Stratigraphy and depositional evolution of the uppermost Oligocene – Miocene succession in western Denmark

ERIK SKOVBJERG RASMUSSEN

Rasmussen, E.S. 2004–12–15: Stratigraphy and depositional evolution of the uppermost Oligocene – Miocene succession in western Denmark. *Bulletin of the Geological Society of Denmark*, Vol. 51, pp. 89–109. © 2004 by Geological Society of Denmark. ISSN 0011–6297.
https://doi.org/10.37570/bgsd–2004–51–07

The uppermost Oligocene – Miocene succession in Denmark is subdivided into six depositional sequences. The development of the succession was controlled both by tectonic movements and eustatic sea-level changes. Tectonic movements generated a topography, which influenced the depositional pattern especially during low sea level. This resulted in sediment by-pass on elevated areas and the confinement of fluvial systems to structural lows. Structural highs further created re-stricted depositional environments behind the highs during low sea level. The structural highs were also the locus for sandy spit deposits during transgression and high sea level. Initially sediment supply was from the north and north-east but shifted within the Middle Miocene to an easterly di-rection indicating a significant basin reorganisation at this time. Eustatic sea-level changes mainly controlled the timing of sequence boundary development and the overall architecture of the sequences. Consequently, the most coarse-grained sediments were deposited within the forced regressive wedge systems tract, the lowstand systems tract and the early transgressive systems tract. The most dis-tinct progradation occurred in the Aquitanian (Lower Miocene) and was associated with a cold pe-riod in central Europe. The subsequent rise of sea level until the Serravallian (Middle Miocene) resulted in an overall back-stepping stacking pattern of the sequences and in decreasing incision.

Keywords: Oligocene, Miocene, North Sea, Denmark, eustacy, climate, tectonics, sequence stratigraphy.

Erik Skovbjerg Rasmussen [esr@geus.dk], Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K.

The uppermost Oligocene – Miocene succession in Denmark has been studied intensively in pits and boreholes during the past sixty years, and a number of lithostratigraphic units have been defined (Sorgenfrei 1940, 1958; Larsen & Dinesen 1959; Rasmussen 1961; Christensen & Ulleberg 1974). However, a compilation of these lithostratigraphic units has never been published. The most commonly used lithostratigraphic schemes in various publications about the Miocene in Denmark are that of Rasmussen (1961), Buchardt-Larsen & Heilmann-Clausen (1988) and Michelsen (1994).

Systematic studies of seismic data and wells from the North Sea has significantly increased during the past 10 years and thus the understanding of the geological evolution of the eastern North Sea area (Jordt *et al.* 1995; Michelsen *et al.* 1998; Clausen *et al.* 1999). Attempts to correlate the depositional sequences within the North Sea have been made by Michelsen (1994) and Michelsen *et al.* (1998) but due to poor biostratigraphic resolution of outcrop sections (dissolution of foraminifera) only a tentative correlation has been possible. The finding of dinoflagellates, which appear at flooding surfaces throughout the uppermost Oligocene – Miocene succession at outcrops in Denmark (Dybkjær & Rasmussen 2000), has resulted in a confident and consistent onshore and offshore correlation of the succession. A number of stratigraphic boreholes and high resolution seismic data were acquired in eastern and central Jylland in order to establish a new stratigraphic subdivision of the uppermost Oligocene – Miocene succession onshore Denmark.

The aim of this study is to establish a stratigraphic framework for genetically related depositional packages that can form the basis for a new lithostratigraphic subdivision of the succession. Finally, the processes involved in the deposition of the succession will be discussed.

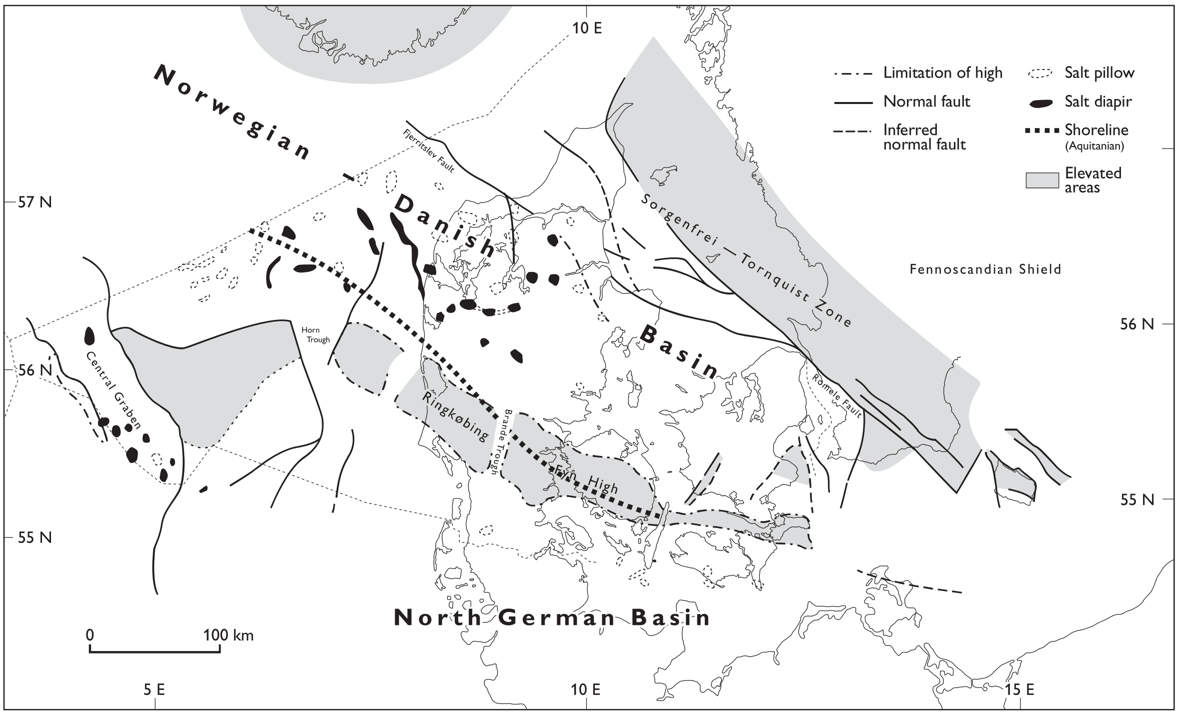


Fig. 1. Structural elements of the Danish North Sea area. Modified after Bertelsen (1978) and Vejbæk (1997).

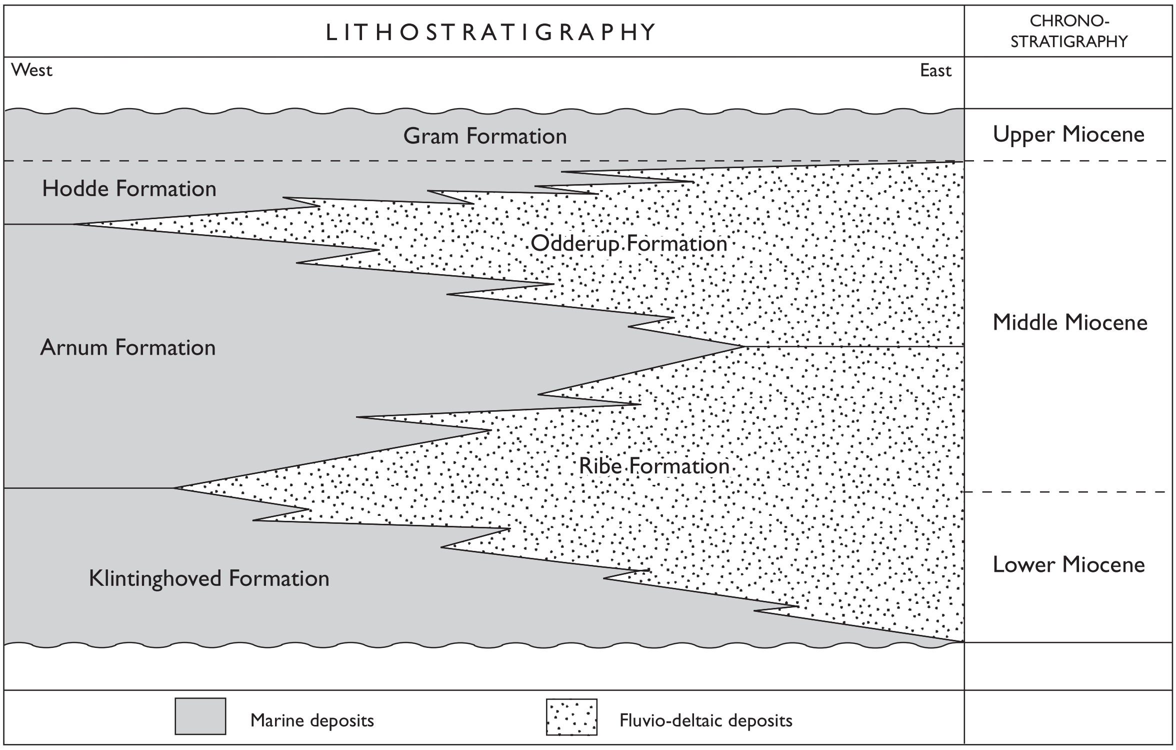


Fig. 2. Lithostratigraphic scheme for the Miocene of Denmark (after Rasmussen 1961).

Geological setting

The development of the eastern North Sea area during the Cenozoic was the result of reactivation of older Mesozoic structural elements and subsidence due to thermal relaxation and interplate stress (Kooi *et al.* 1991; Ziegler 1991). The deepest part of the basin was located in the Central Graben area, whereas the northeastern border was strongly controlled by the Fennoscandian Border Zone also known as the Sorgenfrei–Tornquist Zone (Fig. 1). The Ringkøbing–Fyn High, which divides the Norwegian–Danish Basin and the North German Basin, formed an elevated element with pronounced halokinetic movements both north and south of the structure. The Alpine Orogeny influenced the basin as well as the opening of the North Atlantic also influenced the evolution of the North Sea area (Clausen *et al.* 2000). Inversion resulted in uplift along weakness zones within the Central Graben and along the Fennoscandian Border Zone/Sorgenfrei–Tornquist Zone during the Paleocene (Liboriussen *et al.* 1987; Ziegler 1991; Mogensen & Jensen 1994). Compressional tectonics in the Oligocene and Miocene, related to the collision of Africa and Europe, have also been recognised (Jordt *et al.* 1995; Michelsen *et al.* 1998; Clausen *et al.* 2000). The importance of eustatic sea-level changes during the Oligocene and Miocene has been documented from a number of studies (Rasmussen 1996, 1998; Huuse & Clausen 2001).

The siliciclastic infilling of the North Sea area began in the Late Paleocene (Heilmann-Clausen *et al.* 1985). In the Norwegian–Danish Basin the Paleocene deposits are dominated by clay, but sand-rich gravity sediments were laid down in submarine valleys in the North Sea area (Danielsen *et al.* 1995). The deposition of dominantly fine-grained sediments continued throughout the Eocene, however, with some indication of major progradation from the Middle Eocene. Clear evidence for progradation of major siliciclastic systems and the influx of coarse-grained sediments is documented from the Oligocene (Jordt *et al.* 1995; Michelsen *et al.* 1998). The progradational system was sourced from the western part of the Fennoscandian Shield and prograded southward. This pattern continued throughout the Oligocene and Early Miocene (Clausen *et al.* 1999; Rasmussen *et al.* 2002). The southward prograding system with a dominantly south-east – north-west trending shoreline can be recognised on onshore seismic data and in outcrop sections in eastern Jylland (Rasmussen *et al.* 2002). The onshore studies suggest that the depositional environment was related to spit systems and lagoons on and north of the Ringkøbing–Fyn High with more open marine conditions towards the south (Larsen & Dinesen 1959; Christensen & Ulleberg 1974; Rasmussen 1996; Friis *et al.* 1998). However, this general picture was punctuated by displacement of the shoreline during lowstand of sea level especially in the lowermost Miocene (Aquitanian; Rasmussen 1996, 1998; Dybkjær & Rasmussen 2000). A distinct change in sediment supply occurred in mid-Miocene that may be due to regional tectonic re-organisation related to the Betic tectonic event (Clausen *et al.* 1999). The coincidence of this tectonic phase and a distinct eustatic sea-level rise during the Serravallian (Middle Miocene) (Prentice & Matthews 1988) resulted in major flooding and retreat of the shoreline. Consequently, clay-rich deposits were accumulated in the study area. Evidence of resumed nearshore deposition in the eastern North Sea area is first recognised in the Pliocene approximately 9 Ma years later (Gregersen *et al.* 1998).

