DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2002/89

Miocene depositional systems of the eastern North Sea Basin, Denmark

Development of sedimentological and stratigraphical principals in modern sedimentology

Erik S. Rasmussen, Karen Dybkjær
and Stefan Piasecki

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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Contents

Foreword

The present report is a collection of papers prepared during the 2 years period with sponsor-ship to Erik Skovbjerg Rasmussen by the Carlsberg Foundation.

The aim of the project was partly to study the stratigraphical development of an intercontinental basin, exemplified by the eastern North Sea Basin and partly to establish a new lithostratigraphy for the Upper Oligocene – Miocene succession in Denmark.

The report consists of 5 papers that describe various aspects of the geological evolution of the eastern North Sea Basin: 1) The distribution and origin of uppermost Oligocene- Middle Miocene units in the eastern North Sea Basin by **Rasmussen, E.S. and Dybkjær, K**. This paper presents the first confident correlation of the Upper Oligocene – Lower Miocene Vejle Fjord Formation and Oligocene/Miocene sequences defined in the North Sea area. 2) Stratigraphy and depositional evolution of the uppermost Oligocene – Miocene succession in Denmark by **Rasmussen, E.S**. Here a detailed sequence stratigraphic subdivision of the Miocene succession is presented and the origin of the sequences is discussed. The study also includes a palaeogeographical reconstruction of the eastern North Sea Basin. 3) Sequence stratigraphy of the Upper Oligocene – Lower Miocene of eastern Jylland, Denmark: implications of structural relief and variable sediment supply for paralic sequence development by **Rasmussen, E.S. and Dybkjær, K**. This paper includes a very detailed sedimentological study of outcrops in east Jylland combined with a biostratigraphic study. The study demonstrates a strong interrelationship between topography on the Ringkøbing-Fyn High, sea-level variation and changes in sediment supply on the depositions of the Upper Oligocene – Lower Miocene sediments in east Jylland. 4) The interplay between true eustatic sea-level changes, tectonics, and climatical changes: what is the dominating factor in sequence formation of the Upper Oligocene – Miocene succession in the eastern North Seas Basin, Denmark? by **Rasmussen, E.S**. The emphesis of this paper is to unravel the controling factors; such as climate and tectonics, on the evolution of the North Sea Basin during the Miocene. 5) Upper Oligocene – Miocene marine siliciclastic deposits in East Jylland: An analogue for Jurassic oil fileds in the Central and Viking grabens by **Rasmussen, E.S., Dybkjær, K. and Piasecki, S**. The intent of this paper is to convert the scientific results obtained in this study to research for aquifers and oil exploration world-wide.

Copenhagen 2002-10-10

Erik Skovbjerg Rasmussen

The distribution and origin of uppermost Oligocene - Middle Miocene progradational units in the eastern North Sea Basin

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Abstract

New palynological datings combined with a sequence stratigraphic analysis permits for the first time a confident correlation of the uppermost Oligocene – Middle Miocene succession in the eastern North Sea Basin. The new stratigraphic framework has been applied on onshore and offshore borings and a geological reconstruction has been done. Four progradational units have been identified and the basinal distribution have been mapped. The source area for the succession was the Fenno-Scandian Shield and a huge amount of sediments were transported southward into the basin. The character of the sediments indicate a short transport route and an origin partly from freshly eroded basement and partly from reworking of older deposits. The depositional systems, e.g. braided rivers and spit complexes associated with elevated areas indicate that structural elements played an important role during deposition. Glacio-eustatic sea-level changes were an important factor in controlling the position of the shoreline at specific times.

Keywords: Cenozoic, Climate, Miocene, North Sea Basin, Tectonics

Introduction

During the last decade intensive mapping of the Cenozoic succession of the Danish North Sea has been done (e.g. Jordt et al. 1995; Michelsen et al. 1998; Clausen et al. 1999). This has resulted in the establisment of a stratigraphic model for the North Sea area. A correlation of the units from the North Sea area with lithostratigraphic units defined in onshore sections has been proposed by Michelsen (1994) and Michelsen et al. (1998). Recently published and ongoing studies of the uppermost Oligocene – Miocene succession in Central and southern Jylland has shown that the succession is much more complex and fragmentedly developed than indicated by the established lithostratigraphy (e.g. Dybkjær & Rasmussen 2000).

New biostratigraphic datings, based on dinoflagellate cysts, of outcrops and boreholes in Denmark (Dybkjær et al. 1999; Dybkjær & Rasmussen 2000) and of wells from the North Sea area permits a confident correlation of units and surfaces recognized in the uppermost Oligocene – Middle Miocene succession in the eastern North Sea Basin. In addition new studies of the depositional setting (Rasmussen & Dybkjær 1999) permit mapping of the maximum progradation of units within this time span and thus the changing outline of the palaeoshoreline.

This paper presents regional correlations and datings of a number of units and surfaces throughout the uppermost Oligocene – Middle Miocene succession and the maximum progradation of the palaeoshoreline and shelfbreak at specific times.

Geological setting

The Cenozoic eastern North Sea Basin formed the eastern corner of a large epicontinental basin. The basin was flanked by the Fenno-Scandian Shield to the northeast, the Bohemian Massif/Polish Platform to the southeast, and the British Isle to the west (Ziegler 1990). Huge amounts of siliciclastic sediments were supplied to the basin from the adjacent areas and for the eastern North Sea Basin especially during the Oligocene – Miocene times. The depositional setting was partly controlled by tectonic pulses which influenced the hinterland and structural elements within the basin, e.g. salt structures and the Ringkøbing – Fyn High and partly by glacio-eustatic sea-level changes (Rasmussen 1996; Clausen et al. 1999). Sediments were laid down in shelf, shallow marine and fluvial depositional environments. The shallow marine deposits were strongly controlled by storm and tidal processes with westerly dominated winds (Friis et al. 1998; Rasmussen & Dybkjær 1999). Fluvial deposition within braided river systems indicate some relief on land. The climate was dominantly humid and varied from subtropic to cold (Mai 1967, Koch 1989).

Material

This paper presents results from an ongoing multidisciplinary study of the Eastern North Sea at the Geological Survey of Denmark and Greenland. Data from onshore Jylland includes detailed sedimentological studies of outcrops in East- and Central Jylland, sedimentology and petrophysical logs (Gamma, Induction) from 5 new high-quality borings in Jylland, gammalogs from more the 20 water supply borings and a reinterpretation of 10 onshore deep wells.

The biostratigraphic data are based on detailed studies of the dinoflagellate cyst assemblages from outcrop sections and wells in East- and Central Jylland, presented in Dybkjær et al. (1999) and Dybkjær & Rasmussen (2000), and new data from a number of wells onshore and offshore Jylland. Borings and seismic data referred to in the text are shown in (Fig. 1).

Methods

Four progradational units, hereafter named as Unit 1-4, have been identified and mapped based on outcrops, gammalog patterns and seismic data. The stratigraphic architecture of the succession is illustrated by a correlation panel of borings and outcrops in Jylland (Fig. 2) and a seismic line from the North Sea (Fig. 3). The boundaries of the units are indicated on the diagrams.

The regional correlation and dating of the units are based on a number of selected bioevents, last occurrences of dinoflagellate cyst species. A number of events (last occurrences datums, LOD's) turned out to be especially usefull for correlating between the onshore borings and the offshore wells and for dating the maximal progradation of each unit; 1) LOD *Wetzeliella gochtii*, 2) LOD *Deflandrea phosphoritica*, 3) LOD *Chiropteridium galea*, 4) LOD *Caligodinium aceras* (synonym to *C. amiculum*) 5) LOD *Thalassiphora pelagica* and 6) LOD *Cousteaudinium aubryae*. The first appearance datums (FAD's) of *Hystrichosphaeropsis obscura* and *Cousteaudinium aubryae* were used for supporting the datings of the units from the onshore borings and outcrops. These could not be recognized from the offshore wells, as only cuttings samples were available. The chronostratigraphic location and dating of the bioevents, according to Williams et al. (1998), is shown in figure 4. The chronostratigraphic location and the exact age of these events in NW Europe is currently not very well known, as indicated on the scheme by Williams et al. (1998). In spite of the very sporadic published informations from NW Europe we have chosen here to use the chronostratigraphy and the datings of the used bioevents as indicated in the column for the Mediterranean and North Atlantic area. The ongoing studies from NW Europe may result in changes. The LOD of *T. pelagica* is not included in the Williams et al. (1998) scheme, but according to Coccioni et al. (1997) this event is located in the middle part of the Burdigalian in the Santa Croce di Arcevia (Umbria-Marche Basin, Central Italy).

Stacking pattern

The onshore succession (Unit 1) shows a latest Oligocene outbuilding into the basin from the north (figs. 2; 3). The wedging out of Unit 1 towards the south corresponds to the transition from upper shoreface deposits to lower shoreface and offshore sediments near the Lille Bælt area (Fig. 2) (e.g. Rasmussen & Dybkjær 1999).

Following this section, a distinct displacement of the shoreline occurs (figs. 2; 3). A major progradational unit (Unit 2) in South Jylland is associated with a marked unconformity in central Jylland (Rasmussen 1998; Dybkjær & Rasmussen 2000). On seismic lines from South Jylland this can be seen as prograding clinoforms that terminates in the southwestern most part of Jylland (Rasmussen 1998). Borings penetrating this section (e.g. Løgumkloster-1) indicate a fluvial – deltaic depositional environment. Above this a regional withdrawal of the shoreline occurred. This is indicated by fully marine deposits above the fluvial-deltaic deposits of the Ribe Formation as indicated by the palynomorph assemblage in the Gram borehole (Dybkjær et al. 1999).

A new progradational unit, Unit 3, follows above the marine deposits. The unit is characterised by a total dominance of terrestrially derived palynomorphs, as seen in the Gram borehole (Dybkjær et al. 1999). The maximum seaward displacement of the shoreline of Unit 3 can be mapped to a location south of Gram. Pinching out of fine-grained sand occurs towards the Arnum boring where no sand has been encountered (Fig. 2). Resumed fully marine conditions were established above Unit 3 as indicated by the distinct change in the palynomorph assemblage (Dybkjær et al. 1999).

This is followed by another progadational unit, Unit 4. Similarly to Unit 3, this unit is dominated by terrestrially derived palynomorphs and fluvial sediments have been described in nearby borings (Dinesen 1976). The southernmost displacement of the shoreline associated with this unit is also south of the Gram area (Fig. 2).

Upon this, the major Middle Miocene transgression followed and fully marine conditions dominated during Middle and Late Miocene times.

The uppermost Oligocene – Middle Miocene succession in the North Sea shows a similar development as the onshore section (Fig. 3). It is characterised by a series of three aggradational/progradational units (Unit 1, 3, and 4). Unit 2 is different in being isolated off the offlap break zone of the older Oligocene succession. Regional mapping shows that this unit is characterised by both down lap and onlap on the underlying succession. The units successively infill the basin and the clinoformal break points are continuously displaced towards the south. The units from the North Sea consists of clayey to silty sediments with shells and the palynological study indicate fully marine depositional conditions. In the R-1 well a sand and gravel bed has been found at top of Unit 4.

The described section is succeeded by sediments deposited during the major Middle Miocene transgression similarly to the onshore section. This transgression can be recognized in the whole North Sea region (e.g. Michelsen et al. 1998).

Distribution

The mapped units demonstrate a general infill of the North Sea from the north and northeast towards the south and southwest. The maximum progradation of each unit is shown in (Fig. 5). In this figure both the position of the shoreline and shelf break is indicated. It must be stressed that periodic displacement of the shoreline to the shelf break may have occurred during lowstand, but better data are needed to confirm this. For instance, the position of the shoreline of unit 4 is well documented to have been located just southwest of Gram, but the shelf break is located ca. 50 km further towards the southwest.

The maximum progradation of Unit 1 is shown in (Fig. 5a) and the shoreline was trending SE-NW in the study area. The shoreline of this unit can be recognised from outcrops in East Jylland and in borings across Central Jylland and in the Inez-1 well in the North Sea.

The trend of the maximum progradation of Unit 2 is also SE-NW along the whole study area, but with a distinct lobe located in the southern part of Jylland Fig. 5b). The shoreline of this unit can be mapped in South- and West Jylland. The offshore extension can be followed on seismic lines close to the Danish west-coast and the extension further offshore is possible to map on seismic lines.

The outline of the maximum progradation of Unit 3 is very similar to the underlying units, but this unit is displaced a little more to the south (Fig. 5c). The shoreline of this unit can be found in onshore borings and lower to upper shoreface deposits have been found in the R-1 well. Similarly the trend of Unit 4 is like unit 1 and 3, but the maximum displacement is a little bit further to the southwest (Fig. 5d). The location of the shoreline is known from outcrops, onshore borings and the offshore well R-1.

Origin

Source area

Seismic studies (Jordt et al. 1995; Michelsen et al. 1998) and also sedimentological investigations (Larsen & Dinesen 1959; Rasmussen 1996; 1998; Rasmussen & Dybkjær 1999) clearly demonstrates that the source area for the uppermost Oligocene – Middle Miocene deposits was the Fenno-Scandian Shield and the transport direction was from the north and northeast towards the south and southwest. The results of the present study support this.

The sediments are petrographically very immature and in fluvial deposits the grains are often very angular (Larsen & Dinesen 1959; Radwanski et al. 1975; Rasmussen 1995). This indicates that fresh basement have been exposed within the hinterland and that the sediments have been transported relatively fast to the area of deposition without being involved in several sedimetological cycles or heavy weathering.

Depositional environments

Sedimentological studies, during the last 50 years, provides a detailed knowledge about the petrology and depositional systems of these deposits (Larsen & Dinesen 1959; Radwanski et al. 1975; Hansen 1985; Rasmussen 1995; Friis et al. 1998, Rasmussen & Dybkjær 1999).

Shallow marine sediments deposits of the Oligocene Vejle Fjord Formation and Lower Miocene Arnum Formation are exposed in East Jylland. These sediments were deposited in spit and barrier systems with lagoonal clay laid down north of the systems and shoreface deposits south of the systems. Southeast-wards accretion of spit systems and similar measured directions on anisotropic hummocky cross-stratified beds indicate strong sediment transport along the coast towards the southeast. The marine depositional environment was strongly influenced by storm and tidal processes (Friis et al. 1998; Rasmussen & Dybkjær 1999).

Fluvial deposits of the Lower to Middle Miocene Odderup Formation are exposed in sand pits in Central Jylland and is interpreted to have been deposited mainly in braided river systems (Hansen 1985).

Tectonic influence

The interpretations of the fluvial systems in Central Jylland as being deposited by braided river systems (Hansen 1985) strongly indicate that a topographic relief existed in the paleolandarea, e.g. as anticlines or domes formed above salt structures or depressions associated with fault movements (Miall 1996). Such a relief within the basin and hinterland may have been formed during various tectonic pulses in the early part of the Cenozoic (Clausen et al. 1999). The "Lavische" phase in the mid Oligocene could have caused elevation of the flanks of the North Sea basin and consequenctly have resulted in a high sediment supply into the Basin in the late Oligocene, but it is difficult to imagine that such features should influence the depositional setting more than 15 m.y. after its formation. There are also evidences in the studied succession of tectonic pulses periodically in the latest Oligocene – Early Miocene period. For example, at a certain level within the uppermost Oligocene – lowermost Miocene Vejle Fjord Formation (Unit 1) slumping has been recognized (Mikkelsen 1983). These slumped sediments could be related with earth quake activities. In the offshore well Frida-1 reworked Jurassic spores and pollen have been recognised from the Early Miocene.

There is also evidences for tectonic movements later in the Early Miocene. The strong coincidence of Lower Miocene brown coal deposits and former structural grabens in Central Jylland indicate reactivity along the older graben faults. A late Early Miocene tectonic pulse correlates to the Betic tectonic phase of the Alpine orogeny.

From the above, there seems to be at least three tectonic pulses during the latest Oligocene – Early Miocene: 1) the "Lavische Phase" in mid Oligocene, 2) at the transition from the Oligocene – Miocene, and 3) in the late Early Miocene. These tectonic movements strongly influenced the development of the succession and the pulses correlate to the Alpine Orogeny (Ziegler 1990).

Climatic influence

A climatic influence on the evolution of the Oligocene – Miocene succession in South Jylland was suggested by Rasmussen (1994; 1996). Various studies of climatical changes during the uppermost Oligocene – Miocene times shows changing climates during the period (Prentice & Matthews 1988; Mai 1967; Zevenboom et al. 1994). The relationship between climatic forced sea-level changes and the development of the Miocene succession is shown in (Fig. 4). However, a few comments on the most distinct sea-level changes will be made here: The most marked sea-level fall as indicated from oxygene isotope curves of Prentice & Matthews (1988) occurred in the Aquitanian. This sea-level drop correlates to a cold period in Central Europe (Mai 1967) and new studies of climatic changes in the Mediterian area also indicate a cold period in the Aquitanian (Zevenboom et al. 1994). Therefore, the outbuiling of Unit 2 was related to a period with glacio-eustatic controlled fall and lowstand of sea level in the Aquitanian.

The marked change in deposition within the Middle Miocene (Langhian) where a cessation of progradational units occurred clearly correlates to a marked sea-level rise shown on the curve of Prentice & Matthews (1988) (Fig. 4).

Conclusions

The uppermost Oligocene – Middle Miocene succession has been subdivided into four progradational units. The succession shows a progressive infill of the eastern North Sea Basin from north to south.

The source area for the sediments within the succession was the Fenno-Scandian Shield.

The sediment is immature indicating erosion of basement in the hinterland.

Structural movements must have occurred during deposition because fluvial deposits were laid down in braided river systems, spit complexes were associated with structural highs and thick coal deposits are located above older Mesozoic grabens indicating rejuvenation of the graben faults.

The migration of the shoreline during deposition was mainly controlled by glacio-eustatic sea-level changes.

Acknowledgement

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Figures

Figure 1. *Map of study area. Outcrops and borings referred to in the text, location of seismic section (Fig. 3) and of log panel (Fig. 2) are indicated.*

Figure 2. *Log correlation of outcrops and borings in Jylland. The location of biostratigraphic events are shown. The location of maximum progradation of the shoreline for each of the 4 units are indicated.*

Figure 3. *Seismic section from the North Sea. The biostratigraphic events occurring close to the seismic horizons are indicated. The location of maximum progradation of each unit is indicated on the section with an arrow. Seismic data courtesy Danpec and Fugro Geoteam.*

Figure 4. *Correlation between the maximum progradation of the mapped units and timing of eustatic sea-level changes and climatic changes on the continent. Datings of bioevents are from Williams et al. (1998). The dating of the bioevents marked by an asteriks is based on studies from low latitudes, western North Atlantic or the eastern USA.*

Figure 5. *Maps showing the distribution of the shoreline and shelf break during the uppermost Oligocene and Middle Miocene times.*

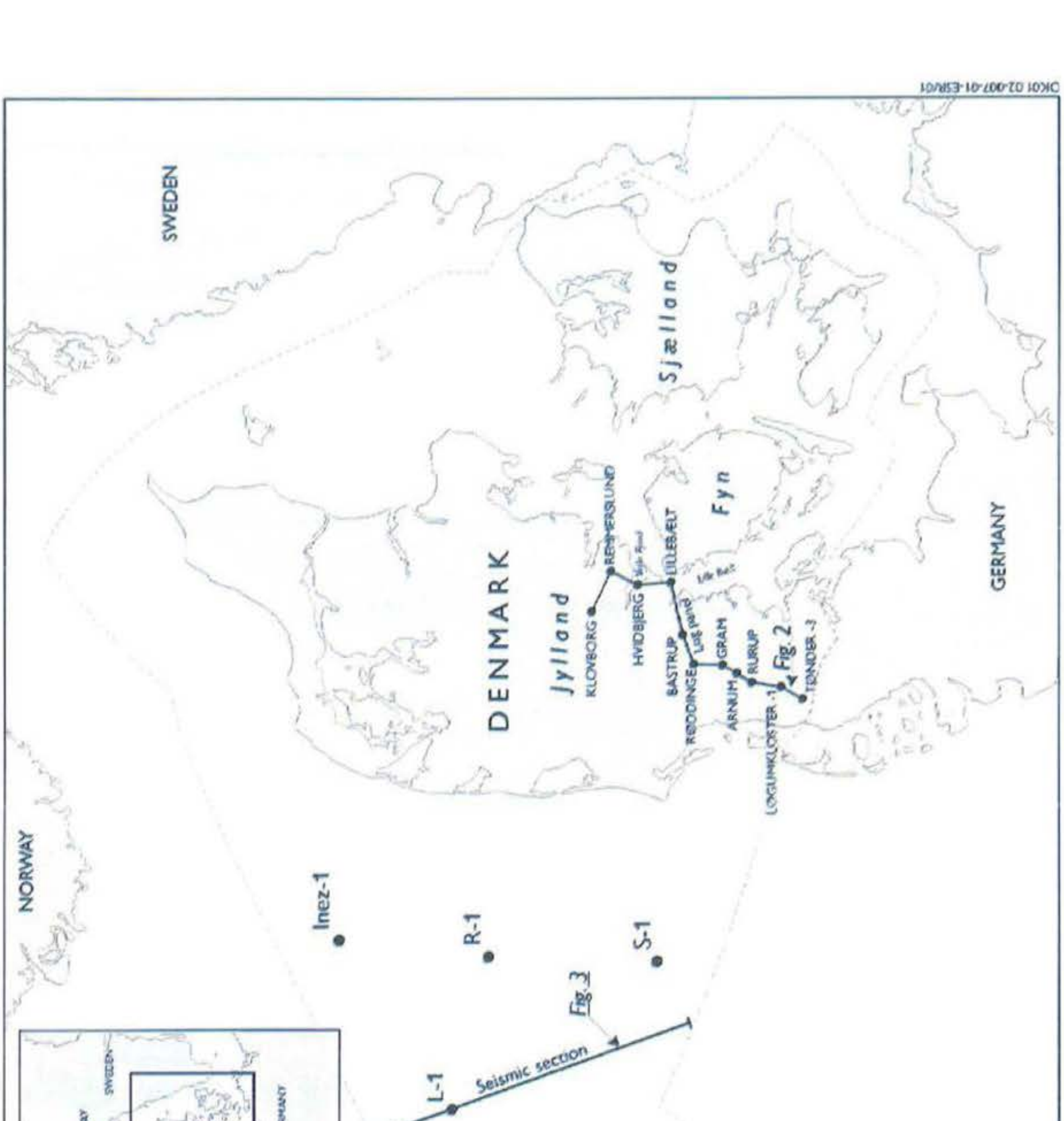

SWEDEN
NORWAY
DENMARK
Jylland
Sjælland
Fyn
GERMANY
KLOVBORG
HVIDBJERG
LILLEBÆLT
BASTRUP
RØDDING
GRAM
ARNUM
RURUP
LØGUMKLOSTER-1
TØNDER-3
Fig. 2
Inez-1
R-1
S-1
L-1
Frida-1
Seismic section
Fig. 3
0
100 km
200 Km
GREAT BRITAIN

Fig 1

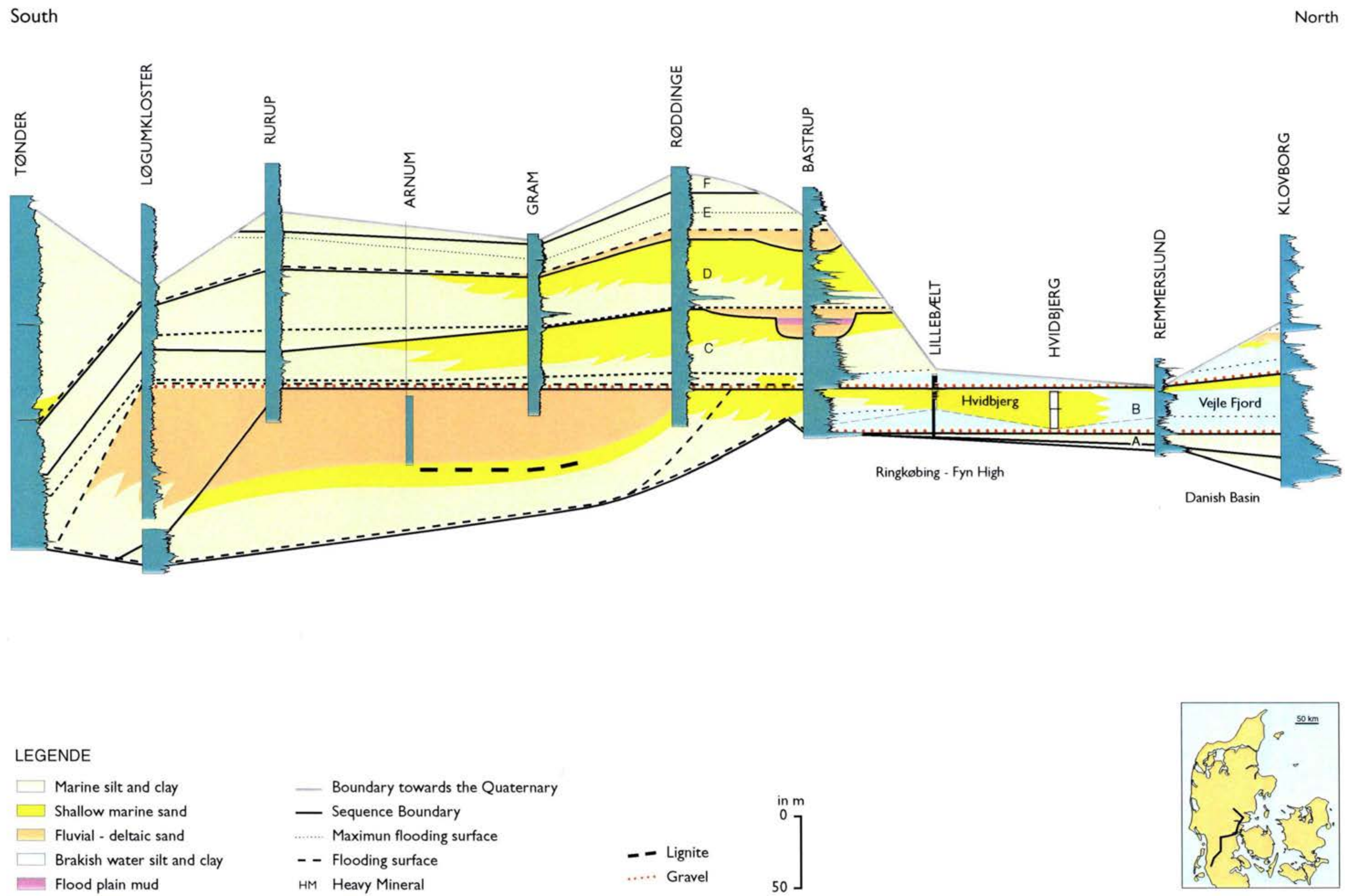


Fig 2

DKM02.014.023.02 ESR

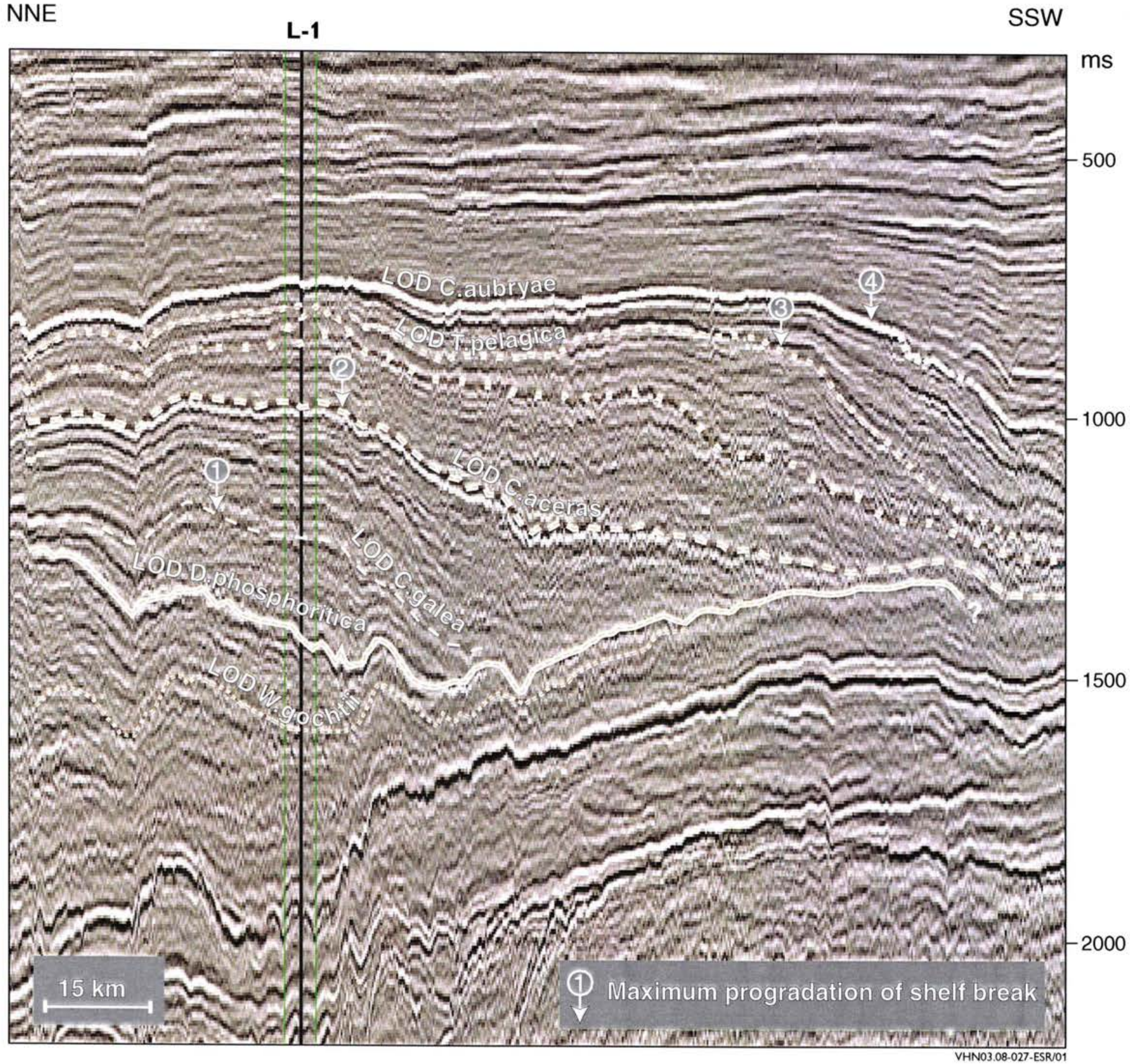
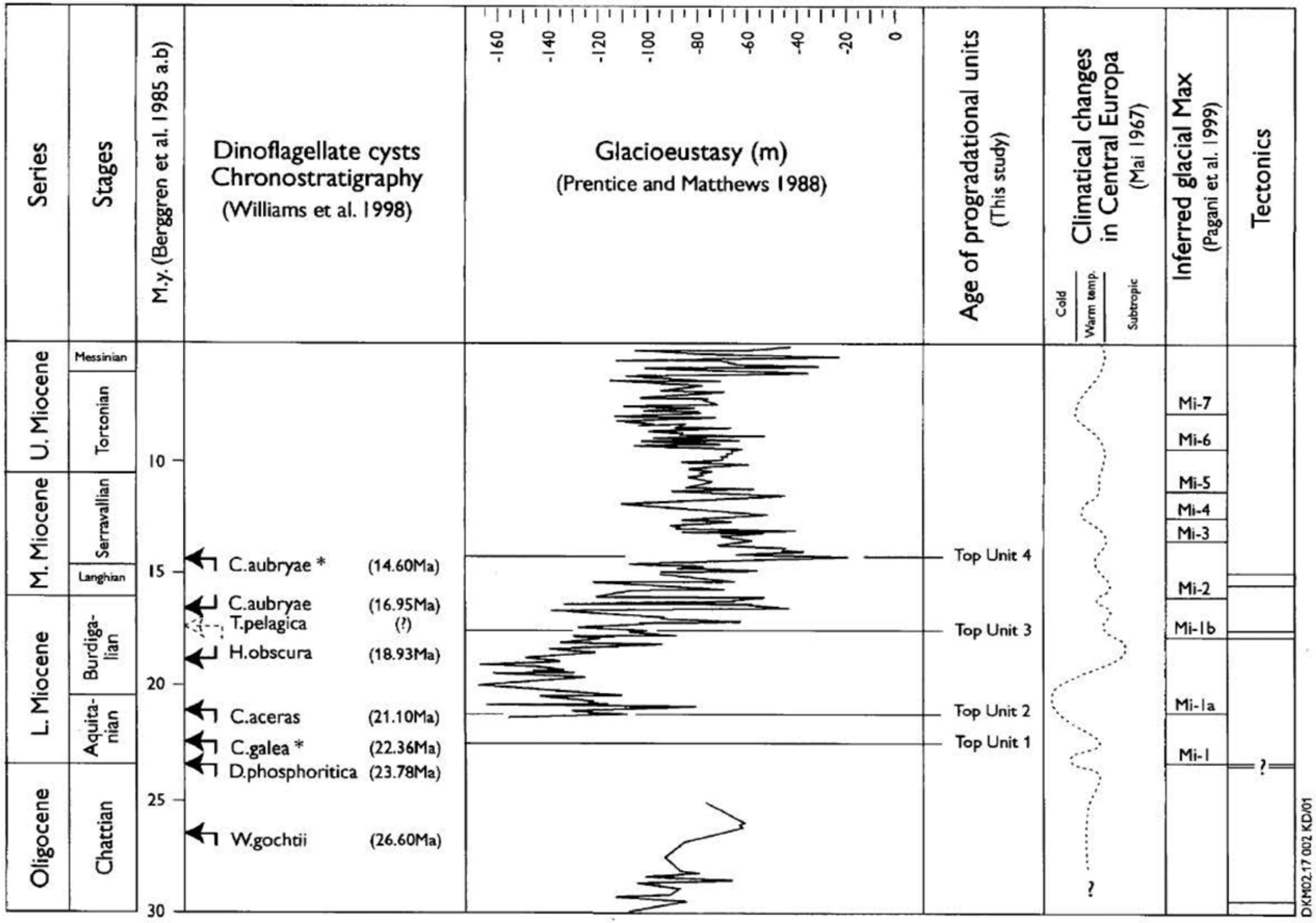

