Tectonic vs climatic control on the sequence development, examples from the Paleogene succession in the eastern North Sea area

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A sequence stratigraphic subdivision of the upper Paleocene and the Oligocene is used to exemplify the influence of regional tectonism, local tectonism and climatic changes onto sedimentation in an epicontinental basin. The analysis shows that the low sedimentation rate and the condensed character of the Paleocene sediments disable any identification of climatic changes, whereas the Oligocene sequence boundaries are controlled by glacio-eustatic sea level changes. Regional tectonism played a major role in generating areas exposed for erosion located east of the present North Sea Basin. These exposed areas generated sand rich mass flows during the late Paleocene and generated the large amount of sedi-ments which prograded into the Norwegian-Danish Basin during the Oligocene. Local tectonics controlled generation of topographic depressions in the western part of the Norwegian-Danish Basin. The subtle depressions controlled the loca-tion of the sand rich mass flow deposits both during the late Paleocene and the latest Oligocene.

Keywords: Eastern North Sea, Paleogene, tectonism, climate, sedimentation.

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The North Sea constituted an epicontinental basin with marginal uplift during the Cenozoic. The Cenozoic tectonic evolution in the eastern North Sea Basin was dominated by the uplift in the eastern part and subsidence in the central parts of the North Sea (Jensen & Schmidt 1992, Jensen & Michelsen 1992, Michelsen 1998). Superposed onto the regional tectonism, local subsidence and local uplift was a result of reactivation of basement attached faults and salt structures (and salt related faults) which created local depressions and local highs (Clausen & Korstgård 1993, Clausen 1998).

The Paleogene siliciclastic sediments deposited in the North Sea Basin are, based on the principles outlined by Vail (1987), subdivided into major sequence stratigraphic units: Unit 1–4 (second-order sequences) (Michelsen et al. in press, Michelsen et al. 1995) as shown in Figure 1. Unit 1 and unit 4 are subdivided into 2 and 5 third-order sequences, respectively (Fig. 1). The youngest Paleogene sequence is sequence 5.1, which is the lowermost (third order) sequence in unit 5. Unit 1 comprises upper Paleocene and lowermost Eocene deposits whereas unit 4 and sequence 5.1 constitutes the Oligocene deposits. The major (second order) sequence boundaries reflect major events in the basin development such as differential subsidence, changes in sediment transport directions; events which are reflected in the geometry and the composition of the sediment content of the sequences deposited (Michelsen et al. 1995).

The objective of this paper is to investigate the interaction between climatic variations and tectonic events (both regional and local tectonism) onto the Paleogene sequence development in the eastern North Sea (Fig. 2). The late Paleocene and the Oligocene basin developments are used as case studies. These two stratigraphic successions are chosen because they represent different basin geometry and basin fill.

Data used

The data used in this study are petrophysical logs from the wells shown in Figure 2, a grid of conventional 2-D seismic sections which covers the entire area link-

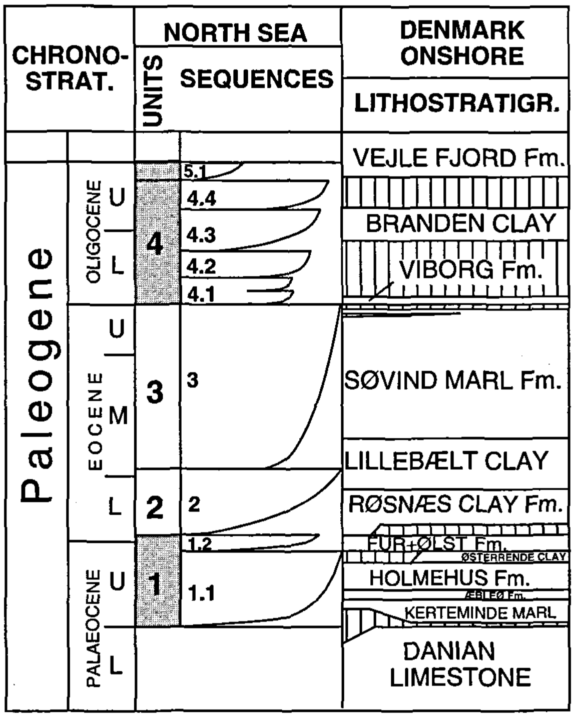


Fig. 1. The sequence stratigraphic framework used in this study (modified from Michelsen et al. 1995). The late Paleocene and the Oligocene intervals, which are the intervals dealt with here, are indicated with grey. The correlative lithostratigraphic subdivision onshore Denmark is also indicated. In the north eastern part of the Norwegian-Danish Basin is sequence 1.2 subdivided into sequence 1.2a and 1.2b (Danielsen et al. 1995). However, sequence 1.2b is not observed in the Central Trough area probably due to a poor seismic resolution compared to the small thickness of the sequence.

ing the wells, and an open grid of high resolution seismic sections located in the eastern part of the Norwegian-Danish Basin. The biostratigraphic data from Laursen (1995) and Michelsen et al. (1995) and available commercial well reports are used for dating the sequences.