Uppermost Oligocene – Miocene lithostratigraphy

A number of papers have defined lithostratigraphic units of the uppermost Oligocene – Miocene succession in Denmark (Sorgenfrei 1940, 1958; Larsen & Dinesen 1959; Rasmussen 1961; Christensen & Ulleberg 1974).

The uppermost Oligocene – ?Lower Miocene clays and sands are referred to the Vejle Fjord Formation (Larsen & Dinesen 1959). This formation consists of marine sediments and based on lithology it has been subdivided into the Brejning Clay Member, the Vejle Fjord Clay Member and the Vejle Fjord Sand Member (Larsen & Dinesen 1959; Heilmann-Clausen 1995). Christensen & Ulleberg (1974) defined the Ulstrup and Sofienlund Formations in northern Jylland. These formations are, however, normally included in the Vejle Fjord Formation (Buchardt-Larsen & Heilmann-Clausen 1988).

The Miocene succession of Denmark consists of six formations (Fig. 2; Rasmussen 1961). The Lower – Middle Miocene marine clays are referred to the Klintinghoved and Arnum Formations, whereas the fluvio-deltaic sediments are referred to the Ribe Formation and the Odderup Formation. The youngest sediments of the Odderup Formation were deposited during the early Middle Miocene. The Middle – Upper Miocene marine, organic-rich, silty clay and glaucony-rich clays are referred to the Hodde and Gram Formations (Piasecki 1980).


New stratigraphic boreholes
Old boreholes
Outcrops
City
Seismic section
Correlation panel
0 25 km
9 E
N
Norway
Sweden
North Sea
DENMARK
England
Germany
200 Km
Søndbjerg
Jylland
Fig. 4A
Isenvad
56 N
Addit Mark
Fig. 4B
Klovborg
Skjern
Eg-3
Store Vorslunde
Jensgård
Grindsted-1
Remmerslund
Vejle
Dykær
Billund
Vandel Mark
Sanatoriet
Vejle Fjord
Skansebakke
Fig. 4C
Hvidbjerg
Egtved Skov
Vorbasse
Pjedsted
Holsted
Hagenør
Børup
Esbjerg
Kolding Fjord
Hindsgavl
Rønshoved
Bastrup
Odense
Rødding
Lillebælt
Fyn
Gram
Gram II
Fig. 10
Brøns-1
Arnum-1
Rurup
Åbenrå
Borg-1
Løgumkloster-1
Høruphav-1
Tønder-3
Germany
9 E

Data

The study is based on seismic data, gamma logs, samples from new stratigraphic boreholes, washed samples from older boreholes, and sedimentological studies of outcrops in Jylland (Fig. 3).

The following seismic surveys were available for the study: NP 85, DCJ81, ST87, DN90 and Vorbasse 2000. Gamma logs from the boreholes Tønder-3, Borg-1, Løgumkloster-1, Brøns-1, Rurup (DGU-150.642), Gram (DGU-141.852), Rødding (DGU-150.642), Holsted (DGU-141.808), Bastrup (DGU-133.1298), Egtved Skov (DGU-124.1159), Grindsted-1, Grindsted (DGU-122.1342), Remmerslund (DGU-116.1549), Store Vorslunde (DGU-104.2325), Klovborg (DGU-106.1373), and Addit Mark (DGU-98.928) provided data for the correlation diagrams. Biostratigraphy and samples were available from Høruphav-1, Løgumkloster-1, Brøns-1, Arnum-1, Gram-II, Bastrup (DGU-133.1298), Store Vorslunde (DGU-104.2325), Klovborg (DGU-106.1373), and Addit Mark (DGU-98.928). In addition to these data, geological descriptions from outcrops in eastern Jylland, at Isenvad and Søndbjerg (Rasmussen & Dybkjær 1999) and shallow boreholes at Store Vorslunde and Skjern (Knudsen 1998) are included in the study.

Major architectural elements of the Miocene succession

Three seismic sections from Jylland and the adjacent offshore area are used to illustrate the major architectural elements of the uppermost Oligocene – Miocene succession (Fig. 4).

Distinct seismic markers are indicated on the seismic sections in Figure 4. The base Oligocene marker is a regional unconformity showing truncation of the underlying succession. From onshore studies in southern Jylland this unconformity is known to separate the uppermost Oligocene glaucony-rich Brejning Clay Member from the Middle to Upper Eocene Søvind Marl Formation (Heilmann-Clausen *et al.* 1985; Rasmussen 1996). In central and northern Jylland the Brejning Clay Member unconformably overlies the Upper Oligocene Branden clay (Dybkjær *et al.* 1999). In the northern part of the seismic sections, where uppermost Oligocene deposits are present, the surface correspond to the top occurrence of the dinoflagellate species *Wetzeliella gochtii* (Karen Dybkjær, personal communication 2001). Above the base Oligocene marker, clinoforms show a successive outbuilding from north-east to south-west as illustrated by the intra Aquitanian marker (Fig. 4). A correlation of the clinoformal break point of the intra Aquitanian marker indicates a NW-SE trend of the shoreline during the Aquitanian (Lower Miocene). Thick deltaic sand was identified in two boreholes at Vandel Mark penetrating the succession below and above the Aquitanian marker. This delta sand can be correlated with a spit system outcropping in eastern Jylland and referred to the Vejle Fjord Formation (Larsen & Dinesen 1959; Dybkjær & Rasmussen 2000). The intra Burdigalian marker (Fig. 4), which represents the base of the Arnum Formation separates the succession characterised by a clinoformal reflection pattern below from a parallel to transparent and sometimes chaotic reflection pattern above (Fig. 4). The resolution of the uppermost part of the seismic section is very poor and therefore cannot add much to the understanding of architectural elements of the succession.

Facing page:
Fig. 3. Map showing the location of outcrops, boreholes, and seismic lines referred to in this study.

Sequence stratigraphy

The uppermost Oligocene – Miocene succession has been subdivided into six depositional sequences on the basis of seismic data, log correlation and lithology (Fig. 5). The reference level for the log panels is the sequence boundary between sequences B and C. This level has been chosen because it represents the time when most structural elements were covered by sediments and therefore did not influence the overall architecture of the succession. The lithology and sequence subdivision of six new stratigraphic boreholes in central Jylland is shown in Figure 6.

Sequence A

Description. The lower boundary corresponds to the base Oligocene marker on the seismic lines and forms a regional unconformity (Fig. 4). On and south of the Ringkøbing–Fyn High this boundary is lithologically sharp and separates green, glaucony-rich clay above from greenish-grey marl below. North of the Ringkøbing–Fyn High the boundary separates glaucony-rich clay from brownish, mica-rich clay. The boundary is often evident on the gamma logs as a distinct peak representing the glaucony-rich deposits overlying marly sediments (Figs 5, 6).

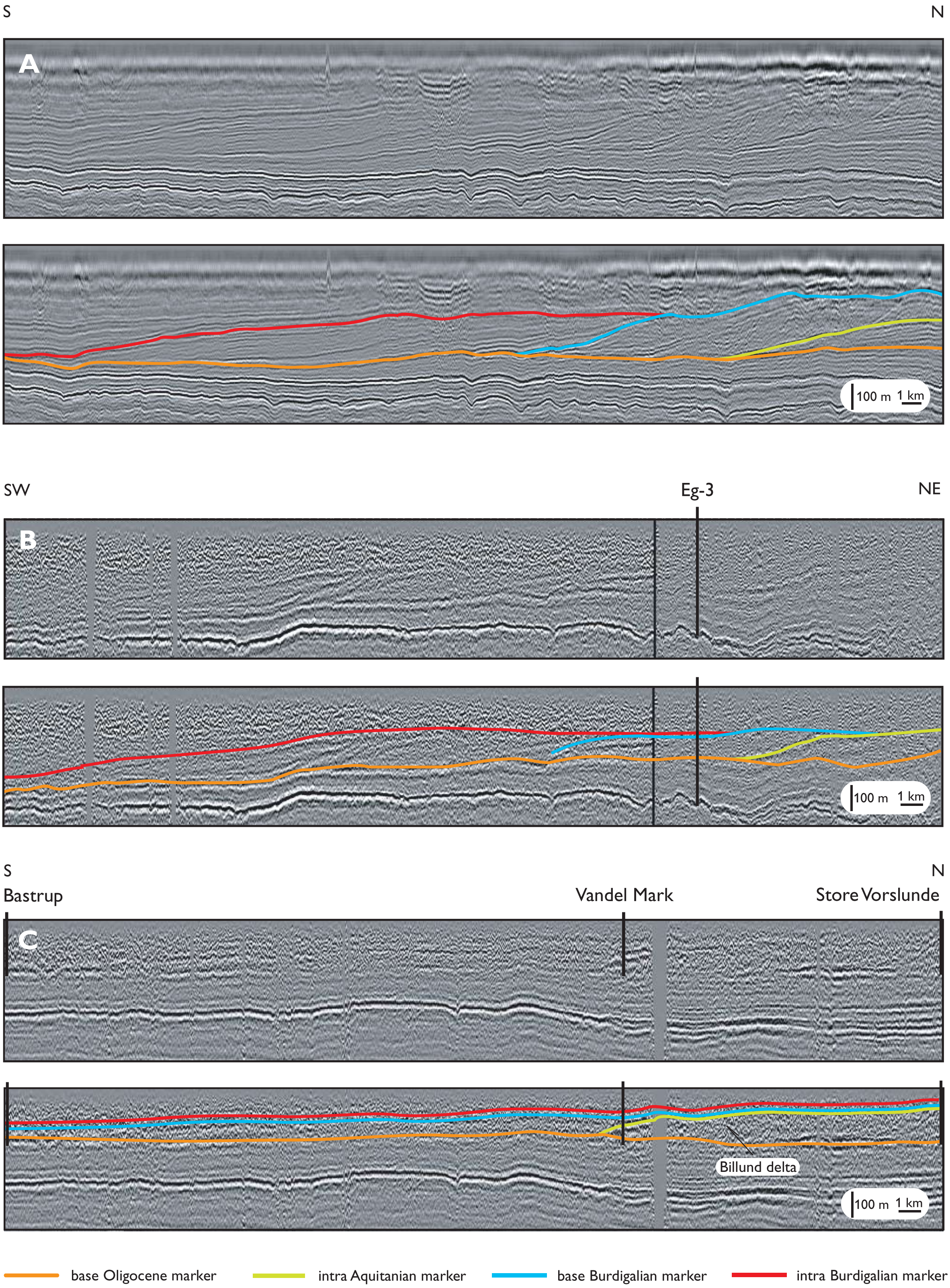


Fig. 4. Three seismic lines from Jylland and adjacent areas. Note that the progradation is generally from north to south and the lowering of the offlap level just below the Base Burdigalian marker. For location see Figure 3.