NNE
SSW
L-1
ms
500
1000
1500
2000
LOD C.aubryae
LOD T.pelagica
LOD C.aceras
LOD C.galea
LOD D.phosphoritica
LOD W.gochtii
15 km
Maximum progradation of shelf break
VHN03.08-027-ESR/01

Fig 3



Series
Stages
M.y. (Berggren et al. 1985 a.b)
Dinoflagellate cysts Chronostratigraphy
(Williams et al. 1998)
Glacioeustasy (m)
(Prentice and Matthews 1988)
-160
-140
-120
-100
-80
-60
-40
-20
0
Age of progradational units
(This study)
Climatical changes in Central Europa
(Mai 1967)
Cold
Warm temp.
Subtropic
Inferred glacial Max
(Pagani et al. 1999)
Tectonics
U. Miocene
M. Miocene
L. Miocene
Oligocene
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
10
15
20
25
30
C.aubryae * (14.60Ma)
C.aubryae (16.95Ma)
T.pelagica (?)
H.obscura (18.93Ma)
C.aceras (21.10Ma)
C.galea * (22.36Ma)
D.phosphoritica (23.78Ma)
W.gochtii (26.60Ma)
Top Unit 4
Top Unit 3
Top Unit 2
Top Unit 1
?
Mi-7
Mi-6
Mi-5
Mi-4
Mi-3
Mi-2
Mi-1b
Mi-1a
Mi-1
?
DKM02.17 002 KD/01

Fig 4

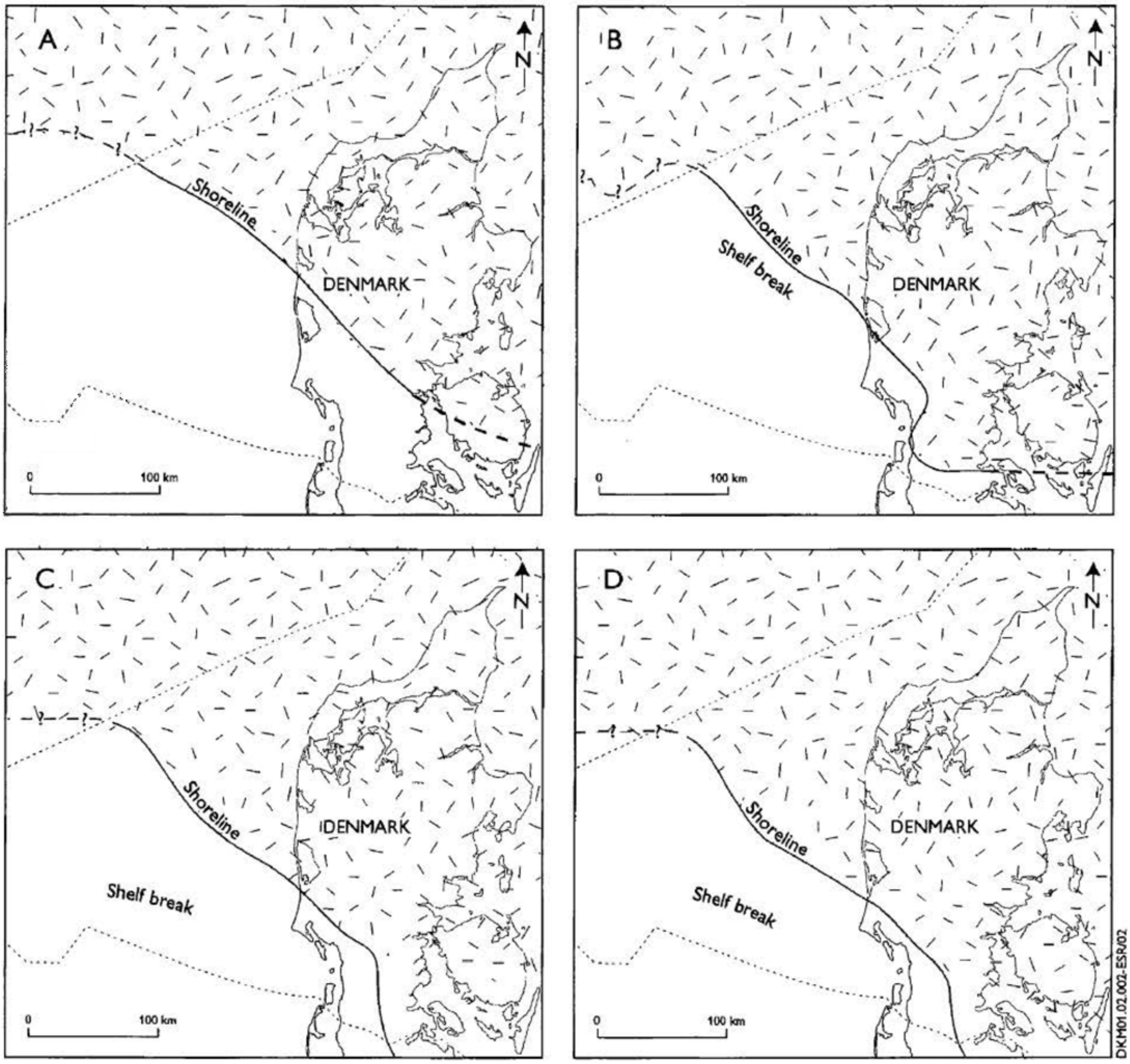

A
B
C
D
N
Shoreline
Shelf break
DENMARK
0
100 km
DKM01.02.002-ESR/02

Fig 5

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

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The uppermost Oligocene – Miocene succession in Denmark has been subdivided into 6 sequences; A to F. The development of the succession was controlled both by tectonic movements and eustatic sea-level changes. Tectonic movements resulted in the generation of a topography which influenced the depositional pattern especially during lowstand of sea-level. This is illustrated in sediment by-pass on elevated areas and that the fluvial systems were confined to structural lows. Structural highs further created restricted depositional environments behind the highs during lowstand of sea level. The structural highs were also the locus for concentration of sandy spit deposits during transgression and highstand of sea level. Sediment supply was initially from the north and northeast but shifted within the Middle Miocene to a more easterly direction indicating a significant basin reorganisation at this time. Eustatic sea-level changes mainly controlled the timing of sequence boundaries and the overall architecture of the sequences. Consequently the deposition of the most coarse-grained sediments were deposited within the forced regressive wedge systems tract, lowstand systems tract and early transgressive systems tract. Especially the most distinct progradation in the Aquitanian was associated with a cold period in Central Europe. The succeeding sea-level rise until the Serravallian is illustrated in an overall backstepping stacking pattern of the sequences and decreasing incision.

The new insight in the development of the uppermost Oligocene – Miocene succession, presented here, indicate that a new lithostratigraphy must be erected in order to make it applicable in a regional mapping of the succession.

Keywords: Miocene, North Sea, eustacy, tectonics, sequence stratigraphy.

The uppermost Oligocene – Miocene succession of Denmark was studied intensively in pits and borings during the last century (Sorgenfrei 1940; 1958; Larsen & Dinesen 1959; Rasmussen 1961, Christensen & Ulleberg 1974). These studies have resulted in the definition of a number of lithostratigraphic units. However, a compiled lithostratigraphic scheme including all these lithostratigraphic units have never been published. More simplified schemes, e.g. that of Rasmussen (1961), Buchard-Larsen & Heilmann-Clausen 1988, and Michelsen 1994, are normally used in various publications.

During the last 10 years the understanding of the geological evolution of the Eastern North Sea Basin has increased significantly due to a systematically study of seismic data and wells from the North Sea (e.g. Jordt, Faleide, Bjørlykke & Ibrahim 1995; Clausen, Gregersen, Michelsen & Sørensen 1999; Michelsen Thomsen, Danielsen, Heilmann-Clausen, Jordt & Laursen 1998). Attempts to correlate the depositional sequences within the North Sea has been done by Michelsen (1994) and Michelsen et al. (1998), but due to poor biostratigraphical resolution of outcrop sections (dissolution of foraminifera) only a tentative correlation has been possible. The finding of dinoflagelates, which appears at flooding surfaces throughout the uppermost Oligocene – Miocene succession at outcrops in Denmark (Dybkjær & Rasmussen 2000) has, however, resulted in a confidence and consistent correlation of the succession, both onshore and offshore. Therefore a number of stratigraphic borings and high resolution seismic data were acquisited in East and Central Jylland in order to make a new stratigraphic subdivision of the uppermost Oligocene - Miocene succession.

This paper concentrates on the results of this study in Jylland. The aim of the study is to establish a stratigraphic framework for genetically related packages and to make a new basis for lithostratigraphic subdivision of the succession. Finally, there will be a discussion on the processes involved in the deposition of the succession.

Geological setting

The configuration and development of the eastern North Sea Basin during the Cenozoic was a result of a complex interaction of former Mesozoic structural elements and subsidence due to thermal relaxation and interplate stress (Ziegler 1990; Kooi hettema & Cloetingh 1991). The deepest part of the basin was concentrated to the Central Graben area, while the northeastern border was strongly controlled by the Sorgenfrei-Tornquist Zone (Fig. 1). The Ringkøbing-Fyn High, which subdivide the Norwegian-Danish subbasin and the German Basin, formed an elevated element with pronounced halogentic movements both north and south of the structure. The Alpine Orogeny influenced the basin as well as the opening of the North Atlantic (Clausen, Nielsen, Huuse & Michelsen 2000). In the Paleocene inversion tectonics resulted in uplift along weakness zones within the Central Graben and along the Sorgenfrei – Tornquist Zone (Ziegler 1991; Liboriussen, Aston & Tygesen 1987; 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, from the Oligocene and Miocene, has been documented from a number of studies (Rasmussen 1996; 1998; Huuse & Clausen 2001).

The siliciclastic infill of the basin was initiated in the Late Paleocene (Heilmann-Clausen, Nielsen & Gersner 1985). In the Danish Basin the Paleocene deposits are dominated by clay, but within submarine valleys in the North Sea sand-rich gravity deposits were laid down (Danielsen, Clausen & Michelsen.1995). The deposition of dominantly fine-grained deposits continued throughout the Eocene, however, with some indication of major progradation from the Middle Eocene. Clear evidence for progradation of major systems and 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 Fenno-Scandia (present day Norway) and prograded southward. This pattern continued throughout the Oligocene and Lower Miocene (Clausen et al. 1999; Rasmussen & Dybkjær submitted). The southward prograding system, with a dominantly southeast – northwest trending shoreline can be followed onshore on seismic lines and tied to outcrop sections in East Jylland (Rasmussen & Dybkjær submitted). The studies onshore indicate that the depositional environment was related to spit systems and lagoons on and north of the Ringkøbing – Fyn High and more open marine conditions towards the south (Larsen & Dinesen 1959; Christensen and Ulleberg 1974; Rasmussen 1996; Friis, Mikkelsen & Sandersen. 1998). However, this general picture was punctuated by displacement of the shoreline during lowstand of sea level (Rasmussen 1996; 1998), especially in the Aquitanian (Dybkjær & Rasmussen 2000). In the mid Miocene a distinct change in sediment supply occurred (Clausen et al. 1999). From the mid Miocene the sediment influx was from the northeastern and eastern parts of the Fenno-Scandia Shield. This change may be related to the Betic tectonic event and consequently caused by regional tectonic re-organisation. The coincidence of this tectonic phase and a distinct eustatic sea-level rise in the Serravallian (Prentice & Matthews 1988), resulted in a major flooding and retreat of the shoreline. Consequently clay-rich deposits were laid down in the study area. Evidence of resumed nearshore deposits is first recognised in the Pliocene approximately 9 m.y. years later (Gregersen, Sørensen & Michelsen 1998).

Uppermost Oligocene – Miocene lithostratigraphy

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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 and Ulleberg 1974). Compilations of these lithostratigraphic units have been performed by Rasmussen (1961), Buchard-Larsen & Heilmann-Clausen (1988), and Michelsen (1994).

The uppermost Oligocene and ? Lower Miocene is commonly referred to as the Vejle Fjord Formation (Larsen & Dinesen 1959). This formation consists of marine deposits and is subdivided into three members: The Brejning Clay Member, the Vejle Fjord Clay Member and the Vejle Fjord Sand Member. In northern Jylland the Ulstrup and Sofienlund formations is defined by Christensen & Ulleberg (1974). These formations are most likely of similar age and therefore normally included in the Vejle Fjord Formation (Buchard-Larsen & Heilmann-Clausen 1988). The Lower Miocene consists of the marine Klintinghoved and Arnum formations, and the fluvial/limnic Ribe and Odderup formations (Fig. 2). Middle and Upper Miocene is represented by fully marine deposits of the Hodde and Gram formations (Rasmussen 1961).

Data

The study is based on seismic data, gamma logs, samples from new stratigraphic borings and washed samples from older borings, 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 borings: 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), Grindsted-1, Grinsted (DGU-122.1342), Remmerslund (DGU. 116-1549), Vorslund (DGU-104-2325), Klovborg (DGU-106-1373), and Addit (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), Vorslund (DGU-104-2325), Klovborg (DGU-106-1373), and Addit (DGU-98-928). In addition to this, outcrops in East Jylland, at Isenvad and Søndbjerg (Rasmussen & Dybkjær 1999) and shallow borings at Vorslunde and Skjern (Knudsen 1998) is included in the study.

Major architectural elements of the succession as indicated from the seismic data

Seismic data provide a tool for the reconstruction of major architectural elements of sedimentary successions. Therefore seismic data is important when establishing the overall stratigraphic framework. A serie of three seismic sections from Jylland and the adjacent offshore area is used here to illustrate the major architectural elements of the uppermost Oligocene – Miocene succession (Fig. 4).

On the seismic sections in (Fig. 4) distinct seismic markers are indicate. The base Oligocene marker is a regional unconformity showing truncation of the underlying succession. From onshore studies in southern Jylland this unconformity separates the uppermost Oligocene glaucony-rich Brejning Clay from Middle Eocene Søvind Marl (Rasmussen 1996). In Central and North Jylland the Brejning Clay is unconformaly overlying the Upper Oligocene Branden Clay (Heilmann-Clausen et al. 1985; Dybkjær, Piasecki & Rasmussen 1999). In the northern part, where uppermost Oligocene deposits are present, the surface correspond to top of the dinoflagellate *W. Gochtii* (pers. Comm. Karen Dybkjær 2001). Above the base Oligocene Marker clinoforms show a successive outbuilding from northeast to southwest as illustrated by the Intra Aquitanian Marker (Fig. 4). A correlation of the clinoformal break point of the Intra Aquitanian Marker indicate a NW-SE trend of the shoreline during the Aquitanian (Lower Miocene). At Vandel massive deltaic sand has been found in two borings penetrading the succession represented the Aquitanian Marker. This delta sand can be correlated with spite system outcropping in East Jylland referred to as the Vejle Fjord Formation (Larsen & Dinesen 1959; Dybkjær & Rasmussen 2000). The Intra Burdigalien Marker (Fig. 4) which represent the base of the Arnum Formation (Laursen & Kristoffersen 1999) separates the succession characterised by a clinoformal reflection pattern from a parallel to transparent and sometimes chaotic reflection pattern above. The uppermost part of the seismic section is of very poor resolution, therefore this part cannot add much to the understanding of architectural elements of the succession.

Sequence stratigraphy

The uppermost Oligocene – Miocene succession has on the bases of seismic data, log correlation and lithology been subdivided into 6 sequences; A to F (Figs. 5, 6). The reference level for the log panels is the sequence boundary between sequence B and C. This level has been chosen because it represents the time were most structural elements were covered by sediments and therefore did not influenced overall architecture of the succession.

The overall lithology and sequence subdivision of six new stratigraphic borings in central Jylland is shown in (Fig. 7).

Sequence A

Description:

The lower boundary correspond to the base Oligocene Marker on the seismic lines and forms a regional unconformity (Figs. 5, 6). This boundary is lithologically sharp and separates green glaucony-rich clay above from greenish-grey marl below (on and south of the Ringkøbing – Fyn High). 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 by a distinct peak representing the glaucony-rich deposits above marly sediments.

The lower part of the sequence is characterised by totally bioturbated greenish clay, with rip-up clast. There is an increase in the content of glaucony in the lowermost 1 m and shells (bivalves and snails) are common here. In the upper part of the section there is an increase of silt, fine-grained sand, and the content of organic matter is generally high here. The increasing sand content is reflected on the gamma log, as a general decrease in gamma-log response in the uppermost part of the unit. The section is thin to absent in the southern part of the area and increases in thickness towards the North (Fig. 5).

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

Interpretation:

The lower sequence boundary forms a major hiatus in the succession, especially in the southern part of Denmark. On the Ringkøbing – Fyn High and south of this high the boundary separates the Middle Eocene Søvind Marl and uppermost Oligocene Brejning Clay Member. North of the high it 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 high content and diversity of a marine fauna indicate fully marine conditions during the deposition of the succession.

The maximum flooding surface is placed were the highest amounts of glaucony is found (Amorosi 1995; 1997). This correspond to distinct peak on the gamma log.

Geochemical studies of the glaucony at this level also show a high postasium content of the glaucony which is characteristic for a maximum flooding surface (Rasmussen 1995; Amorosi 1995; 1997).

Above the maximum flooding surface an increase in siliciclastics and terrestrial organic matter reflect an initial progradation of a distant shoreline during highstand. The upper boundary is marked by a regional gravel layer, which is coincident with a change from a marine fauna to a fauna characteristic for a restricted environment (Larsen & Dinesen 1959; Rasmussen & Dybkjær 1999). This change from fully marine conditions towards a brackish water environment was probably a consequence of a sea level drop in the latest Oligocene which resulted in partly disconnection from marine conditions northeast of the Ringkøbing – Fyn High. Thus the barrier was topographic controlled.

Sequence B

Description:

The lower boundary towards sequence A corresponds to the base of the gravel layer described above.

The log pattern of the sequence is characterised by high gamma readings in the lower part, which upward show a general decrease in gamma log response (Figs. 5, 6). Lithologically a high lateral variation has been recognised within the sequence. In the northern part fine-grained, organic-rich sediments dominate the whole succession, e.g. at Klovborg and Remmerslund (Fig. 6). At Hvidbjerg and Lillebælt sandy deposits are common. In the southern part clayey-silty deposits dominate again in the lower part of the sequence while the uppermost part is very sand rich. In the Arnum well ca. 40 m of clean sand has been penetrated (Fig. 5). On the gamma log, the uppermost part of the sequence shows very low readings and especially close to the upper boundary the values are extremely low. These low values correspond to sand-rich horizons.

The upper boundary is placed where a change in gamma readings from generally decreasing gamma log response to a often distinct increase occurs. In southern Jylland, however, a more gently changes in gamma log response is seen in the boreholes south of Bastrup. At Remmerslund and Lillebælt a gravel layer has been found at this level. On seismic lines the upper boundary shows offlap and a stepwise lowering of the offlap level (Fig. 4A). In the Tønder well (Fig. 5) the correlation is based on the seismic interpretation which indicate a pinch out of the succession towards the south (Fig. 8).

Interpretation:

The sequence boundary towards sequence A corresponds to a gravel layer in the northeastern part of the study area (Fig. 5, 6). At this boundary a change in depositional environment from fully marine to brackish water has been documented in a number of studies (e.g. Larsen & Dinesen 1959; Dybkjær et al. 1999; Dybkjær, Rasmussen & Piasecki 2001). In the log panel (Fig. 5, 6) the Ringkøbing – Fyn High is shown. This high probably acted as a barrier during low sea level and thus brackish water conditions were established northeast of the high similarly to the deposition of the Lower Cretaceous deposits on Bornholm

(Noe-Nygaard & Surlyk 1988). Sedimentological studies of the succession reveals that spit systems forms in association to structural highs as demonstrated at Hvidbjerg and Lillebælt (Rasmussen & Dybkjær 1999). Northeast of the spit systems, lagoons were formed during the successive transgression and progradation during highstand (Remmerslund and Klovborg). The maximum flooding surface is placed at a distinct gamma peak and high abundances of dinoflagellate cysts and diversity occur (Pers. Comm. Karen Dybkjær 2002). Above the maximum flooding surface normal progradation is seen in the northern part and consequently interpreted as highstand systems tract. The normal prograation is in the southern part overtaken by forced regression elucidated in the stepwise lowering of the offlap level on seismic panels (Fig. 4A) and in the section of extreme clean sand, e.g. at Arnum. During the time of forced regression the area on the Rinkøbing – Fyn High was subaerially exposed and a fluvial depositional environment dominated here (Rasmussen and Dybkjær 1999). The sequence boundary formed on top of sequence B correspond to the sequence boundary described in Rasmussen (1998) and the hiatus in East Jylland is in the order of 3.5 m.y. (Dybkjær & Rasmussen 2000).

Sequence C

Description:

The lower boundary is recognised on the gamma logs by a change from a general decreasing log trend towards an upward increasing log response.

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. 7). At Bastrup and Vorslunde very high gamma readings are recognised above the boundary. These high gamma readings correspond to organic-rich mud immediately above the sequence boundary at these locations. This is, however, relatively quickly overtaken by a general decrease in the gamma log response reflecting an increase in silt and sand content upwards (Figs. 5, 7). At Vorbasse and Egtved abrupt falls in the gamma log response are found. This change correspond to sharp based, clean sand layers deposited in a marine realm.

The upper boundary towards sequence D is placed where a turnover of gamma log readings from a general low gamma log response towards an overall increasing trend in most boreholes, but at Bastrup and Addit the boundary is placed where a marked decrease in gamma readings take place (Fig. 5). This dramatic change in gamma log response represents a change from marine to fluvial deposits (pers. Comm. Karen Dybkjær 2002) and thus represents a sequence boundary (e.g. Plint, McCarthy & Faccini 2001)

Interpretation:

The sequence boundary towards sequence B corresponds to the sequence boundary described in Rasmussen (1998). The boundary is in outcrops characterised by a gravel layer and is interpreted as a ravinement surface coalescing the sequence boundary (Rasmussen 1998; Rasmussen & Dybkjær 2000). The relatively thin interval characterised by a gradual increase in gamma log readings, most common 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. However, locally, at Rødding, Bastrup and Vorslunde, the distinct gamma readings represent sediments deposited in a restricted depositional environment (pers. Comm. Karen Dybkjær 2001). Therefore this part is also interpreted as part of the transgressive systems tract and represent barrier-lagoonal complexes. Above the maximum flooding surface the relatively thick interval, showing normal progradation, is interpretated as the highstand systems tract. The sharp based and clean sand layers at Egtved and Vorbasse boreholes is interpreted as sand deposited above a regressive surface of erosion and this part of the succession thus represent the forced regressive wedge systems tract (Hunt and Tucker 1993; Proust, Mahieux & Tessier 2002). The distinct boundary in the upper part at Bastrup and Addit is interpreted to be a result of fluvial incision during falling stage of sea level (e.g. Plint et al. 2001).

Sequence D

Description:

The boundary towards sequence C is placed as described above.

Except from very low gamma readings at Bastrup and Addit, the lower part of sequence D is characterised by extreme high gamma readings (Figs. 5, 7). Most of these gamma peaks correspond to a high concentration of heavy minerals and are thus facies dependent. Ignoring these high gamma peaks, a very thin interval with increasing gamma log response is seen in the lower part of the sequence. The increasing gammalog readings correspond to a higher mud content of this part of the succession. This is upward succeeded by an overall decreasing gamma log trend, which is correlated to increasing sand content in the succession (Fig. 7). South of Gram the sequence is dominated by mud.

The upper boundary of the sequence is again placed where lowest gamma readings are found. At Bastrup and Addit, however, the boundary is placed at a distinct decrease in gamma log response (Fig. 5). The low gamma readings here reflect an abrupt increase of sand (Fig. 7).

Interpretation:

The sequence boundary towards sequence C (at the lowest gamma readings) is lithologically very similar to the boundary between sequences B and C. In the Arnum-1 well the changes from an overall coarsening upward section to a general fining upward interval is characterised by 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. Lowstand/transgressive deposits are found at Bastrup and Addit, and fluvial deposits are exposed at the nearby sand pit at

Addit. Here the section is interpreted as fluvial deposits being deposited in a braided river system (Hansen 1985). The overall pattern in the sand pit is massive sand in the lower part which in the upper part is more fine-grained and finally top by a brown coal layer. This is a typical development for early transgressive deposits (e.g. Plint et al. 2001). The transgressive systems tract outside incised valleys, is very thin and the maximum flooding surface corresponds to the changes 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 indicate heavy minerals. From the exploitation of these heavy minerals (Knudsen 1998) it is found that heavy minerals are found in two facies associations: A lower shoreface association with fine-grained, immatured heavy minerals deposited in storm beds, and a beach association with matured, medium-grained heavy minerals deposited in the swash zone. These facies associations were laid down during normal progradation of a shoreface and thus the high gamma readings cannot be used in identifying the maximum flooding surface. The highstand systems tract is, as described above, characterised by normal progradation of a shoreline.

The location of the upper sequence boundary is based on the gamma logs at the turn around of gamma responds from decreasing towards increasing gamma readings. This boundary corresponds to a major transgression in the North Sea and correlates seismically to the Mid Miocene unconformity (Michelsen et al. 1998).

Sequence E

Description:

The lower boundary is placed as described above.

Sequence E is characterised by an overall increasing gamma log response, especially at Rurup (Fig 5). This increase in gamma log response correlates to an increase in mud. Above the general trend of increasing gamma log readings a relatively thin interval of decreasing gamma log represent the upper part of the sequence.

The boundary towards sequence F cannot be recognised on gamma logs. In borings at Gram a distinct changes in lithology from clayey glaucony-rich sediments to silty goethite-rich deposits characterised this boundary.

Interpretation:

The lower part of the sequence reflects a major transgression which culminated with the deposition of glaucony-rich sediments. Above these deposits a thin section dominated by more silty and goethite-rich sediments are found. These goethite-rich deposits indicate a period with shallower water (Dinesen 1976). Consequently, the top of the goethite horizon is interpreted as a sequence boundary, but it cannot be defined on either log or seismic criteria.

Sequence F

Description:

The lower boundary is described above.

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

The upper boundary is characterised by strong erosion and a distinct lithological change. The lithological change is characterised by a change from silty clay or fine sand, mica-rich sediments to chert-rich, often conglomeratic sediments.

Interpretation:

Sequence F was deposited in a marine environment (Rasmussen 1961; Rasmussen & Larsen 1989). The succession demonstrates an overall progradation of a shoreline. Initially, deposition occurred on ca. 50 m of water (Rasmussen 1966) and the sediments in the upper part at the type locality, at ca. 20 m of water (Rasmussen & Larsen 1989). The upper boundary forms the boundary between Cenozoic deposits and Quaternary deposits.

Palaeogeography

Based on the above interpretation of sequences a palaeogeographical reconstruction of the uppermost Oligocene – Miocene succession has been done.

During the late Chattian (latest Late Oligocene) the trend of the shoreline was WNW-ESE and located in the northern part of the study area (Fig. 9a). In figure 9a the maximal distribution of the sea is shown and corresponds to the maximum flooding during deposition of sequence A. The shoreline was characterised by barrier islands and associated lagoons which was 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 shells of foraminifera (Rasmussen 1996). A major displacement of the shoreline towards the SW occurred in latest Chattian and the shoreline migrated south of the Ringkøbing – Fyn High (Fig. 9b). The maximal progradation corresponds to the sequence boundary between sequence A and B. Intensive formation of the autigenic mineral; siderite and weathering of glaucony to goethite took place in this period of subaerial exposure similarly to the recent Skjern Å delta (Postma 1980). Fluvial systems were probably confined to the topographic low of the Brande Trough. South of the Ringkøbing – Fyn High fully marine conditions prevailed and nearshore marine sand was deposited along the high. During the subsequent sea-level rise in the early Aquitanian, the area north of the elevated part of the Ringkøbing - Fyn High formed a major silled basin predominated by brackish water (Fig. 9c). Parts of the nearshore sand deposited along the Ringkøbing – Fyn High was redeposited as tempesites similar to washoverfans of a barrier system and sandy storm deposits (hummocky cross-stratified sand beds). During the high-stand of sea-level (sequence B) normal progradation of the shoreline occurred (Fig. 9d). The shoreline was dominated by spit systems formed in association with structural highs (e.g. Noe-Nygaard & Surlyk 1988). During this period the main delta was located in central part of the study area partly controlled by the Brande Trough (Fig. 9d). Within the late Aquitanian major southwestwards displacement of the shoreline occurred and fluvi-nal/deltaic sediments were deposited (Fig. 9e). This progradation was associated with a major sea-level fall (Prentice & Mathews 1988) which resulted in deposition of forced re-gressive wedge systems tract of sequence B and lowstand systems tract of sequence C. Resumed transgression occurred in the mid-Burdigalian (Fig. 9f) and the shoreline was displaced towards the Northeast. This resulted in the deposition of the transgressive sys-tems tract of sequence C. The influence of the Ringkøbing – Fyn High is at a minimum at this time and brackish water conditions were only associated with back barrier environ-ments. The maximum distribution of the sea in the mid-Burdigalian is shown in figure (9g). New progradation of the shoreline took place in the late Burdigalian (Fig. 9h). The dis-placement, however, was not that far southwestwards as for the Aquitanian system and occurred without a major sea-level fall. Therefore, most progradation was during highstand of sea level. In this phase there is a tendency for a concentration of sands on topographic elements on the Ringkøbing – Fyn High. In the latest part of Burdigalian, the area was flooded again and fully marine conditions occurred in the southwestern part of the study area (Fig. 9i). At the boundary between Burdigalian and Langhian resumed progradation took place (Fig. 9j). This progradation was associated with widespread delta swamp de-posits, especially in connection with lows formed by active tectonic movements on the Ringkøbing – Fyn High (Koch 1989). Associated with this progradation the lower shoreface and beach sediments were enriched with heavy minerals. This also indicate tectonics and erosion of new rocks in the hinterland. The major sea-level rise in the early Langhian (Prentice & Matthew 1988), resulted in a distinct withdrawal of the shoreline in the late Langhian – Serravallian times (Fig. 9h). This major transgression contradicts an overall climatic cooling during the Serravallian and Tortonian (Prentice & Matthew 1988; Zachos 2001). Therefore the most likely explanation for this transgression is due to accelerated subsidence of the North Sea basin in Late Miocene time. Additionally the trend of the shoreline also changed to a dominantly NNW-SSE strike. This change in the orientation of the shoreline was possibly a result of tectonic movements on the Fenno – Scandian Shield. During the transgression strong rework of former coal-rich deposits resulted in very or-ganic-rich sediments which forms the lower part of the transgressive systems tract of se-quence E. During the Tortonian progradation of the shoreline towards the west occurred (Fig. 9l).