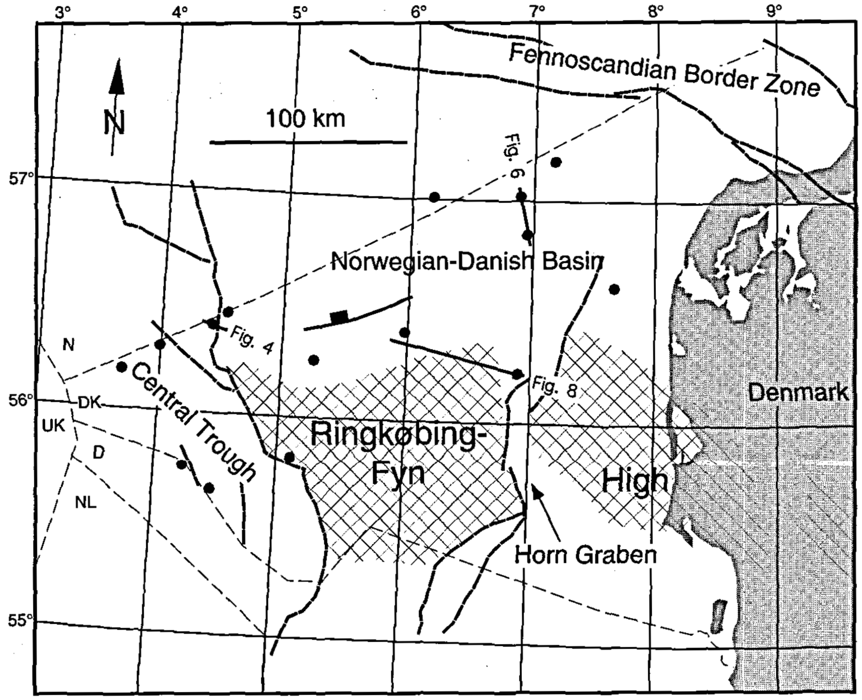
Late Paleocene

The late Paleocene sedimentation was dominated by fine-grained hemipelagic conditions, both onshore Denmark (Heilmann-Clausen et al. 1985, Heilmann-Clausen 1995) but also offshore (Kristoffersen & Bang 1982). The upper Paleocene in the eastern North Sea Basin is characterised by low sedimentation rates. The "condensed" deep shelf clay deposit was previously interpreted as representing the distal parts of sequences sourced from the Shetland area, which suffered uplift during the Late Paleocene (Rochow 1981, Ziegler 1990). The Upper Paleocene has a depositional centre north of the study area (Michelsen et al. 1995, Jordt et al. 1995). However, sand bodies are interbedded into the upper Paleocene clays, interpreted as density currents originating from the northeastern basin margin (Danielsen et al. 1995).

Figure 3 shows the present thickness and the decompacted thickness in a number of Danish North Sea wells. The decompaction is carried out according to the principles of Sclater & Christie (1980). The porosity parameters presented by Sørensen (1986) and the Cenozoic uplift calculated by Jensen & Schmidt (1992) (Fig. 3) are taken into account. The decompacted thickness distribution shows that the Upper Paleocene succession is thickest in the northern part of the Danish Central Trough. The northern well-section shows that the decompacted thicknesses decrease towards the east, becoming significantly thinner in the Norwegian-Danish Basin compared to what is seen in the Central Trough area. The seismic section SP82–45 (Fig. 4) shows that the differential subsidence across the Coffee Soil Fault accounts for the increased thicknesses within the northern Central Trough area since the extra infill at the base of the sequence 1.1 is located in the area where antithetic collapse of the hangingwall takes place during reactivation of the Coffee Soil Fault. The southern well-section runs across the Central Trough and along the Ringkøbing-Fyn High (Fig. 3) and shows uniform thickness which is significantly thinner than the thicknesses seen in the northern well section. However, the E-1 well located within the Central Trough shows a smaller thickness than the other wells. The thinning within the Central Trough is interpreted to be a consequence of the inversion which took place in the southern Danish Central Trough and along fault trends favourablely oriented for inversion in the northern Danish Central Trough (Clausen & Korstgård 1993, Vejbæk & Andersen 1987).

A number of wells in the Central Trough area and in the western Norwegian-Danish Basin encountered sand-rich deposits of Paleocene age (Fig. 5). Danielsen et al. (1995) show that the location of the sands coincides with the location of depressions related to reactivating of normal faults (both Palaeozoic and Mesozoic fault orientations) which were favourably orientated for reactivation in the Late Paleocene tectonic regime (Clausen & Korstgård 1993) and to depressions related to moving salt structures (Korstgård et al. 1993). The sands are interpreted as mass flow deposits originating from the eastern margin of the basin (Danielsen et al. 1995) and the subtle depressions in the basin topography controlled by local tectonics are interpreted as pathways controlling the deposition of the mass flows.

Fig. 2. The study area with indications of the seismic sections shown in this paper, and the wells used in this study.