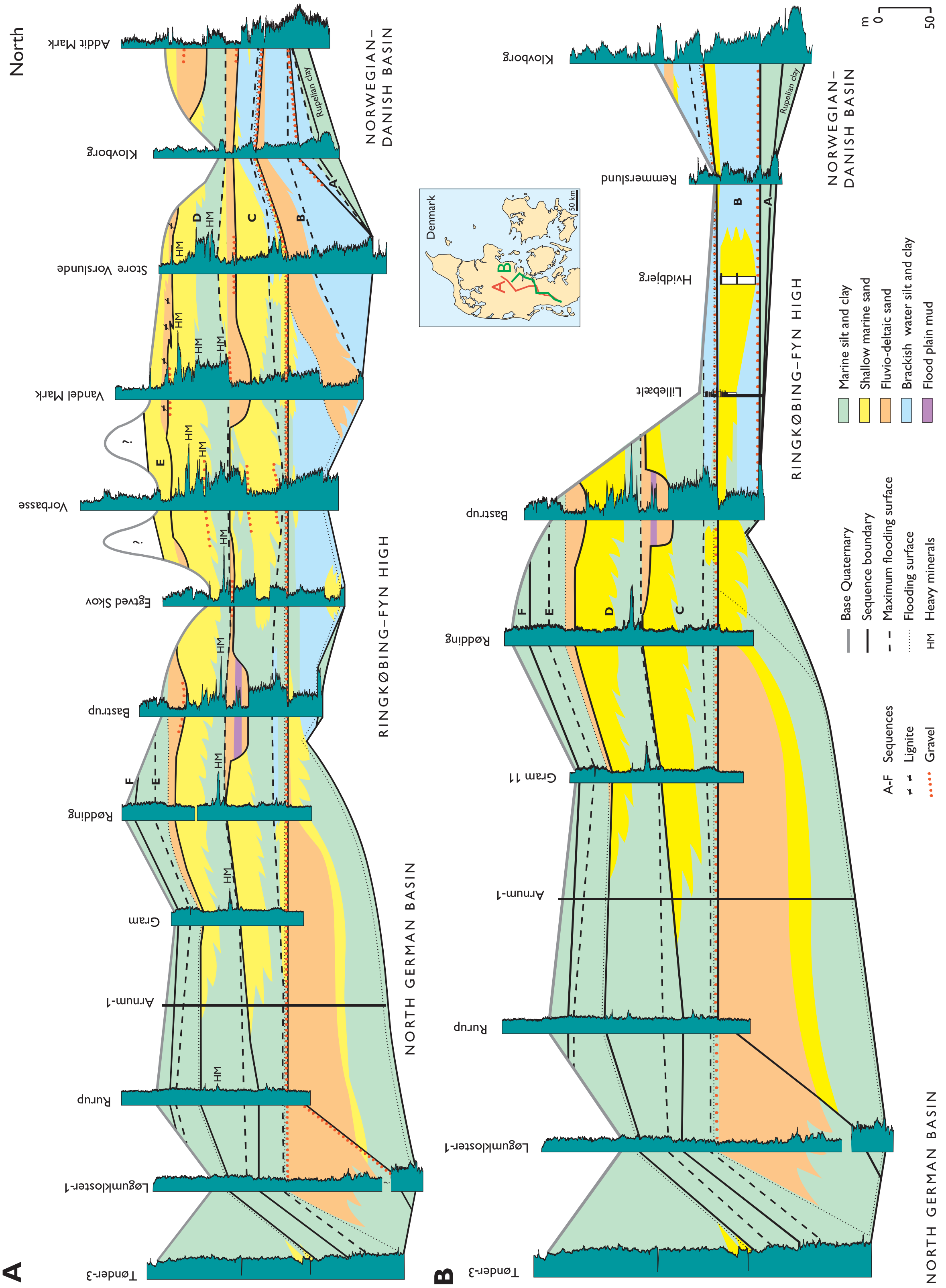
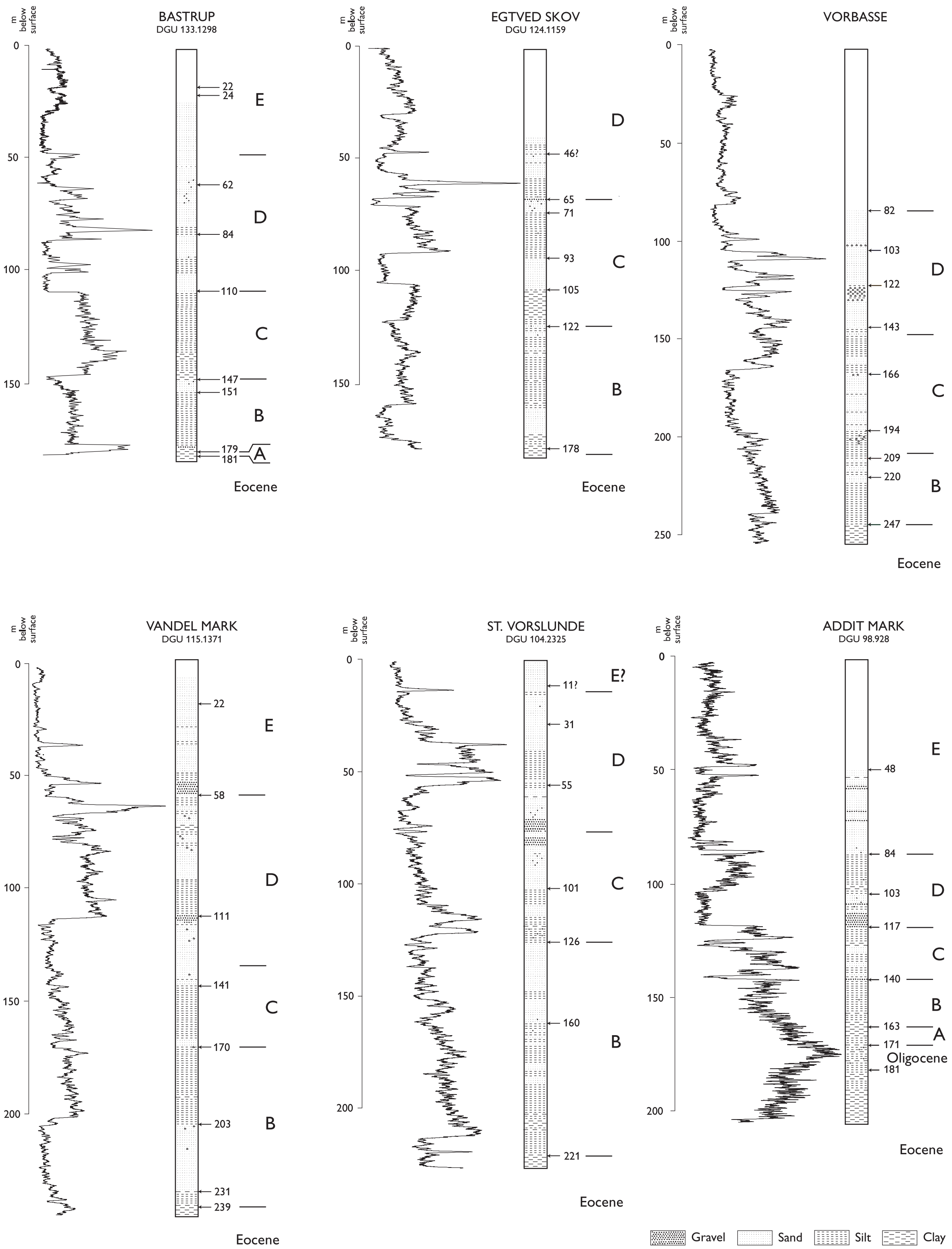


Fig. 5. A. Correlation panel of boreholes with gamma-ray logs from central and southern Jylland.
B. Correlation panel of boreholes with gamma-ray logs and outcrops in eastern and southern Jylland. Sequences A–F are indicated.


m below surface
BASTRUP
DGU 133.1298
22
24
E
62
D
84
110
C
147
151
B
179
181
A
Eocene
EGTVED SKOV
DGU 124.1159
D
46?
65
71
93
C
105
122
B
178
Eocene
VORBASSE
82
103
D
122
143
166
C
194
209
220
B
247
Eocene
VANDEL MARK
DGU 115.1371
22
E
58
D
111
141
C
170
203
B
231
239
Eocene
ST. VORSLUNDE
DGU 104.2325
11?
E?
31
D
55
101
C
126
160
B
221
Eocene
ADDIT MARK
DGU 98.928
48
E
84
103
D
117
C
140
B
163
A
171
Oligocene
181
Eocene
Gravel
Sand
Silt
Clay

The lower part of the sequence is characterised by strongly bioturbated greenish clay, with rip-up clast. The content of glaucony increases upward in the lowermost metre of the sequence and shells of bivalves and gastropods are common. In the upper part of the section there is an increase in silt and fine-grained sand, and the content of organic matter is generally high. The increasing sand content is reflected on the gamma log, which shows a general decrease in the log response in the uppermost part of the unit. The sequence is thin to absent in the southern part of the area and increases in thickness towards the north (Fig. 5A).

Interpretation. The lower sequence boundary represents a major hiatus in the succession, especially in the southern part of Denmark. On and to the south of the Ringkøbing–Fyn High the boundary separates the Middle Eocene Søvind Marl Formation and uppermost Oligocene Brejning clay. North of the high the lower sequence boundary separates the Upper Oligocene Branden clay from the Brejning Clay Member (Larsen & Dinesen 1959; Heilmann-Clausen *et al.* 1985; Dybkjær *et al.* 1999; Dybkjær & Rasmussen 2000). The abundance and diversity of the marine fauna indicate open marine conditions during deposition of the succession.

The maximum flooding surface is placed were the highest amounts of glaucony is found (Fig. 5; Amorosi 1995, 1997). This corresponds to a distinct peak on the gamma log. Geochemical studies of the glaucony at this level also show a high potassium content of the glaucony, which is characteristic for a maximum flooding surface (Amorosi 1995, 1997; Rasmussen 1995).

An increase in the proportion of siliciclastic deposits relative to glaucony and in terrestrial organic matter above the maximum flooding surface reflects the initial progradation of a distant shoreline during highstand.

Sequence B

Description. The lower boundary is placed at the base of a thin gravel layer separating glaucony-rich deposits in the top of sequence A from fine-grained, micaceous and organic-rich deposits at the base of sequence B (Fig. 5). This change is seen on some gamma logs as a low gamma response followed by a marked increase in gamma response (Fig. 5B; Klovborg at 160 m).

The log pattern of the sequence is characterised by high gamma readings in the lower part and with a general decrease in gamma log response (Fig. 5). A high degree of lateral variation has been recognised within the sequence. Fine-grained, organic-rich sediments dominate the whole succession in the northern part (Fig. 5B; Klovborg and Remmerslund). Sandy deposits are common at Hvidbjerg and Lillebælt. In the southern part of Jylland clayey-silty deposits dominate in the lower part of the sequence whereas the uppermost part is sand-rich. Approximately 40 m of clean sand has been penetrated in the Arnum-1 well (Figs 3, 5). On the gamma log, the uppermost part of the sequence shows very low readings, especially close to the upper boundary, where values are extremely low. On seismic sections the upper part of the sequence shows offlap and a stepwise lowering of the offlap level (Fig. 4A). In the Tønder-3 well (Figs 3, 5) the correlation is based on the seismic interpretation, which indicates a pinch out of the succession towards the south (Rasmussen 1996, 1998).