Lithostratigraphy

The lithostratigraphy presented here is based on the sequence stratigraphic interpretation of new stratigraphic borings, seismic data, out crops and pits in Jylland. The datings of the lithostratigraphic units indicated above are based on Piasecki (1982), Dybkjær et al. (1999; 2001) and Dybkjær & Rasmussen (2000) and correlated to the biostratigraphy of (Harden-bol, J., Thierry, J., Farley, M. B., Jacquin, T., de Graciansky, P. and Vail, P. R., 1998)(Fig. 10). The time scale is from Berggren, Kent & Van Couvering (1985a; 1985b)

The oldest unit in the lithostratigraphic scheme (Fig. 10) is of late Chattian in age (latest Oligocene) and belongs to the Brejning Clay Member of the Vejle Fjord Formation (Larsen & Dinesen 1959). The lowermost Miocene is subdivided into the Vejle Fjord Clay Member and the Vejle Fjord Sand Member and two new informal lithostratigraphic units: The Hvidbjerg sand and Billund sand. The Hvidbjerg sand is outcropping at a number of localities at Vejle Fjord, Lillebælt and at Søndbjerg on Thyholm, NW Jylland. It is dominated by fine- to medium-grained sand with some horizons dominated by coarse-grained sand and gravel. The sand is very well exposed at Hvidbjerg on the south side of the Vejle Fjord. The Billund sand has been penetrated in a number of boreholes in Central Jylland (Vorslunde, Vandel, Klovborg)(Fig. 5) and it is represented by a clinoformal seismic reflection pattern on a seismic line from the Billund area. The seismic data indicate a deltaic depositional system for the Billund sand. The age of the Vejle Fjord Clay and Sand and the Hvidbjerg and Billund sand is most likely earliest Aquitanian. The Hvidbjerg and Billund sand are followed by the sand- and gravel-rich Ribe Formation (Sorgenfrei 1958), which is of Aquitanian to early Burdigalian in age. In the southern part of Jylland the fine-grained, prodelta deposits of the Ribe Formation is defined as 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. This sand-rich section is here referred to the informal lithostratigraphic unit: Bastrup sand. The Arnum Formation and Bastrup sand are of Burdigalian in age (Piasecki 1982; Dybkjær et al. 1999). Above the Arnum Formation the sand- and lignite-rich Odderup Formation follows (Rasmussen 1961). This formation is referred to the uppermost Burdigalian – lowermost Langhian. The fine-grained lower shoreface deposites of the Odderup Formation, which is enriched in heavy minerals (Fig. 6) is suggested to be defined as the Stauning sand. The lignite-rich part of the Odderup Formation has earlier been referred to as the Fasteholt Member by Koch (1989) and this suggestion will be followed in the present lithostratigraphical scheme. The Odderup Formation is succeed by the clayey and organic-rich Hodde Formation (Rasmussen 1961) of Langhian – Serravalian in age (Piasecki 1980). Finally, the Miocene succession is completed by the Gram and Sæd formations of Tortonian and ? Messinian age. These two latter formations forms an overall coarsening upward section terminated by the sandy Sæd Formation.

Allochtoneous control on the development of the sequences

Climatical control

Several studies of the Cenozoic succession of the eastern North Sea Basin reveals a close relationship between the development of the succession 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 is compared with glacio-eustatic sea-level changes as indicated from oxygen isotope studies, and palaeoclimatical changes estimated from marine faunas and terrestrial floras. The sea-level curves are from Prentice &

Matthews (1988) and Zachos (2001). The palaeoclimate during the Oligocene – Miocene in Central Europe is from (Mai 1967). All these data are compiled in figure 11.

The general impression of the data is that serious climatical changes occurred throughout the uppermost Oligocene – Miocene time (Fig. 11). The correlation between the different curves is good and the period of changes varies between 2 m.y. and 4 m.y. In Central Europe, which partly corresponds to former East Germany (pits near Berlin) and thus a part of the East North Sea Basin, variation from a cold temperate climate to subtropical climate prevailed. This is in good agreement to the study by Buchart (1978) for the North Sea. It is likely that corresponding climatic zones prevailed in the study area.

The knowledge of the variation of sea level at the end of the Oligocene is only represented by the curve of Zachos (2001). The deposition of sequence A correlates the sea level rise within the Late Oligocene as indicated from the glacio-eustatic curve. This is followed by a sea-level fall which is related to the glacial maximum Mi 1(Fig. 11). The deposition of Sequence B fells in between the two glacial maximums of Mi 1 and MI1a corresponds to a period of higher sea level (Fig. 11). The most distinct cold period occurred in the Aquitanian – early Burdigalian time (Fig.11). This cold period corresponds to the development of sequence boundary between B and C, the most marked boundary found in this study and also in the studies of Rasmussen (1996; 1998; In prep.). Consequently, this cold period resulted in the evolution of well developed forced regressive wedge systems tract and lowstand systems tracts. The general sea-level rise during the Burdigalian is evidenced in an overall transgression illustrated in a general back stepping stacking pattern of sequences C and D and decreasing incision. The timing of the sequence boundary between sequence C and D seems to correlate the glacial maximum Mi 1b and a cooler period in the late Burdigalian. The development of Sequence D mainly occurred during high sea level, this may explain the extensive deposition of brown coal within this sequence. The marked glacio-eustatic sea-level rise in the early Langhian (Fig. 11) is in good agreement with the distinct change in the deposits from dominantly nearshore and terrestrial deposits to fully marine sedimentation, which dominate within Sequence E. However, neither the curve from the continental climate no the glacial maximums from the CO2 study indicate a warm period during the Serravallian. The timing of the sequence boundary between sequence E and F, however, correlates a cooler period in the Serravallian and Mi 4. A general fall in sea level and a more cooler climatic conditions in the Tortonian (Fig. 11) is reflected in the overall regression found in the succession and particularly demonstrated by the distinct progradation seen in Pliocene succession (Gregersen et al. 1998).

In conclusion the climatic influence on the development of the studied succession is obvious which of course most be expected in this part of the Cenozoic where polar glaciations were increasing (Miller 1987; Prentice & Matthews 1988; Abreu & Anderson 1998). However, the development of the succession, especially the progradation of Sequence D and the overall transgression reflected by the deposition of sequences E and F are not correlated to climatic changes and contradicts climatically induced sea-level changes.

Tectonic influence

Similarly to the indications of a climatical control on the development of the succession; tectonic movements also seems to be important for evolution of the succession. Four tectonic pulses have been recognised from seismic mapping, studies of sedimentary structures from outcrops, and from palynological studies (pers. Comm. Karen Dybkjær; 2000) (Fig 11). The first tectonic movement was in the begining of the Chattian. This phase is well known in Central Europe (Lotsch 1968) and known as the "Savishe Phase" and is also recognised on seismic data from the eastern North Sea (e.g. Clausen et al. 2000). The second tectonic phase indicated in the uppermost Chattian is, however, questionable. In outcrops in East Jylland the deposits below the Hvidbjerg Sand (Dybkjær & Rasmussen 2000) show sedimentary structures, e.g. convolute bedding and synsedimentary listric faults, which may have been caused by earthquakes (Rasmussen and Dybkjær 1999). This interval is called: "the tectonic layer" by Mikkelsen (1983). The third tectonic pulse is reflected in the palynological studies from a number of borings. At a certain level within the upper Burdigalian sediments, an abrupt occurrence of reworked Jurassic spores and pollen and high amounts of Paleocene and Eocene Dinoflagellates occurs. Above this level a distinct increase in heavy minerals have been found regionally in the Miocene sediments. This level is also equivalent to a thickning of the Arnum Formation adjacent to saltstructures indicating salt movements at this time (Fig. 12). The fourth and final tectonic phase, found in this study, is indicated by faults within the Odderup Formation seen in brown coal pits in Central Jylland (Koch 1989). These faults do not continue into the overlying Langhian – Serravallian Hodde Formation. Therefore a tectonic pulse within the Langhian must have occurred. A distinct tectonic reorganisation in the mid Miocene is also demonstrated by the cessation of major south-westward progradation from the Fenno-Scandian Shield and the initiation of major westward progradation from the Baltic and East European platforms during the Late Miocene – Pliocene times. This marked shift in source area cannot soley be attributed to eustatic sea-level changes or global climatical change, because this should have produced a basin wide progradation.

A likely interpretation of these observations mentioned above is that tectonic rejuvenation occurred within the Fenno-Scandian Shield during the Oligocene – Miocene times.

Studies of the sediments, e.g. Larsen & Dinesen (1959), Radwanski, Friis & Larsen (1975), Rasmussen (1987) and investigation of shallow borings in Jylland support the interpretation of tectonic movements in the hinterland. The shallow marine deposits composed of immature sediments except from sediments laid down in the swash zone of a beach. The quartz grains found within fluvial deposits are angular indicating erosion from newly exposed basement. The Miocene fluvial deposits were laid down by braided river systems (Hansen 1985) which exclude a low relief hinterland and tectonic quiescence during deposition as suggested by Huuse and Clausen (2001). Many studies have shown an interrelationship 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. Furthermore a close interrelationship between the deposition/preservation of brown coal and fault pattern in Central Jylland also support tectonic activity at this time. All these observations strongly indicate tectonic rejuvenation and erosion of basement in the hinterland during the time of deposition of the uppermost Oligocene – Miocene succession.

The tectonic four events indicated above shows an almost prefect timing with pulses in the Alpine Orogene (e.g. Ziegler 1990; Ribeiro, Kullberg, Kullberg, Manuppells & Pripps 1990) and the theory of interplate stresses and the consequences on depositional system is therefore interesting for the studied succession (Cloetingh 1988). The tectonic pulses is, however, of a lower order than the climatically induced cycles. But interaction of tectonic and climatic processes is 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 was from the Fennoscandia Shield (Larsen & Dinesen 1959; Spjeldnæs 1975; Michelsen et al. 1998; Gregersen and Sørensen 199; Rasmussen & Dybkjær 1999). Especially, south of the present day Norway huge progradational features have been recognised on seismic data from the North Sea. Much of the sediments are immature containing feldspar, angular quartz grains, gibbsite etc. (Larsen & Dinesen 1959; Radwanski et al. 1975; Rasmussen 1987). This indicate that the transport has been relatively fast and from newly exposed basement and uplifted sedimentary rocks. The highest input of sediments was within the area south of present day Norway, but minor supply came from the eastern part of the North Sea basin from mainly present day Central Sweden. The topography of the North Sea Basin, which was formed partly due to regional tectonism and partly due to salt movements, influenced the deposits both with respect to deposition and to pathways for the sediments. Especially, topographic lows on the Ringkøbing – Fyn High acted as conduits for sediments during lowstand of sea level in the Early Miocene.

In the Middle Miocene a distinct change in sediment influx occurred (Clausen et al. 1999). From the Middle Miocene the main sediment transport was from the area covered by present day southern Sweden and the Baltic area. The change was probably tectonic induced by the formation of the South Scandic Dome (Lidmar-Bergstrøm 1996 ; Japsen & Bidstrup 2000). Kaolinitic Pliocene deposits on the Island of Sylt (North Germany) reveals erosion of weathered basement and thus supports the hypothesis of tectonic movements in southern Scandinavia in Miocene times.

Discussion

Different studies from the North Sea have identified both sequences (third order) and major sequences (second order) of the Cenozoic succession (Jordt et al. 1995; Michelsen et al. 1998; Huuse & Clausen 2001). The studies from the North Sea is based on seismic data and petrophysical logs, mainly the gamma log. To some degree side-wall cores and cuttings are also included in the interpretation. However, generally this is of distinct lower stratigraphic resolution than the data used in the present study. Here outcops, high quality borings (without caving), shallow seismic data and biostratigraphy based on a high sample rate have been used. In the following a comparison of these studies and the present study will be performed (Fig. 13).

Most of the major sequences of Jordt et al. (1995), Michelsen et al. (1998) and Huuse & Clausen (2001), and the sequences of this study are coincident (Fig. 13). The lower boundary of Sequence A corresponds partly to the major sequence boundary 4/5 of Michelsen et al. (1998) and the seismic sequence boundary Css4/Css5 and near-top Oligocene of Jordt et al. (1995) and Huuse and Clausen (2001) respectively. The second major sequence boundary recognised by Michelsen et al. (1998) and Jordt et al. (1995) (5/6 and Css5/Css6) correlates the sequence boundary B/C of this study. This sequence boundary is one of the most pronounced in the onshore area and corresponds to a classical Type I sequence boundary associated with the deposition of the Ribe Formation (Forced regressive systems tract of Sequence B and lowstand systens tract of Sequence C) and formerly discribed by Rasmussen (1998). The third major sequence Boundary is the so-call mid-Miocene unconformity renown from the North Sea area (Jordt et al. 1995; Michelsen et al. 1998; Huuse & Claused 2001). This boundary is correlated to the sequence boundary of D/E of this study. In the onshore area this boundary represent a major flooding and change from dominantly shallow marine and terrestrial deposition to fully marine shelf deposition. The studies of Jordt et al. (1995), Michelsen et al. (1998), and this study claims an influence of tectonics on the formation of major sequence boundaries. Huuse and Clausen (2001) prefer a climatic control on sequence formation. It is also concluded in this study that there is a close relationship between climatic changes and the evolution of the uppermost Oligocene – Miocene succession, but the development of the succession cannot be fully explained without considering tectonics. Consequently the most likely explanation for the development of the section is a combination of climatic variation and tectonics. It is, however, strange that Huuse and Clausen (2001) could make a clear conclusion about the origin of the sequences without recognising the major sequence boundary within the early Burdigalian, which correlate to the most distinct climatically changes during the Miocene according to most studies (Prentice & Matthews 1988; Mai 1967; Lotsch 1968; and Zachos 2001). This is interesting because this sequence boundary (Type I sequence boundary) is the most distinct boundary in the onshore area and have all 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, the early Burdigalian sequence boundary (Fig. 13) found in this study is a classical Type I sequence boundary, including incision and deposition of lowstand deposits. This boundary have not been recognised by the studies, based on seismic data, from the North Sea area. A probably explanation of this is that the studies mainly based on seismic data in most cases recognises major flooding events, e.g. the late Oligocene major sea-level rise and mid Miocene (Intra Langhian) sea-level rise (Fig. 11). A major flooding will often result in very different lithologies below and above a boundary, for instance, marine clay above nearshore and fluvial sand and gravel. Sequence boundaries formed due to a marked lowering of base level which often are characterised by truncation surfaces, coarse-grained lag deposits and sand to sand contacts are poor seismic markers, and therefore difficult to identify. A study can of cause only build on the data which are available, but it seems to be a handicap in the relatively low resolution data used in the North Sea.

This study has shown that climatic changes are very important for the development of the sequences. But it also stated that tectonics have influenced the evolution of the succession. The tectonic events found in this study (Fig. 11) correlates to major tectonic phases of the Alpine Orogeny and also movements associated with the opening of the

North Atlantic, all though the datings of the latter is less constrained (Boldreel & Andersen 1993; Roberts, Thomson, Mitchener, Hossack, Carmichael & Bjørnseth 1999). The development of the sequences was partly controlled by structural elements 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 fully 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). Therefore the processes involved in the evolution of the studied succession were related to both climatic changes and tectonic movements.

Conclusions

The sequence stratigraphic study of the uppermost Oligocene – Miocene succession in Denmark has resulted in a subdivision into 6 depositional sequences named A to G.

The development of the sequences was both controlled by glacio-eustatic sea-level changes and tectonics.

Structural highs were important in the distribution of depositional environments, e.g. brackish water and marine water in the latest Oligocene and earliest Miocene. Similarly sturctural highs also periodically controlled the distribution of the sediment, e.g. spit system.

The overall trend of the shoreline during the deposition of the uppermost Oligocene – early Middle Miocene succession was NW-SE. From the late Middle Miocene and the remaining part of the Miocene the shoreline strike NNW-SSE.

The new insight in the development of the uppermost Oligocene – Miocene succession, presented here, indicate that a new lithostratigraphy must be erected in order to make it applicable in a regional mapping of the succession.

Dansk Sammendrag

I løbet af de sidste 3 år er en mængde nye data om den miocæne lagpakke blevet indsamlet. Det drejer sig om 7 stratigrafiske boringer i Østjylland og shallow seismiske data fra land. Blotningerne i Østjylland er blevet undersøgt og resultaterne er sammenstillet med de nye boringer. Alt dette er blevet integreret med seismiske data fra Nordsøen, samt med ældre dybe boringer i Jylland, således at der nu er en konsistent tolkning af den miocæne lagserien i det danske område.

Den miocæne lagpakke er opbygget af både marine og terrestriske aflejringer. Fra Nedre Miocæn og til nedre Mellem Miocæn forekom 3 markante udbygninger af kysten fra nordøst mod sydvest. Disse progradérende enheder benævnes Billund sand (ny uformel enhed) Ribe Formationen, Bastrup sand (ny uformel enhed) og Odderup Formationen. Det foreslåes endvidere at Odderup Formationen opdeles yderligere i Stauning sand (ny uformel enhed) og Fasterholt led (Koch 1989). De mellemliggende marine aflejringer udgøres af Vejle Fjord Formationen, Hvidbjerg sand (ny uformel enhed) og Arnum Formationen. I Mellem og Øvre Miocæn aflejredes kun marine sedimenter, disse er kendt som Hodde- og Gram formationerne.

De regressive og transgressive faser var i starten af Miocæn styret af globale havniveausvingninger, specielt Ribe Formationen blev aflejret under et markant havniveau-fald. Udbygningen af Odderup Formationen kan formodentligt korreleres til et havniveau-fald, men tolkes desuden til at være et resultat af jordskorpebevægelser på Det fennoskandiske Skjold. Ligeledes skyldtes den markante transgression i Mellem/Øvre Miocæn at være forårsaget af en markant øgning i indsynkningsraten for Nordsøbassinet da det globale havniveau generelt faldt i denne periode.

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Figure captions

Figure 1. *Structural elements of the Danish North Sea Basin.*

Figure 2. *Miocene lithostratigraphy of Denmark. Modified after Rasmussen (1961).*

Figure 3. *Location map showing the location of outcrops, boreholes, and seismic lines. Note that new stratigraphic boreholes are marked with an asterisk*

Figure 4. *Three seismic lines from Jylland and adjacent area. Note that the progradation is generally from north to south. For location see figure 3.*

Figure 5. *Correlation panel of boreholes from Central Jylland and South Jylland.*

Figure 6. *Corelation panel of boreholes and outcrops in East Jylland and South Jylland.*

Figure 7. *Lithology and gammalogs from 6 new stratigraphic boreholes in Central Jylland.*

Figure 8. *Seismic section from South Jylland showing the maximum progradation during the Aquitanian – early Burdigalian. For location see figure 3.*

Figure 9. *Palaeogrographical maps showing general changes in the location of the shoreline throughout the latest Oligocene – Miocene time.*

Figure 10. *Proposed revision of the lithostratigraphy of the latest Oligocene – Miocene succession in Jylland. All units, which should be redefined, are in open (informal) nomenclature.*

Figure 11. *A scheme comparing eustatic sea-level curves, climatical changes, glacial maximum, tectonic puslses, and age of the sequences found in this study.*

Figure 12. *Gamma log correlation of four boreholes in South Jylland showing the thickness variation of the upper Burdigalian succession. See figure 3 for location.*

Figure 13. *Comparison of the timing of sequences of this study and Michelsen et al. (1998), Jordt et al. (1995), and Huuse and Clausen (2001).*

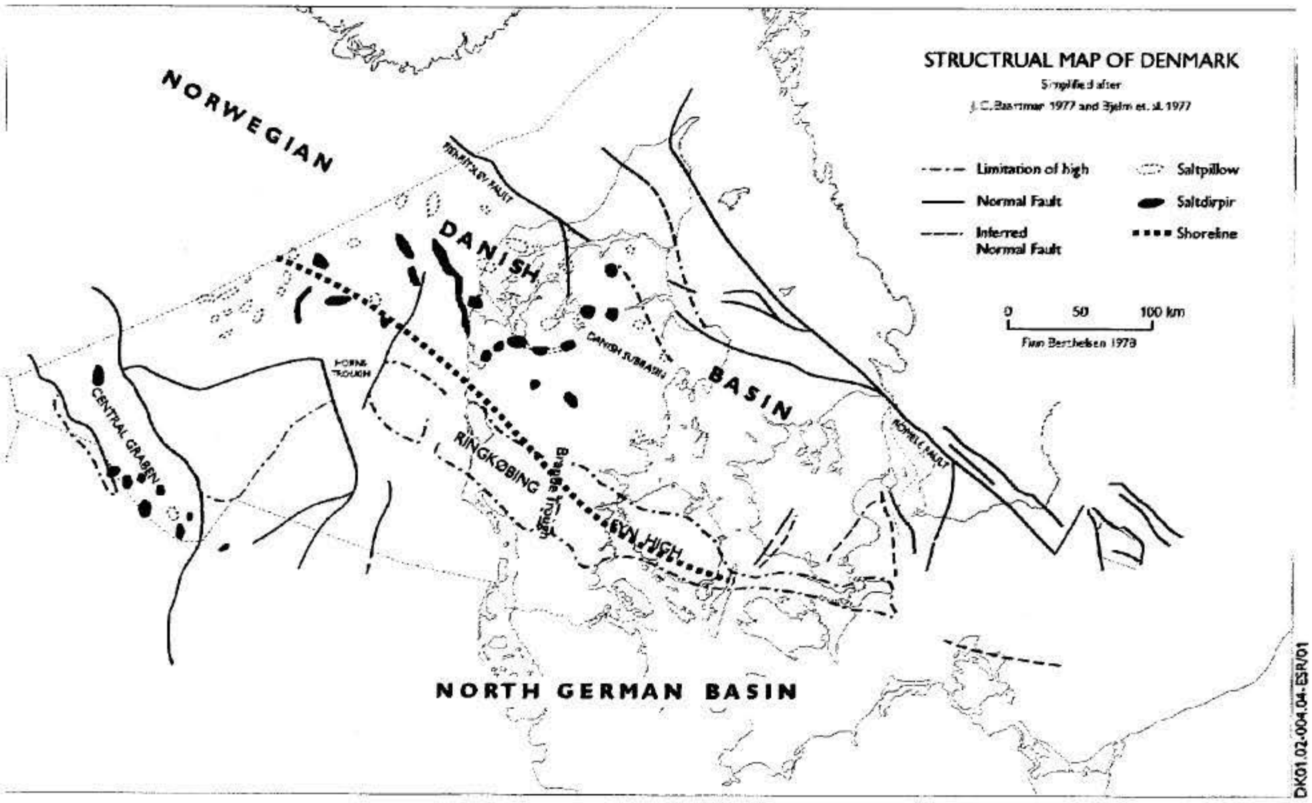

STRUCTRUAL MAP OF DENMARK
Simplified after
J. C. Baartman 1977 and Bjelm et. al. 1977
Limitation of high
Normal Fault
Inferred Normal Fault
Saltpillow
Saltdirpir
Shoreline
0
50
100 km
Finn Berthelsen 1978
NORWEGIAN
DANISH
BASIN
CENTRAL GRABEN
HORN TROUGH
DANISH SUBBASIN
RINGKØBING
Brande Trough
FYN HIGH
NORTH GERMAN BASIN
DK01.02-004.04-ESR/01

Fig 1

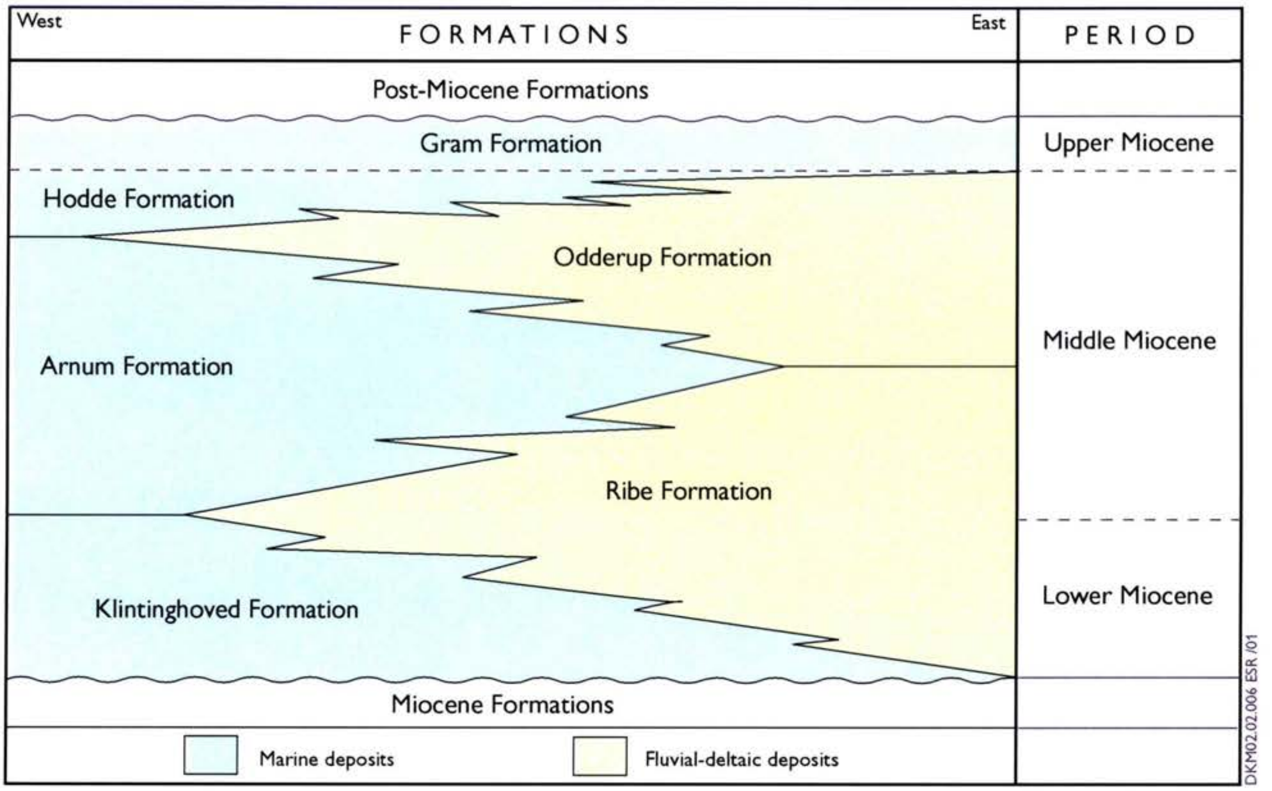

West
FORMATIONS
East
PERIOD
Post-Miocene Formations
Gram Formation
Upper Miocene
Hodde Formation
Odderup Formation
Arnum Formation
Middle Miocene
Ribe Formation
Klintinghoved Formation
Lower Miocene
Miocene Formations
Marine deposits
Fluvial-deltaic deposits
DKM02.02.006 ESR /01

Fig 2

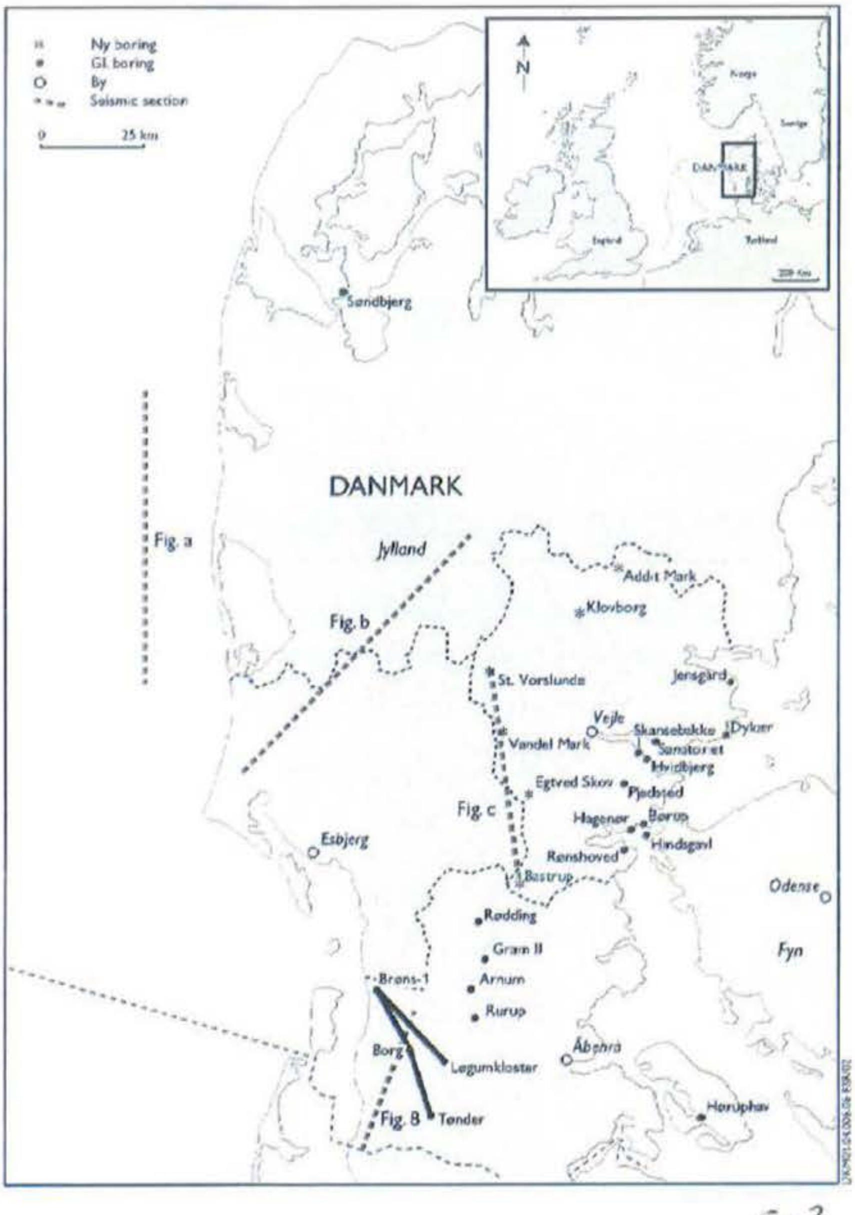

Ny boring
Gl. boring
By
Seismic section
0
25 km
N
Søndbjerg
DANMARK
Jylland
Fig. a
Fig. b
Addit Mark
Klovborg
St. Vorslunde
Jensgård
Vejle
Skansebakke
Dyrlær
Vandel Mark
Hvidbjerg
Egtved Skov
Fig. c
Hagenør
Børup
Hindsgavl
Esbjerg
Rønshoved
Bastrup
Odense
Rødding
Gram II
Fyn
Brøns-1
Arnum
Rurup
Borg
Løgumkloster
Åbenrå
Fig. B
Tønder
Høruphav

Fig 3

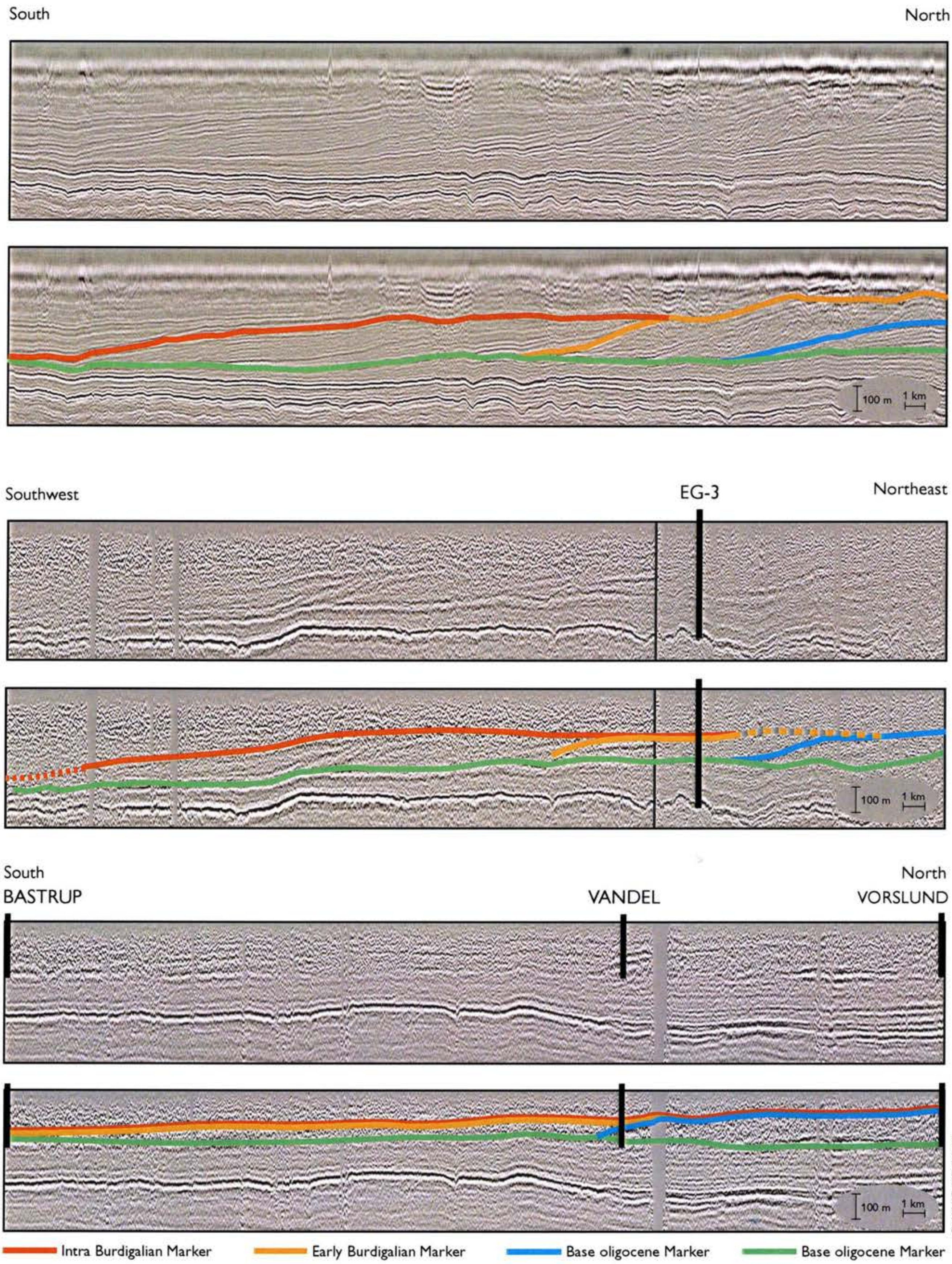

South
North
100 m
1 km
Southwest
EG-3
Northeast
100 m
1 km
South
North
BASTRUP
VANDEL
VORSLUND
100 m
1 km
DK03.07-005 ESR/02
Intra Burdigalian Marker
Early Burdigalian Marker
Base oligocene Marker
Base oligocene Marker