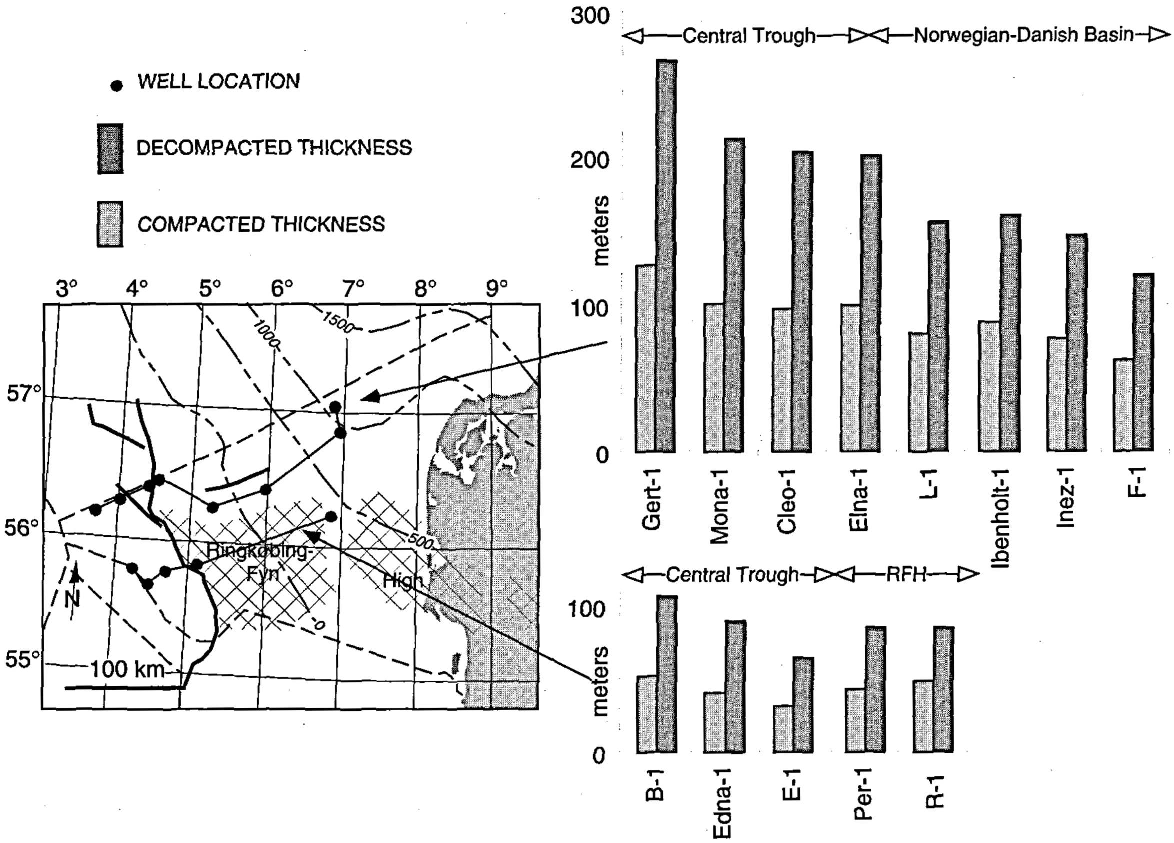


Fig. 3. The location of two well sections showing the variations in thickness of the late Paleocene sediments (both present thickness and the decompacted thickness) is indicated on the map. The well sections strike approximately SW-NE and the northern section covers the Central Trough and the Norwegian-Danish Basin whereas the southern section covers the southern part of the Danish Central Trough and the Ringkøbing-Fyn High. The contours in the map shows the Cenozoic uplift from Jensen & Schmidt (1992). See text for further discussion of the thickness variations.