Interpretation. The base of sequence B correspond to a change in depositional environment from open marine to brackish water documented in a number of studies (e.g. Larsen & Dinesen 1959; Dybkjær *et al.* 1999; Dybkjær *et al.* 2001). The Ringkøbing–Fyn High probably acted as a barrier during low sea level (Fig. 5). Brackish conditions were established north-east of the Ringkøbing–Fyn High and the depositional environment was similarly to that reported by Noe-Nygaard & Surlyk (1988) for Lower Cretaceous deposits on Bornholm. Sedimentological studies of the succession reveal that spit systems formed in association with structural highs as demonstrated at Hvidbjerg and Lillebælt (Rasmussen & Dybkjær 1999). North-east of the spit systems, lagoons formed during the successive transgression and progradation during highstand (Fig. 5; Remmerslund and Klovborg). The maximum flooding surface is placed at a distinct gamma peak (Fig. 5). A palynological study indicates that dinoflagellate cysts are diverse and abundant at this level (Karen Dybkjær, personal communication 2002). Above the maximum flooding surface, progradation is seen in the northern part of the study area and is consequently interpreted as a highstand systems tract. The presence of a forced regressive wedge systems tract in the southern part of the area is indicated by the stepwise lowering of the offlap level seen on the seismic panels and the deposition of extremely clean sand at Arnum-1 (Fig. 5). During the time of forced regression the Ringkøbing–Fyn High was subaerially exposed and a fluvial depositional environment dominated in this area (Rasmussen & Dybkjær 1999).

Facing page:
Fig. 6: Lithology and gamma logs from 6 new stratigraphic boreholes in central Jylland.

Sequence C

Description. The sequence boundary of sequence C is recognised on the gamma logs by a change from generally decreasing gamma log values towards an upward increasing log response. In some boreholes the change in gamma log response is distinct (e.g. Bastrup; Figs 3, 5).

In most boreholes the succession immediately above the boundary shows an increase in gamma log readings indicating a lithological change from sandy silt to more muddy sediments (Fig. 6). At Bastrup and Store Vorslunde very high gamma readings are recognised above the boundary corresponding to organic-rich mud immediately above the sequence boundary. This is, however, relatively quickly overtaken by a general decrease in the gamma log response reflecting an upwards increase in the silt and sand content (Figs 5, 6). At Vorbasse and Egtved Skov abrupt decreases in the gamma log response are found.

Interpretation. Sequence boundary C is interpreted as a coalescing ravinement surface and sequence boundary (Rasmussen 1998; Dybkjær & Rasmussen 2000). The relatively thin interval characterised by a gradual increase in gamma log readings, most commonly seen in the southern part of the area, is interpreted as a transgressive systems tract with the maximum flooding surface placed at the highest gamma log readings (Fig. 5). However, at Rødding, Bastrup and Store Vorslunde, the distinct gamma readings represent deposition in a restricted marine environment (Karen Dybkjær, personal communication 2001). This part is therefore interpreted as part of the transgressive systems tract and represents barrier–lagoonal complexes. The highstand systems tract is relatively thick and shows progradation of shallow marine sands over marine silt and clay. The sharp based and clean sand layers in the Egtved Skov and Vorbasse boreholes are interpreted as sand deposited above a regressive surface of erosion and this part of the sequence thus represent a forced regressive wedge systems tract (Hunt & Tucker 1992; Proust *et al.* 2002).

Sequence D

Description. In most boreholes the sequence boundary is placed where a turnover of gamma log readings from a general low gamma log response towards an overall increasing trend is observed. However, at Bastrup and Addit Mark the boundary is placed where a marked decrease in gamma readings takes place (Fig. 5).

Except from very low gamma readings at Bastrup and Addit Mark, the lower part of sequence D is characterised by very high gamma readings (Figs 5, 6). Ignoring these high gamma peaks (heavy minerals, see below), a very thin interval with increasing gamma log response is seen in the lower part of the sequence. The increasing gamma log readings correspond to a higher mud content of this part of the succession. This is succeeded upwards by an overall decreasing gamma log trend, which is correlated to increasing sand content (Fig. 6). At Addit Mark an abrupt decrease in gamma log response occur at 84 m (Fig. 6). This decrease reflects a sudden increase in the sand content. Upwards a gentle increase in gamma log response characterise the upper part of the sequence. However, the maximum grain-size is seen at 58 m (Fig. 6). South of Gram the sequence is dominated by mud (Fig. 5B).

Interpretation. The prominent change in gamma log response represents a change from marine to fluvial deposits at Bastrup and Addit Mark (Karen Dybkjær, personal communication 2002) and thus represents a sequence boundary (e.g. Plint *et al.* 2001). In the Store Vorslunde borehole the change from an overall coarsening upward section to a generally fining upward interval occurs at a gravel layer. The gravel is concentrated within a thin layer and the grains are angular. This is interpreted as an indication of a ravinement surface and the sequence boundary is placed at the base of the gravel layer. Thick lowstand/transgressive deposits are found at Bastrup and Addit Mark. The transgressive systems tract in the other boreholes is very thin and the maximum flooding surface corresponds to the change from the fining upward trend of the gamma log readings to an overall coarsening upward trend. It is not placed at any of the extreme gamma log peaks, which corresponds to heavy minerals. From heavy mineral exploitation it was found that there are two facies associations: 1) a lower shoreface association with fine-grained, immature heavy minerals deposited in storm beds, and 2) a beach association with mature, medium-grained heavy minerals deposited in the swash zone (Knudsen 1998). These facies associations were laid down during progradation of a shoreface. The highstand systems tract is, as described above, characterised by normal progradation of a shoreline. The upper part of the sequence at Addit Mark, where an abrupt increase in the sand content occurs, is interpreted as a result of a sudden increase in sediment supply in to the area (Milana & Tietze 2002) possibly due to tectonic movements (Koch 1989; Rasmussen 2004). Fluvial deposits which correlates with the penetrated succession are exposed at the nearby sand pit at Addit Mark. Here the section is interpreted as fluvial sediments deposited in a braided river system referred to the Odderup Formation (Hansen 1985). The overall stacking pattern of the Odderup Formation in the Addit Mark area is that of a progradational unit succeeded by an aggradational unit capped by a retrogradational unit (Jesse 1995). The two lower units probably correlate with the highstand systems tract of this study.

Sequence E

Description. In most places the sequence boundary is placed where lowest gamma readings are found (Figs 5, 6). At Bastrup and Addit Mark the boundary is placed where a decrease in gamma log response occurs above the most coarse-grained sediments (Figs 5, 6).

Sequence E is characterised by an overall increasing gamma log response, especially at Rurup (Fig. 5A). This increase in gamma log response correlates with an increase in the content of mud and glaucony. The upper part of the sequence is characterised by a relatively thin interval of decreasing gamma log readings. Goethite-rich, silty sediments dominate this part of the sequence.

Interpretation. The depositional environment of the lowermost part of Sequence E varies laterally from fluvial deposition (e.g. at Bastrup and Addit Mark) to marine offshore environment elsewhere (Fig. 5A). The sequence boundary corresponds to a major transgression recognised in the North Sea area and correlates with the Mid-Miocene unconformity (e.g. Huuse & Clausen 2001). The lower part of the sequence reflects a major transgression, which culminated with the deposition of glaucony-rich sediments. The overlying goethite-rich silt is interpreted as deposited in shallower marine water (Dinesen 1976) and thus represent the forced regressive wedge systems tract of sequence E.

Sequence F

Description. The sequence boundary of sequence F cannot be recognised on gamma logs. Instead, this boundary is characterised by a distinct change in lithology from silty goethite-rich deposits to clay-rich deposits as recognised in boreholes at Gram (Dinesen 1976).

The gamma log response of this sequence shows a generally decreasing log pattern. In boreholes and outcrops the lower part of the succession is characterised by clayey deposits, which become more silty upwards. A few thin, fine-grained, wave rippled sand beds are found in the uppermost most part of the succession (Rasmussen & Larsen 1989).

Sequence F is characterised by a distinct upward change from silty clay or fine micaceous sand to chert-rich, often conglomeratic sediments. Sequence F is truncated by an erosional surface with strong relief forming the boundary to the overlying Quaternary deposits (Fig. 5).

Interpretation. The sequence boundary towards E is placed above the goethite-rich deposits as these were laid down during falling sea level (Dinesen 1976). Sequence F was deposited in a marine environment and represents an overall progradation of a shoreline (Rasmussen 1961; Rasmussen & Larsen 1989). Sediments in the lower part of this sequence were deposited in about 50 m of water (Rasmussen 1966) and the sediments in the upper part in about 20 m of water (Rasmussen & Larsen 1989).

Palaeogeography

Based on the sequence stratigraphic interpretation, a palaeogeographic reconstruction of the uppermost Oligocene – Miocene succession in western Denmark has been developed (Fig. 7).

The trend of the shoreline was WNW–ESE and located in the northern part of the study area during the late Chattian (latest Oligocene; Fig. 7A). The shoreline was characterised by barrier islands and associated lagoons, which were connected with a major delta located west of the study area (Huuse & Clausen 2001). In the marine realm, a very low sediment influx permitted the formation of glaucony both associated with pellets and foraminifera (Rasmussen 1996). A major displacement of the shoreline towards the south-west occurred during latest Chattian and the shoreline migrated south of the Ringkøbing–Fyn High (Fig. 7B). Intensive formation of the autigenic mineral siderite and weathering of glaucony to goethite took place during this period of subaerial exposure, and is similar to the Recent Skjern Å delta (Postma 1982). Fluvial systems were probably confined to the topographic low of the Brande Trough. South of the Ringkøbing–Fyn High open marine conditions prevailed and nearshore marine sand was deposited along the high.

During the subsequent sea-level rise in the early Aquitanian (Early Miocene), the area north of the elevated part of the Ringkøbing–Fyn High formed a major silled basin dominated by brackish water (Fig. 7C). Parts of the nearshore sand deposited along the Ringkøbing–Fyn High was redeposited as tempestites