Fig 4

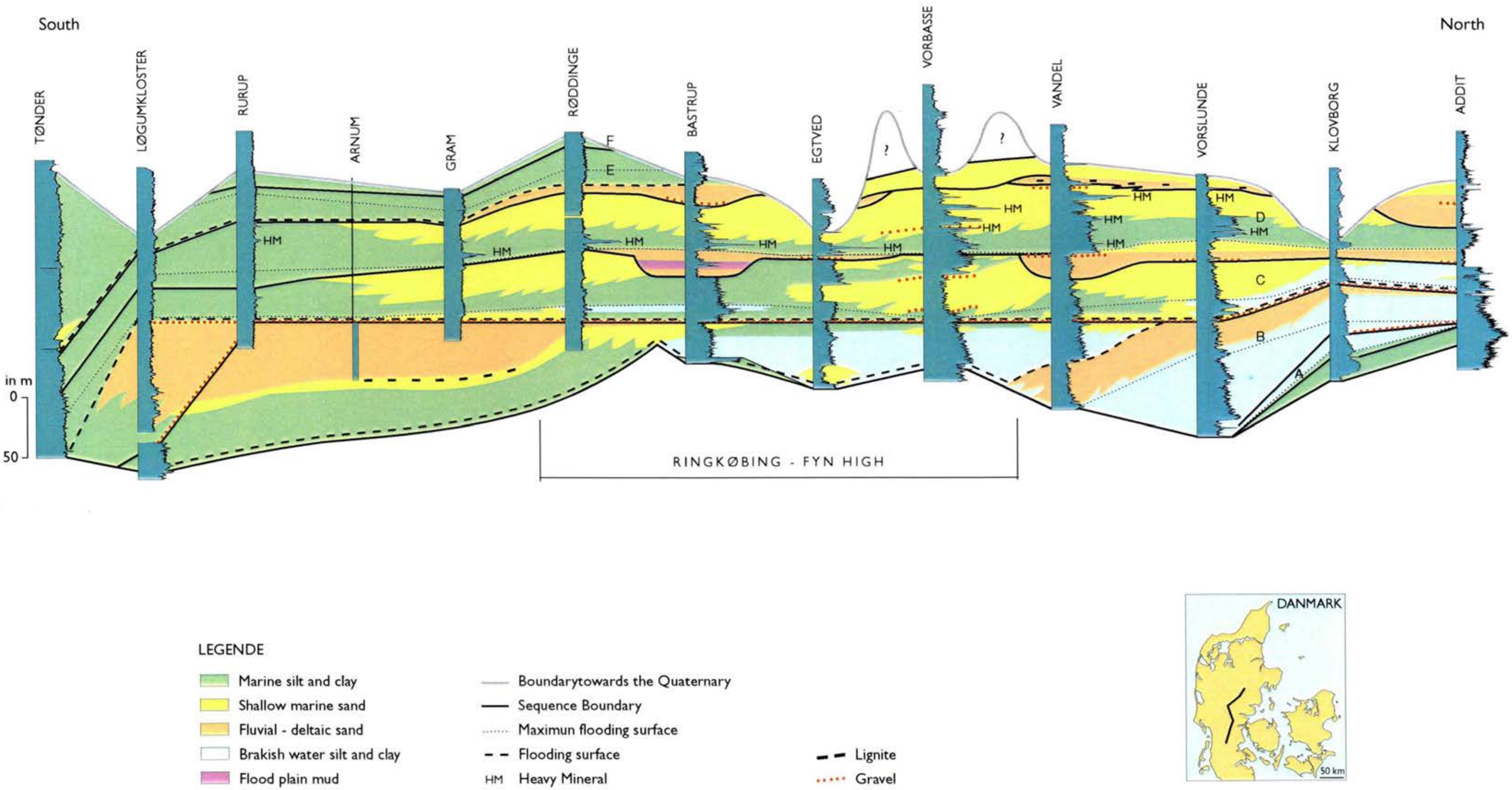


Fig 5

DKM02.14.021-02 ESR /01

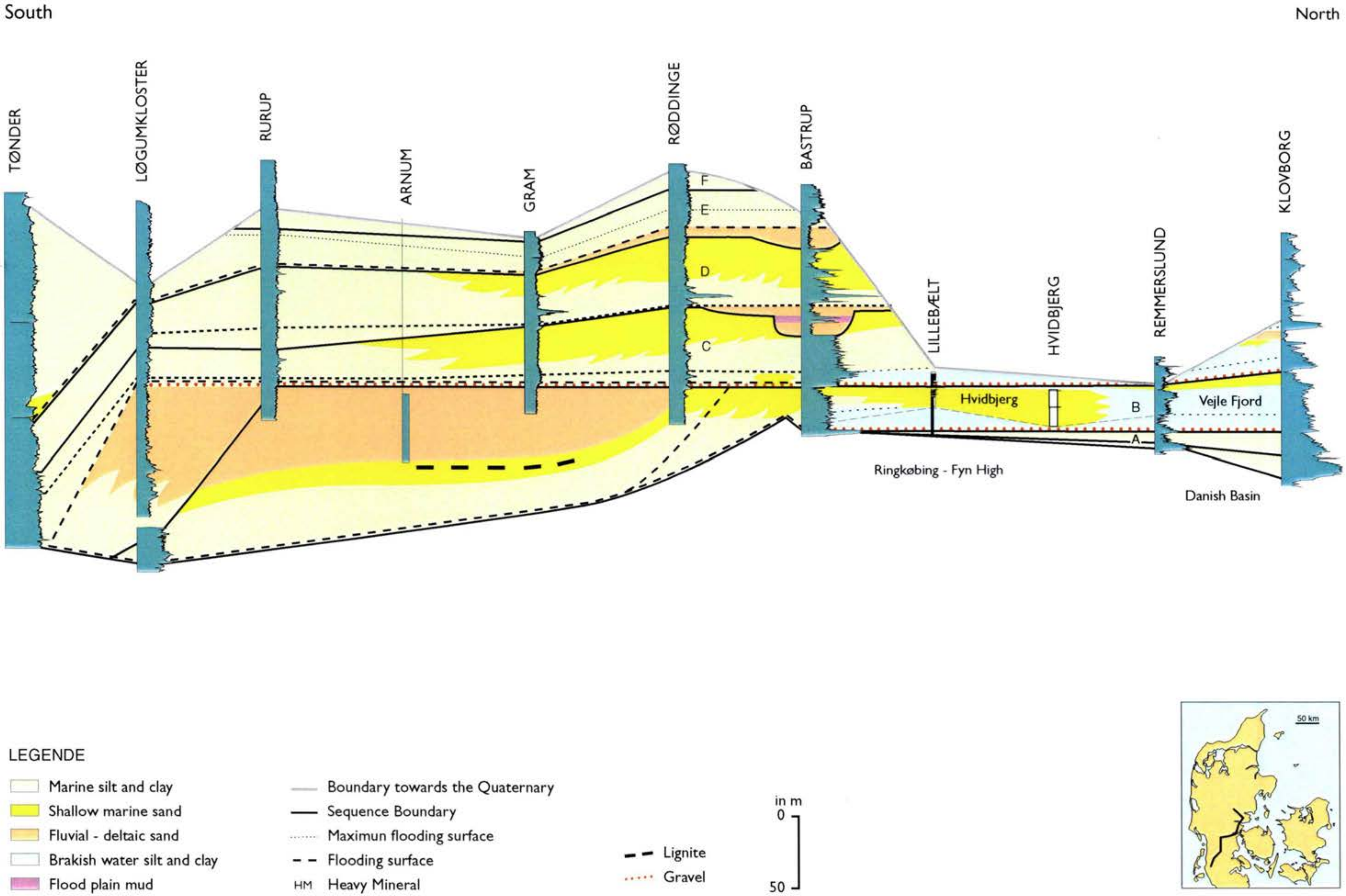


Fig 6

DKM02.014.023.02.ESR

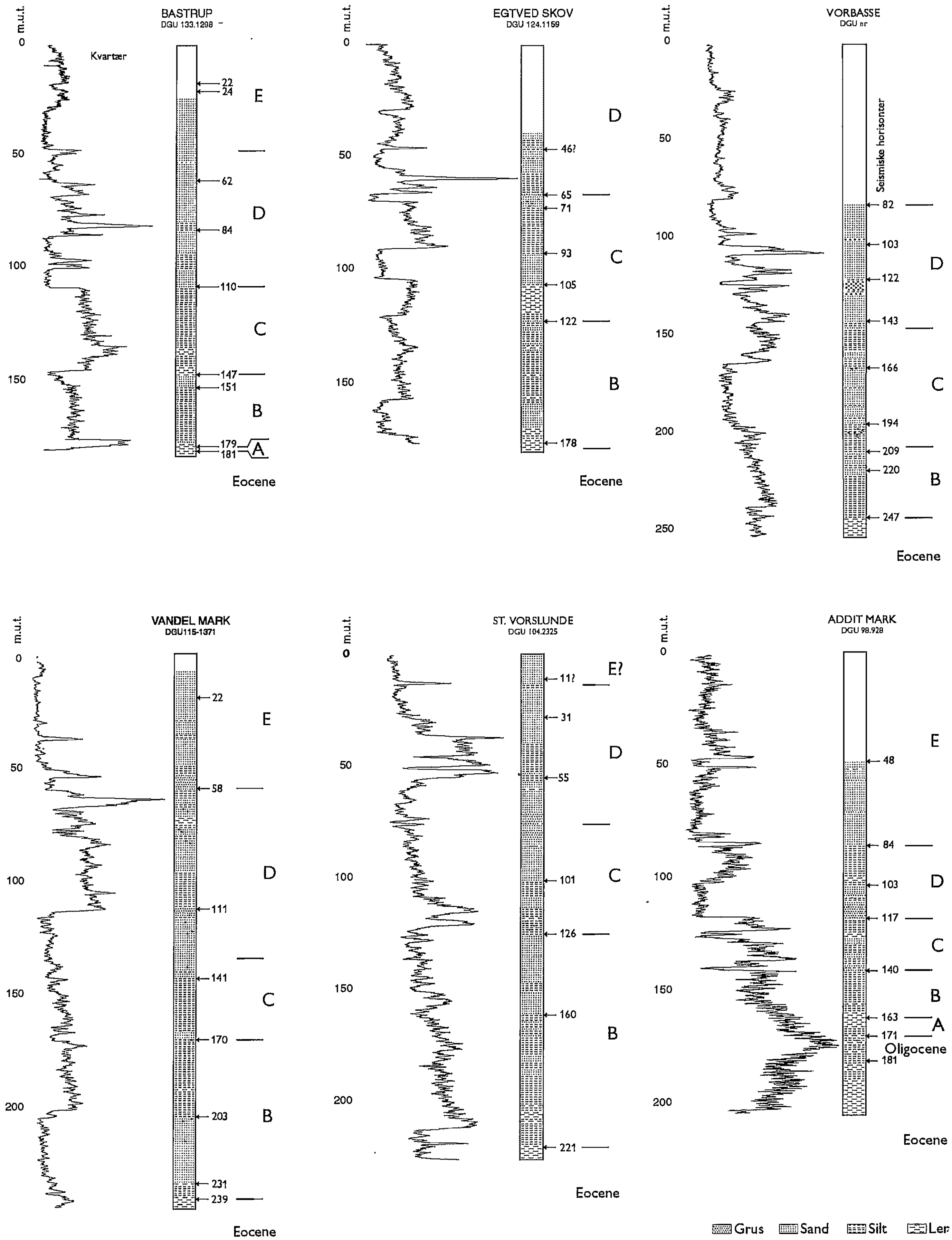

BASTRUP
DGU 133.1298
m.u.t.
Kvartær
22
24
E
62
D
84
110
C
147
151
B
179
181
A
Eocene
EGTVED SKOV
DGU 124.1159
D
46?
65
71
93
C
105
122
B
178
Eocene
VORBASSE
DGU nr
Seismiske horisonter
82
103
D
122
143
166
C
194
209
220
B
247
Eocene
VANDEL MARK
DGU115-1371
22
E
58
D
111
141
C
170
203
B
231
239
Eocene
ST. VORSLUNDE
DGU 104.2325
E?
11?
31
D
55
101
C
126
160
B
221
Eocene
ADDIT MARK
DGU 98.928
E
48
84
D
103
117
C
140
B
163
171
A
Oligocene
181
Eocene
Grus
Sand
Silt
Ler

Fig 7

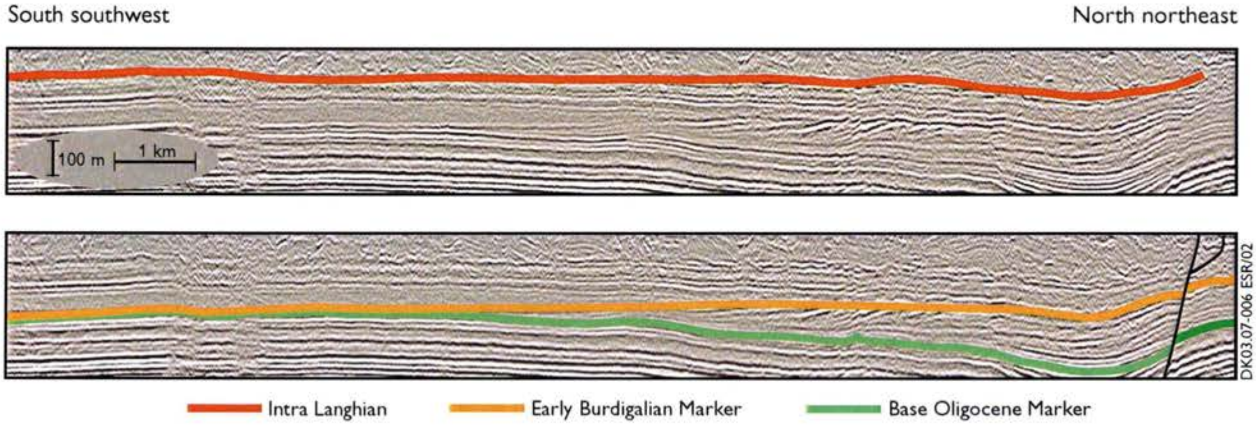

South southwest
North northeast
100 m
1 km
DK03.07-006 ESR/02
Intra Langhian
Early Burdigalian Marker
Base Oligocene Marker

Fig. 8

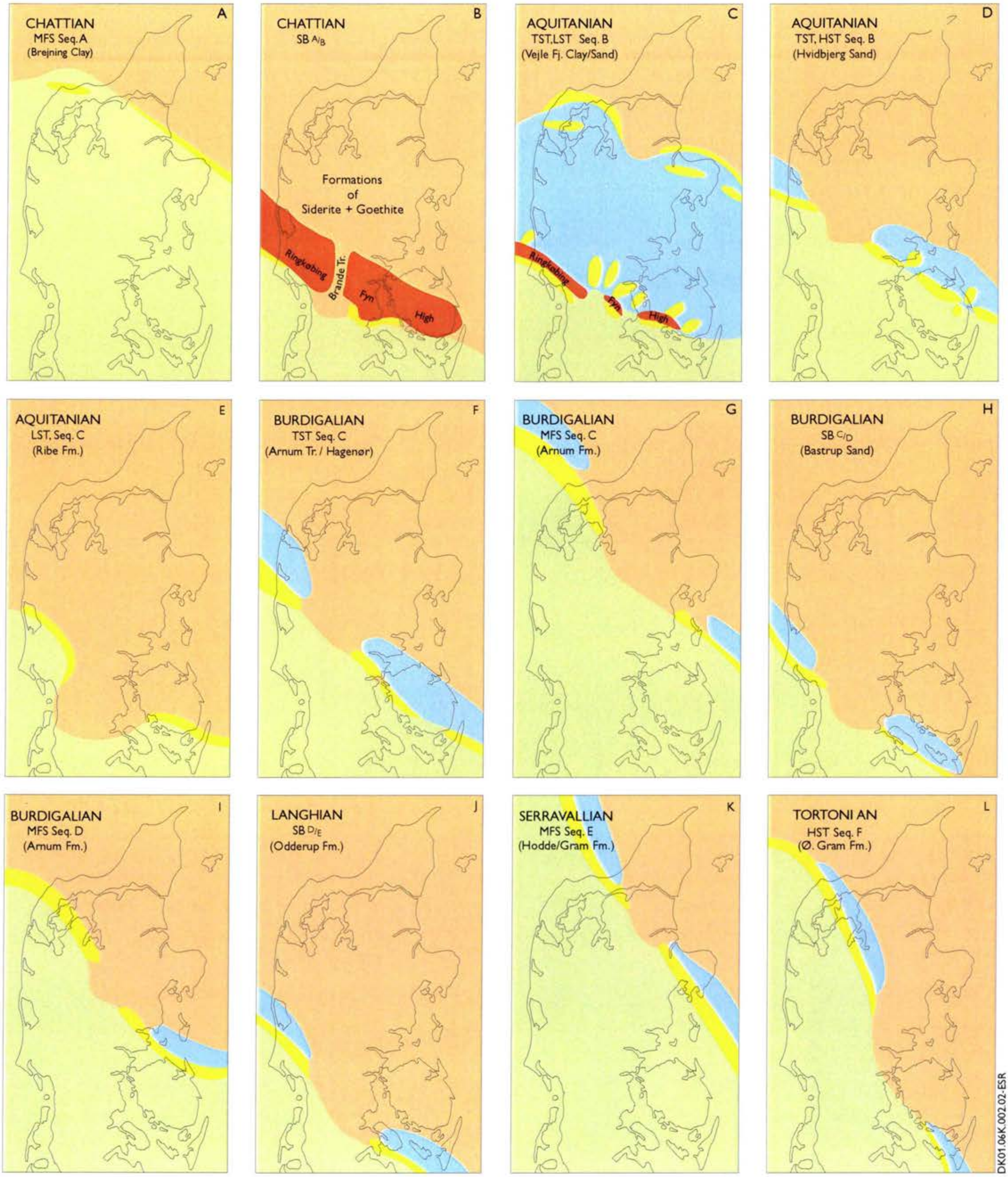

CHATTIAN
MFS Seq. A
(Brejning Clay)
A
CHATTIAN
SB A/B
B
Formations of Siderite + Goethite
Ringkøbing
Brande Tr.
Fyn
High
AQUITANIAN
TST,LST Seq. B
(Vejle Fj. Clay/Sand)
C
Ringkøbing
Fyn
High
AQUITANIAN
TST, HST Seq. B
(Hvidbjerg Sand)
D
AQUITANIAN
LST, Seq. C
(Ribe Fm.)
E
BURDIGALIAN
TST Seq. C
(Arnum Tr. / Hagenør)
F
BURDIGALIAN
MFS Seq. C
(Arnum Fm.)
G
BURDIGALIAN
SB C/D
(Bastrup Sand)
H
BURDIGALIAN
MFS Seq. D
(Arnum Fm.)
I
LANGHIAN
SB D/E
(Odderup Fm.)
J
SERRAVALLIAN
MFS Seq. E
(Hodde/Gram Fm.)
K
TORTONIAN
HST Seq. F
(Ø. Gram Fm.)
L
DK01.06K.002.02-ESR

Fig 9

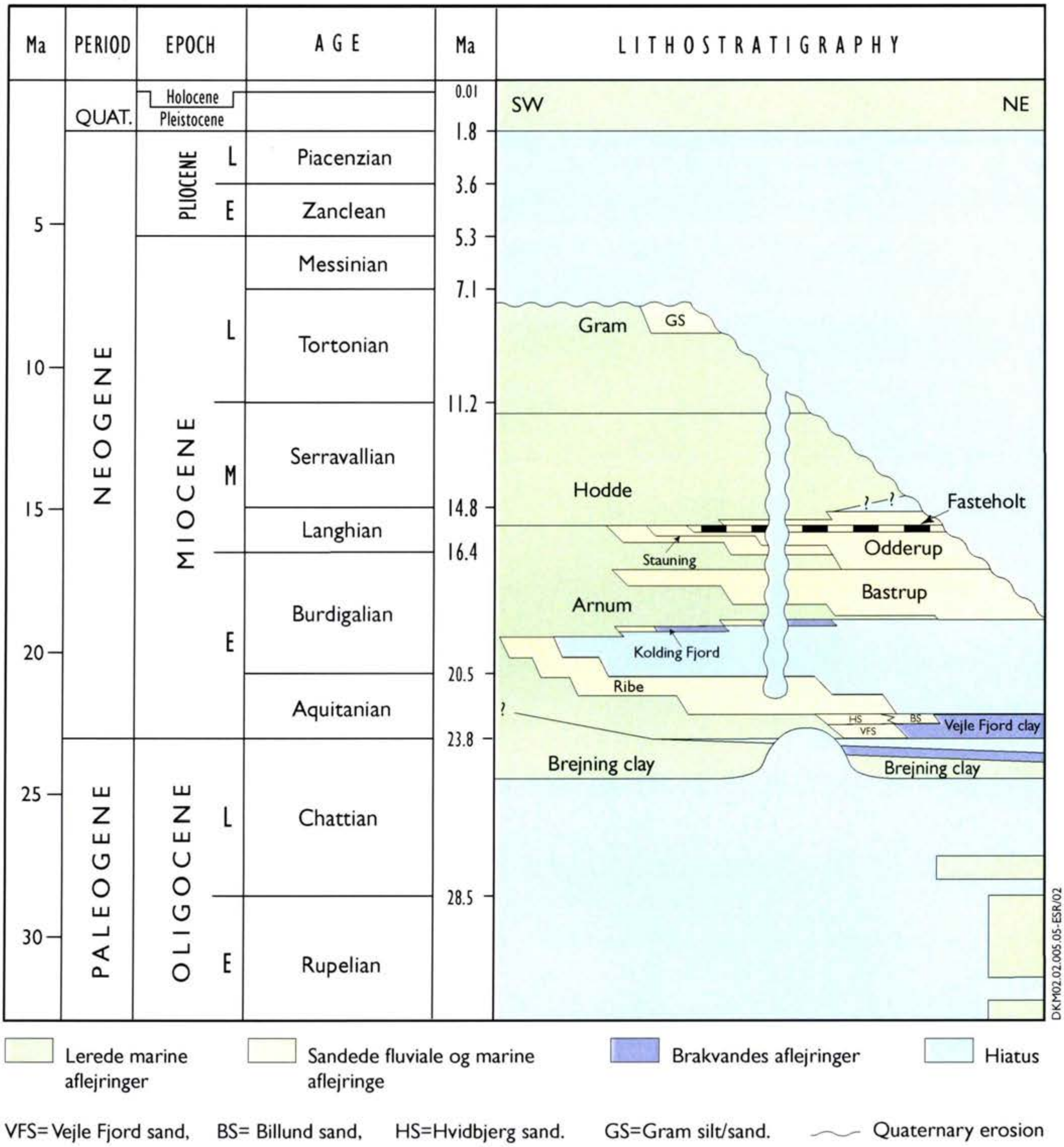

Ma
PERIOD
EPOCH
AGE
Ma
LITHOSTRATIGRAPHY
QUAT.
Holocene
Pleistocene
NEOGENE
PALEOGENE
PLIOCENE
MIOCENE
OLIGOCENE
L
E
M
Piacenzian
Zanclean
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
5
10
15
20
25
30
0.01
1.8
3.6
5.3
7.1
11.2
14.8
16.4
20.5
23.8
28.5
SW
NE
Gram
GS
Hodde
Fasteholt
Odderup
Stauning
Bastrup
Arnum
Kolding Fjord
Ribe
HS
BS
VFS
Vejle Fjord clay
Brejning clay
Brejning clay
DKM02.02.005.05-ESR/02
Lerede marine aflejringer
Sandede fluviale og marine aflejringe
Brakvandes aflejringer
Hiatus
VFS= Vejle Fjord sand, BS= Billund sand, HS=Hvidbjerg sand. GS=Gram silt/sand.
Quaternary erosion

Fig 10

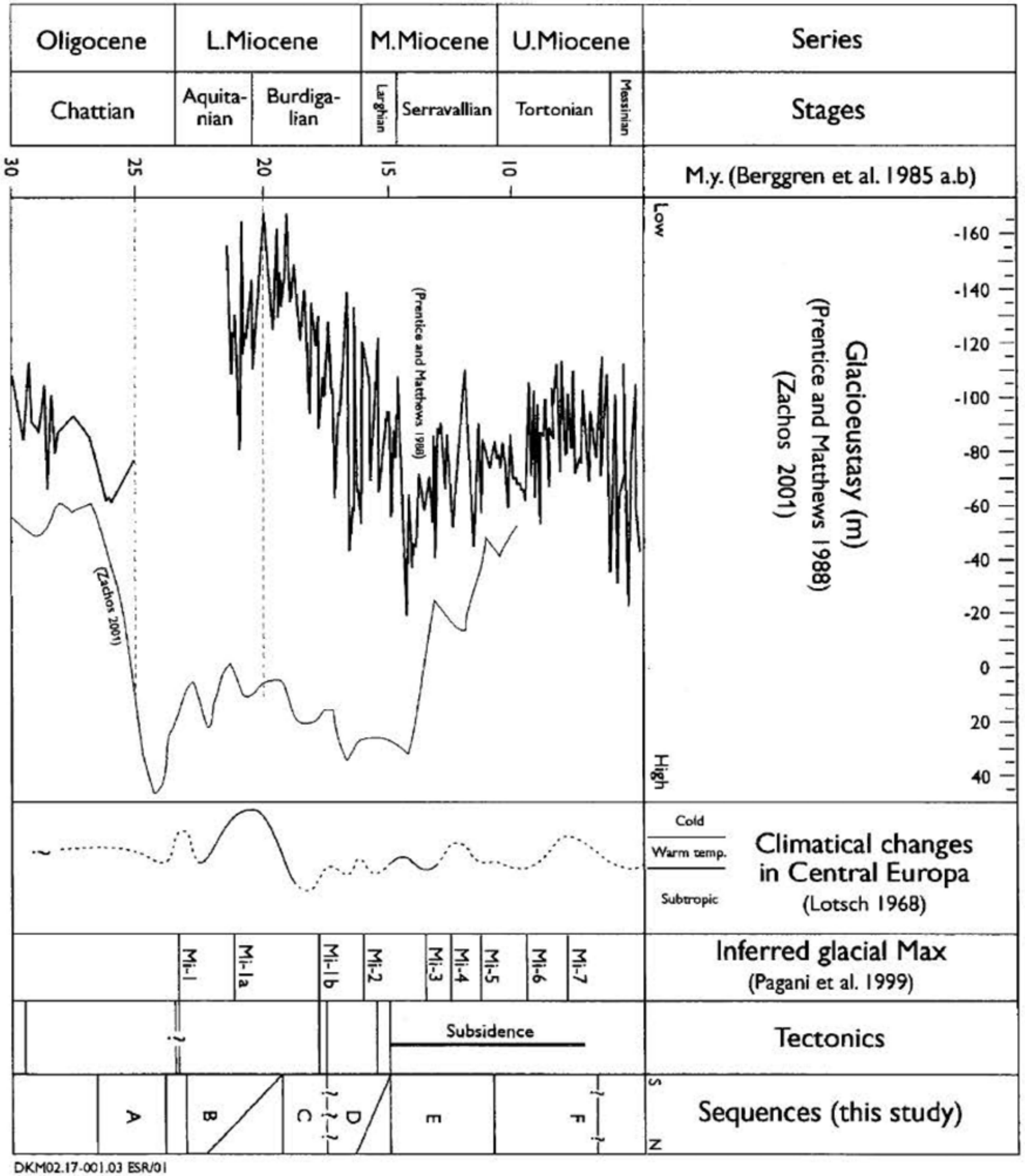

Oligocene
L.Miocene
M.Miocene
U.Miocene
Series
Chattian
Aquita-nian
Burdiga-lian
Larghian
Serravallian
Tortonian
Messinian
Stages
30
25
20
15
10
M.y. (Berggren et al. 1985 a.b)
Low
High
(Prentice and Matthews 1988)
(Zachos 2001)
Glacioeustasy (m)
(Prentice and Matthews 1988)
(Zachos 2001)
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
Cold
Warm temp.
Subtropic
Climatical changes in Central Europa
(Lotsch 1968)
Mi-1
Mi-1a
Mi-1b
Mi-2
Mi-3
Mi-4
Mi-5
Mi-6
Mi-7
Inferred glacial Max
(Pagani et al. 1999)
Subsidence
Tectonics
A
B
C
D
E
F
S
N
Sequences (this study)
DKM02.17-001.03 ESR/01

Fig 11

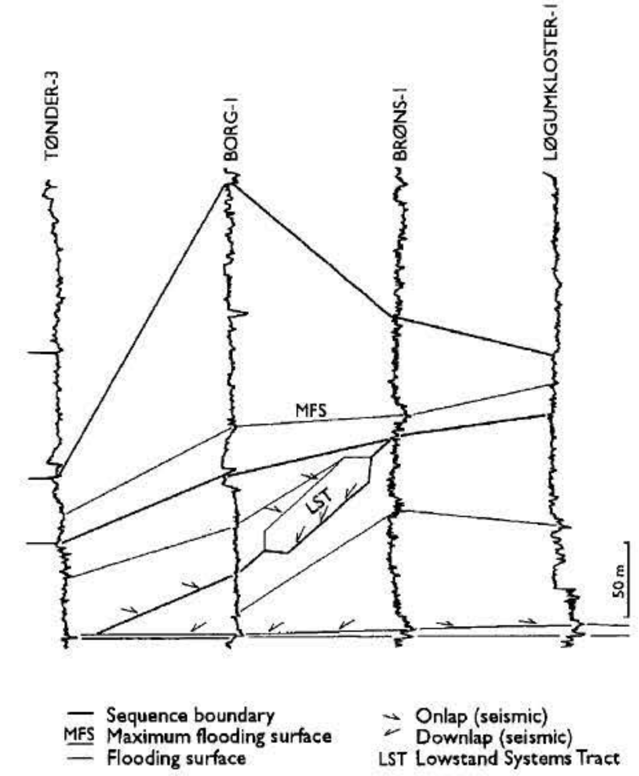
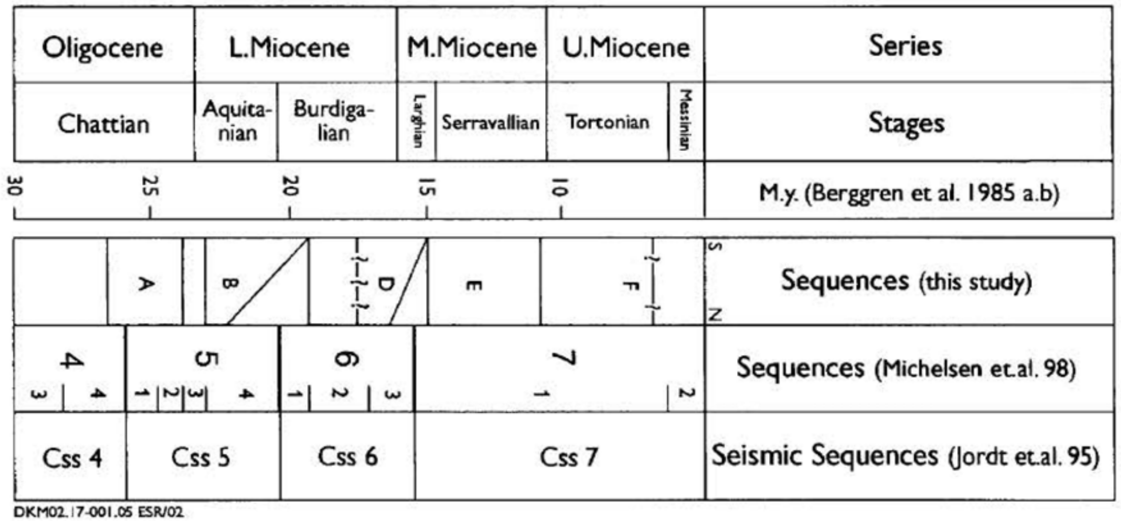


Fig 12

DKM02.14.011-03 ESR/01



Oligocene
L.Miocene
M.Miocene
U.Miocene
Series
Chattian
Aquita-nian
Burdiga-lian
Larghian
Serravallian
Tortonian
Messinian
Stages
30
25
20
15
10
M.y. (Berggren et al. 1985 a.b)
A
B
D
E
F
S
N
Sequences (this study)
4
3
4
5
1
2
3
4
6
1
2
3
7
1
2
Sequences (Michelsen et.al. 98)
Css 4
Css 5
Css 6
Css 7
Seismic Sequences (Jordt et.al. 95)
DKM02.17-001.05 ESR/02

Fig 13

Sequence stratigraphy of the Upper Oligocene – Lower Miocene of eastern Jylland, Denmark: implications of structural relief and variable sediment supply for paralic sequence development

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Abstract

Outcrops in eastern Jylland permit a study of Upper Oligocene – Lower Miocene shallow marine siliciclastic deposits. The study includes detailed sedimentological investigations of a series of outcrops combined with palynology and correlated with a regional study including borehole and seismic data. The succession in eastern Jylland is subdivided into three sequences (A – C). This study demonstrates the development of these three sequences deposited on the Ringkøbing-Fyn High, which was characterised by topographic highs and lows. The topographic relief resulted in subaerial exposure of elevated areas and deposition in brackish silled basins during lowstands of sea level. During rising sea level these silled basins were flooded and gradually became fully marine during high sea-level stands (late TST and HST). In addition to the topographic control on sequence development sediment supply into the study area changed dramatically during the deposition of the three sequences. Initially the basin was sediment starved, but sediment input gradually increased and was high during the deposition of the upper part of the studied succession. A high frequency of storms promoted longshore sediment transport and development of spit systems adjacent to structural highs. As a consequence, sequence boundaries and flooding surfaces are not always developed as described in the literature; sequence boundaries or flooding surfaces may only be recognisable by subtle changes in depositional environment rather than a physical boundary such as erosional surface or an abrupt lithological change. The influence of the topography resulted in the development of brackish water basins that were sufficiently large to permit the deposition of hummocky cross-stratified sands with muds. These deposits are overlain by clean hummocky and swaley cross-stratified sands laid down in a fully marine and permanently high energy environment. This evolution from mud-rich storm-influenced sediments to sand-dominated shoreface sediments resulted from a rise in sea level contrasting with the classical interpretation of such succession i.e. the result of shoreface progradation under falling relative sea level. Following the increase in the rate of sedimentation, the influence of structural elements decreased and both sequence boundaries and flooding surfaces are characterised by erosional surfaces, lithological changes and other diagnostic features as described in the literature.