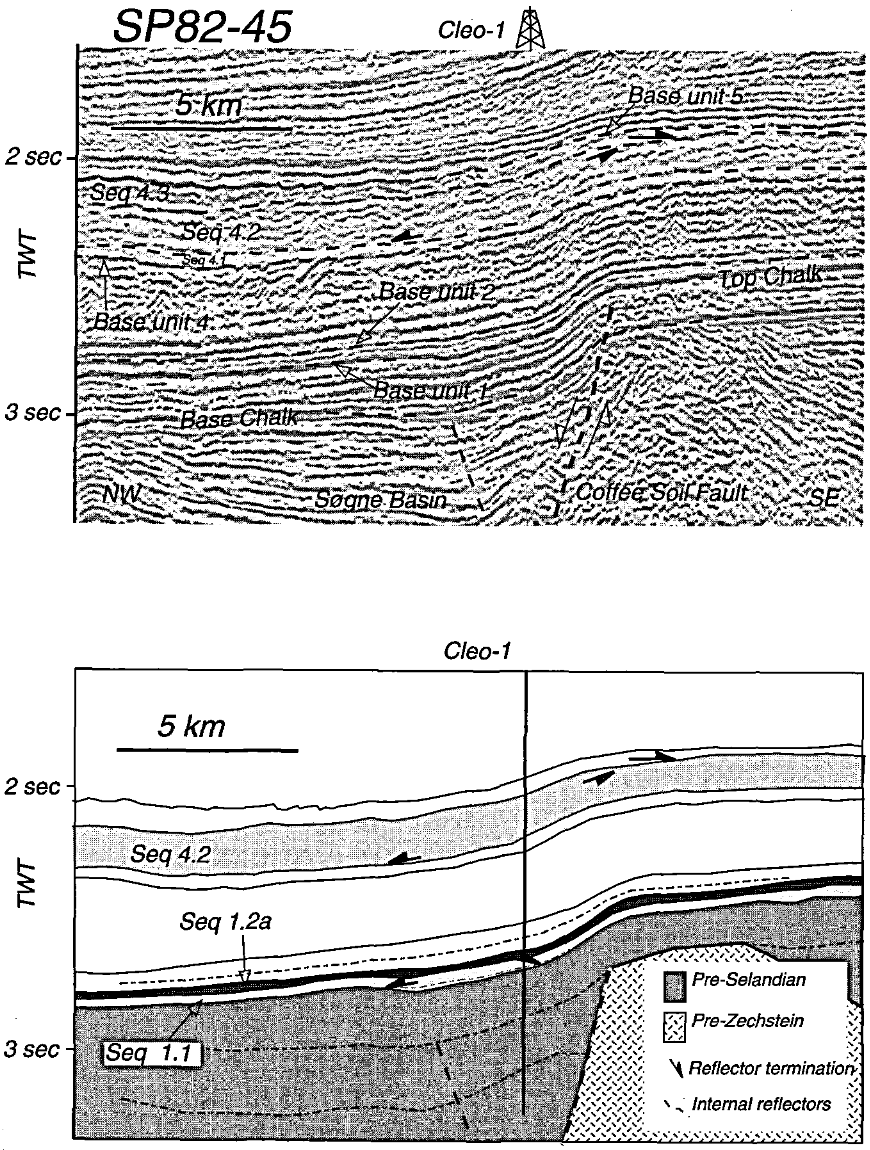


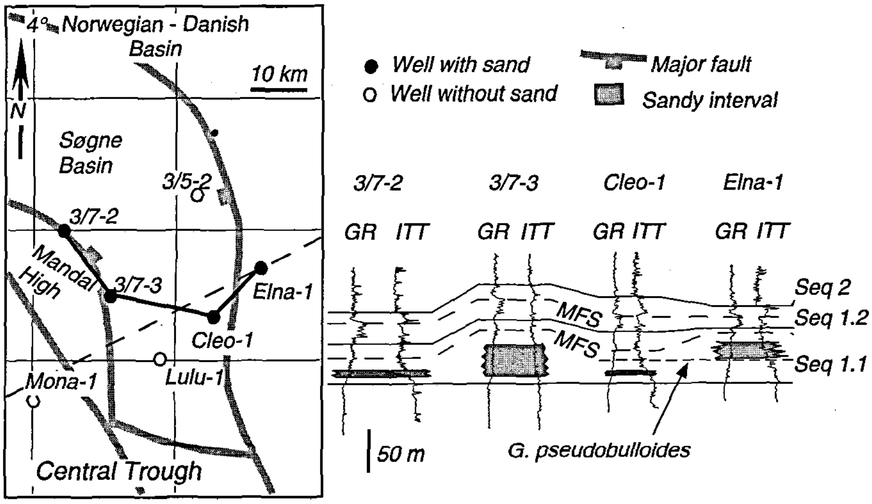
Fig. 4. Seismic section and line drawing striking NW-SE (for location see Fig. 2). The section shows the differential subsidence taking place across the Coffee-Soil Fault during the late Paleocene and the Oligocene (seq. 4.2). See text for further discussion.

Oligocene

The Oligocene is dominated by deposition of olive grey to brownish grey silty clay with thick successions of sand in the north-eastern part of the study area. The sands are interpreted as beeing deposited in an upper sublittoral near shore environment (Michelsen & Danielsen 1996). The lithological interpretations by Kristoffersen & Bang (1982) in the Central Trough and especially by Danielsen et al. (1997) from the Norwegian-Danish Basin show that the Oligocene sediments are significantly coarser than the fine-grained late Paleocene and Eocene sediments. The Eocene-Oligocene transition is also characterised by a significant change in mineral composition of the sediments (Danielsen et al. 1997). The base of unit 4 is a major downlap surface in the Norwegian-Danish Basin and the sequences 4.1–5.1 show a progradational pattern (Fig. 6) indicating that the sediments were transported from the northnortheast. Southwestward migrating depositional centres characterise the individual Oligocene sequences (Fig. 7). These observations indicate that the uplift of the eastern basin margin (i.e. uplift of the Fennoscandian Shield) took place during the Oligocene, and that large amounts of sediments were made available close to the Norwegian-Danish Basin. The sequence stratigraphic analysis of Michelsen & Danielsen (1996) shows that the sequences of unit 4 are deposited in a deep ramp setting.

The seismic section RTD81–38 (Fig. 8) shows that

Fig. 5. Well section and location of the section. The section shows the stratigraphical and structural location of sand intervals in the late Paleocene succession. The sand is located within sequence 1.1 and the different sand layers are separated stratigraphically by the key bio-marker G. pseudobulloides.