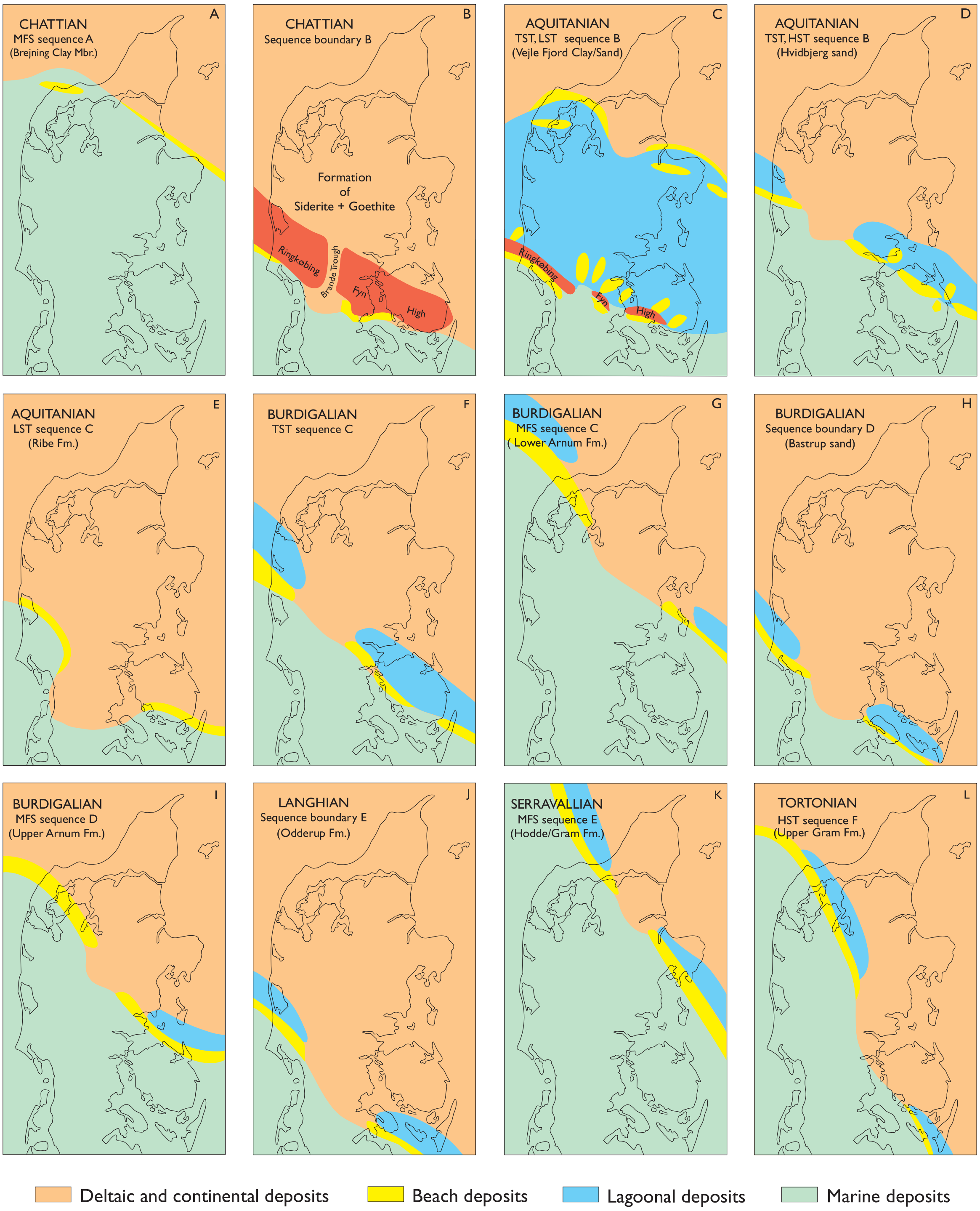


Fig. 7: Palaeogeographical maps showing distribution of depositional environments during latest Oligocene – Miocene time.

similar to washover fans of a barrier system and sandy storm deposits; e.g. hummocky cross-stratified sand beds (Rasmussen *et al.* 2002). Progradation of the shoreline occurred during the highstand of sea level (sequence B) (Fig. 7D). The shoreline was dominated by spit systems formed in association with structural highs. The main delta was located in the central part of the study area just north of the Brande Trough (Fig. 7D).

A major south–westward displacement of the shoreline occurred during the late Aquitanian and fluvio-deltaic sediments were deposited (Fig. 7E). This progradation was associated with a major sea-level fall (cf. Prentice & Matthews 1988), which resulted in deposition of forced regressive wedge systems tract (sequence B) and lowstand systems tract (sequence C). Resumed transgression occurred in the mid–Burdigalian (Fig. 7F), and the shoreline was displaced towards the north-east (transgressive systems tract of sequence C). The influence of the Ringkøbing–Fyn High was low at this time and brackish water conditions were associated with back barrier environments (Fig. 7G). A new progradation of the shoreline took place during the late Burdigalian (Fig. 7H). This regression did, however, not extent as far to the south-west as the older Aquitanian regression (sequence C) and occurred without a major sea-level fall (cf. Prentice & Matthews 1988; Zachos *et al.* 2001). Therefore, most of the progradation occurred during highstand of sea level.

In the later part of the Burdigalian, the area was once again flooded and open marine conditions prevailed in the south-western part of the study area (Fig. 7I). At the Burdigalian–Langhian (Early – Middle Miocene) boundary progradation resumed (Fig. 7J), and was associated with the accumulation of widespread delta swamp deposits, especially in connection with lows formed by tectonic movements along the Ringkøbing–Fyn High (Koch 1989).

The major sea-level rise in the early Langhian (cf. Prentice & Matthews 1988) resulted in a prominent transgression, which continued during Langhian–Serravallian times (Fig. 7K). This contradicts an overall climatic cooling during the Serravallian (Prentice & Matthews 1988; Zachos *et al.* 2001) and accelerated subsidence of the North Sea area is therefore suggested to be an additional factor (Clausen *et al.* 1999; Rasmussen 2002). Additionally, the trend of the shoreline changed to NNW–SSE, which probably was a result of tectonic movements along the Fennoscandian Shield. Strong reworking of former coal-rich deposits during the transgression resulted in the deposition of very organic-rich sediments in the lower part of the transgressive systems tract of sequence E.

The shoreline began to prograde towards the west again during the Tortonian (Late Miocene; Fig. 7L).

Stratigraphic distribution of lithological units

This study demonstrates that the lithostratigraphy of the Danish Miocene succession is in need of revision. It is, however, beyond the scope of this study to define new lithostratigraphic units but the distribution of sand-rich and clay-rich deposits within the present lithostratigraphic framework is shown in Figure 8.

The lithostratigraphy presented here is based on the sequence stratigraphic interpretation of new stratigraphic boreholes, seismic data, outcrops and pits in Jylland (Fig. 8).

The oldest unit investigated here is late Chattian in age (latest Oligocene) and belongs to the basal Brejning Clay Member of the Vejle Fjord Formation (Fig. 8; Larsen & Dinesen 1959). The precise age of the Vejle Fjord Clay Member and Vejle Fjord Sand Member is most likely earliest Aquitanian (lowermost Miocene). The Vejle Fjord Formation is succeeded by the sand- and gravel-rich Ribe Formation (Sorgenfrei 1958), which is of Aquitanian to early Burdigalian age. In the southern part of Jylland the fine-grained deposits underlying the Ribe Formation are referred to the Klintinghoved Formation (Sorgenfrei 1940; Rasmussen 1961). The Ribe and Klintinghoved formations are overlain by the Arnum Formation (Sorgenfrei 1958; Rasmussen 1961). This formation is generally fine-grained, but in central Jylland a sand-rich section is intercalated in the Arnum Formation (Fig. 8). The Arnum Formation is of Burdigalian age (Piasecki 1980; Dybkjær *et al.* 1999). Above the Arnum Formation follows the sand- and lignite-rich Odderup Formation (Rasmussen 1961). This formation is referred to the uppermost Burdigalian – lowermost Langhian. The lignite-rich part of the Odderup Formation has been referred to the Fasterholt Member by Koch (1989). The Odderup Formation is succeeded by the clayey and organic-rich Hodde Formation (Rasmussen 1961) of Langhian–Serravalian age (Piasecki 1980). Finally, the Miocene succession is completed by the Gram Formation of Serravalian–Tortonian age. The Gram Formation forms an overall coarsening upward succession terminated by the Gram sand.

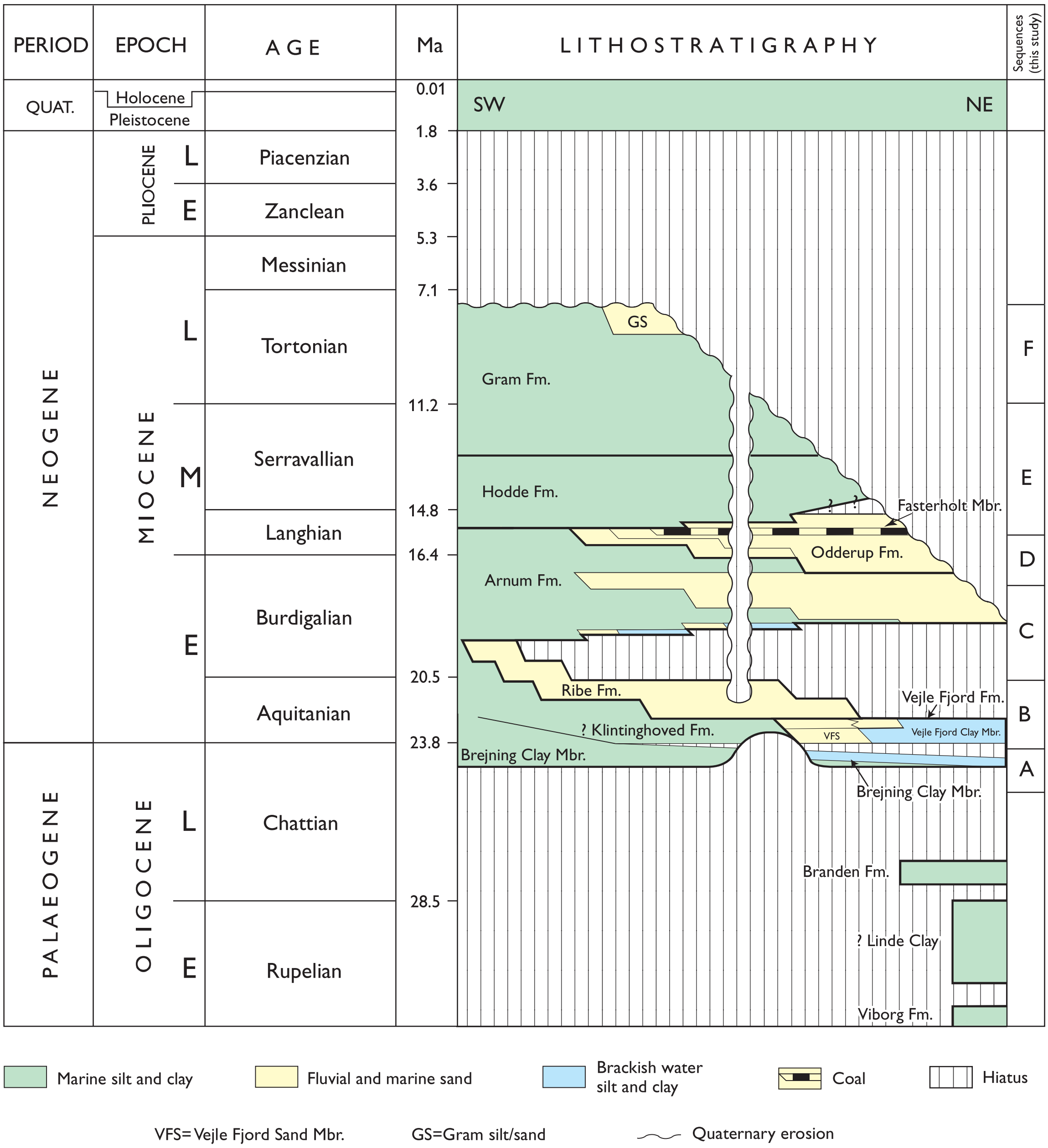


Fig. 8: Lithostratigraphy of the latest Oligocene – Miocene succession in Jylland. The Oligocene lithostratigraphic units: Viborg Formation, Linde Clay and Branden Formation are from Heilmann-Clausen (1995) and Dybkjær *et al.* (1999). The dating of the lithostratigraphic units indicated above are based on Piasecki (1980), Dybkjær *et al.* (1999, 2001) and Dybkjær & Rasmussen (2000) and correlated to the biostratigraphy of Hardenbol *et al.* (1998). The time scale is from Berggren *et al.* (1985a, b).