Introduction

The basic concepts of sequence stratigraphy are commonly illustrated in the form of 2-dimensional simplified geological settings with constant sediment influx from one side. Although the warnings of this simplification many studies is bias of this. In a sedimentary basin, sediment input may occur from many directions both caused by fluvial and marine processes. Topographic highs and lows may form as a consequence of tectonics and superposed on this, climatical changes causing sea-level changes and variations in precipitation further add to the complexity by changing accommodation space and sediment supply. In addition to this, sequence stratigraphic concepts is further problematic in paralic deposits (e.g. Surlyk *et al.* 1995). For instance, sharp-based shoreface sand overlying muds in paralic depositional systems may represent either forced regression (e.g. Walker & Plint 1992) or transgression (Surlyk *et al.* 1995) i.e. progradation of the shoreface into a marine realm or retreat of a shoreface above lagoonal/protected mud deposits. In fact this reflect two different positions on a relative sea-level curve. A traditional sedimentological study of outcrops and especially well-cores may thus lead to a wrong interpretation and consequently incorrect palaeogeographical reconstruction if the origin of fine-grained sediments (marine or non marine) is unsolved. Consequently, prediction of lithology will be problematic. In the studied setcions in east Jylland a complex physiography and variation in sediment supply further complicate the depositional evolution. This paper uses a multi disciplinary approach combined with seismic mapping (Rasmussen 1996; 1998; submitted) in order to unravel the depositional evolution.

The purpose of the paper is to present a combined sedimentological, palynological, and sequence stratigraphic study of a complex depositional system that has been influenced by eustatic sea-level changes, physiography and a significant shift in the sedimentation rate.

Previous work

In the Vejle Fjord area, shallow marine deposits were studied by Larsen and Dinesen (1959) and resulted in the definition of the Vejle Fjord Formation. The Vejle Fjord Formation was referred to the Upper Oligocene – lower Miocene (Eriksen, 1937; Rasmussen, 1961) and subdivided into three members: The Brejning Clay Member, the Vejle Fjord Clay Member and the Vejle Fjord Sand Member (Fig. 1). At Lillebælt, two outcrops at Børup and Hagenør were described by Radwanski *et al.* (1975). These exposures were referred to the Vejle Fjord Sand Member. They interpreted the succession to represent nearshore to offshore deposits with low tidal influence. In particular they described the ichnofauna and discussed its significance for the interpretation of the palaeoenvironment. A model of the depositional environment of the Vejle Fjord Formation and related sections at Lillebælt and the Vejle Fjord area was published by Friis *et al.* (1998). The study concluded that deposition occurred in a back-barrier environment under the influence of both storms and tidal processes. However, the influence of storm processes was interpreted to be of minor importance in the Lillebælt area and Friis *et al.* (1998) concluded that sedimentation was tida-dominated in this area. Re-study of localities in East Jylland by the present authors, however, combined with data from new landslide exposures suggests that processes related to storms were also of major importance in the Lillebælt area. New biostratigraphic data also reveal that there is a major hiatus in the succession at Lillebælt (Dybkjær & Rasmussen, 2000). The combined sedimentological – palynological study presented in this paper indicates that the depositional history is far more complicated than previously thought (see also Dybkjær & Rasmussen 2000). The use of sequence stratigraphy, combined with palynostratigraphy and palynofacies, has made it possible to correlate all outcrops in East Jylland (Fig. 2).

Geological setting

The Late Cretaceous – Cenozoic North Sea Basin formed as a result of thermal relaxation after the Jurassic-Early Cretaceous rift tectonics and a relatively regular basin formed. During the Late Cretaceous and early Paleocene, former graben structures were elevated due to inversion tectonics (Vejbæk & Andersen, 1987; Liboriussen *et al.*, 1987; Ziegler, 1982). This occurred both within and at the margins of the basin. Progradation from Fenno-Scandia and infill of the eastern North Sea Basin probably started in the Cretaceous and Palaeocene but is first demonstrated within the Oligocene (Michelsen *et al.*, 1998). Infill of the North Sea Basin by progradation from the north spanned the Oligocene to early middle Miocene with a change to a more west-ward progradation began (Clausen *et al.*, 1999; Rasmussen and Dybkjær, submitted). The latter was the result of mid Miocene (Langhian) focussed subsidence of the central part of the North Sea Basin associated with differential uplift of the Fenno-scandian Shield.

In the late Oligocene - early Miocene, the sediment input in the eastern North Sea was from the Fenno-Scandian Shield, especially Norway (Fig. 3). This resulted in the progradation of an almost WNW – ESE striking shoreline from Norway towards the south (Jordt *et al.*, 1995; Rasmussen & Dybkjær, submitted). In the area of present-day Jylland the coastline turned from a dominantly WNW – ESE strike to have a more NW – SE to NNW – SSE orientation (Rasmussen & Dybkjær, submitted). In the central North Sea area, where the sediment supply was highest, the depositional environment was probably dominated by deltaic deposition. South-eastward along the eastern limit of the North Sea, a sand-dominated coastline formed as the result of strong sediment transport along the shelf from the major deltas in the Central North Sea Basin. During the late Oligocene and earliest Miocene, the coastline was situated across East Jylland and dominated by spit and barrier complexes (Rasmussen, 1996; Friis *et al.*, 1998). As a result of a distinct fall in relative sea level in the early Miocene, the coastline was displaced some 100 km towards the south-west (Rasmussen, 1996; Rasmussen, 1998; Rasmussen & Dybkjær, submitted) former marine deposits was sub-aerially exposed and fluvial deposition occurred. Resumed rise in relative sea level re-established shallow marine conditions in eastern Jylland. Alternating marine and terrestrial environments prevailed throughout the Miocene.

The climate conditions during the Oligocene and Early Miocene was humid and warm temperate with cooler periods at the begining and at the end of the Miocene (Sorgenfrei, 1958; Radwanski *et al.*, 1975; Buchardt, 1978; Koch, 1989). There have been no reports of significant changes in precipitation during the period.

Palynology

Methods

A total of 47 samples were collected. The profile from Dykær was sampled at regular intervals, whereas other outcrops were sampled more selectively in order to cover all parasequences and major lithological changes (Fig. 4). The samples were processed using palynological standard preparation methods including treatment with HCl, HF, heavy liquid separation, brief oxygenation with HNO_3 and sieving on 11μm filters (see Poulsen *et al.*, 1990).

For dating purposes, a minimum of 200 dinoflagellate cysts (dinocysts) from each sample were identified to species level. In a few samples, it was not possible to count 200 specimens. In palynofacies studies, organic sedimentary particles can be grouped in different ways depending on the purpose of the study and on the organic matter occurring in the samples. In the present study, the organic sedimentary particles comprise palynomorphs, wood particles and brownish amorphous organic matter (AOM), probably of terrestrial origin. Partly degraded wood particles, showing a transitional stage between wood and AOM occur commonly. Firstly, a minimum of 200 organic particles were identified and referred to one of the three main categories. Secondly, a minimum of 200 palynomorphs were identified and referred to one of the groups: microspores, non-saccate pollen, bisaccate pollen, freshwater algae, acritarchs, dinocysts. The general environmental significance of these categories and groups are shown in Table 1 and 2. For more detailed discussion of the methodology and principles of palynofacies, the reader is referred to Dybkjær (1991, appendix F), Tyson (1995) and Batten (1996).

Results

The dinocysts recorded from the Dykær-profile is shown in Fig. 5. The ages of the sequences, based on the occurrences of dinocysts, are discussed on p. **xx-yy.**
The general results from the palynofacies study from the Dykær and Hindsgavl-profiles are shown in figs. 6 and 7. The results from the other outcrops are presented in Appendix 1. The results and the interpretations are referred in the following description and interpretation of each sequence and parasequence.

Sedimentology and sequence stratigraphy

A total of 11 outcrop sections form the basis for this study (Fig. 2). The distribution of the outcrops is tentatively perpendicular to the NW – SE trending palaeoshoreline (Fig. 3). Consequently, most marine deposits are found in the south-western part of the study area.

The Upper Oligocene – Lower Miocene succession is bounded by two major unconformities. The lower boundary separates Middle Eocene marls from Upper Oligocene glaucony-rich sediments (Larsen & Dinesen, 1959; Heilmann-Clausen *et al.*, 1985; Dybkjær & Rasmussen, 2000). The upper boundary corresponds to the Quaternary unconformity. The succession is subdivided into 3 sequences. These sequences are, when possible, further subdivided into shoaling-upward units bounded by flooding surfaces, i.e. parasequences.

Sequence A

This sequence is dominated by intensively bioturbated, greenish silty clay. In the upper part some fine-grained sand beds may occur. It has not been possible to subdivide the sequence into parasequences firstly due to bioturbation which has destroyed any primary sedimentary structures and secondly because it represents a condensed section of Upper Oligocene deposits within the study area (Rasmussen, 1987; 1996).

Description

The lower boundary is distinct and separates greenish-grey marls from glaucony-rich and organic-rich mud (Fig. 4). The lower part of the succession is characterised by bioturbated mud with rip-up clasts, pyritised burrows and large amounts of glaucony. Upwards, the section becomes more silty with intercalation of sand beds. Some of the sand beds are cross-stratified and consist of iron oolites. Distinct horizons with siderite concretions occur and locally the sand beds are cemented by siderite. In the northeastern part of the study area (e.g. at Dykær Fig. 4), the upper boundary is placed at the base of a thin gravel layer, with clasts up to 3 cm. Elsewhere, this boundary is characterised by a change from glaucony-rich clay with a low content of organic matter to dark, silty/sandy clay, rich in organic matter and with a low content of macrofossils.

The sedimentary organic particles are dominated by palynomorphs in the lower part and by brownish AOM and palynomorphs in the upper part of the sequence. Among the palynomorphs, bisaccate pollen are dominant. Dinocysts occur in all samples. The relative abundance and the diversity of dinocysts decreases distinctly from the lower part of the sequence towards the upper part, both at Jensgård and Dykær (Figs. 4, 6; Appendix 1). The relative abundance of non-saccate pollen and freshwater algae (*Botryococcus* and *Pediastrum*) increases in the upper part (Figs. 5, 6).

Interpretation

The lower boundary represents a major hiatus separating the Upper Eocene Søvind Marl from the Upper Oligocene – Lower Miocene Vejle Fjord Formation (Larsen & Dinesen, 1959; Heilmann-Clausen *et al.*, 1985). Previous palaeontological investigations of the succession, including studies of the foraminifera and mollusc assemblages, all indicate a fully marine depositional environment in the lower part of the Brejning Clay, while decreased marine influence (lowered salinity and circulation) and shallower water depths were suggested by (Larsen & Dinesen, 1959) based on changes in the foraminifer-assemblage.

The high content of glaucony in the lower part of Sequence A indicates a sediment starved, open marine depositional environment (Odin & Matter, 1981; Rasmussen, 1996). The shallower water depth in the upper part probably resulted in winnowing and reworking of iron ooids. These iron oolites were then deposited during lower sea level stand. A brackish water environment or even subaerial exposure prior to deposition of sequence B could explain the high siderite and goethite content in the upper part of the sequence. The upper boundary of the sequence is placed above the oolitic ironstone (Fig. 4) which is often interpreted to form the roof of a regressive phase (Van Houten & Purucker, 1984).

The abundance of bisaccate pollen and the occurrence of a diverse dinocyst assemblage in the lower part strongly indicate a nearshore, fully marine depositional environment. The distinct decrease in relative abundance and diversity of dinocysts in the upper part of the sequence indicates an increased freshwater influx. This is supported by the increase in abundance of non-saccate pollen and of freshwater algae. In spite of the high relative abundance of brownish AOM in the upper part of the sequence, the depositional environment does not generally appear to have been anoxic, as bioturbation occurs in this interval and benthic molluscs and foraminifera are present. The high preservation of the organic matter probably result from a high influx of terrestrial organic matter and a high sedimentation rate combined with a reduced circulation.

The lower part of Sequence A was deposited in a fully marine, sediment-starved basin. During deposition of the upper part of the sequence more shallow water conditions prevailed and an increase in sediment supply, including freshwater and terrestrially derived organic matter occurred. The development of a brackish water environment is interpreted to have resulted from a combination of the topography of the Ringkøbing – Fyn High and a sea-level fall. The increase in sediment supply seen in the upper part of the sequence heralded the progradation of major sedimentary wedges from the Fennoscandian Shield during the Miocene (Rasmussen, 1961).

Sequence B

Sequence B consists of 4 parasequences, all of which show a shallowing-upward tendency. The flooding surfaces are, where possible, defined where upper shoreface sand is overlain by marine clay or lower shoreface sand, but distinct changes in palynofacies, for example an increase in dinocyst diversity and in the relative abundance of dinocysts or a decrease in the relative abundance of non-saccate pollen and freshwater algae, are also used as a criterion. The basal sequence boundary is defined where a regional change from a fully marine to a restricted, possibly brackish water depositional environment can be recognised in the fauna (Larsen & Dinesen, 1959) and in the palynofacies (Figs. 5, 6). Locally, where a thin gravel layer is present, the boundary is placed at the base of this layer.

Parasequence 1

Description

This parasequence is in the south-western and central parts of the study area (Hindsgavl, Hvidbjerg, Skansebakke, Sanatoriet) dominated by homogenous, organic-rich mud (Figs 4, 8a). Laterally, towards the north-east (Dykær, Jensgård), the muds are intercalated with laminated sand showing minor bioturbation (Fig. 8b). These sand-rich intervals show a systematic variation in the dominance of sand and mud; scours are locally common within this interval (Fig. 8c). In detail, these beds show a rhythmic thick thin alternation of sand beds separated by mud layers, especially at Jensgård (Fig. 8d). The thick sand beds show normal grading. At Jensgård, large fine-grained hummocky cross-stratified sand beds are present (Fig. 8e). These beds are characterised by a sharp base, well-sorted structure less sand in the lower part grading up into laminated sand with low angle internal truncation surfaces. The sand beds have a wave-rippled top (Fig. 8f).

The sedimentary organic particles are dominated by terrestrial palynomorphs, while brownish AOM occurs commonly although showing variable abundances (Fig. 6). Among the palynomorhps bisaccate pollen dominates. Dinocysts occur in all samples, generally with low abundances and diversities. The dinocyst assemblage at Dykær is dominated by *Homotryblium plectilum* and *Spiniferites* (Fig. 5). At Skansebakke, *Homotryblium tenuispinosum* dominates. At Dykær, the abundance of dinocysts is highest in the middle part of the parasequence (Fig. 6). In the upper part, the relative abundance of dinocysts is low while the abundance of freshwater algae is relatively high, especially the brackish-water tolerant *Botryococcus*. At Skansebakke the relative abundance of dinocysts is generally lower than at Dykær. Here the relative abundance of dinocysts shows a distinct decrease towards the top of the parasequence (Fig. 4; Appendix 1).

Interpretation

The organic-rich homogenous section was probably deposited below wave base. The occurrence of alternating sand and mud layers in the north-eastern part of the study area, with evidence of diurnal inequality and spring – neap cycles, points towards a tidal influence (Nio & Yang, 1991). These alternating thick and thin sand beds were deposited from suspension in connection with turbid tidal currents in a distal setting below wave base (Williams, 1991). In these rhythmic deposits the thick sand beds were laid down by the dominant current and the thin during the subordinate current, the mud layers accumulating during the slack-water period. The lack of bioturbation in the sand-rich intervals in the extreme north-eastern part (the outcrops at Dykær and Jensgård) indicates a high sedimentation rate in this area. At Jensgård, where hummocky cross-stratified sand beds are intercalated with the tidal influenced sediments and where scours are frequent, a strong influence of oscillatory processes must have been superposed on tidal deposition in connection with storms (Southhard *et al.*, 1990; Cheel & Leckie, 1993). The increased influence of wave action at Jensgård, reflecting a shallower water depth, could indicate a topographic influence on deposition at this locality, such as the main fault of the Horsens Graben (Fig. 3).

The dominance of terrestrial palynomorphs combined with the presence of marine dinocysts in all samples (Figs. 6, 7) indicate a marine depositional environment with a high influx of terrestrial organic matter. The common occurrence of brownish AOM indicates a high influx of terrestrially derived organic matter and restricted circulation, but the intensive bioturbation of the homogenous mud deposits indicates that anoxic conditions cannot have prevailed. The generally low dinocyst abundances and diversities and the dominance among the dinocysts of the genus *Homotryblium* indicates a restricted marine depositional environment (Brinkhuis, 1994), probably a brackish water environment in this case. A general shallowing-upward trend towards the upper boundary is indicated by the decrease in the relative abundance of dinocysts at Dykær as well as at Skansebakke and is further supported by the increase in the relative abundance of freshwater algae at Dykær (Fig. 4, 6).

The dominance of mud-dominated brackish-water deposits in Parasequence 1 also on a regional scale (Rasmussen, submitted) points towards significant palaeotopographic control. The succession is consequently interpreted to represent deposition within a tidally influenced restricted basin (silled subbasin) with seasonal storms.

Parasequence 2

Description

In the southwestern part of the study area (Hindsgavl), Parasequence 2 comprises alternating black mud and grey, fine-grained sand beds (Fig. 4). Scours are common. The sand beds often show erosive and sharp basal contacts. The unit includes wave rippled sand, climbing ripples, laminated beds showing a thick/thin alternation of sand laminae separated by thin clay layers, and micro-hummocky cross-stratified sand interbedded with black clay (Figs 9a - c). Scours draped by mud are common (Fig. 9a). Discrete macro- hummocky cross-stratified sand beds with wave rippled tops occur especially in the middle part of the unit and both isotropic and anisotropic hummocks are present (Fig. 9b). The uppermost part of the parasequence is characterised by lenticular bedding and alternating clay and wavy sand beds. Current direction measured on ripple cross-laminated beds and anisotropic hummocky beds both indicate easterly directions.

In the central part of the study area (Skansebakke and Sanatoriet) alternating fine- to medium-grained sand and clay layers dominate. The sand beds are sharp based and commonly homogenous in the lower part becoming laminated upwards (Figs 9d, e) and some of the sand beds are hummocky cross-stratified. Wave ripples may occur in the uppermost part of the beds. Gutters filled with trough cross-stratified sand are also common (Fig. 9e) and convolute bedding of discrete sand beds occurs in the upper part of the parasequence (Fig. 9f).

In the north-eastern part (Dykær and Jensgård) organic-rich mud dominates. At Dykær, however, the upper levels of the parasequence consist of alternating sharp based, laminated sand beds and intensively bioturbated sand layers.

The sedimentary organic particles at Hindsgavl are dominated by bisaccate and non-saccate pollen and wood-particles. Dinocysts occur in all samples but constitute only 1.5-3% of the palynomorphs (Figs. 4, 7). The dinocyst assemblage is dominated by *Homotryblium tenuispinosum* and the diversity is low. The freshwater algae *Pediastrum* and *Botryococcus* occur commonly.

At Skansebakke, the organic particles are totally dominated by bisaccate pollen, most often torn apart (Appendix 1). The dinocysts comprise less than 0.5% of the palynomorphs (Fig. 4) and the dinocyst assemblage is dominated by *Homotryblium plectilum*. The diversity is very low. The brackish-water tolerant freshwater algae, *Botryococcus*, is common.

At Dykær, the organic particles are dominated by bisaccate pollen and brownish AOM. Upwards the relative abundance of wood-particles increases gradually while the abundance of palynomorphs decreases concurrently. Dinocysts occur in all samples (Figs. 4, 6). The dinocyst assemblage is dominated by *Homotryblium tenuispinosum* and *Spiniferites* (see Fig. 5). A distinct increase in both diversity and abundance of dinocysts can be seen from the uppermost sample in Parasequence 1 to Parasequence 2. In the middle part of Parasequence 2, lower abundances and slightly lower diversities was recorded. The uppermost part is characterized by high abundances but slightly lowered diversities of dinocysts, due to a strong dominance of *Homotryblium tenuispinosum* (Figs 5, 6).

Interpretation

The abundance of hummocky cross-stratified beds at Hindsgavl is interpreted to reflect a depositional environment dominated by storms (Dott & Bourgeois, 1982; Leckie & Walker, 1982). Sedimentary structures generated by both oscillatory and unidirectional currents, anisotopic hummockies and climbing ripples, indicate deposition under a combined flow storm regime (Swift, 1985; Nøttvedt & Kreisa, 1987). The evolution from a sharp based hummocky cross-stratified sand to climbing ripples and finally into aggrading ripples (Fig. 9d) was a result of a progressive decrease in energy during deposition (Seguret *et al.*, 2001). The high frequency of scours indicates periodically high turbulence within the water column. Beds showing diurnal inequality further indicate a tidal influence (Nio & Yang, 1991). The uppermost part, which is characterized by wavy and lenticular bedding is interpreted as tidal deposits (Reineck & Wunderlich, 1968).

In the central part of the study area (Skansebakke and Sanatoriet), Parasequence 2 is dominated by sharpbased sand bed interpreted as washover fans. Hummocky cross-stratified sand beds and beds with wave rippled tops are rare. Consequently the depositional environment was not dominated by oscillatory movements, but interpreted to represent washover fans within a back barrier depositional environment.

In the north-eastern part (Dykær and Jensgård) where organic-rich mud dominates the overall depositional environment was clam. However, the sand layers at Dykær are very similar to storm sand layers deposited in the recent Skagen Spit complex in ca. 10 m of water (Nielsen & Johannessen, 1998).

The dominance of wood particles and bisaccate pollen, the relatively high abundance of non-saccate pollen and the very low dinocyst abundance and diversity indicate a well-oxygenated environment with a high influx of freshwater at Hindsgavl and Skansebakke (Figs 4, 7).

At Dykær, the abundance and diversity of dinocysts show a distinct increase from Parasequence 1 to Parasequence 2, strongly indicating a marine flooding (Figs. 4, 6). The low relative abundance of dinocysts and the high abundance of bisaccate and non-saccate pollen in the middle part probably reflects an increased influx of freshwater. The general increase in wood-particles in the upper part probably reflects a gradual increase in energy level. The high relative abundance of dinocysts and acritarchs in the uppermost part of the parasequence probably reflects a change towards more open marine conditions. The relatively high abundance of freshwater algae (*Botryococcus*) indicate, however, a continuous influx of freshwater. The relative abundance of brownish AOM is clearly higher at Dykær than at Hindsgavl and Skansebakke (Figs 6, 7, Appendix 1). This probably reflects a more restricted marine, possibly lagoonal, depositional environment at Dykær.

In general, deposition took place in a restricted marine environment with a high influx of freshwater and of terrestrially derived organic matter. The above mentioned sedimentary structures, hummocky cross-stratification, frequent scours, beds showing diurnal inequality, and the high amounts of wood particles, pollen and freshwater algae indicated by the palynofacies study, points towards an outer estuarine environment for the southern part (Allen, 1991; Dalrymple *et al.*, 1992; Surlyk *et al.*, 1995), while deposition occurred in more protected, possibly lagoonal environments in the northern part of the study area.

Parasequence 3

Description

In the south-western part of the study area (Hindsgavl), the lower part of this unit is characterized by discrete hummocky cross-statified beds ca. 30 cm thick (Fig. 10a). These beds often show an ideal hummocky unit with a scoured base, a relatively thick H zone with several second-order surfaces, a thinner F zone, an X zone with wave ripples, and finally a M zone (Dott and Bourgeois, 1982) (Fig. 10a). Each bed is separated by an up to 2 cm thick light brown clay layer. Cut-off of clay layers and amalgamation occurs frequently. The hummocky cross-stratified sand are overlain by swaley cross-stratified sand beds (Fig. 10b) and sand beds characterized by a plan-laminated lower part and a wavy upper part. The base of the swaley cross-stratified beds are often pebbly. Upwards plan-laminated beds dominate and scattered pebbles are seen (at 9.5 m; Fig. 4). Heavy minerals are concentrated along the laminae. This is followed by a 40 cm thick plan-laminated bed with a high content of pebbles (Fig. 10c). The parasequence is capped by a section dominated by gently dipping laminated beds at the Hindsgavl locality (Fig. 4). The laminae dips towards the south-east.

In the central and northeastern part of the study area the base of the unit is characterised by a pebbly sand layer and in the borehole of Morsholt, shells were found at this level (Dybkjær & Rasmussen, 2000). The sedimentary structures recognised in this parasequence are dominated by flaser bedding and homogenous to laminated sand beds. The sand beds are locally bioturbated. At Dykær, a section of organic-rich muds is present in this parasequence (Fig. 4). The mud gradually changes upwards into alternating rippled sand and clay (Fig. 10d). The sand ripples often show bi-directional current directions (Fig. 10e).

The organic sedimentary particles at Hindsgavl show a distinct increase in the relative abundance of wood particles and in the relative abundance of dinocysts from Parasequence 2 to 3 (Figs. 4, 7). *Homotryblium tenuispinosum* dominates the assemblage.

At Dykær, the organic sedimentary particles are strongly dominated by brownish AOM which constitutes more than 90%. Among the few palynomorphs non-saccate pollen dominates. Dinocysts, mainly *Homotryblium tenuispinosum*, were however found in both samples (Fig. 5).

Interpretation

The distinct change in palynofacies at Hindsgavl across the Parasequence 2/Parasequence 3 boundary probably reflects a marked change towards more open marine conditions at the basal part of Parasequence 3. This corresponds to the relative sharp boundary from clay-dominated hummocky and rhythmic tidal dominated sediments of Parasequence 2 to thick hummocky and swaley cross-stratified sand-rich deposits of Parasequence 3. This transition probably represents a change from deposition under partly restricted conditions e.g. estuarine or bay environment to deposition under more open marine conditions. The evolution of hummocky cross-stratified beds from ideal hummocky beds, showing H to M zones, separated by thin clay layers to total amalgamation and stacked H – H zones with distinct erosional surfaces and swaley cross-stratification indicate an evolution from lower shoreface to upper shoreface on a storm dominated coast (Dott &

Bourgeois, 1982; Leckie & Walker, 1982; Surlyk & Noe-Nygaard, 1986; Walker & Plint, 1992; Cheel & Leckie, 1993). The occurrence of laminated pebbly sand beds overlain by gently dipping laminated sand of the top of the section demonstrates further deposition in the upper shoreface and swash zone (Miller & Ziegler, 1958; Clifton, 1969; Clifton, 1981; Harms *et al.*, 1975).

In the central and northeastern part of the study area (including Dykær), an evolution from open marine conditions in the lowermost part of the parasequence (not represented by samples for palynofacies) to a more restricted depositional environment occurred. The very high relative abundances of brownish AOM in the upper part of Parasequence 3 at Dykær strongly indicate a restricted marine environment, possibly lagoonal, with oxygen deficiency at the seafloor.
This is interpreted to be the result of the development of a spit complex at the bay entrance. The alternating sand and clay layers and reversal of ripple migration indicate tidal influence.

In general the depositional environment was fully marine over most of the study area. Towards the south lower and upper shoreface sand dominates. In the central part of the study area spit complexes formed and migrated towards the south-east. This resulted in mud-rich lagoonal deposition towards the northeast.

Parasequence 4

Description

The lower boundary of this parasequence is placed where medium- to coarse-grained sand is sharply overlain by fine- to medium-grained sand beds (Fig. 4). In the south-western part of the study area (Børup), this parasequence is characterised by a series of fining-upward units consisting of a relatively thick (20-30 cm) laminated fine-grained sand bed capped by wave ripples (Fig. 11a). The F-U units are overlain by alternating laminated and wave rippled sand beds with occasional scour and fill, some of which are 20 cm deep and several metres wide. An upward widening of troughs towards the overlying laminated sand layer occurs. Upwards, each cycle is dominated by thin bioturbated sand beds separated by a clay layers and flaser bedding. Scours with a fill of pebbly sand occur sporadically at the base of each unit. The cyclic bedding evolved into a ca. 2 m thick medium-grained, weakly laminated sand. The laminae dip towards the SE of ca. 2^0. The uppermost part of this unit is trough cross-bedded. Sporadically burrows of *Ophiomorpha* occur.

In the central part of the study area, at Pjedsted, medium scaled cross-stratified beds showing bundles and clay drapes are common (Fig. 11b, c). The clay drapes are concentrated in the lower part of the foresets and clay balls and rip-up clasts are frequent. The clay drapes often show thick/thin alternations. Reactivation surfaces on top of the beds are often seen (Fig. 11d). The current directions measured on the forsets of the 2-D dunes indicate a SW direction. The upper part of the section is characterised by ca. 4 m of laminated sand. Discrete beds are sharp based and the tops are locally wave rippled. Some of the bed boundaries are gently curved (convex upward). Rip-up clay clasts are common found and scattered burrows of *Ophiomorpha* occur.

At Dykær, 6 m section of inclined beds are exposed (Fig. 11e). The dip of the beds is 20^{o}. These beds consists of medium-scale trough cross-bedded pebbly to coarse- and medium-grained sand. The trough cross-bedded section is arranged in four fining-upward units. Each unit generally thickens and coarsens upwards. Palaeocurrent data from on cross-stratified beds indicate flow towards the NE and the SW (Fig. 12). Burrows of *Ophiomorpha* are moderate and the walls are well consolidated.

The organic sedimentary particles from Pjedsted are dominated by wood particles and bisaccate pollen and show very low abundances of non-saccate pollen (Appendix 1). The dinocysts comprise 1-14% of the palynomorphs, with a dominance among the dinocysts of the species *Glaphyrocysta* cf. *vicina*, while *Homotryblium plectilum* and *H. tenuispinosum* occur commonly. In addition *Botryococcus*, large spheres and several taxa of acritarchs occur commonly.

At Dykær, the organic sedimentary particles show a distinct change from the AOM-dominated samples below. In the lower part of Parasequence 4 palynomorphs dominate, mainly bisaccate and non-saccate pollen. In the uppermost of the studied samples AOM is common (Fig. 6). A distinct increase in dinocyst abundance and diversity is also seen from Parasequence 3 to -4.

Interpretation

The sharp based, laminated sand layers with wave rippled tops, found in the south-western part of the study area, record deposition during storms. They show similarities to storm beds deposited in ca. 10 m of water as described by Roep *et al.* (1979). The transition from narrow troughs towards wider troughs and finally laminated sand beds indicates increasing wave activity during deposition. The intensively bioturbated layers demonstrate that deposition was periodic and calm periods prevailed between storms or periods with storms (winter) allowing colonisation of burrowing animals. The scour and fill structures elongated perpendicular to the dip of the laminated storm beds are interpreted as runnels (Clifton *et al.*, 1971; Davidson-Arnott & Greenwood, 1976; Roep *et al.*, 1979). The uppermost part of the parasequence is interpreted as having been deposited in the swash zone and in beach runnels with migrating small 3-dimensional dunes.

In the central part of the study area, deposits related to a current dominated environment predominate. A strong tidal influence is indicated by the high frequency of bundles and prominent reactivation surfaces were formed in association with spring tides (Visser, 1980; Mowbray & Visser, 1984; Nio & Yang, 1991) (Figs. 11b-d). The south-westerly dip of foresets shows that the system was ebb-dominated as the generally trend of the shoreline was NW-SE (Rasmussen & Dybkjær, submitted). The upper part of the parasequence, which is dominated by planar laminated sand indicate energy conditions too high for the development of dunes and was probably deposited in a storm dominated upper shoreface environment. The inclined sand unit characterised by trough cross-bedded sand beds in the upper part of the section at Dykær is very similar to the deposits described from an estuarine channel complex by MacEachern and Pemberton (1994). The palaeocurrent directions N-S to NE-SW measured also indicate a system transverse to the trend of the shoreline. The dominance of northerly flow directions further indicate a flood dominated channel deposits.