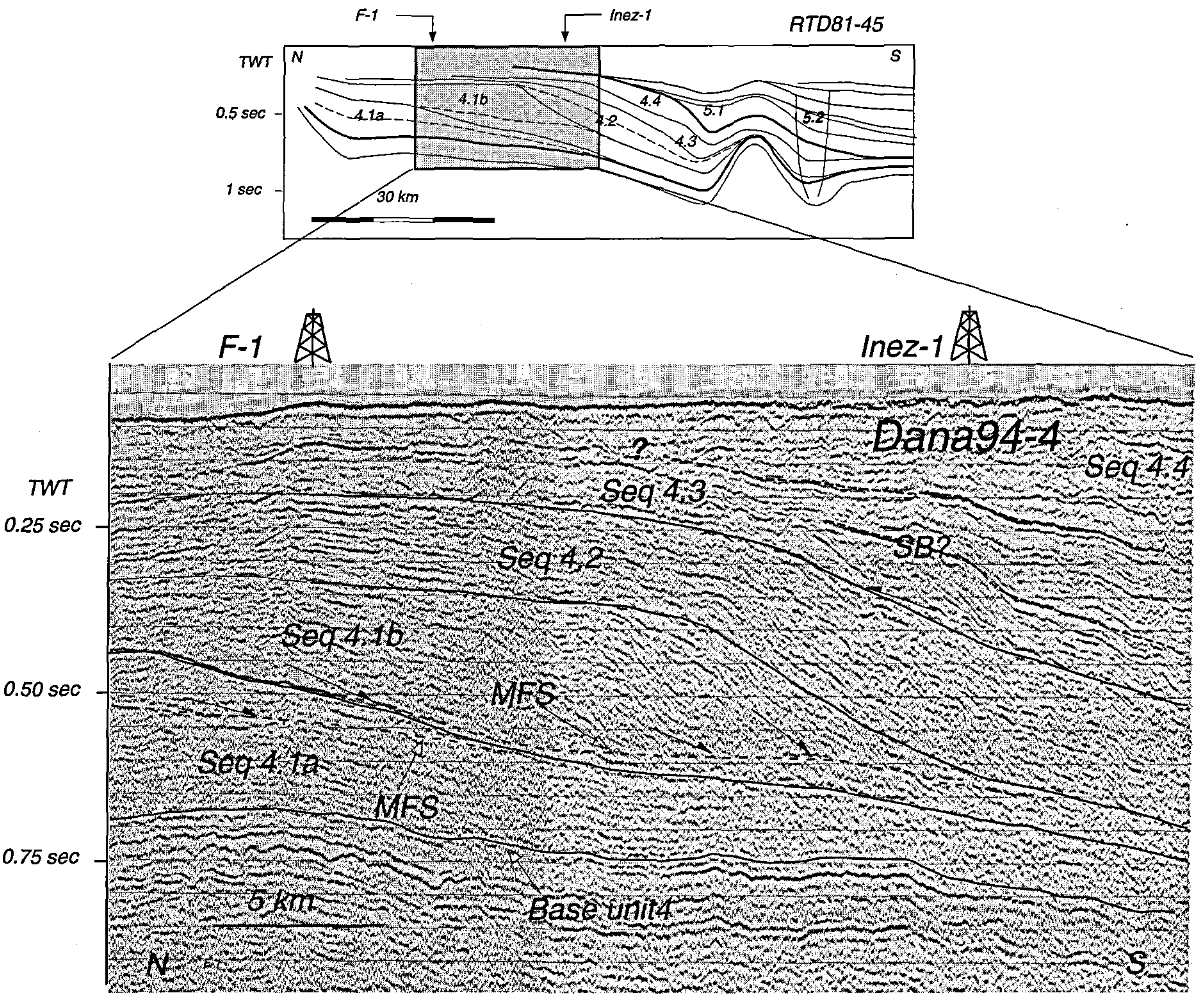


Fig. 6. N-S striking line drawing of the post Eocene succession in the central part of the Norwegian-Danish Basin. The section shows the progradational character of the sequences. The internal architecture of the Oligocene sequences is shown in the high resolution seismic section Dana94–4. The location of the maximum flooding surface (MFS) is indicated in sequence 4.1a and 4.1b. Within the sequence 4.3 a possible sequence boundary is indicated with SB?, which may suggest that it is possible to subdivide the sequence 4.3 into two sequences.