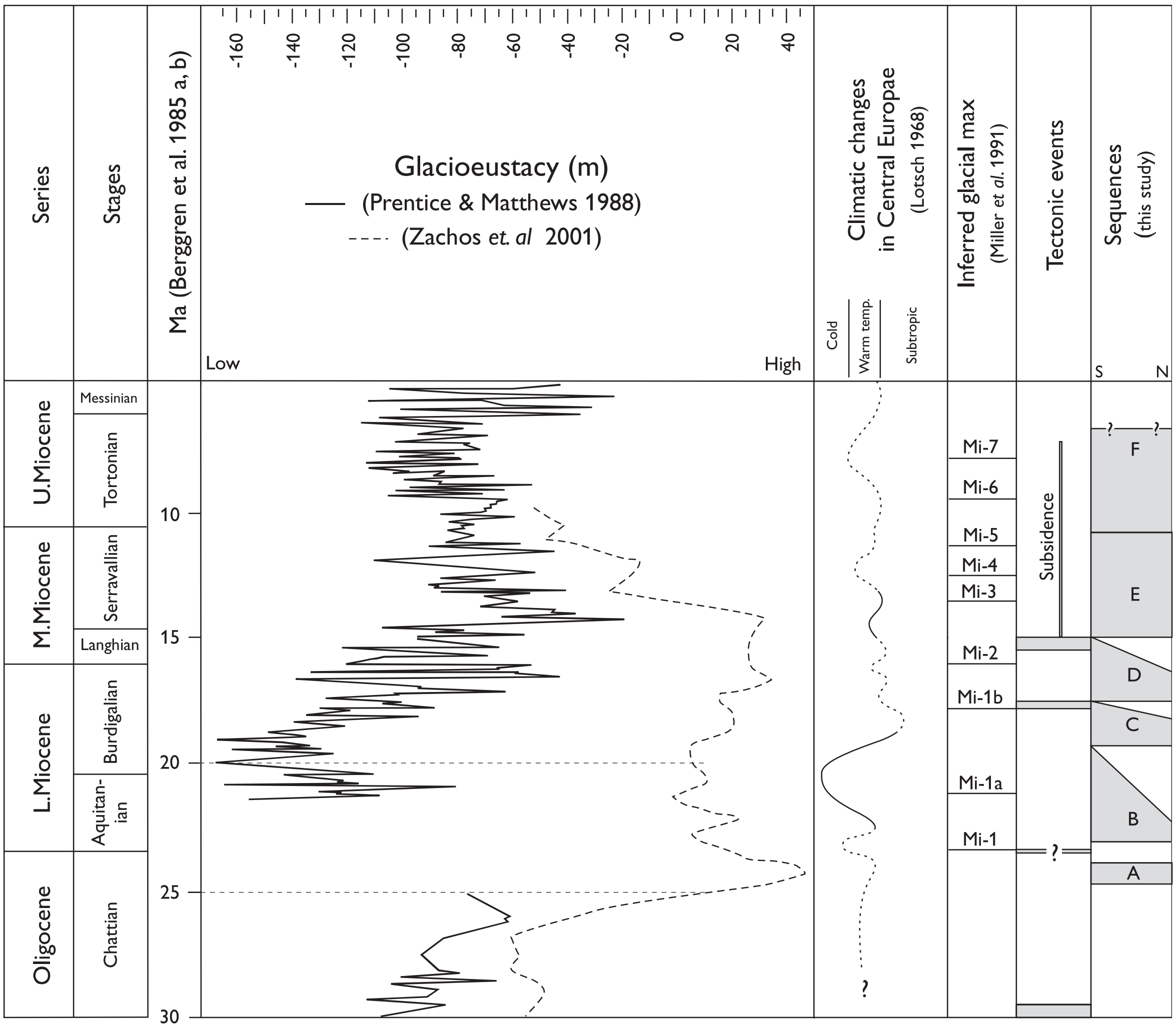


Fig. 9: Comparison of eustatic sea-level curves, climatical changes, glacial maxima, tectonic pulses, and age of the sequences recognised in this study.

Allochtonous control on sequence development

Climatic control

Several studies of the Cenozoic succession of the eastern North Sea area have revealed that close relationships existed between the development of the sedimentation and changes in eustatic sea level (Rasmussen 1996; Michelsen *et al.* 1998; Huuse & Clausen 2001). In the following, the development of the sequences defined in this study are compared with glacio-eustatic sea-level changes as indicated from oxygen isotope studies and palaeoclimatical changes estimated from marine faunas and terrestrial floras (Fig. 9).

The data suggest that climatic changes occurred throughout the latest Oligocene – Miocene time (Fig. 9). The correlation between the different curves is good and the period of changes varies between 2 Ma and 4 Ma. In Central Europe variations from cold temperate climates to subtropical climates occurred. This is in good agreement with the study by Buchardt (1978) for the North Sea.

The variation of sea level at the end of the Oligocene is only represented by the curve of Zachos *et al.* (2001). The deposition of sequence A coeval with a sea-level rise within the Late Oligocene as indicated by the glacio-eustatic curve. This is followed by a sea-level fall, which relates to the glacial maximum Mi-1 (Fig. 9). The deposition of sequence B mainly falls in between the two glacial maxima of Mi-1 and Mi-1a, and corresponds to a period of higher sea level (Fig. 9). The coldest period occurred during the Aquitanian – early Burdigalian (Fig. 9) and is coeval with to the development of sequence boundary between B and C. This boundary is the most distinct sequence boundary found in the region (Rasmussen 1996, 1998, 2002) showing a well-developed forced regressive wedge systems tract and lowstand systems tract. The following general sea-level rise and overall transgression during the Burdigalian is seen from the general backstepping stacking pattern of sequences C and D accompanied by decreasing incision. Sequence boundary D probably formed during the glacial maximum Mi-1b and a cooler period in the late Burdigalian (Fig. 9). The development of sequence D occurred mainly during high sea level, which may explain the extensive deposition of lignite within this sequence. A distinct general glacio-eustatic sea-level rise during the late Langhian, as indicated on the curve of Prentice & Matthews (1988) (Fig. 9), is in good agreement with the change from dominantly nearshore and terrestrial deposition of sequence D to open marine sedimentation dominating sequence E. However, neither

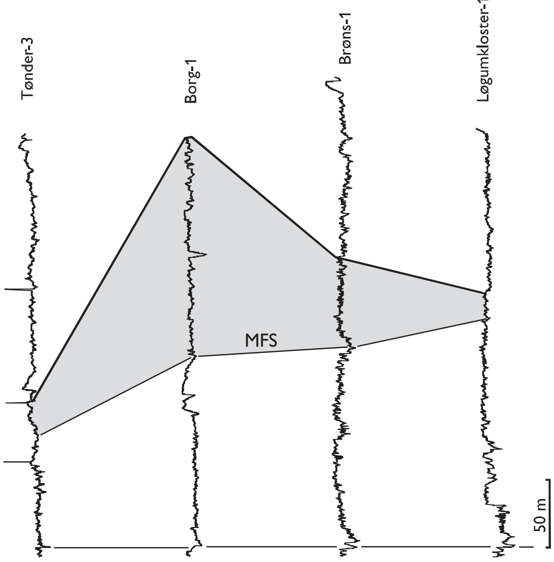


Fig. 10: Gamma log correlation of four boreholes in southern Jylland. Movement of Zechstein salt during the late Burdigalian is reflected by marked thickness variation of the upper part of the Arnum Formation (shaded). See Figure 3 for location of boreholes.

the curve from the continental climate nor the glacial maxima indicate a warmer period during the Serravallian. The timing of sequence boundary F correlates, however, to a cooler period in the Serravallian and Mi-5. A general fall in sea level and cooler climatic conditions in the Tortonian (Fig. 9) is reflected in the overall regression found in the succession and particularly demonstrated by the distinct progradation seen in the Pliocene succession (Gregersen *et al.* 1998).

The climatic influence on the development of the studied succession is obvious, which of course should be expected during this part of the Cenozoic, when the extent of polar ice caps were increasing (Prentice & Matthews 1988; Miller *et al.* 1991; Abreu & Anderson 1998). However, the marked progradation seen within sequence D, and the overall transgression reflected by the deposits of sequences E and F cannot readily be correlated with climatically induced sea-level changes.

Tectonic influence

Four tectonic events during the Oligocene–Miocene have been recognised from seismic mapping, studies of sedimentary structures in outcrops, and from palynological studies (Fig. 9).

The earliest tectonic event was in the beginning of the Chattian. This phase, known as the 'Savische Phase' (Fig. 9; Lotsch 1968), is well known in Central Europe and is also recognised on seismic data from the eastern North Sea area (e.g. Clausen *et al.* 2000).

The second tectonic phase indicated in the uppermost Chattian is, however, uncertain. Convolute bedding and synsedimentary listric faults have been described from outcrops in eastern Jylland, which may have been caused by earthquakes (Mikkelsen 1983; Rasmussen & Dybkjær 1999).

An abrupt occurrence of reworked Jurassic spores and pollen and high amounts of Paleocene and Eocene dinoflagellates within the upper Burdigalian sediments reflect the third tectonic event (Dybkjær *et al.* 2001). Above this level, a distinct regional increase in heavy minerals is observed in the Miocene sediments. Furthermore a marked thickening of the Arnum Formation adjacent to the Tønder salt structures (below the Tønder-3 well), suggests that salt movements were active at this time (Fig. 10).

The fourth tectonic event in the Langhian (Fig. 9) is suggested by faults within the Odderup Formation as seen in brown coal pits in central Jylland (Koch 1989). These faults do not continue into the overlying late Langhian–Serravallian Hodde Formation. Furthermore, a tectonic reorganisation in the mid-

Miocene is also suggested by the cessation of major south-westward progradation from the Fennoscandian Shield and the initiation of major westward progradation from the Baltic and eastern European platforms during Late Miocene – Pliocene times (Clausen *et al.* 1999). This marked shift in source area cannot solely be attributed to eustatic sea-level changes or global climatical change, since this should have produced basin-wide progradation.

Studies of outcrops (e.g. Larsen & Dinesen 1959; Radwanski *et al.* 1975; Rasmussen 1987) and investigations of shallow boreholes in Jylland support the interpretation of tectonic movements in the hinterland during this time. The shallow marine deposits are composed of immature sediments apart from sediments that accumulated in the swash zone of a beach. The quartz grains found within the fluvial deposits are angular indicating that the newly exposed basement became eroded. The Miocene fluvial deposits were laid down by braided river systems (Hansen 1985), which do not favour a low relief hinterland and tectonic quiescence during deposition as suggested by Huuse & Clausen (2001). Many studies have shown a relationship between river pattern and tectonics (Miall 1996 and references therein), which is similar to the pattern of the fluvial systems and salt structures in central Jylland. Alternatively, the dominance of braided river systems of the Odderup Formation may have been a result of high sediment supply caused by the increased erosion of the hinterland. The close relationship between the deposition and preservation of brown coal and fault pattern in central Jylland (Koch 1989) also supports the idea that tectonic disturbance was active at this time.

The four tectonic events discussed above correlate well with the timing of pulses in the Alpine Orogen (Ziegler 1991; Ribeiro *et al.* 1990) and the theory of intraplate stress (Cloetingh 1988) and the consequences on depositional system are therefore interesting for the studied succession. The tectonic events are, however, of a lower frequency than the climatically induced cycles, but the interaction of tectonic and climatic processes is a likely explanation for the evolution of the uppermost Oligocene – Miocene succession.

Sediment supply

The influx of sediments during the Oligocene and most of the Miocene came from the Fennoscandian Shield (Larsen & Dinesen 1959; Spjeldnæs 1975; Michelsen *et al.* 1998; Gregersen *et al.* 1998; Rasmussen & Dybkjær 1999). Progradational features have been recognised on seismic data from the North Sea south of the Norwegian coast. Much of the sediment contains feldspar, angular quartz grains, and gibbsite and are interpreted as immature (Larsen & Dinesen 1959; Radwanski *et al.* 1975; Rasmussen 1987). This indicates that sediment transport was relatively fast and from newly exposed basement. The highest input of sediment was from the area south of present-day Norway with a minor supply from central Sweden. The topography of the North Sea area, which reflected both regional tectonism and salt movements, influenced the deposits with respect to both transport pathways and deposition. Especially, topographic lows on the Ringkøbing–Fyn High acted as conduits for sediments during lowstand of sea level in the Early Miocene.