The high abundance of wood particles at Pjedsted indicate an environment with relatively high energy. The dominance of bisaccate pollen relative to non-saccate indicates some distance to freshwater-sources while the co-occurrence of large spheres and acritarchs indicates a near-shore marine depositional environment. A low abundance of *Homotryblium* among the dinocyst assemblage indicates a more fully marine environment.

At Dykær, the marked change from a strong dominance of AOM in Parasequence 3 to a strong dominance of bisaccate and non-saccate pollen and brown wood in Parasequence 4 probably reflects a marine flooding. This is further supported by the distinct increase in dinocyst abundance and diversity.

The depositional environment was fully marine. In the southern and central part of the study area, upper shoreface sand dominates. At Pjedsted, an ebb-dominated tidal delta in front of the shoreline is recognised. In the northe-astern part, at Dykær, a flood-dominated tidal channel dominates the depositional environment.

Sequence C

Sequence C consists of two parasequences. The lower boundary with Sequence B is characterised by a regional unconformity (Fig. 4). At this boundary, a distinct change in lithology occurs from a dominance of fine- and medium-grained sand with few gravel layers below to gravel immediately above the boundary. The most coarse-grained beds are concentrated within erosional lows. Biostratigraphic data indicate a latest Chattian or early Aquitanian age for the section below the boundary and an early to mid-Burdigalian age for the sediments above the sequence boundary (Dybkjær & Rasmussen, 2000). A hiatus of at least 3.5 m.y. is thus represented by the sequence boundary between sequence B and C.

Parasequence 1

The base of this parasequence is very sharp and erosional, especially at Børup and Pjedsted (Figs 13a - c) and overlain by a gravel layer (Fig. 4). At Børup, the section consists of two gravel layers capped by strongly bioturbated medium-grained sand beds. The gravel layers are very poorly sorted with well-rounded clasts. The grain size distribution is 2 – 30 mm. The most coarse-grained part seems to be confined to erosional lows (channels). Bioturbation into the gravel layers is common. Each gravel layer shows a fining-upward trend and the upper sandy part of the unit is particularly intensively bioturbated. At Pjedsted, the sharp boundary is associated with a number of scours ca. 150 mm deep (Fig. 13c), which are filled with gravel with a grain size up to 50 mm. At Galsklint and Rønshoved the gravel layer is relatively thin ca. 250 mm and the grain-size strongly reduced (Fig. 4). At both the Galsklint and Rønshoved, ca. 2 m sand bed, which is strongly bioturbated in the upper part, occurs above the gravel layer. At all localities studied, the basal coarse-grained layer is sharply overlain by black, homogenous organic-rich silty clay (Fig. 4). The organic content is very high, 10-20 % (Rasmussen, 1995). In the south-western part of the study area, at Rønshoved, the organic-rich section is thinner and interbedded with thin sand streaks (Fig. 4). A thin cross-stratified sand layer is found in the upper part of the parasequence which dip towards the NE.

The sedimentary organic particles, both at Rønshoved and Hagenør are strongly dominated by brownish AOM (Appendix 1). Among the palynomorphs, pollen dominates totally, especially non-saccate pollen, while marine palynomorphs only occur sporadically (1-3%). Most of the recorded dinocysts are torn or otherwise physically degraded.

Interpretation

Rasmussen (1998) interpreted the base of the parasequence as a ravinement surface associated with a sequence boundary. This was confirmed subsequently by biostratigraphic data indicating a hiatus of at least 3.5 m.y. (Dybkjær & Rasmussen, 2000). The concentration of the most coarse-grained, well-rounded gravel and poorly sorted sediments confined to lows is interpreted to represent former fluvial channel fill which was reworked during storms as the sea transgressed the area (Leithold & Bourgeois, 1984; Plint, 1988; Rasmussen, 1998). The intense bioturbation of the sand and gravel layers is indicative of sediment starvation for a long period. The homogenous organic-rich deposits in the upper part of the parasequence are interpreted to represent lagoonal deposition due to the high content of brownish AOM and the dominance of non-saccate pollen. The few, often torn, dinocysts are interpreted mainly to have been washed into the lagoon during storms. The cross-stratified beds, dipping towards the NE in the upper part of this parasequence are interpreted represent a flood delta based on palaeogeographic considerations (see below).

Parasequence 2

Description

This parasequence sharply overlies Parasequence 1 (Fig. 4). At Rønshoved, Parasequence 1 is erosively overlain by hummocky cross-stratified sands (Figs 14a, b). These grade upwards into sand showing swaly cross-stratification and climbing ripples; the succession is capped by a homogenous sand bed (Fig. 14c). At Børup, Hagenør, and Galsklint, a medium- to coarse-grained sand bed of varying thickness (0. 25 – 1 m) is seen. Coarse-grained rippled sand has been recognised at the base of the sand layer, especially at Pjedsted (Fig. 4). At many localities, the sand bed is intensively bioturbated but at Galsklint, five discrete rippled sand layers occur within the section showing a thickening/coarsening upward trend (Fig. 4). The sand at Hagenør is capped by a coarse-grained ripple layer (Fig. 14d). Thin mud drapes are seen within these ripples. These coarse-grained ripples have a crest spacing of 0.5 – 1 m with amplitudes up to 30 cm. The crests of the ripples strike NW-SE. Cross-lamination within the ripples indicate flow towards the SW. At all outcrops except Rønshoved, a homogenous, organic-rich silty clay section overlies the sand (Fig. 4). This organic-rich layer is at Hagenør and Børup gradually overlain by sharp based, homogenous and laminated sand beds (Fig. 14e). The sand beds are often characterised by a wave rippled top occasionally showing bi-directional dips of cross-stratified ripples.

The sedimentary organic particles at Rønshoved show a distinct change from the samples representing Parasequence 1 to the sample representing Parasequence 2. In Parasequence 2 palynomorphs and wood particles dominate while AOM only occurs in minor amounts. The palynomorphs are dominated by bisaccate and non-saccate pollen but the dinocysts are much better represented here than in parasequence 1 (Appendix 1) and show a higher diversity and better preservation.

At Hagenør, the lower sample of this parasequence shows a dominance of palynomorphs, while brownish AOM occurs commonly. Among the palynomorphs, non-saccate pollen dominates while bisaccate pollen are common. The dinocysts generally show a slightly higher abundance, a higher diversity and better preservation than in Parasequence 1 (Appendix 1). The sedimentary organic particles in the upper sample are dominated by brown wood, but palynomorphs also constitute a major part of the sedimentary organic particles. Brownish AOM occurs only sporadically. Among the palynomorphs, bisaccate pollen dominates, while non-saccate pollen are common. Dinocysts occur only sporadically while acritarchs and freshwater algae occur in distinctly higher numbers than in the previous two samples (Appendix 1).

Interpretation

The base of Parasequence 2 is interpreted as a flooding surface on which fully marine conditions were established. This is indicated in the palynofacies study by the increase in the content of marine dinocysts (Fig. 4). The most marine conditions have been identified at the Rønshoved outcrop, where the amounts of marine increases distinctly along the transgressive surface of erosion. The strike of the coarse-grained ripples indicates a shoreline trending NW-SE (Leckie, 1988; Cheel and Leckie, 1993) which is compatible with the trend of the regional shoreline (Rasmussen & Dybkjær, submitted) and with the Rønshoved outcrop being located in the most offshore position. The wave rippled sand and gravel beds and hummocky cross-stratified beds indicate periods with storms. Some tidal influence is indicated by the mud drapes of the coarse-grained ripples and diurnal bedding. The climbing ripples at Rønshoved demonstrate a high sediment supply to the area. As for Parasequence 1, a spit was formed at the coast as a result of the longshore sediment supply. A restricted depositional environment was thus re-established and deposition of organic-rich muds resumed. The palynological data from Hagenør with very sporadic occurrences of dinocysts in the upper sample indicate that a brackish-water dominated environment prevailed throughout the succession; the sharp based and laminated sand beds interbedded in muds at Hagenør and Børup are thus interpreted as washover fans from a barrier-complex under progressive transgression (see also Friis *et al.*, 1998).

Stratigraphy and palaeogeography

Biostratigraphic data and correlation of keysurfaces of the succession in East Jylland provides the framework for a sequence stratigraphic subdivision (Fig. 4). Seismic data from Jylland also add to the understanding of the sedimentary architecture of the Upper Oligocene - Lower Miocene succession (Rasmussen, 1998). The general palaeo-shoreline during the early Miocene trended NW – SE with the major sediment input in the northern part, south of Norway (Michelsen *et al.*, 1998; Rasmussen, 1995; Rasmussen & Dybkjær, submitted). From the interpretation of the depositional environment, the succession in East Jylland represents the north-eastern limit of the Late Oligocene and Early Miocene North Sea basin during periods of high sea level. Initially, the basin was sediment-starved but during the latest Oligocene progressively more coarse-grained siliciclastic sediments were supplied into the area. The deposits bear many diagnostic features of a combined storm and tidal depositional environment: hummocky cross-stratification, coarse-grained ripples, washover fans, diurnal deposition and tidal bundles. Although there are only few unequivocal measurements of palaeocurrents in the succession; coarse-grained ripple crests strike NW – SE, spit systems prograded towards the SE, tidal bundles dip towards the SW, and tidal channel deposits indicate a dominent flow towards the NNE, these data all agree with the NW – SE-trending suggested by the seismic data (Rasmussen & Dybkjær, submitted).

Sequence A

The base of the investigated succession, the lower boundary of Sequence A, separates the Upper Eocene Søvind Marl Formation from the uppermost Oligocene – lowermost Miocene Vejle Fjord Formation. The lacuna at this surface spans most of the Late Eocene and the Oligocene and was probably the result of eustatic sea-level variations and tectonic movements during the Oligocene (Rasmussen, 1996; Clausen *et al.*, 1999). A regional transgression of the study area is testified by the deposition of the glaucony-rich, and fully marine Brejning Clay in the latest Chattian (Fig. 15a). The high content of siderite and goethite in the upper part of the Brejning Clay (Rasmussen, 1995) may indicate shallower water and even aerial exposure at the top of the sequence. A distinct change in the palynofacies also indicates an increased influx of freshwater in the upper part of the Brejning Clay. The maximum flooding surface is placed where the highest amounts of glaucony are found and also most K-enriched (Fig. 4) (Amorosi, 1995; Rasmussen, 1995). The sequence boundary defining the top of Sequence A is placed at the base of a gravel layer at Dykær and elsewhere where the palynofacies data indicate a change from marine to brackish water deposits (Fig. 4).

Age: Latest Chattian. The dinocyst assemblage in the deposits referred to Sequence A at Jensgård and Dykær is especially characterised by common occurrences of *Deflandrea phosphoritica* and *Chiropteridium galea* in the HST (Fig. 5). The assemblage is comparable to that recorded in Sequence A in the Addit Mark and Klovborg boreholes in the central parts of Jylland (Dybkjær, submitted, Figs. 3, 4), referred to the latest Chattian.

Sequence B

The base of Sequence B is not characterised by a distinct lithological change at all outcrops, but is recognizable in the palynofacies data by evidence of a change from fully marine conditions to a brackish water environment. The change is believed to reflect the influence of antecedant topography the Ringkøbing-Fyn High which formed a barrier between the open sea towards the south-west and restricted depositional conditions or even subaerial exposure north-east of the high during the lowstand of sea level (Fig. 15b). Above the sequence boundary, brackish water deposits predominate and these deposits represent the lowstand systems tract/transgressive systems tract. The lowstand systems tract is only represented by Parasequence 1. As a result of an increased sea-level rise transgressive back-barrier deposits were laid down, as revealed by Parasequence 2 (Fig. 15c). In the Lillebælt area more open marine conditions prevailed and sediments deposited under the influence of both storms and tidal processes dominated here. In the Vejle Fjord area deposits related to the backbarrier flat, such as washover fans are present. The washover sands originated from sand laid down along structures of the Ringkøbing-Fyn High during lowstand of sea level. Maximum flooding occurred at the base of Parasequence 3, where a marked increase in marine palynomorphs occurs (Hindsgavl, Dykær) (Figs. 4, 6, 7). At Morsholt, a shell layer is associated with the surface (Dybkjær & Rasmussen, 2000). Above the maximum flooding surface, two parasequences (3 and 4) constitute the highstand systems tract and reflect a gradual development of shorefaces and beaches with the most marine conditions towards the SW (Fig. 15d).

Age: Latest Chattian and/or early Aquitanian. The dinocyst assemblage in Sequence B of the present study is characterised by abundance of *Homotryblium* cysts (Fig. 5). Of stratigraphical significance is the sporadic occurrence of *Caligodinium amiculum*, *Chiropteridium galea* and *Membranophoridium aspinatum*. This assemblage compare to the dinocyst assemblage of Sequence B in a series of boreholes in the southern and central parts of Jylland, referred to the latest Chattian and/or early Aquitanian (Dybkjær, submitted).

Sequence C

The highstand systems tract of Sequence B is sharply overlain by a gravel layer. The gravel layer is interpreted to be the result of a fluvial depositional environment during falling sea level and lowstand of sea level and indicates a distinct change in depositional environment (Fig. 15e) (Rasmussen, 1998). Consequently the gravel was laid down during the lowstand and early transgression (Plint *et al.*, 2001). The period of sub-aerial exposure in this part of Jylland lasted most of the Aquitanian – early Burdigalian, corresponding to 3.5 m.y. (Dybkjær & Rasmussen, 2000). During this period, the coastline was displaced ca. 100 km towards the south-west, where it can be correlated with a delta south of the town of Ribe in South Jylland (Rasmussen, 1996; 1998). During the subsequent sea-level rise, the gravel bed was reworked by marine process so it now forms a ravinement surface at the base of the transgressive systems tract (Nummedahl & Swift, 1987). As a consequence of the transgression, marginal marine conditions were re-established in the study area (Figs 15f, 16a). The high degree of bioturbation in the sediments above the transgressive surface of erosion indicates a period of sediment starvation. Resumed sand supply to the area resulted in the accretion of spit/barrier-complexes and lagoonal conditions were established for a period (Fig. 16b). Minor variation in sea level or sediment supply resulted in a new flooding of the area and consequently, a flooding surface is placed at the lower boundary of the sand-rich sediments seen at Rønshoved, Galsklint, Hagenør (Fig. 4). The sand section above the flooding surface is generally strongly bioturbated, but locally shows several coarse-grained ripple layers arranged in a general coarsening/thickening upward trend. This section contains a rich marine fauna and is therefore interpreted to represent normal progradation into a marine realm (Fig. 16c). The marine sand is succeeded by organic-rich lagoonal mud (Hagenør) and therefore back-barrier conditions were re-established due to accretion of a new spit seaward (Fig. 16d). The succession terminates with a gradual increase in deposition of washover fans within lagoonal muds indicating renewed transgression of the barrier-complex (Fig. 16e). It is thus assumed that this part of the succession was deposited during rising sea level.

Age: Early to mid Burdigalian. The dinocyst assemblage is dominated by *Spiniferites* and *Systematophora* placacantha while no *Homotryblium* occur. The appearance of several new species, e.g. *Hystrichosphaeropsis obscura* and *Polysphaeridium zoharyi* and the presence of *Thalassiphora pelagica* and *Tityrosphaeridium cantharellus* are of stratigraphic significance (see rangechart for Hagenør and Rønshoved figure 4 in Dybkjær and Rasmussen (2000). This dinocyst assemblage is comparable to the assemblage recorded in Sequence C in the central and southern parts of Jylland, referred to the early to mid Burdigalian (Dybkjær, submitted).

The relationship between the succession in east Jylland and eustatic sea-level

During the Cenozoic time, periods of glaciations have occurred since the Eocene (e.g. Prentice & Matthews, 1988; Abreu & Anderson, 1998; Zachos *et al.*, 2001). Global sea-level changes may therefore be a major controlling factor in the development of the studied sedimentary succession. The sequences recognised in this study are thus compared to sea-level curves constructed by Prentice & Matthews (1988) and Zachos *et al.* (2001) based on oxygen isotope records. Comparison with climatic changes in Central Europe based on floristic changes (Lotsch, 1968) and periods of maximum glaciations during the Miocene (Miller *et al.* 1991;Wright & Miller, 1992) have also been made (Fig. 17).

During the latest Chattian, a distinct sea-level rise is indicated on the oxygen isotope curve (Fig. 17). This is in good agreement with the overall transgression resulting in the deposition of Sequence A. The indication of a sea-level fall near the Oligocene/Miocene boundary on the glacio-eustatic sea-level curve of Zachos *et al.* (2001) is also compatible with the development of the studied succession and probably responsible for the sequence boundary between sequences A and B. The timing of this sequence boundary also correlates with the glacial maximum Mi-1 of Miller *et al.*, (1991) and Wright & Miller (1992). A hiatus between Sequence A and B is not provem by the biostratigraphic data but is inferred. The resumed sea-level rise resulting in deposition of Sequence B possibly corresponds to the major sea-level rise in the late Chattian indicated on the sea-level curve of Zachos *et al.* (2001).

Above Sequence B a marked hiatus (ca. 3.5 m.y.) is indicated by the biostratigraphic data from the study area (Dybkjær & Rasmussen, 2000) corresponding to the lower sequence boundary of sequence C. On the sea-level curves of Prentice and Matthews (1988) and Zachos *et al.* (2001) a marked sea-level fall is recorded in the Early Miocene (Aquitanian – early Burdigalian) and a cool climate during this period is also indicated by floristic changes in Central Europe (Lotsch, 1968) (Fig. 17). This sea-level fall corresponds to the sequence boundary between sequences B and C and is further indicated by glacial maximum Mi 1a of Miller *et. al.* (1991)/ Wright and Miller (1992). This sea-level fall resulted in the displacement of the shoreline 100 km southwestwards (Rasmussen, 1998; Rasmussen & Dybkjær, submitted). The resumed rise of sea-level during the Burdigalian resulted in deposition of sequence C.

The above correlation between sea-level changes, climatic changes in Central Europe, periods with glaciations and the development of the sequences defined in this study show a significant interrelationship between eustatic sea-level changes and the formation of the studied succession in East Jylland.

Discussion

This study provides an integrated sedimentological and palynological investigation of paralic deposits. Deposition of the succession was strongly controlled by the palaeo-relief, eustatic sea-level changes and variation in sediment supply. Recognition of sequence boundaries and flooding surfaces is not straight forward due to a number of facts: 1) initially the area was sediment-starved and consequently the sequence boundary between sequences A and B is not developed in the classical fashion. This boundary is not marked by a regional facies change and is often recognisable solely on the basis of the change in depositional environment as revealed by the palynofacies study or in places where a thin gravel layer is sandwiched between two clay layers. 2) coarse-grained deposits were, however, locally laid down in the basinal areas during the lowstand of sequence B. These coarse-grained sediments were thus available during the succeeding transgression, partly to form spit systems in association with structural highs and partly to be redeposited as sand-rich storm layers interbedded in brackish water fine-grained sediments of the succeeding transgressive systems tract of sequence B. This has resulted in the atypical development of the maximum flooding surface between Parasequences 2 and -3 within sequence B; this surface is defined were fine-grained hummocky cross-stratified sand beds interbedded with mud are overlain by massive fine-grained hummocky cross-stratified sand beds deposited under fully marine conditions. The cause of the abrupt shift to fully marine conditions and the increase in storm wave activity was the flooding of structural highs in the area and increased free stretch. The latter causing increasing wave activity. Fully marine conditions were thus established over the whole study area for the first time within Sequence B during the deposition of Parasequence 3.

The development of these surfaces is discussed in more detail below in relation to the regional framework.

Antecedant topography

The development of Sequence A, the sequence boundary between A and B, and the lower part of Sequence B are of particular interest for a number of reasons. Firstly, Sequence A does not show the normal facies development of a sequence e.g. from offshore mud through sandy shoreface to beach deposits etc. due to the condense nature of the sequence. Secondly, the boundary between Sequence A and B does not have a distinct regional marker horizon such as a coarse-grained transgressive lag deposit. Thirdly the brackish water deposits of the lower part of Sequence B show an evolution similar to a transgressive lagoonal/barrier system, but in reality the brackish water environment was the result of both structural elements and the later formation of spit systems. The question here is how coarse-grained (sand) was supplied to this system without the above mentioned characteristics. There may be two reasons for this. 1) The major sediment input via deltaic systems was in the central part of Jylland, ca. 30 km away from the studied area, and consequently sand transport occurred along the coastline on the seaward side of the structural elements (Fig. 3). Therefore sand was continuously supplied to the system in the offshore area, but evidence cannot be traced in a dip-section as studied in eastern Jylland. 2) The coastline was sub-parallel with the Ringkøbing-Fyn High. During a late Oligocene transgression, clayey, glaucony-rich sediments were laid down in a fully marine environment because of high sea level. During the subsequent sea-level fall in the latest Oligocene, brackish water conditions prevailed in minor silled basins on the Ringkøbing-Fyn High and restricted conditions developed within these subbasins. During this lowstand, sand was supplied into the area both on the seaward side of structural highs and directly into the silled subbasins from the hinterland (Fig. 18a). As the sea-level rose, spit systems developed on the structural highs (e.g. Noe-Nygaard & Surlyk, 1988) and during the succeeding sea-level rise, these were reworked and deposited as washover fans and other storm deposits intercalated with the lagoonal mud (Fig. 18b). The evolution of this part of the succession was thus dependent on the interaction between the antecedant topography and the timing of major input of coarse-grained sediments (sand) into the study area (Fig. 18b, 18c).

Flooding surface or forced regression between Parasequence 2 and 3 (sequence B)

The sedimentological evolution from Parasequence 2 to Parasequence 3 is also atypical. At Hindsgavl, brackish water muddy sediments (semi-restricted environment due to the rough topography) alternate with hummocky cross-stratified beds (Fig. 9b). Upwards these are overlain by sand-rich hummocky cross-stratified deposits that were laid down in a fully marine environment (Fig. 10a). In the literature mud-rich hummocky cross-stratified beds overlain relatively abruptly by sand-rich hummocky and swaley cross-stratified beds are often interpreted to record a forced regression (e.g. Walker & Plint, 1992). In this case, however, the transition from clay-dominated hummocky cross-stratified deposits to sand-rich hummocky cross-stratified deposits at Hindsgavl is interpreted to record a flooding event rather than a facies shift associated with a sea-level fall. The sedimentological interpretation is illustrated in Figure 18c. This flooding event can be traced over the whole study area as a sharp boundary between back barrier deposits and the succeeding marine sands of Parasequence 3 (Fig. 4). The interpretation is suggested particularly by the increase in relative abundance of marine dinocysts across this boundary at Hindsgavl and the closely located outcrops at Pjedsted and Skansebakke (Fig. 4). This again is a complex interaction between structural elements, sea-level changes, and the influx of coarse-grained sediments into the study area.

The location of the maximum flooding surface between Parasequences 2 and 3 (Sequence B) and the interpretation of a highstand system tract above this surface rather than a forced regressive systems tract, is consistent with the regional correlation shown in figure 19. In this figure the evolution of sequences A, B and C (in part) is shown from 10 boreholes in central Jylland. On this section (Fig. 19), the highstand systems tract is characterised by normal progradation with the frequent alternation of sand lobes and clay deposits (between the Addit and Bastrup boreholes) and this part correlates to the section studied here. South of this, massive sand is recognised in all boreholes (Rødding to Arnum-1). This part is interpreted to represent the forced regressive systems tract of sequence B. Southward, this is followed by the lowstand systems tracts of sequence C described by Rasmussen (1998). Finally, the transgressive systems tract of sequence C covers the whole section (Fig. 19).

Sequence boundary between Sequences B and C

The most important surface in the correlation of the succession in east Jylland is the sequence boundary between Sequences B and C. This boundary is characterized by a distinct sedimentological facies change where a gravel layer is sandwiched by fine- to medium-grained sand. The gravel layer can be followed from the Lillebælt area over the Vejle

Fjord area (Fig. 4) to the Morsholt borehole (Dybkjær & Rasmussen, 2000). A regionally distributed coarse-grained layer is here recognised for the first time. This development show that a complete suite of sediments were available and consequently coarse-grained lag-deposits from now of (within Sequence C) marks important environmental changes. The final introduction of coarse-grained material was the result of ca. 3.5 my years of sea-level lowstand, which lasted most of the Aquitanian and resulted in deposition of fluvial sediments in east Jylland (Dybkjær & Rasmussen 2000).

Friis *et al.* (1998) interpreted this gravel layer as a transgressive lag deposit associated with a landward migration of a barrier complex in a more or less stable depositional situation confined to east Jylland. However, they never explained how pebbles up to 50 mm across were transported into the area. Observations from more than 100 boreholes penetrating the shoreface – beach zone of the regressive shoreline of the Middle Miocene Odderup Formation in Denmark indicate grain sizes of up to 20 mm during normal progradation (highstand). This is also consistent with the grain size distribution in the upper part of the highstand deposits of Sequence B in this study. Such a distinct change in grain size commonly marks a major change in deposition, e.g. fluvial deposition and/or by pass during lowstand (Plint, 1988). In the Lower Miocene of Denmark, this gravel layer indicate a major displacement (100 km) of the shoreline into the basin (Fig. 19) and consequently predict the sand-rich delta found in the regional mapping of the succession. This was interpreted by Rasmussen (1998) based on sequence stratigraphic principals, but in paralic sediments, where similar sedimentological facies are repeated several times the use of palynology is a fundamental tool, i.e. the recognition of the hiatus of 3.5 m.y. between Sequences B and C. The conclusion of this study, that the succession in east Jylland is builed up by unconformity separated units is vital for the interpretation of the sedimentological evolution of the succession and for the development of sedimentological models.

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FIGURES

Figure 1. *Lithostratigraphy of East Jylland (from Dybkjær and Rasmussen 2000).*

Figure 2. *Location of the studied outcrops.*

Figure 3. *The approximal trend of the shoreline during high sea level during the Late Oligocene – Early Miocene (Jordt et al. 1995; Rasmussen 1996; Rasmussen and Dybkjær submitted). The location of the Ringkøbing – Fyn High is also shown.*

Figure 4. *Correlation panel of the studied sections. Note that the relative abundance of marine dinocysts is indicated by a bar on the left side of the sections.*

Figure 5. *Dinocyst-assemblages and freshwater algae in the Dykær-profile. The sequence stratigraphic boundaries are indicated. Modified from Dybkjær (submitted, Fig. 10).*

Figure 6. *Variations in palynofacies of the Dykær-profile. The sequence stratigraphic boundaries and the interpretations of the depositional environment is indicated. Modified from Dybkjær (submitted, Fig. 11).*

Figure 7. *Variations in palynofacies of the Hindsgavl-profile. The sequence stratigraphic boundaries and the interpretations of the depositional environment is indicated. Note the distinct increase in relative abundance of dinocysts in the lower part of Parasequence 3.*

Figure 8. *Parasequence 1; Sequence B. (a) Organic-rich mud deposited in a brackish water environment (scale is 2 m)(Sanatoriet). (b) Interbedded organic-rich mud and laminated sand and mud (Dykjær). (c). Rhythmic laminated sand and mud reflecting neap and spring tidal variation. Note that the section is intensively faulted due to glacial tectonics (pencil for scale) (Jensgård). (d) Close-up of c showing diurnal inequality of the beds. Double clay layers are indicated by arrows. (e) Hummocky cross-stratified beds intercalated in tidal deposits (Jensgård). (f) Close-up of a hummocky cross-stratified bed. Internal second order surfaces are indicated by arrows (Jensgård).*

Figure 9. *Parasequence 2; Sequence B. (a) A section dominated by hummocky cross-stratified beds. Note that the beds are frequently scoured and often draped by mud. Note also the bed showing diurnal inequality (rule for scale)(Hindsgavl). (b) Hummocky cross-stratified sand beds interbedded in wave-influenced heterolithic clay and sand. Note the bed in the middle part of the photo shows scour and drape. The drape above the second order scoured surface (arrows) shows anisotropy indicating combined flow regime (spade for scale)(Hindsgavl). (c) Hummocky cross-stratified sand in a wave influenced heterolithic sand and clay. Some of the hummocky sand are laterally passing into wave ripples (Hindsgavl). (d) Hummocky cross-stratified sand bed grading upward into climbing ripples and further into aggrading ripples (Hindsgavl). (e) Discrete washover fan characterised by a sharp lower boundary and homogenous to laminated internal structures (pencil for*

scale)(Skansebakke). (f) Gutter cast (upper part) and a discrete washover fan (Skansebakke). (f) washover fan showing convolute bedding (pencil for scale)(Skansebakke).