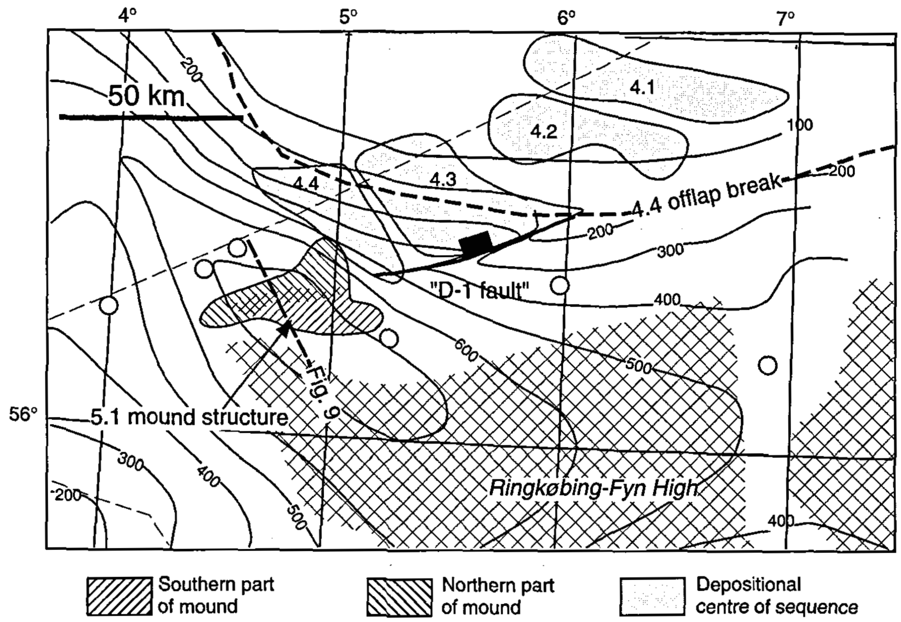


Fig 7. The map shows the reconstructed paleo-topography of the base of sequence 5.1 in the eastern part of the Norwegian-Danish Basin. The depositional centres of the sequences 4.1–4.4 emphasised the progradation. The location of the mound structure in sequence 5.1 with respect to underlying structures and the paleo-topography is discussed in the text. The subdivision of the mound is indicated by different hatching.

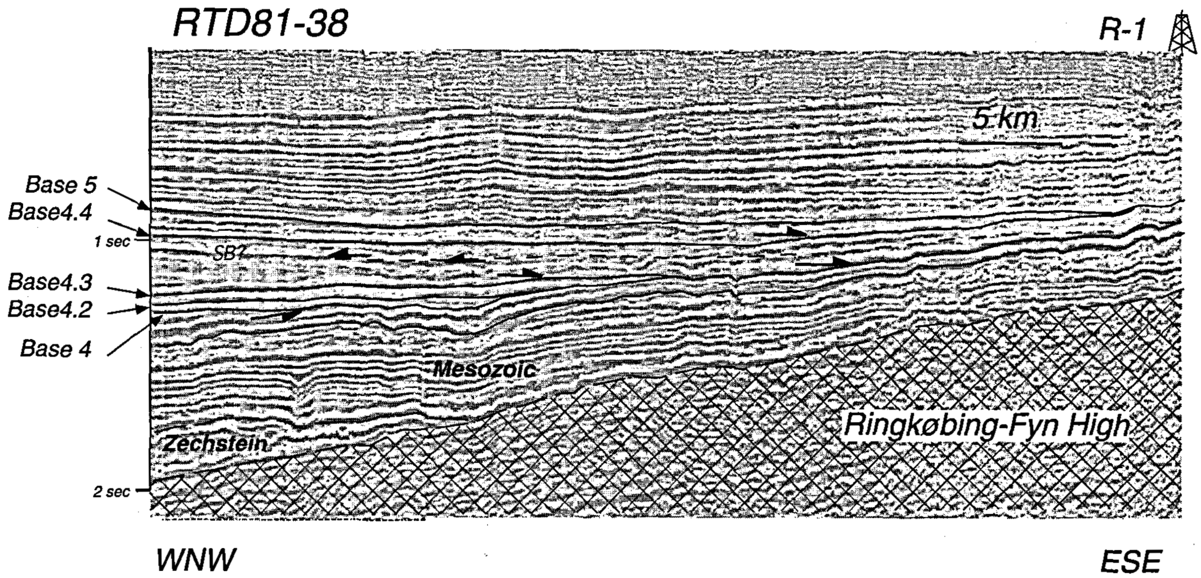


Fig. 8. The seismic section strikes WNW-ENE and shows the onlapping of the Oligocene sequences onto the Ringkøbing-Fyn High. The surface which may represent at sequence boundary within sequence 4.3 is indicated with a SB?. See text for further discussion of the geometry of the Oligocene sequences. for location of the section see Fig. 2.

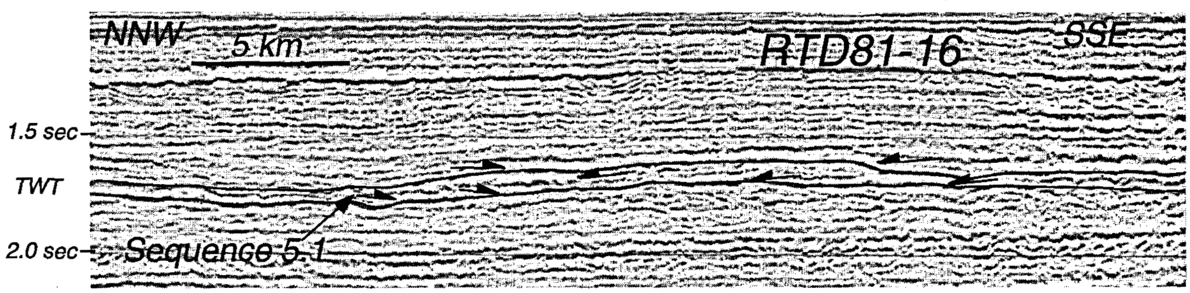


Fig. 9. The seismic section strikes NNW-SSE and shows the mound structure located within sequence 5.1. The internal geometries of reflectors show that the sequence can be subdivided into different phases. For location of the section see Fig. 2.