A distinct change to a westerly transport direction occurred in the Middle Miocene with a source in present-day southern Sweden and the Baltic area (Clausen *et al.* 1999). The change was probably tectonically induced by the formation of the South Scandic Dome (Lidmar-Bergstrøm 1996; Japsen & Bidstrup 2000). Kaolinitic Pliocene deposits in northern Germany reveal erosion of weathered basement in the hinterland and thus support the hypothesis of tectonic movements in southern Scandinavia in Miocene times (Lidmar-Bergstrøm 1996; Japsen & Bidstrup 2000).

Discussion and conclusions

Jordt *et al.* (1995), Michelsen *et al.* (1998) and Huuse & Clausen (2001) have identified both 2nd and 3rd order sequences in the Cenozoic succession from the North Sea area. These studies are mainly based on seismic data and petrophysical logs, mainly gamma logs. Sidewall cores and cuttings have also been used in the study. The stratigraphic resolution is, however, considerably lower than for the data used in the present study in which the use of outcrops, stratigraphic boreholes, shallow seismic data and biostratigraphy based on high sample rates revealed six depositional sequences in the uppermost Oligocene – Miocene succession.

Most of the major sequence boundaries of Jordt *et al.* (1995), Michelsen *et al.* (1998) and Huuse & Clausen (2001) can be correlated with sequence boundaries of this study (Fig. 11). The base of sequence A corresponds to the major sequence boundary 4/5 of Michelsen *et al.* (1998) and to the seismic sequence boundary Css4/Css5 and the near-top Oligocene horizon of Jordt *et al.* (1995) and Huuse & Clausen (2001), respectively (Fig. 11).

Correlation from the Frida-1 well in the Danish

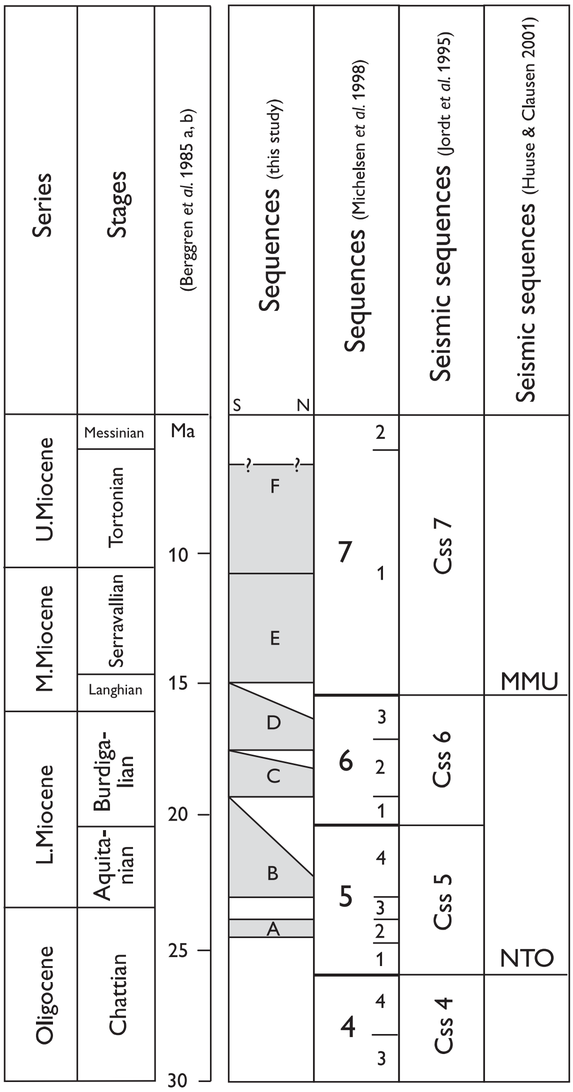


Fig. 11: Timing of sequences of this study compared to studies by Michelsen *et al.* (1998), Jordt *et al.* (1995), and Huuse & Clausen (2001). NTO: Near Top Oligocene and MMU: Mid-Miocene Unconformity. In this study, biostratigraphic data from the Oligocene–Miocene boundary type section in the Lemme–Carrosio section in northern Italy (Zevenboom *et al.* 1994) have been used to constrain the age of sequence boundary A, which therefore appears younger than shown in previous studies.

North Sea to this type section (based on dinoflagellate cysts) has shown that the base of sequence A is of latest Late Oligocene (Fig. 11; Dybkjær 2004). The next major sequence boundary (5/6 and Css5/Css6) recognised by Michelsen *et al.* (1998) and Jordt *et al.* (1995) correlates with sequence boundary C of this study. This sequence boundary is one of the most pronounced in the onshore area associated with the deposition of the Ribe Formation (Forced regressive systems tract of sequence B and lowstand systems tract of sequence C) and formerly described by Rasmussen (1998). The third major sequence boundary is the so-called mid-Miocene unconformity (sequence boundary 6/7 and Css6/Css7) known from the North Sea area (Jordt *et al.* 1995; Michelsen *et al.* 1998; Huuse & Clausen 2001) that is correlated with the sequence boundary E of this study. The onshore development above this boundary is that of a regional flooding and a change from predominantly shallow marine and terrestrial deposition that dominated during the Early Miocene to open marine shelf deposition during the Middle and Late Miocene. This relative sea-level rise has been suggested to be controlled either by tectonic movements and increased subsidence (Jordt *et al.* 1995; Michelsen *et al.*1998; Clausen *et al.* 1999; Rasmussen 2002) or by climatic changes (Huuse & Clausen 2001). A pure climatic control on the development of this sequence boundary is unlikely since it is developed as an overall transgressive event during relative sea-level fall (Zachos *et al.* 2001; Rasmussen 2004). Consequently, the most likely explanation for the development of sequences E and F is a combination of climatic variation and tectonic movements.

Huuse & Clausen (2001) made a clear conclusion about the origin of the sequences without recognising the major sequence boundary C within the early Burdigalian, which correlates to the most distinct climatic change recorded in the Miocene (Prentice & Matthews 1988; Mai 1967; Lotsch 1968; Zachos *et al.* 2001). However, this sequence boundary is the most distinct boundary in the onshore area showing all of the characteristics of classical systems tracts associated with falling sea level and lowstand of the sea (e.g. forced regressive wedge systems tract and lowstand systems tract; Rasmussen 1998). Similarly, sequence boundary D shows both incision and deposition of lowstand deposits. These boundaries have not been recognised by the studies based on seismic data from the North Sea area (Jordt *et al.* 1995; Huuse & Clausen 2001). An explanation for this could be that studies based mainly on seismic data in most cases recognise major flooding events such as the late Oligocene and mid-Miocene (intra Langhian) sea-level rises (Fig. 9). Major flooding will often result in very different lithologies below and above a boundary, e.g. marine clay occurs above nearshore fluvial sand and gravel. Sequence boundaries formed due to a marked lowering of base level, which are often characterised by truncation surfaces, coarse-grained lag deposits and sand to sand contacts, are poor seismic markers and therefore difficult to identify especially on the relatively low-resolution data in the North Sea.

This study shows that both climatic changes and regional tectonic events play a major role in the development of the sequences. The tectonic events revealed by this study correlate with the major tectonic phases of the Alpine Orogeny (Fig. 9) and also to movements associated with the opening of the North Atlantic, although the dating of the latter is less constrained (Boldreel & Andersen 1993; Roberts *et al.* 1999). The development of the sequences was partly controlled by structural highs especially in the lower part of the succession due to the topography formed during the 'Savische' tectonic phase and at the end of the Burdigalian, corresponding to the Betic tectonic event. These structural elements partly controlled the distribution of open marine conditions and partly the concentration of sand on the crests of structural highs similarly to the Lower Cretaceous of Bornholm (Noe-Nygaard & Surlyk 1988).

Acknowledgement

The author is indebted to the Carlsberg Foundation for financial support to the project and to the counties in Jylland for access to data. Stefan Piasecki and Karen Dybkjær are acknowledged for their co-operation and valuable comments on the manuscript. Eva Melskens is acknowledged for preparation of the figures. William Harrar improved the English. Thanks are due to Gunver K. Pedersen, Ole V. Vejbæk, Martin Sønderholm and Svend Stouge for constructive criticism and valuable comments on the manuscript.

References

Abreu, V.S. & Anderson, J.B. 1998: Glacial eustacy during the Cenozoic: sequence stratigraphic implications. American Association of Petroleum Geologist Bulletin 82, 1385–1400.

Amorosi, A. 1995: Glaucony and sequence stratigraphy: a conceptual framework of distribution in siliciclastic sequences. Journal of Sedimentary Research 65, 419–425.

Amorosi, A. 1997: Detecting composition, spatial, and temporal attributes of glaucony: a tool for provenance research. Sedimentary Geology 109, 135–153.

Berggren, W.A. Kent, D.V. & van Couvering, J.A. 1985a: Paleogene geochronology and chronostratigraphy. In: Snelling N.J. (ed.): The chronology of the geologic record. Memoir of the Geological Society (London) 10, 141–195.

Berggren, W.A., Kent, D.V. & van Couvering, J.A. 1985b: Neogene geochronology and chronostratigraphy. In: Snelling, N.J. (ed.): The chronology of the geologic record. Memoir of the Geological Society (London) 10, 211–260.

Bertelsen, F. 1978: The Upper Triassic – Lower Jurassic Vinding and Gassum Formations of the Norwegian–Danish Basin. Danmarks Geologiske Undersøgelse Serie B 3, 26 pp.

Boldreel, O. & Andersen, M.S. 1999: Late Palaeocene to Miocene compression in the Faeroe–Rockall area. In: Parker, J.R. (ed.): Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Journal of the Geological Society (London), 1025–1034.

Buchardt, B. 1978: Oxygen isotope palaeotemperatures from the North Sea area. Nature 275, 121–123.

Buchardt-Larsen, B. & Heilmann-Clausen, C. 1988: The Danish subbasin, southern Jylland. In: Vinken R. (compiler): The southwest European Tertiary Basin; results of the International Geological Correlation Program No 124. Geologisches Jahrbuch 100, 83–91.

Christensen, L. & Ulleberg, K. 1974: Sedimentology and micropalaeontology of the Middle Oligocene sequence of Sofienlund. Bulletin of the Geological Society of Denmark 22, 283–305.

Clausen, O.R., Gregersen, U., Michelsen, O. & Sørensen, J.C. 1999: Factors controlling the Cenozoic sequence development in the eastern parts of the North Sea. Journal of the Geological Society (London) 156, 809–816.

Clausen, O.R., Nielsen, O.B., Huuse, M. & Michelsen, O. 2000: Geological indications for Palaeogene uplift in the eastern North Sea Basin. Global and Planetary Change 24, 175–187.

Cloetingh, S. 1988: Intraplate stress: a new element in basin analysis. In: Kleinspehn, K. & Paolo, C. (eds): New perspective in basin analysis. 205–230. Springer Verlag, Berlin.

Danielsen, M., Clausen, O.R. & Michelsen, O. 1995: Stratigraphic correlation of late Paleocene sand deposits in the Søgne Basin area of the Danish and Norwegian central North Sea. Terra Nova 7, 516–527.

Dinesen, B. 1976: Geochemical properties of the marine Younger Miocene at Gram, SW Jylland. Danmarks Geologiske Undersøgelse Årbog 1975, 5–29.

Dybkjær, K. 2004: Dinocyst stratigraphy and palynofacies studies used for refining a sequence stratigraphic model–uppermost Oligocene to lower Miocene, Jylland. Denmark. Review of Palaeobotany and Palynology 131, 201–249.

Dybkjær, K. & Rasmussen E. S. 2000: Palynological dating of the Oligocene – Miocene successions in the Lille Bælt area, Denmark. Bulletin of the Geological Society of Denmark 47, 87–103.

Dybkjær, K. Piasecki, S. & Rasmussen, E.S. 1999: Dinoflagellatzonering og sekvensstratigrafi i den miocæne lagpakke i Midt- og Sønderjylland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1999/73, 33 pp.

