower Upper Paleocene deposits may have been removed during a regression prior to deposition of the Holmehus Formation, which is encountered in Femarn Bælt (Hansen 1996). High-resolution seismic sections in the eastern North Sea show that the upper Paleocene and lower Eocene deposits onlap the Top Chalk surface in the southern part of the Ringkøbing-Fyn High. This indicates that the North Sea Marl was never deposited on the southern parts of the Holmsland and East North Sea blocks. However, North Sea Marl or its equivalents may be present in local depressions in the

Top Chalk surface in between mound structures on the Holmsland and Grindsted blocks. Similarly, the absence of North Sea Marl in the Femarn Belt area indicates that this area was shallower than wave base and possibly subaerially exposed during the earliest parts of the Late Paleocene.

Conclusions

Danian mound structures, possibly analogous with bryozoan mound complexes onshore Denmark, have been observed on seismic sections across the Ringkøbing-Fyn High offshore Jutland, indicating that the Ringkøbing-Fyn High constituted a regional bathymetric high during the Danian.

Mid-Paleocene erosional features at the Top Chalk surface include regional basin-margin erosion, erosional valleys, local erosional channels and small-scale depressions. The overlying deposits comprise a basal conglomerate followed by greensand and marl that are indicative of a regional transgression following marked erosion of the Top Chalk surface. The distribution and character of the erosional features and the overlying deposits indicates that large parts of the Top Chalk surface in the eastern part of the Danish area were exposed to erosion at the Danian/Selandian transition.

The mid-Paleocene evolution of the Danish area is depicted by three palaeogeographic maps starting with the time of maximum regression at the Danian/Selandian transition. The intermediate stage of the ensuing transgression (during North Sea Marl deposition) is shown on the second map. The third map shows the likely distribution of marine and terrestrial environments at the time of maximum transgression during the early Selandian (after deposition of the North Sea Marl).

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