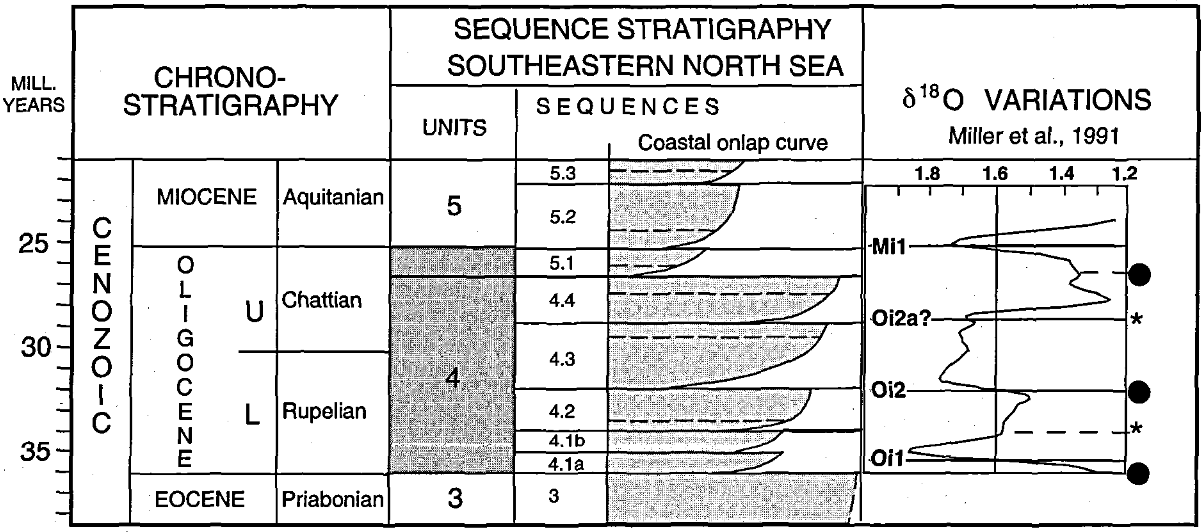


Fig. 10. The correlation between the sequence stratigraphic subdivision and the $\delta^{18}O$ from Miller et al. (1991) is indicated. the filled circles and the asterisk show features on the curve discussed in the text (filled circles indicate the onset of an increase in $\delta^{18}O$ and the asterisk show marked changes in the rate of $\delta^{18}O$ change. See text for further discussion.

the Ringkøbing-Fyn High was a positive structure within the basin during the Oligocene. The top of sequence 4.1 and top sequence 4.2 is at present dipping to the westnorthwest in this section. A southerly sediment transport direction and the migration of depositional centres would result in a horizontal to slightly southerly dipping top as the present east-south-east dip of the top of sequence 4.3 and younger Oligocene sequences. The present dip of the top of sequence 4.1 and 4.2 thus indicate that the Norwegian-Danish Basin subsided with respect to the Ringkøbing Fyn High after deposition of sequence 4.2. The gradually overstepping of the Ringkøbing-Fyn High and the pinch-out of sequence 4.1– and 4.2 also indicate that the Ringkøbing-Fyn High was a topographic high at the onset of the Oligocene, and that the subsidence of the Norwegian-Danish Basin with respect to the Ringkøbing-Fyn High was sufficiently large to influence the deposition of the sequences.

Danielsen et al. (1997) show that sequence 4.2 has a local depositional center located in the Central Trough area. The seismic section RTD81–45 (Fig. 4) shows that the local depositional center is controlled by differential subsidence across the graben bounding Coffee Soil Fault. Lateral facies variations as described by Danielsen et al. (1997) are however not influenced significantly by the differential subsidence across the Coffee Soil Fault.

The deposition of sequences 4.1–4.4 is thus highly influenced by the regional tectonics since the generation of a source area by uplift of the eastern basin margin close to the Norwegian-Danish Basin enables the generation of large amounts of sediments infilling the basin. The presence of the Ringkøbing-Fyn High furthermore seems to influence the direction of progradation since the migration of the depositional centres follow the flank of the Ringkøbing-Fyn High.

Sequence 5.1

The reconstructed palaeotopography of the basin at the time when sequence 5.1 was deposited shows that the basin was characterised by a zone with a topographic gradient steeper than the palaeotopography landward of the seismically defined offlap break. The zone with a high topographic gradient follows the seismically defined offlap break and reflects the prograding front of sequence 4.4. The part of sequence 5.1 which is deposited basin-ward of the offlap break contains a complex mound structure. The internal reflectors of the mound shows that it is possible to subdivide the structure into a southern and a northern part reflecting the existence of several depositional events. The northern part of the complex mound structure was sourced from the area north of the D-1 fault through the hanging wall depression of the "D-1 fault", whereas the southern part of the complex mound structure was sourced through the depression between the footwall uplifted area of the "D-1" fault and the northern flank of the Ringkøbing Fyn High.

The location of the mound at the top of the "slope", the external geometry and internal architecture of the mound indicate that the mound was deposited as a number of mass flow deposits (Fig. 9). The southern pinch out line of the mound follows the flank of the Ringkøbing-Fyn High. The eastern outline of the mound structure was highly influenced by the presence of the "D-1 fault", which bifurcates the mound. The bifurcation corresponds to the above mentioned northern and southern part of the mound. The above described close relations between both the external geometry, the internal architecture and the surrounding structures indicate that the location of the mass flow deposits generating the mound structure was controlled by subtle topographic depressions and highs. The subtle depressions and highs are mainly tectonically related and are superimposed onto a basin topography which is highly controlled by depositional processes.