Figure 10. *Parasequence 3; Sequence B. (a) Discrete hummocky cross-stratified bed. Note the sharp transition from alternating sand and mud layers in the lower part to dominantly alternating sand beds in the upper part. This boundary forms a transgressive surface (hand for scale)(Hindsgavl). (b) Swaly cross-stratification. Note that the stratification is relatively flat. The swales are indicated by arrows (Hindsgavl). (c) Pebbly sand with laminated bedding (Hindsgavl). (d) Organic-rich mud with few intercalated thin sand beds passing upwards into tidally influenced sand (spade for scale)(Dykjær). (e) Details from the tidally influenced sand (Fig. 7d). Note the reverse of cross bedding indicated by arrows (Dykjær).*

Figure 11. *Parasequence 4; Sequence B. (a) Laminated sand beds topped by wave ripples. Note the upward widening of troughs below the overlying laminated sand bed in the middle part of the photo. The upper part is dominated by thin laminated sand beds alternating with intensively bioturbated layers (Børup). (b) Tidal bundles (Pjedsted). (c) Tidal bundles showing spring – neap cycles indicated by alternating sand dominated intervals and clay drapes on forsets (Pjedsted). (d) Scour and fill deposits. Note the reactivation surface on the top of a tidal dune indicated by an arrow (Pjedsted). (e). Small scaled trough cross-stratified sand with moderate bioturbation of Ophiomorpha. Note the dip of the strata (arrows) indicating a progradational sand body (Dykjær).*

Figure 12. *Rose-diagram presenting measurements of tabular cross-beds at Dykær. See also Fig. 4.*

Figure 13. *Parasequence 1; Sequence C. (a) Laminated to trough cross-stratified shoreface sand cut by a pebble layer. The erosive base forms the sequence boundary between Sequence B and C. The size of the pebbles at this locality (Børup) are up to 3 cm (b) The sequence boundary at Pjedsted. Here the grain size are up to 5 cm. (c) Details of the scoured surface (arrow) and gravel filled borrows (Pjedsted).*

Figure 14. *Parasequence 2; Sequence C. (a) In the lower part of the photo tidally influenced bedding showing both diurnal inequality and neap-spring cycles of parasequence 1 is seen. Above the transgressive surface of erosion (TSE) wave influenced marine laminated mud and sand dominates (Rønshoved East). (b) Lagoonal deposits overlain by marine sand. The boundary forms a transgressive surface of erosion (TSE). Note the prominent hummocky cross-stratified bed sharply overlying the gently dipping sand – mud layer. Internal truncation surfaces are indicated by arrows (Rønshoved West). (c) Alternating hummocky cross-stratified sand beds and climbing ripples. In the extreme upper part of the photo a sand bed characterised by low angle cross-stratification is seen. The base of this sand bed represents a regressive surface of erosion. (Rønshoved East). (d) Intensively bioturbated marine influenced sand bed sandwiched in lagoonal mud. The sand bed can be traced regionally and thus represent a transgressive surface (Hagenør). (e) Alternating sand and clay beds. The sand beds are often sharp based and laminated with a rippled top. Some of the ripples interbedded in the muds indicate tidal influence (Hagenør).*

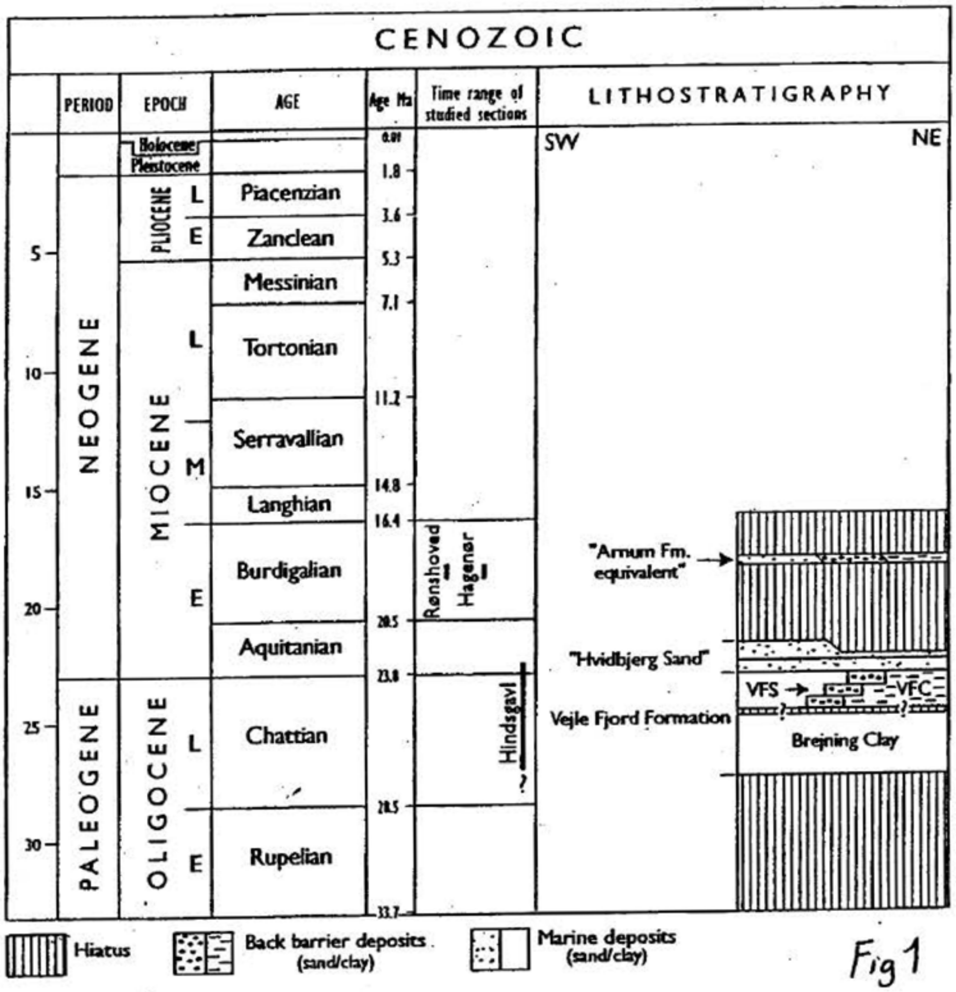
Figure 15. *Paleogeographical reconstruction during the Late Oligocene – Early Miocene. (a) During the late Chattian open marine condition prevails in the study area. The area was sediment starved and ideel conditions for glaucony formation was present.(b) At the Chattian/Aquitanian boundary lowstand of sea level resulted in subaerial conditions in the study area and locally deposition of gravel occurred. Some of the glaucony was oxigenised to goethit and siderite formation to place within the sediments. (c) During the early Aquitanian structural highs controlled the depositional environment. Note that sand was deposited in association with high and near the hinterland. (d) The early Aquitanian sea-level rise resulted in withdrawal of the shoreline. Spit complexes were formed in association with estuaries. (e) Most of the Aquitanian subarial conditions prevailed. (f) In the Burdigalian renewed sea-level rise resulted in deposition of barrier complexes in the study area.*

Figure 16. *Schematic illustration of the development of sequence B. (a) Transgression of the area resulted in the formation of a ravinement surface with overlying pebbly storm deposits. As a result of a period with sediment starvation intense colonisation of a marine fauna occurred and the sediments were strongly bioturbated. (b) Sediment supply into the area resulted in the development of spit/barrier systems with fine-grained deposits on the landward side of the systems. A continued rise in sea-level caused a resumed flooding of the area and backstepping of the shoreline. (c) Subsequent progradation of the shoreline resulted in upward coarsening and thickening trend of the succession. (d) As a result of increased sediment supply due to a lower rate of relative sea-level rise during the deposition of the highstand system tract, resulted in the formation of a new spit/barrier system. (e) Slow backstepping of the system as a result of decreased rate of sea-level rise and increased sediment influx during the deposition of the late highstand.*

Figure 17. *Correlation of the sequences of this study and tectonic phases, glacial maxima, and glacio-eustatic sea-level changes.*

Figure 18. *Schematic reconstruction of the development of Parasequences 3 and 4 which is separated by a maximum flooding surface. (a) During lowstand of sea level the structural high formed a barrier and deposition of large brackish water hummockies took within the silled basin. Some sand deposited during the lowstand was reworked and deposited adjacent to the high in the early phase of transgression. (b) Successive rise in sea level resulted in the development of a spit system on the structural high due to alongshore transport of sand from a delta located ca. 30 km west of the study area. (c) Complete drowning of the strauctural high and establishment of fully marine conditions in the study area. Deposition of marine sand-rich hummockies occurred above brackish water hummockies. Note that the accomodation space decreased inrespectable of the sea-level rise because the high sediment supply to the area resulted in a high sedimentation rate and filling of the topographic lower behind the structural high.*

Figure 19. *Correlation of the studied section in East Jutland to the regional development of the uppermost Oligocene to Lower Miocene succession.*


CENOZOIC
PERIOD
EPOCH
AGE
Age Ma
Time range of studied sections
LITHOSTRATIGRAPHY
SW
NE
Holocene
Pleistocene
NEOGENE
PLIOCENE
L
E
Piacenzian
Zanclean
MIOCENE
L
M
E
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
PALEOGENE
OLIGOCENE
L
E
Chattian
Rupelian
0.01
1.8
3.6
5.3
7.1
11.2
14.8
16.4
20.5
23.8
28.5
33.7
5
10
15
20
25
30
Rønshoved
Hagenør
Hindsgavl
"Arnum Fm. equivalent"
"Hvidbjerg Sand"
VFS
VFC
Vejle Fjord Formation
Brejning Clay
Hiatus
Back barrier deposits (sand/clay)
Marine deposits (sand/clay)
Fig 1

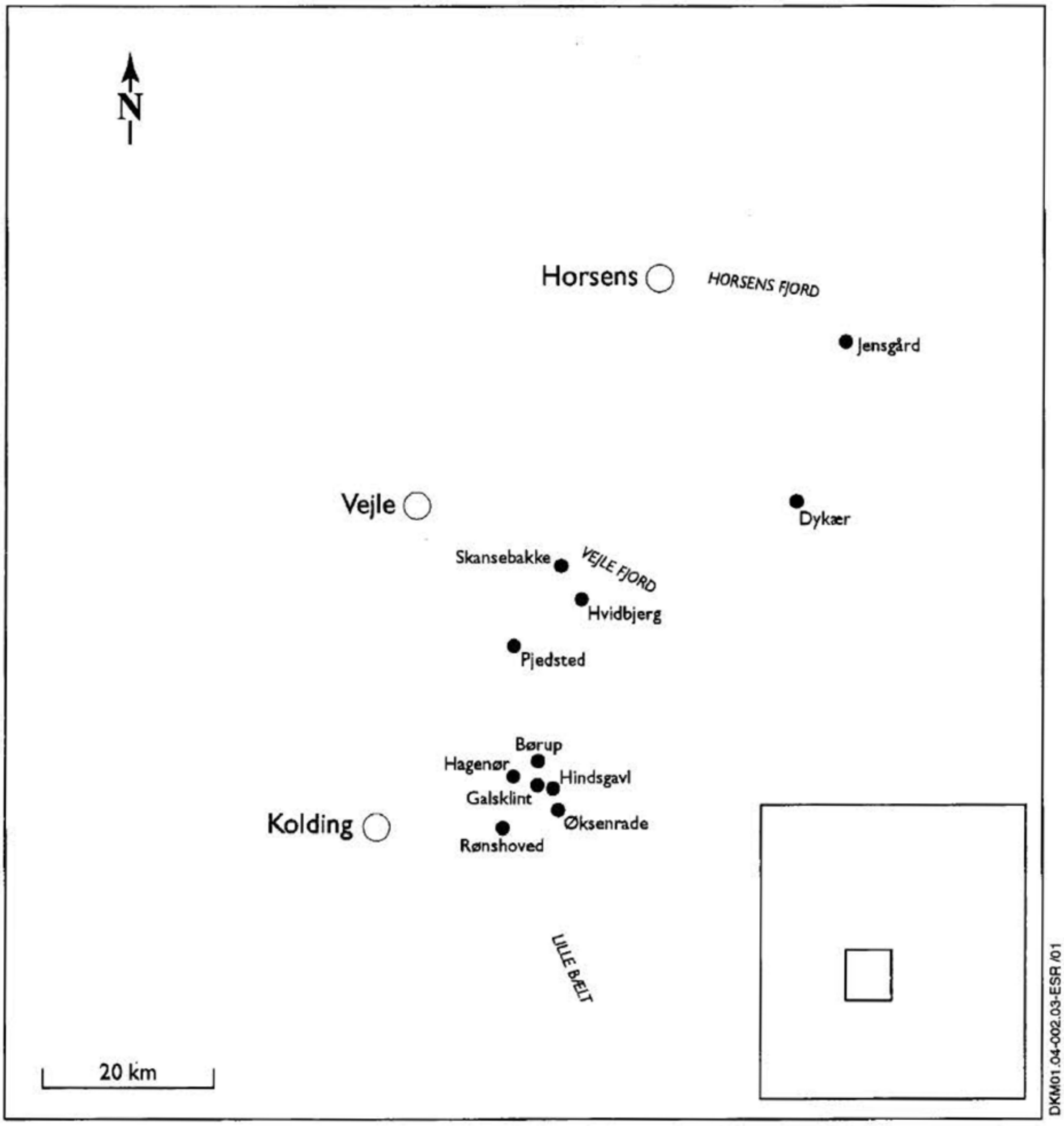

N
Horsens
HORSENS FJORD
Jensgård
Vejle
Dykær
Skansebakke
VEJLE FJORD
Hvidbjerg
Pjedsted
Børup
Hagenør
Hindsgavl
Galsklint
Kolding
Øksenrade
Rønshoved
LILLE BÆLT
20 km
DKM01.04-002.03-ESR /01

Fig 2

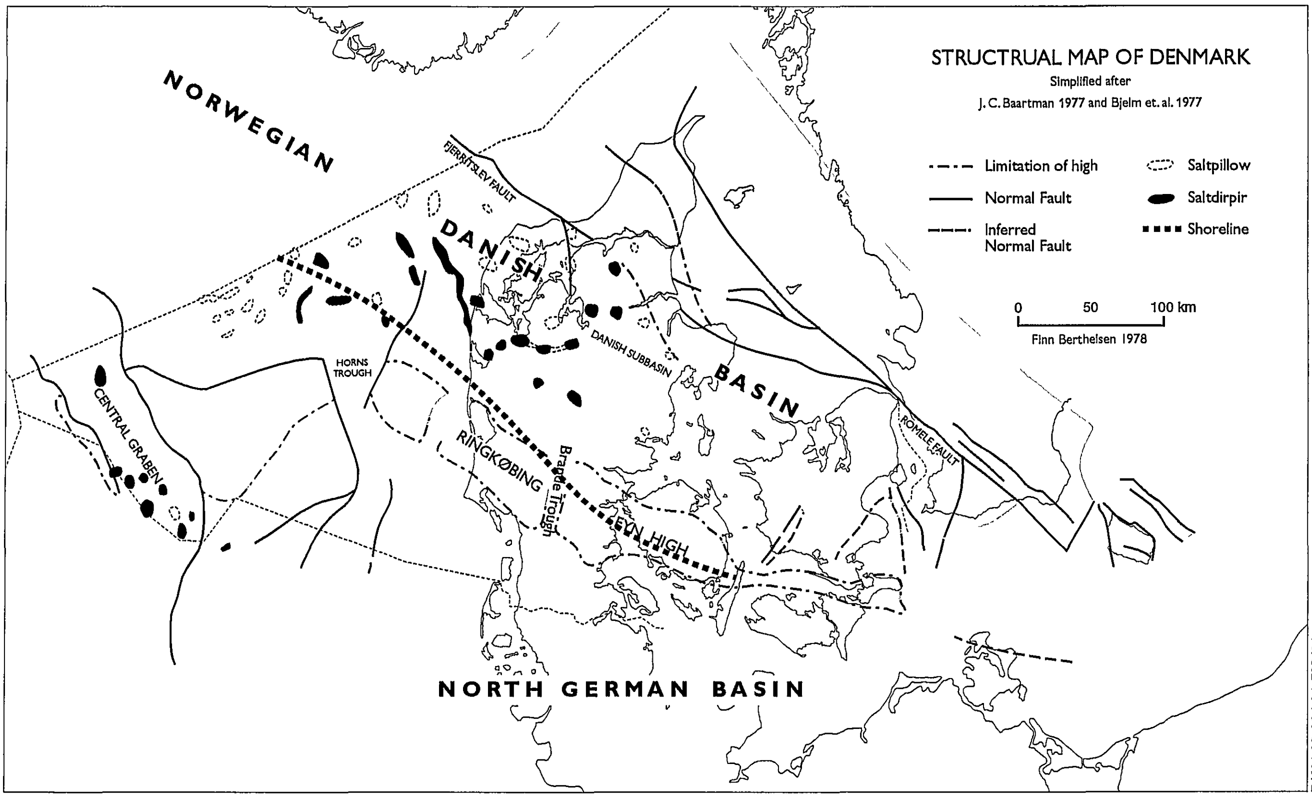
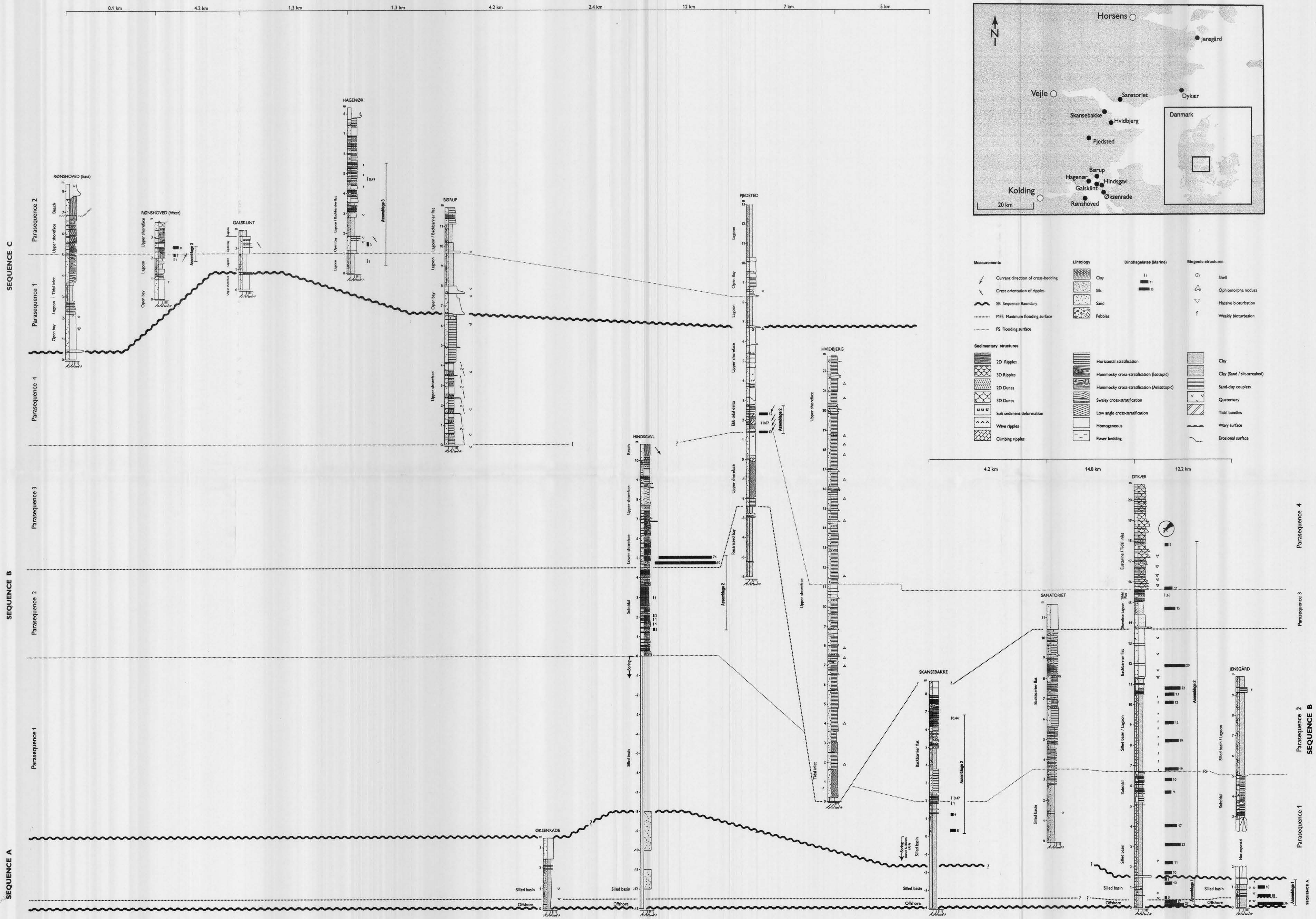

STRUCTRUAL MAP OF DENMARK
Simplified after
J. C. Baartman 1977 and Bjelm et. al. 1977
Limitation of high
Normal Fault
Inferred Normal Fault
Saltpillow
Saltdirpir
Shoreline
0
50
100 km
Finn Berthelsen 1978
NORWEGIAN
DANISH
BASIN
DANISH SUBBASIN
FJERRITSLEV FAULT
HORNS TROUGH
CENTRAL GRABEN
RINGKØBING
Brande Trough
FYN HIGH
ROMELE FAULT
NORTH GERMAN BASIN
DK01.02-004.04-ESR/01

Fig 3


0.1 km
4.2 km
1.3 km
1.3 km
4.2 km
2.4 km
12 km
7 km
5 km
SEQUENCE C
SEQUENCE B
SEQUENCE A
Parasequence 2
Parasequence 1
Parasequence 4
Parasequence 3
Parasequence 2
Parasequence 1
RØNSHOVED (East)
RØNSHOVED (West)
GALSKLINT
HAGENØR
BØRUP
PJEDSTED
HVIDBJERG
HINDSGAVL
ØKSENRADE
SKANSEBAKKE
SANATORIET
DYKÆR
JENSGÅRD
Open bay
Lagoon
Tidal inlet
Upper shoreface
Beach
Lower shoreface
Subtidal
Silled basin
Offshore
Ebb tidal delta
Restricted bay
Backbarrier flat
Silled basin / Lagoon
Estuarine / Tidal inlet
Assemblage 1
Assemblage 2
Assemblage 3
Boring
Horsens
Jensgård
Vejle
Sanatoriet
Dykær
Skansebakke
Hvidbjerg
Pjedsted
Danmark
Børup
Hagenør
Hindsgavl
Galsklint
Kolding
Øksenrade
Rønshoved
20 km
N
Measurements
Current direction of cross-bedding
Crest orientation of ripples
SB Sequence Boundary
MFS Maximum flooding surface
FS Flooding surface
Lithology
Clay
Silt
Sand
Pebbles
Dinoflagellates (Marine)
Biogenic structures
Shell
Ophiomorpha nodosa
Massive bioturbation
Weakly bioturbation
Sedimentary structures
2D Ripples
3D Ripples
2D Dunes
3D Dunes
Soft sediment deformation
Wave ripples
Climbing ripples
Horizontal stratification
Hummocky cross-stratification (Isotopic)
Hummocky cross-stratification (Anisotopic)
Swaley cross-stratification
Low angle cross-stratification
Homogeneous
Flaser bedding
Clay
Clay (Sand / silt-streaked)
Sand-clay couplets
Quaternary
Tidal bundles
Wavy surface
Erosional surface
4.2 km
14.8 km
12.2 km
Parasequence 4
Parasequence 3
Parasequence 2
SEQUENCE B
Parasequence 1
SEQUENCE A
Fig 4

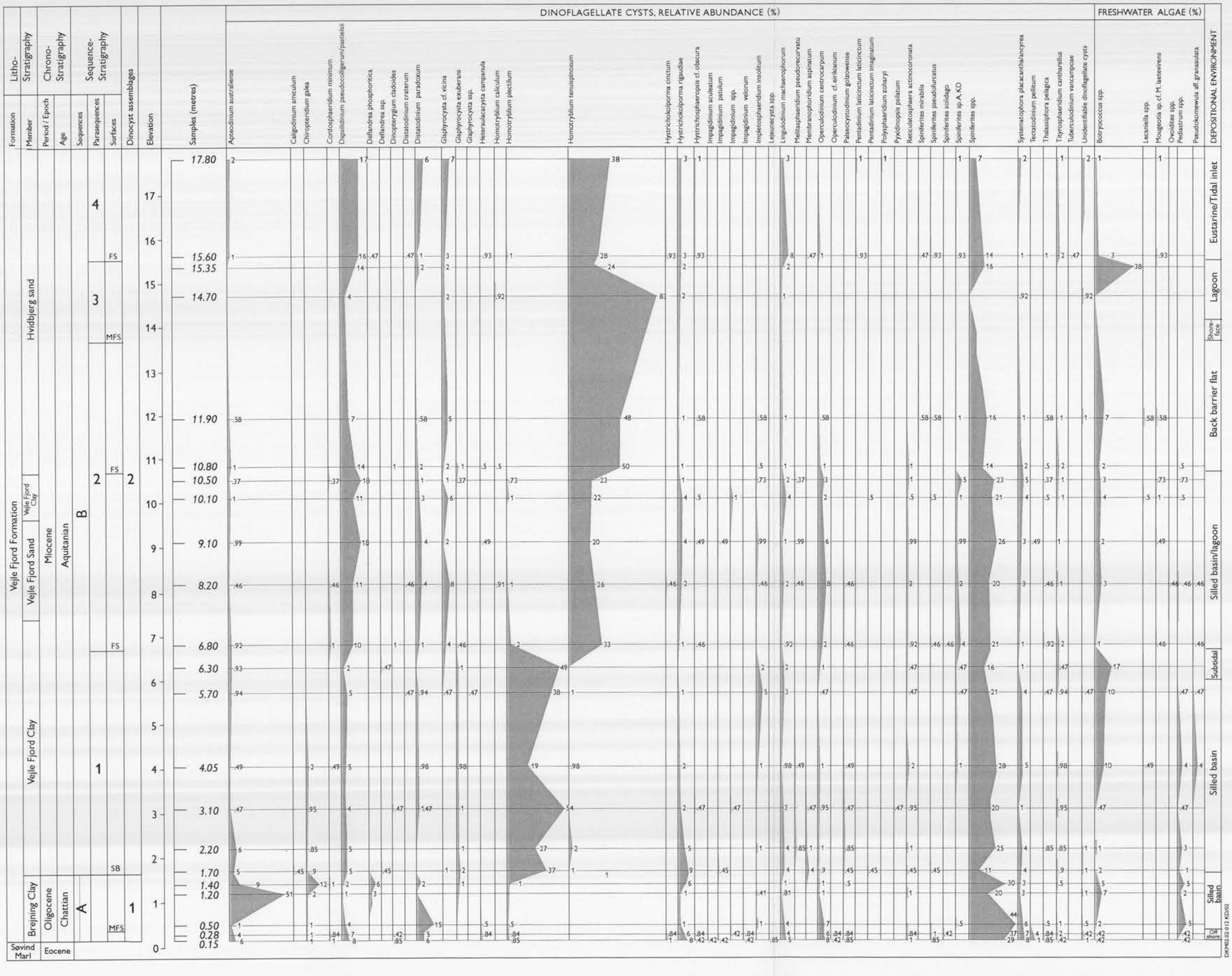
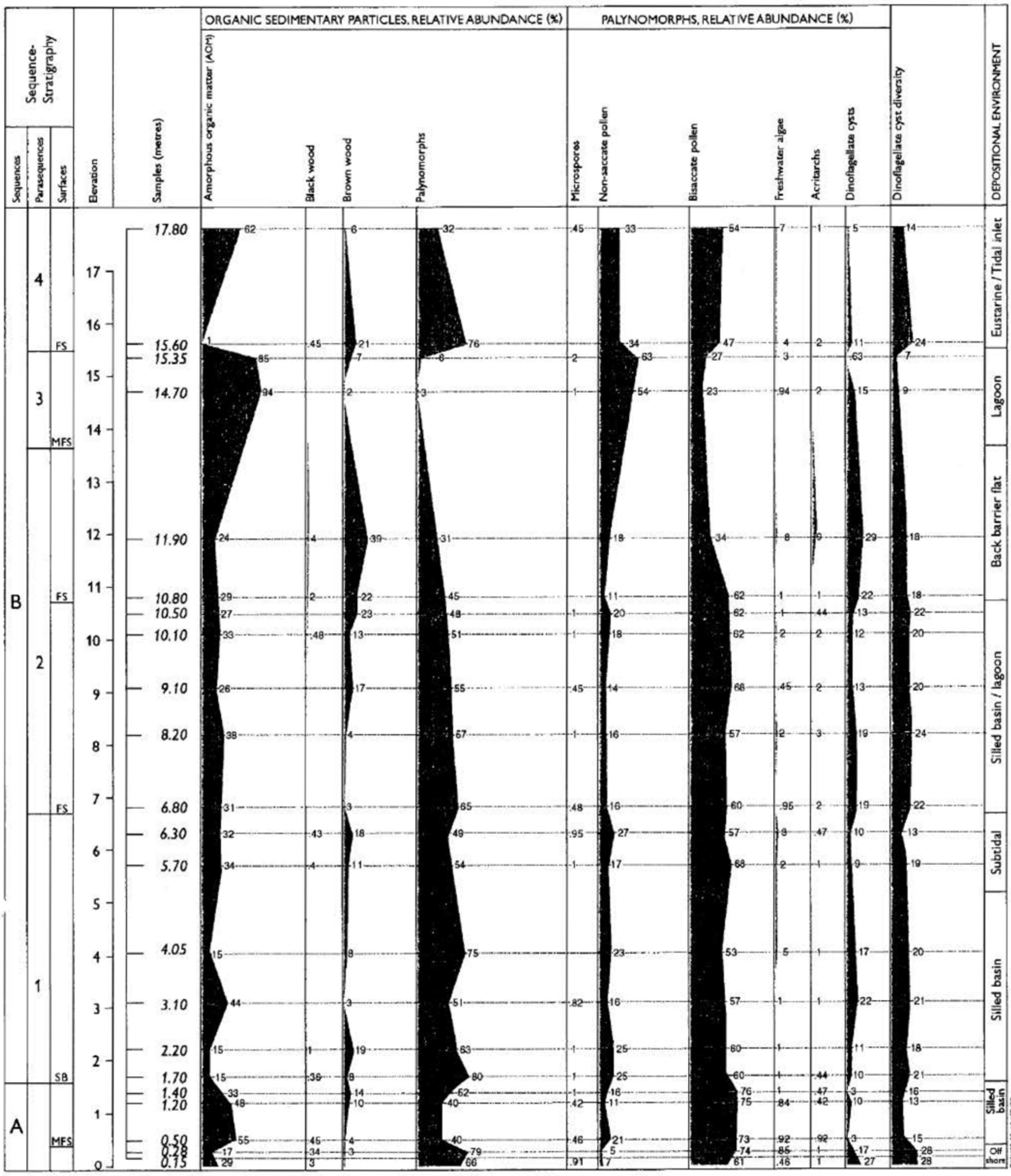
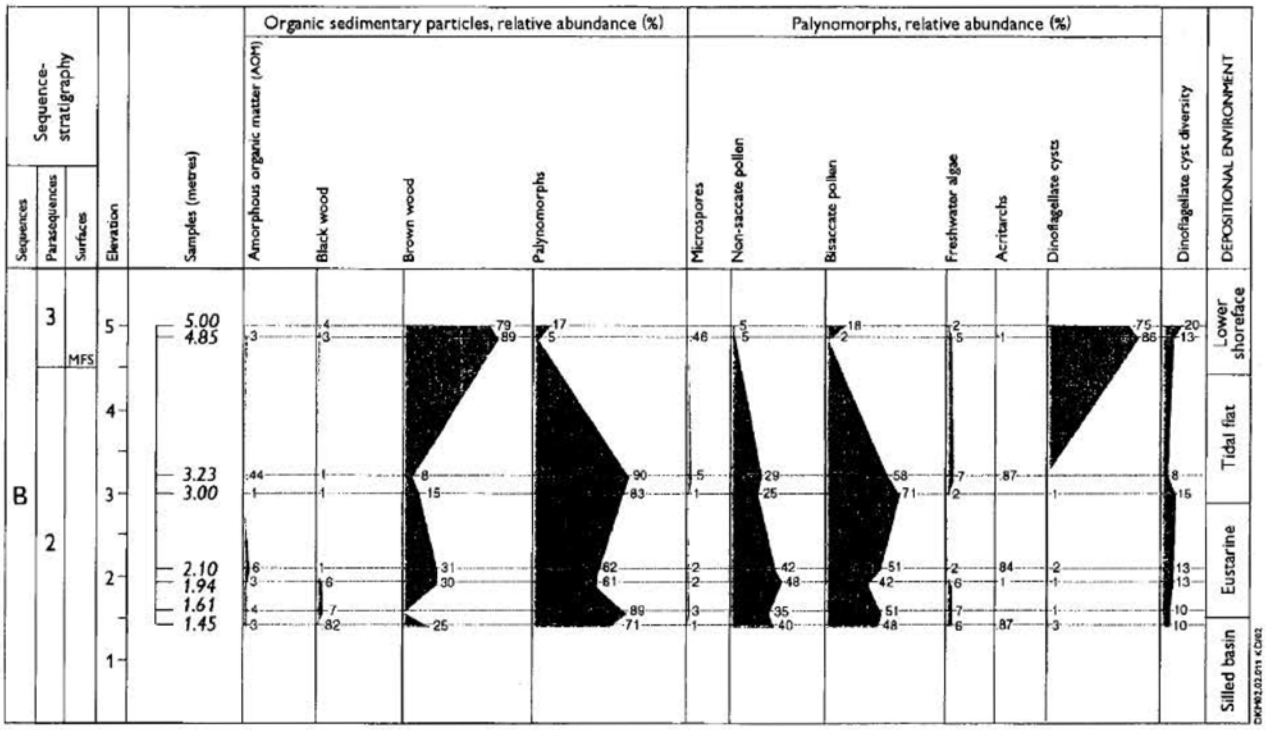

DINOFLAGELLATE CYSTS, RELATIVE ABUNDANCE (%)
FRESHWATER ALGAE (%)
Litho-Stratigraphy
Chrono-Stratigraphy
Sequence-Stratigraphy
Formation
Member
Period / Epoch
Age
Sequences
Parasequences
Surfaces
Dinocyst assemblages
Elevation
Samples (metres)
Vejle Fjord Formation
Brejning Clay
Søvind Marl
Vejle Fjord Clay
Vejle Fjord Sand
Hvidbjerg sand
Oligocene
Miocene
Eocene
Chattian
Aquitanian
Apteodinium australiense
Caligodinium amiculum
Chiropteridium galea
Cordosphaeridium minimum
Dapsilidinium pseudocolligerum/pastielsii
Deflandrea phosphoritica
Deflandrea ssp.
Dinopterygium cladoides
Distatodinium craterum
Distatodinium paradoxum
Glaphyrocysta cf. vicina
Glaphyrocysta exuberans
Glaphyrocysta ssp.
Heteraulacacysta campanula
Homotryblium caliculum
Homotryblium plectilum
Homotryblium tenuispinosum
Hystrichokolpoma cinctum
Hystrichokolpoma rigaudiae
Hystrichosphaeropsis cf. obscura
Impagidinium aculeatum
Impagidinium patulum
Impagidinium spp.
Impagidinium velorum
Impletosphaeridium insolitum
Lejeunecysta spp.
Lingulodinium machaerophorum
Melitasphaeridium pseudorecurvatum
Membranophoridium aspinatum
Operculodinium centrocarpum
Operculodinium cf. eirikianum
Palaeocystodinium golzowense
Pentadinium laticinctum laticinctum
Pentadinium laticinctum imaginatum
Polysphaeridium zoharyi
Pyxidinopsis pylilatum
Reticulatosphaera actinocoronata
Spiniferites mirabilis
Spiniferites pseudofurcatus
Spiniferites solidago
Spiniferites sp. A KD
Spiniferites spp.
Systematophora placacantha/ancyrea
Tectatodinium pellitum
Thalassiphora pelagica
Tityrosphaeridium cantharellus
Tuberculodinium vancampoae
Unidentifiable dinoflagellate cysts
Botryococcus spp.
Lecaniella spp.
Mougeotia sp. cf. M. laetevirens
Ovoidites spp.
Pediastrum spp.
Pseudokomewuia aff. granaulata
DEPOSITIONAL ENVIRONMENT
Eustarine/Tidal inlet
Lagoon
Shore-face
Back barrier flat
Silled basin/lagoon
Subtidal
Silled basin
Off shore
17.80
15.60
15.35
14.70
11.90
10.80
10.50
10.10
9.10
8.20
6.80
6.30
5.70
4.05
3.10
2.20
1.70
1.40
1.20
0.50
0.28
0.15
FS
MFS
SB
DKM02.012 KD/02

Fig5



ORGANIC SEDIMENTARY PARTICLES, RELATIVE ABUNDANCE (%)
PALYNOMORPHS, RELATIVE ABUNDANCE (%)
Sequence-Stratigraphy
Sequences
Parasequences
Surfaces
Elevation
Samples (metres)
Amorphous organic matter (AOM)
Black wood
Brown wood
Palynomorphs
Microspores
Non-saccate pollen
Bisaccate pollen
Freshwater algae
Acritarchs
Dinoflagellate cysts
Dinoflagellate cyst diversity
DEPOSITIONAL ENVIRONMENT
Eustarine / Tidal inlet
Lagoon
Back barrier flat
Silled basin / lagoon
Subtidal
Silled basin
Off shore