Dybkjær, K,. Rasmussen, E.S. & Piasecki, S. 2001: Oligocæn – Miocæn stratigrafi i Vejle Amt. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2001/104, 37 pp.

Friis, H., Mikkelsen, J. & Sandersen, P. 1998: Depositional environment of the Vejle Fjord Formation of the Upper Oligocene – Lower Miocene of Denmark: a back island/barrier-protected depositional complex. Sedimentary Geology 17, 221–244.

Gregersen, U., Sørensen, J.C. & Michelsen, O. 1998: Details of Pliocene sequences resolved on a 3-D data set, central North Sea. In: Gradstein, F.M. *et al.* (eds): Sequence stratigraphy: concepts and applications. Norwegian Petroleum Society Special Publication 8, 403–412.

Hansen, J.Ø. 1985: En lithofaciesundersøgelse af nogle kvarts-

sandsforekomster i Midtjylland. 126 pp. Unpublished cand. scient. thesis, University of Aarhus, Denmark.
Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., de Graciansky, P. & Vail, P.R., 1998: Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: P.-C. de Graciansky *et al.* (eds): Mesozoic and Cenozoic sequence stratigraphy of European basins. Society of Economic Mineralogists and Paleontologists Special Publication 60, Chart 3.
Heilmann-Clausen, C. 1995: Linde-1 borehole: Paleogene dinocysts, palynofacies and stratigraphy. EFP-92 Project: Basin development of the Tertiary of the Central Trough with emphasis on possible hydrocarbon reservoirs. Report 18, 23 pp. Geological Survey of Denmark, Copenhagen.
Heilmann-Clausen, C., Nielsen, O.B. & Gersner, F. 1985: Lithostratigraphy and depositional environments in the upper Palaeocene and Eocene of Denmark. Bulletin of the Geological Society of Denmark 33, 287–323.
Hunt, D. & Tucker, M.E. 1992: Stranded parasequences and the forced regressive wedge systems tract: deposition during base level fall. Sedimentary Geology 81, 1–9.
Huuse, M. & Clausen, O.R. 2001: Morphology and origin of major Cenozoic sequence boundaries in the eastern North Sea Basin: top Eocene, near top Oligocene and the mid–Miocene unconformity. Basin Research 13, 17–41.
Japsen, P. & Bidstrup, T. 2000: Quantification of late Cenozoic erosion in Denmark based on sonic data and basin modelling. Bulletin of the Geological Society of Denmark 46, 79–99.
Jesse, J. 1995: Arkitekturelementanalyse af aflejringer fra den mellem miocæne Odderup Formation. Geologisk Tidsskrift 2, 95.
Jordt, H., Faleide, J.I., Bjørlykke, K. & Ibrahim, T. 1995: Cenozoic sequence stratigraphy of the central and northern North Sea Basin: tectonic development, sediment distribution and provenance areas. Marine and Petroleum Geology 12, 845–879.
Knudsen, C. 1998: Heavy mineral exploration in Miocene sediments, Jylland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1998/45, 44 pp.
Koch, B.E. 1989: Geology of the Søby–Fasterholt area. Danmarks Geologiske Undersøgelse Serie A 22, 177 pp.
Kooi, H., Hettema, M. & Cloetingh, S. 1991: Lithospheric dynamics and rapid Pliocene– Quaternary subsidence phase of the Southern North Sea. Tectonophysics 192, 245–259.
Larsen, G. & Dinesen, A. 1959: Vejle Fjord Formation ved Brejning: Sedimenterne og foraminiferfaunaen (oligocæn–miocæn). Danmarks Geologiske Undersøgelse II Række 82, 114 pp.
Laursen, G. & Kristoffersen, F.N. 1999: Detailed foraminiferal biostratigraphy of Miocene formations in Denmark. Contributions to Tertiary and Quaternary Geology 36, 73–107.
Lidmar-Bergstrøm, K. 1996: Long-term morphotectonic evolution in Sweden. Geomorphology 16, 33–59.
Liboriussen, J., Aston, P. & Tygesen, T. 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21–29.
Lotsch, D.L. 1968: Tertiär (Paläogen und Neogen). Grundriss der Geologie der DDR, Band 1, Geologische Entwicklung des Gesamtgebietes, 356–379. Akademie-Verlag, Berlin.
Mai, D.B. 1967: Die Florenzonen, der Florenwechsel und die Vorstellung über den Klimaablauf im Jungtertiär der DDR. Abhandlungen des Zentralen Geologischen Instituts H 10, 55–81.
Miall, A.D. 1996: The geology of fluvial deposits; sedimentary facies, basin analysis, and petroleum geology, 582 pp. Springer Verlag, Berlin.
Michelsen, O. 1994: Stratigraphic correlation of the Danish onshore and offshore Tertiary successions based on sequence stratigraphy. Bulletin of the Geological Society of Denmark 41, 145–161.
Michelsen, O., Thomsen, E., Danielsen, M., Heilmann-Clausen, C., Jordt, H. & Laursen, G.V. 1998: Cenozoic sequence stratigraphy in the eastern North Sea. In de Graciansky P.C. *et al.* (eds): Mesozoic–Cenozoic sequence stratigraphy of western European basins. Society of Economic Paleontologists and Mineralogists Special Publication 60, 91–118.
Mikkelsen, J. 1983: En lithofaciesundersøgelse af ungtertiæret omkring Vejle Fjord, 100 pp. Unpublished Cand. Scient. thesis, Aarhus University, Aarhus, Denmark.
Milana, J.P. & Tietze, K.-W. 2002: Three-dimensional analogue modelling of an alluvial basin margin affected by hydrological cycles: processes and resulting depositional sequences. Basin Research 14, 237–264.
Miller; K.G., Wright; J.D. & Fairbanks, R.G. 1991: Unlocking the icehouse: Oligocene–Miocene oxygen isotopes, eustacy, and margin erosion. Journal of Geophysical Research 96, 6829–6848.
Mogensen, T. & Jensen, L.N. 1994: Cretaceous subsidence and inversion along the Tornquist Zone from Kattegat to the Egernsund Basin. First Break 12, 211–222.
Noe-Nygaard, N. & Surlyk, F. 1988: Washover fan and brackish bay sedimentation in the Berriasian–Valanginian of Bornholm, Denmark. Sedimentology 35, 197–217.
Piasecki, S. 1980: Dinoflagellate cyst stratigraphy of the Miocene Hodde and Gram Formations, Denmark. Bulletin of the Geological Society of Denmark 29, 53–76.
Plint, A.G., McCarthy, P.J. & Faccini, U.F. 2001: Nonmarine sequence stratigraphy: updip expression of sequence boundaries and systems tracts in a high-resolution framework, Cenomanian Dunvegan Formation, Alberta foreland basin, Canada. Bulletin of the American Association of Petroleum Geologist 85, 1967–2001.
Postma, D. 1982: Pyrite and siderite formation in brackish and freshwater swamp sediments. American Journal of Science 282, 1151–1183.
Prentice, M.L. & Matthews, R.K. 1988: Cenozoic ice-volume history: development of a composite oxygen isotope record. Geology 16, 963–966.
Proust, J.-N., Mahieux, G. & Tessier, B. 2002: Field and seismic images of sharp-based shoreface deposits: implications for sequence stratigraphic analysis. Journal of Sedimentary Research 17, 944–957.
Radwanski, A., Friis, H. & Larsen, G. 1975: The Miocene Hagenør-Børup sequence at Lillebælt (Denmark): its biogenic structures and depositional environment. Bulletin of the Geological Society of Denmark 24, 229–260.
Rasmussen, E.S. 1987: En mineralogisk og geokemisk undersøgelse at Vejle Fjord Formationen (Ø. Oligocæn – N. Miocæn), 230 pp. Unpublished cand. scient. thesis, University of Aarhus, Denmark.
Rasmussen, E.S. 1995: Vejle Fjord Formation: clay mineralogy and geochemistry. Bulletin of the Geological Society of Denmark 42, 57–67.
Rasmussen, E.S. 1996: Sequence stratigraphic subdivision of

the Oligocene and Miocene succession in South Jylland. Bulletin of the Geological Society of Denmark 43, 143–155.
Rasmussen, E.S. 1998: Detached lowstand deposits illustrated through seismic data, lithology and clay mineralogy: an example from the Lower Miocene of Denmark. In Gradstein, F.M. *et al.* (eds): Sequence stratigraphy – concepts and applications. Proceedings of the Norwegian Petroleum Society Conference, 6–8 September 1995, Stavanger, Norway. Norwegian Petroleum Society Special Publication 8, 413–421.
Rasmussen, E.S. 2004: The interplay between true eustatic sea-level changes, tectonics, and climatic changes: what is the dominating factor in sequence formation of the Upper Oligocene – Miocene succession in the eastern North Sea basin, Denmark. Global and Planetary Changes 41, 15–30.
Rasmussen, E.S. & Dybkjær, K. 1999: Excursion: Upper Oligocene – Lower Miocene storm and tidal dominated deposits at Lillebælt and Vejle Fjord. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1999/52, 76 pp.
Rasmussen, E.S. & Larsen, O.H. 1989: Mineralogi og geokemi af det Øvre Miocæne Gram ler. Danmarks Geologiske Undersøgelse Serie D 7, 81 pp.
Rasmussen, E.S., Dybkjær, K. & Piasecki, S. 2002: Miocene depositional systems of the eastern North Sea Basin, Denmark. Danmarks og Grønlands Geologiske Undersøgelse Report 2002/89, 132 pp.
Rasmussen, L.B. 1961: De Miocæne Formationer i Danmark. Danmarks Geologisk Undersøgelse IV Række 4 (5), 35 pp.
Rasmussen, L.B. 1966: Molluscan faunas and biostratigraphy of the marine Younger Miocene Formations in Denmark. Danmarks Geologiske Undersøgelse II, Række 88. 358 pp.
Ribeiro, A., Kullberg, M.C., Kullberg, J.C., Manuppella, G. & Pripps, S. 1990: A review of Alpine tectonics in Portugal: foreland detachment and cover rocks. Tectonophysics 184, 357–366.
Roberts, D.G. Thomson, M. Mitchener, B., Hossack, J., Carmichael, S. & Bjørnseth, H.M. 1999: Palaeozoic to Tertiary rift and basin dynamics: mid-Norway to the Bay of Biscay – a new context for hydrocarbon prospectivity in the deep water frontier. In: Fleet A.J. & Boldy, S.A.R. (eds): Petroleum geology of Northwest Europe: Proceedings of the 5th Conference, 7–40. Geological Society, London.
Sorgenfrei, T. 1940: Marint Nedre Miocæn i Klintinghoved paa Als. Danmarks Geologiske Undersøgelse II Række 65, 143 pp.
Sorgenfrei, T. 1958: Molluscan assemblages from the marine Middle Miocene of South Jylland and their environments. Danmarks Geologiske Undersøgelse II Række 79, 166–171.
Spjeldnæs, N. 1975: Palaeogeography and facies distribution in the Tertiary of Denmark and surrounding areas. Bulletin Norges Geologiske Undersøgelse 316, 289–311.
Vejbæk, O.V. 1997: Dybe strukturer i danske sedimentære bassiner. Geologisk Tidsskrift 4, 1–21.
Zachos, J.C., Pagani, M., Sloan, L.C., Thomas, E. & Billups, K. 2001: Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.
Zevenboom, D., Brinkhuis, H. & Visscher, H. 1994: Dinoflagellate cyst palaeoenvironmental analysis of the Oligocene/Miocene transition in northwest and central Italy. Giornale di Geologia 56, 155–169.
Ziegler, P.A. 1990: Geological atlas of Western and Central Europe, 2nd edition, 239 pp. Geological Society, London.