Influence of climatic changes

The subdivision of the Oligocene succession is related to the $\delta^{18}O$ curve from Miller et al. (1991) as shown in Figure 10. The correlation of the sequence boundaries and the oxygen isotope variations are based on the NP zonations to where both the sequences and the isotope events independently are calibrated (Clausen, Gregersen, Michelsen & Sørensen, submitted). It is important to note that the correlation is based on the assumption that the NP zones used in the different studies are correlatable. The $\delta^{18}O$ curve reflects climatic changes since a regional increase in $\delta^{18}O$ indicates growing ice sheets (Miller et al. 1991, Prentice & Matthews 1991). A positive correlation between the sequence boundaries and changes in $\delta^{18}O$ ($\delta^{18}O$ events) is indicated in Figure 10. The beginning of the isotope events Oi1, Oi2 and Mi3 (indicated with filled circles in Fig. 10) all correlate with a sequence boundary (base sequence 4.1a, 4.3 and 5.1). These sequence boundaries are thus interpreted as highly influenced by glacio-eustatic sea level changes. The change in the rate of $\delta^{18}O$ decrease (indicated by an asterisk in Fig. 10) correlate with the base of sequence 4.2 and 4.4. and the sequence boundaries are thus interpreted as a consequence of an interaction between the rate of basin margin uplift and glacio eustatic sea level changes. The surface characterised as an onlap surface on seismic sections (indicated in Figs 6 and 8 with SB?) indicate a possible subdivision of sequence 4.3 into two subsequences. The minor changes in the $\delta^{18}O$ taking place during deposition of sequence 4.4 is therefore suggested to control the above mentioned subdivision.

Discussion and conclusions

Importance of regional tectonics

Regional tectonic events had significant importance in generating a sedimentary source areas located east of the North Sea Basin during the Oligocene, but also during the late Paleocene. During the Late Paleocene mass flow deposits were the most conspicuos contribution from the easterly located sediment source. The mass flows have resulted in deposition of relatively coarse grained sediments in an area dominated by hemipelagic clay deposition in a deep marine environment. The uplift of Fennoscandia enables the generation of enormous amounts of sediments during the Oligocene. Sediments which have prograded into the Norwegian-Danish Basin and the Central Trough area. The Ringkøbing-Fyn High seems to have played a role as a topographic high during the late Paleocene. The geometry of the Oligocene sequences furthermore shows that the Ringkøbing-Fyn High was an active submarine topographic high during deposition.

Importance of local tectonics in deposition of the Paleogene sediments

Depressions in the basin topography due to reactivation of fault trends and individual faults were generated during the late Paleocene and during the Oligocene. The depressions controlled the path of the late Paleocene mass flows and their final location, i.e. the depressions are of importance when predicting the location of sand-prone Late Paleocene sediments. The influence of local tectonics on the sequence geometry is less prominent during the Oligocene. However, the deposition of a late Oligocene mound structure was controlled by the salt-related "D-1" fault, the topography of the Ringkøbing-Fyn High and reactivations along the border faults of the Central Trough.

The importance of climatic changes

As a consequence of the condensed character of the upper Paleocene sediments, a relatively small number of sequences are identified in the Danish area. It is thus impossible to deduce whether climatic changes has influenced the deposition of the late Paleocene sediments. This is in marked contrast to the Oligocene succession where the positive correlation between glacio-eustatic induced global sea level changes as indicated by the $\delta^{18}O$ variations and the sequence boundaries clearly indicates that the third order sequence boundaries are controlled by climatic changes. This means that the repeated sudden basinward shift in onlap followed by a landward shift of the onlap, which is observed during the Oligocene, was controlled by climatic changes.

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Dansk sammendrag

En sekvensstratigrafisk inddeling af øvre Paleocæn og Oligocæn bruges til at illustrere indflydelsen af regional tektonisme, lokal tektonisme og klimatiske ændringer på sedimentationen i et epikontinentalt bassin. Analysen viser, at den kondencerede karakter af de øvre Paleocæne silliciklastiske sedimenter slører en eventuel indflydelse af klimatiske ændringer. Det er i modsæting til den Oligocæne lagpakke, hvor dannelsen af 3. ordens sekvensgrænser var kontrolleret af glacioeustatiske havspejlsændringer. Regional tektonisme havde en afgørende betydning med hensyn til at danne kildeområder for klastiske sedimenter øst for det nuværende Nordsø bassin. De områder, der var eksponerede for erosion, dannede sandrige "mass-flow" aflejringer i sen Paleocæn og store mængder sillisiklastiske sedimenter, der progradered fra NNØ mod SSW i Oligocænet. Lokale depressioner i den vestlige del af det Norsk Danske Bassin var kontrolleret af reaktivering af dybe forkastninger. Disse lokale depressioner kontrollerede placeringen af de sandrige mass flow aflejringer både i sen Paleocæn og Oligocæn.

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