Fig b



Organic sedimentary particles, relative abundance (%)
Palynomorphs, relative abundance (%)
Sequence-stratigraphy
Sequences
Parasequences
Surfaces
Elevation
Samples (metres)
Amorphous organic matter (AOM)
Black wood
Brown wood
Palynomorphs
Microspores
Non-saccate pollen
Bisaccate pollen
Freshwater algae
Acritarchs
Dinoflagellate cysts
Dinoflagellate cyst diversity
DEPOSITIONAL ENVIRONMENT
B
3
2
MFS
5.00
4.85
3.23
3.00
2.10
1.94
1.61
1.45
Lower shoreface
Tidal flat
Eustarine
Silled basin

Fig 7

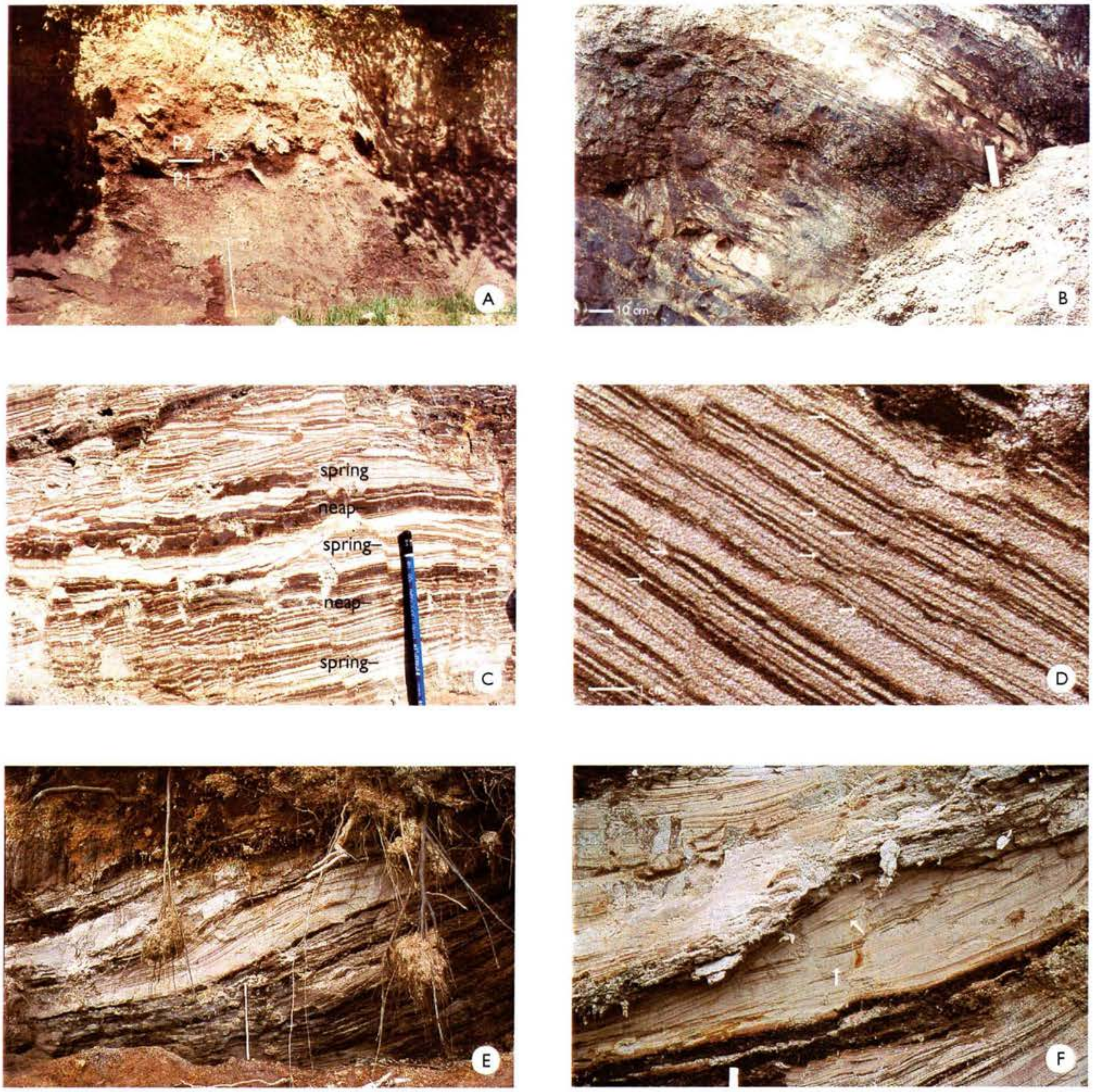


Fig 8

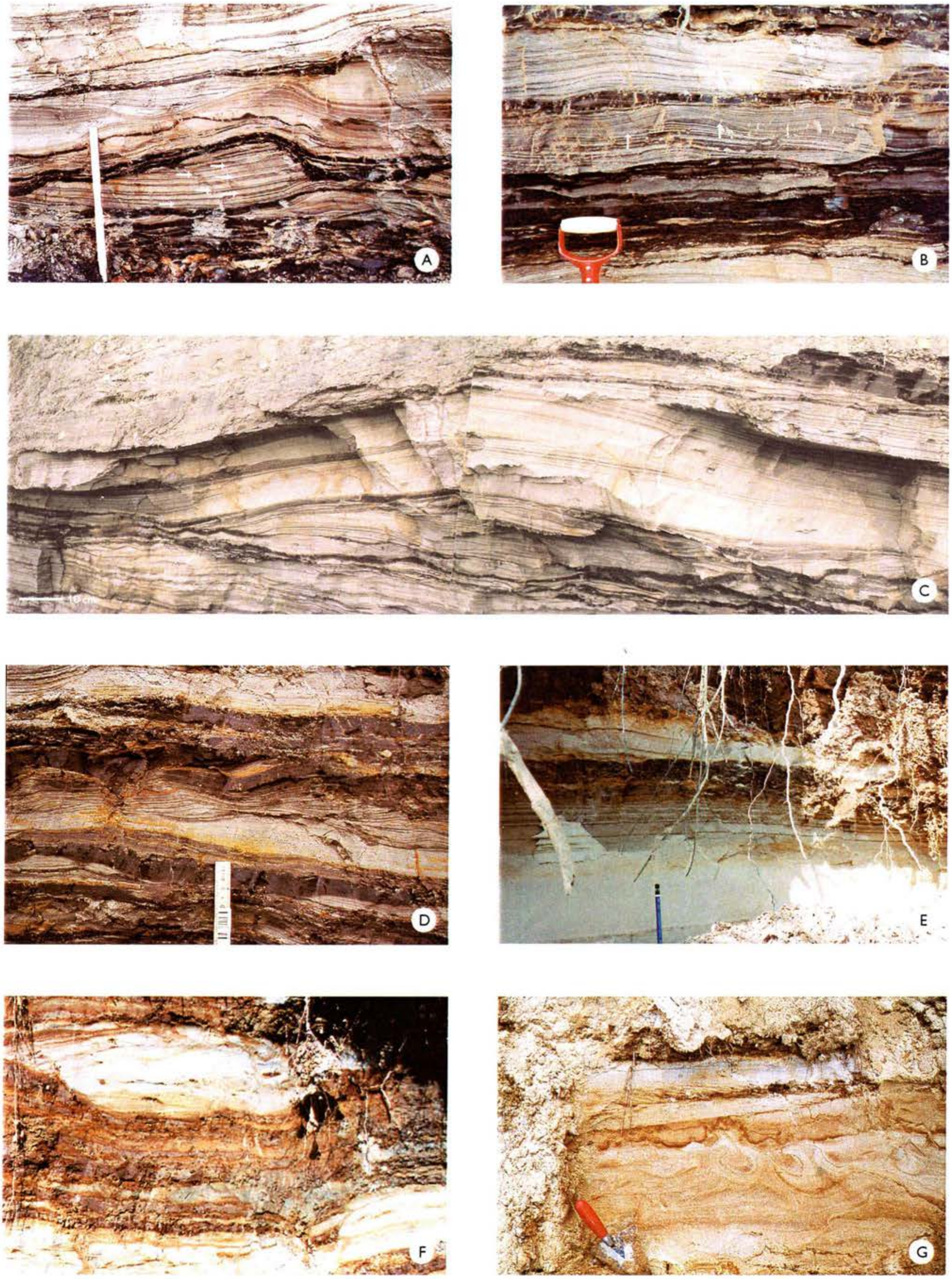


Fig 9

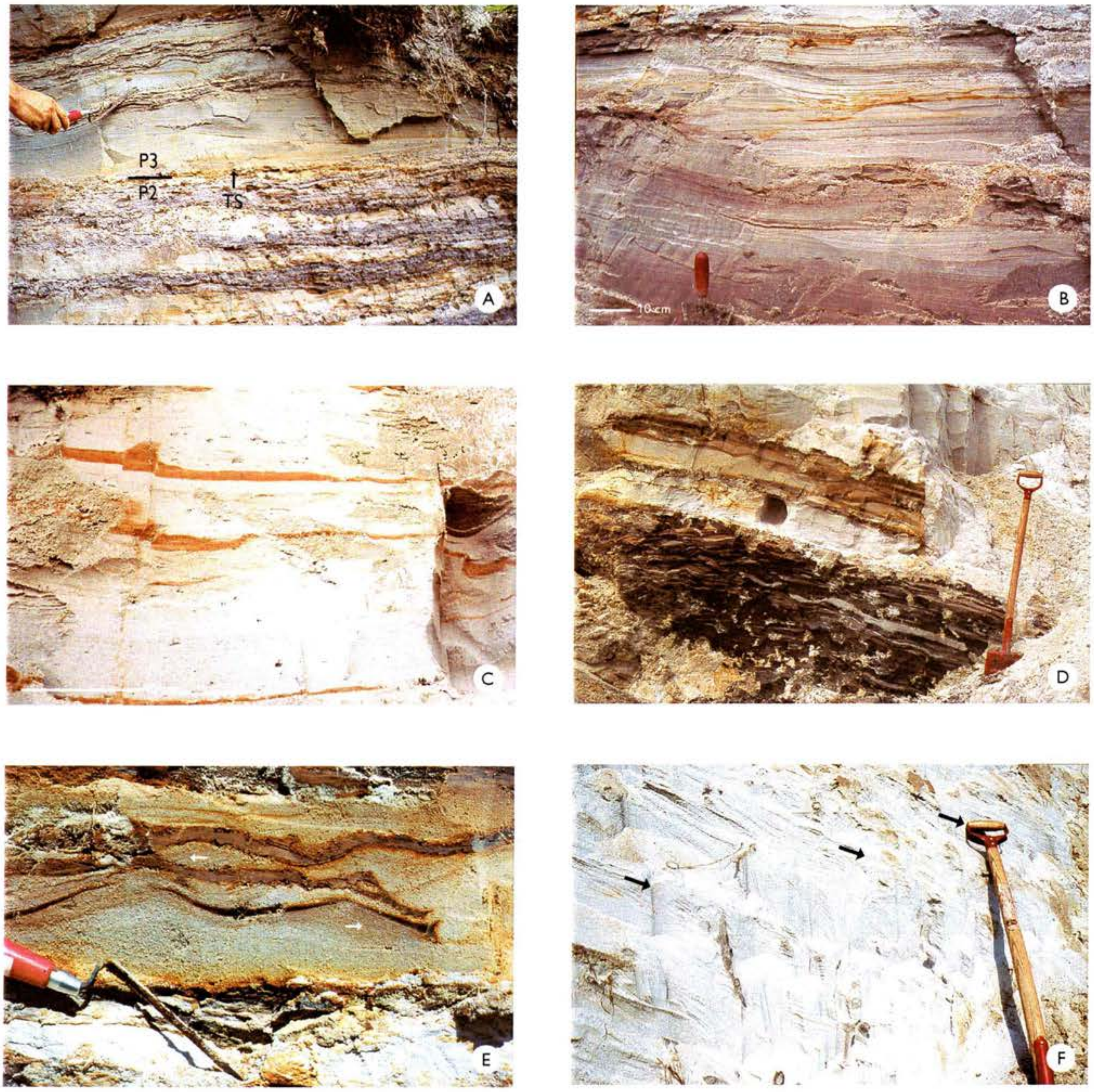


Fig 10

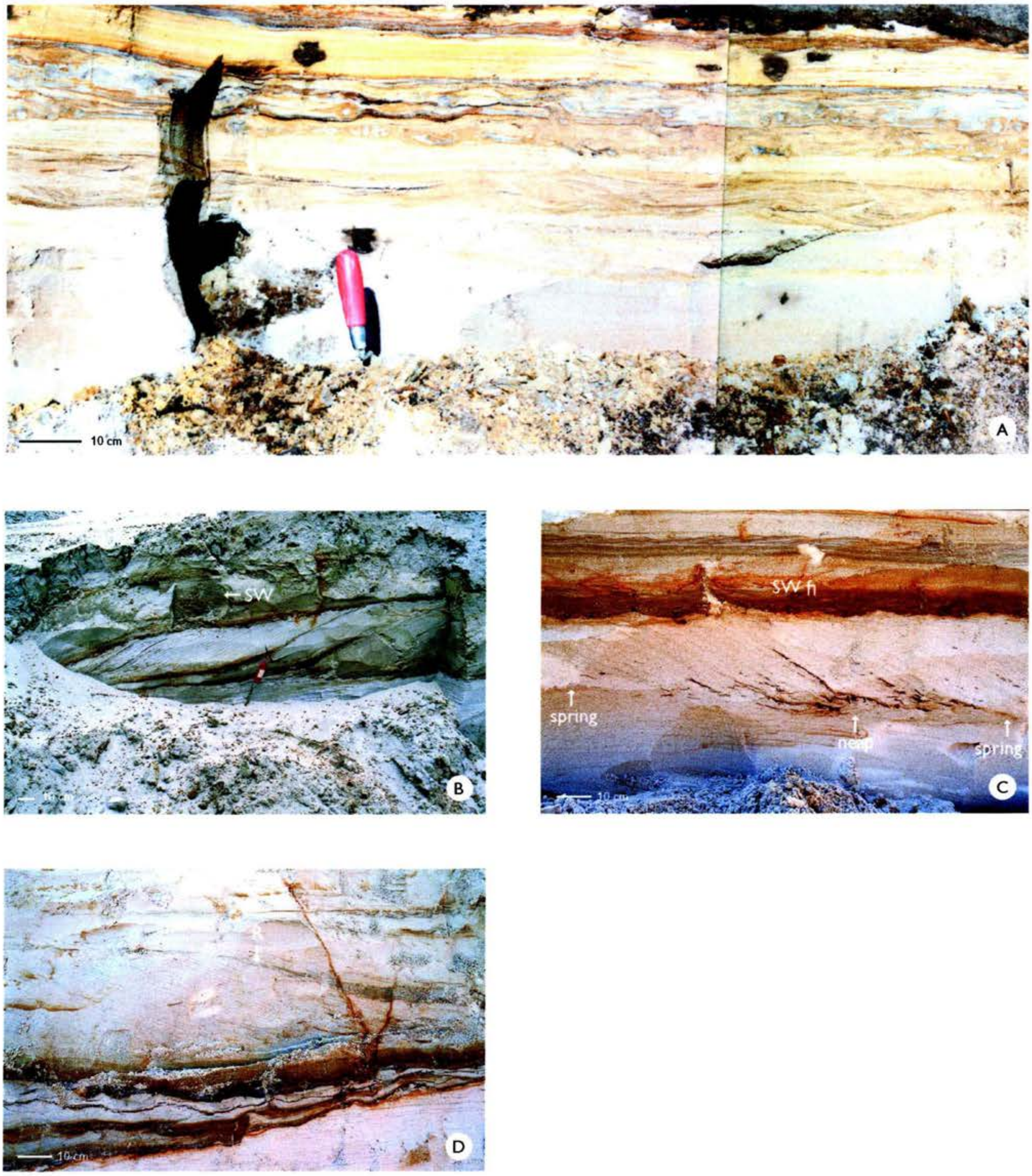


Fig 11

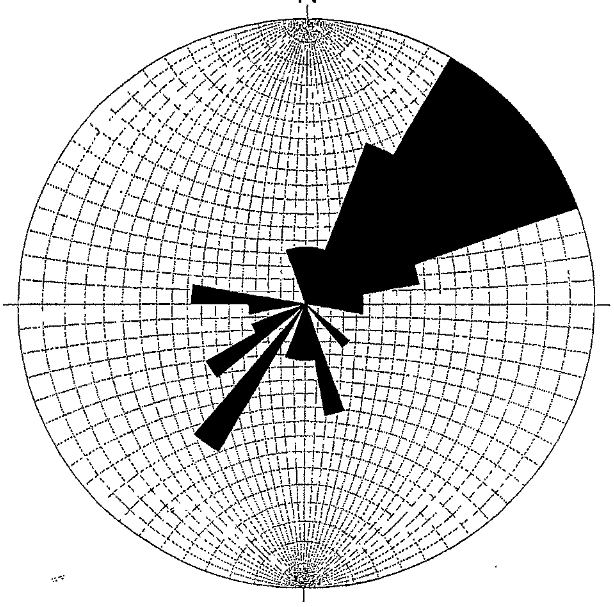


Fig 12

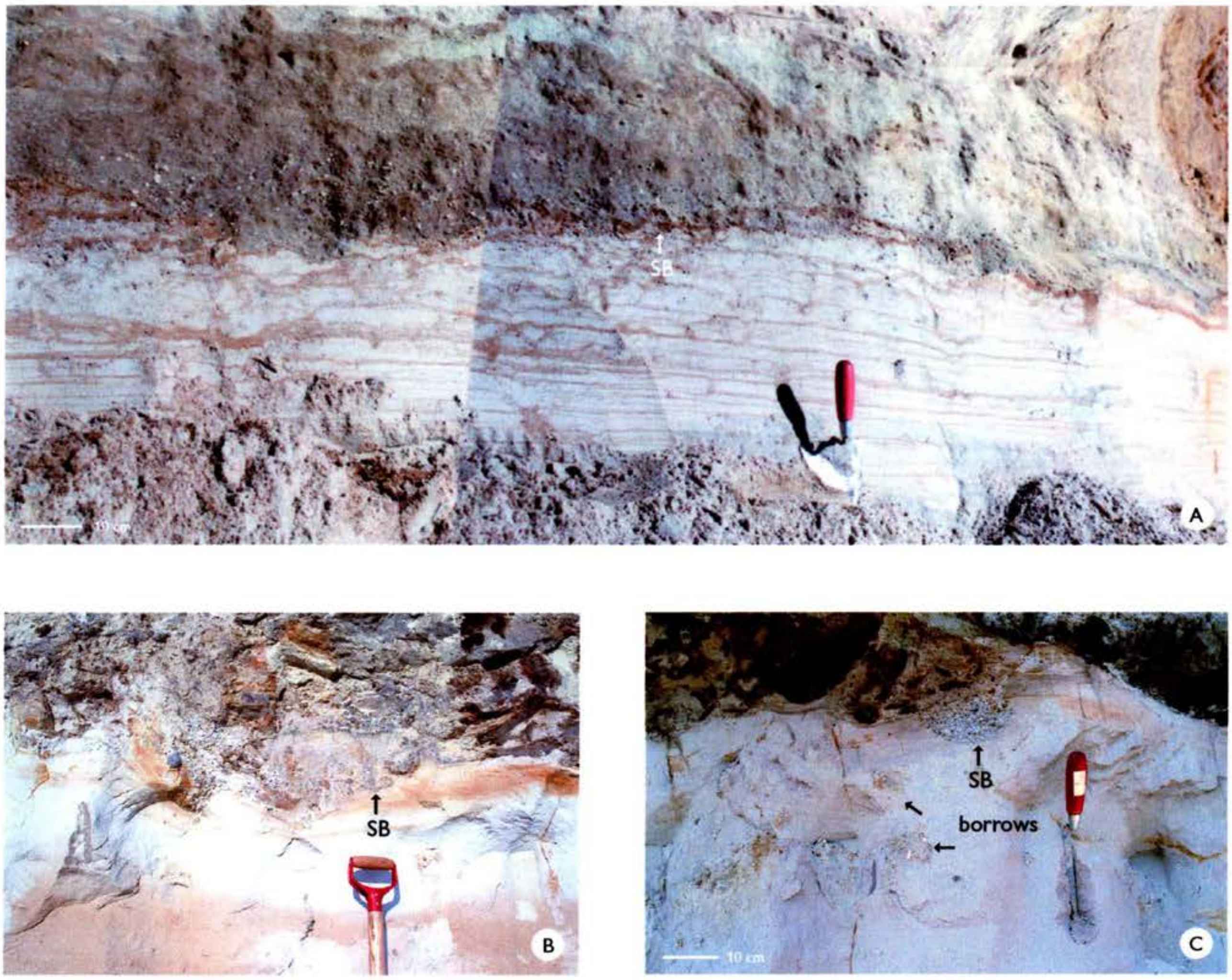


Fig 13

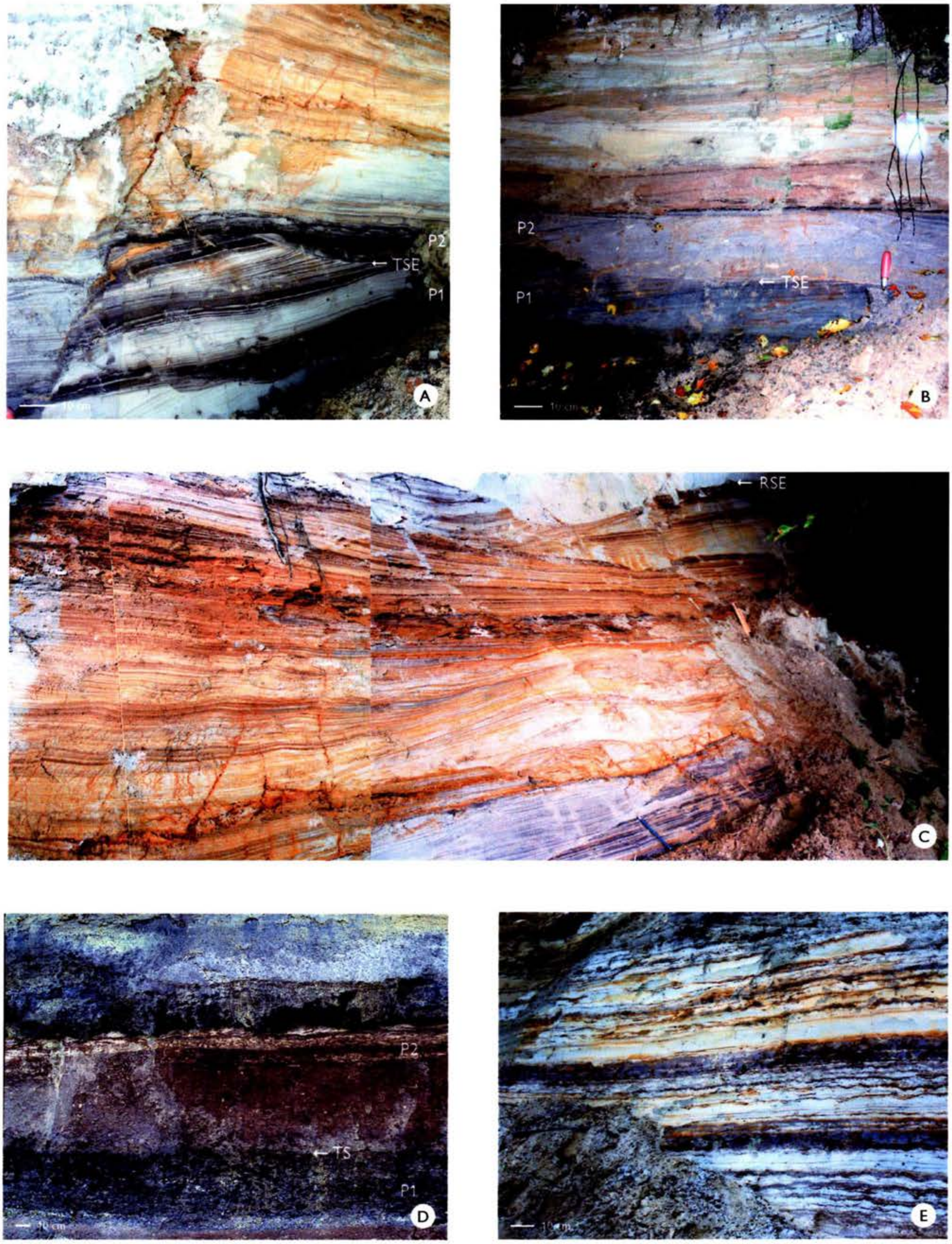


Fig 14

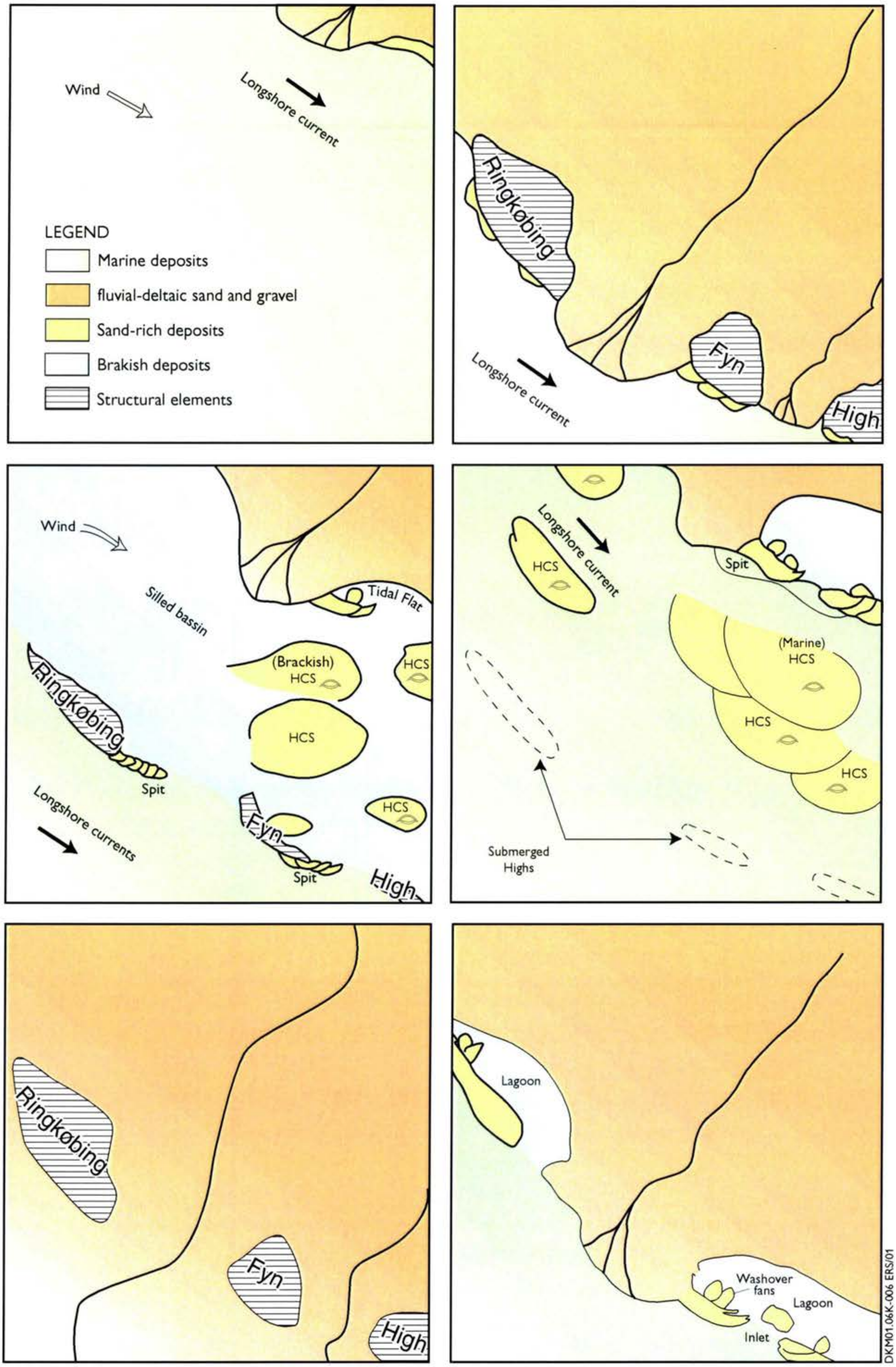

Wind
Longshore current
LEGEND
Marine deposits
fluvial-deltaic sand and gravel
Sand-rich deposits
Brakish deposits
Structural elements
Ringkøbing
Fyn
Longshore current
High
Wind
Silled bassin
Tidal Flat
(Brackish) HCS
HCS
HCS
HCS
Ringkøbing
Spit
Longshore currents
Fyn
Spit
High
Longshore current
HCS
Spit
(Marine) HCS
HCS
HCS
Submerged Highs
Ringkøbing
Fyn
High
Lagoon
Washover fans
Lagoon
Inlet
DKM01.06K-006 ERS/01

Fig 15

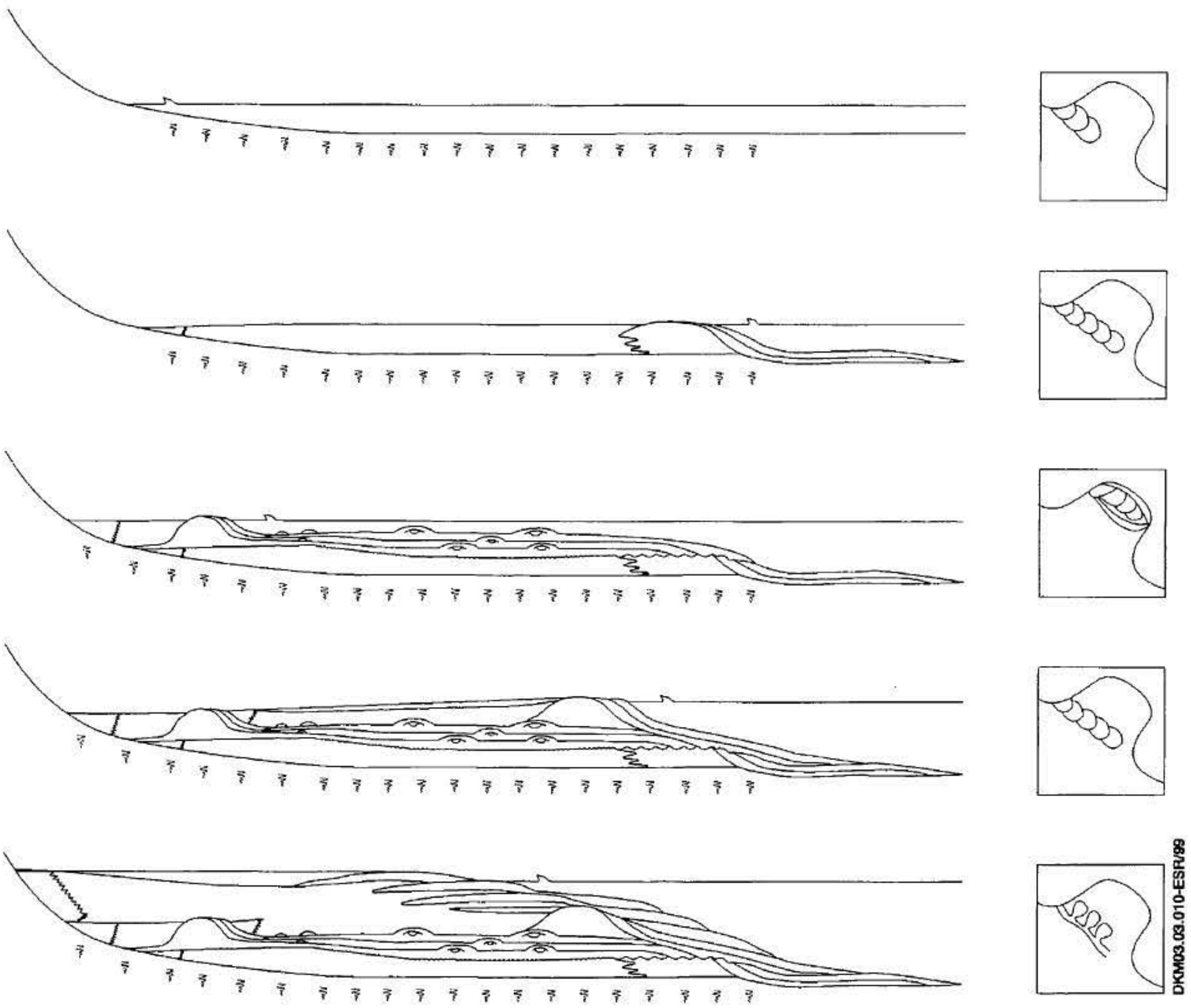
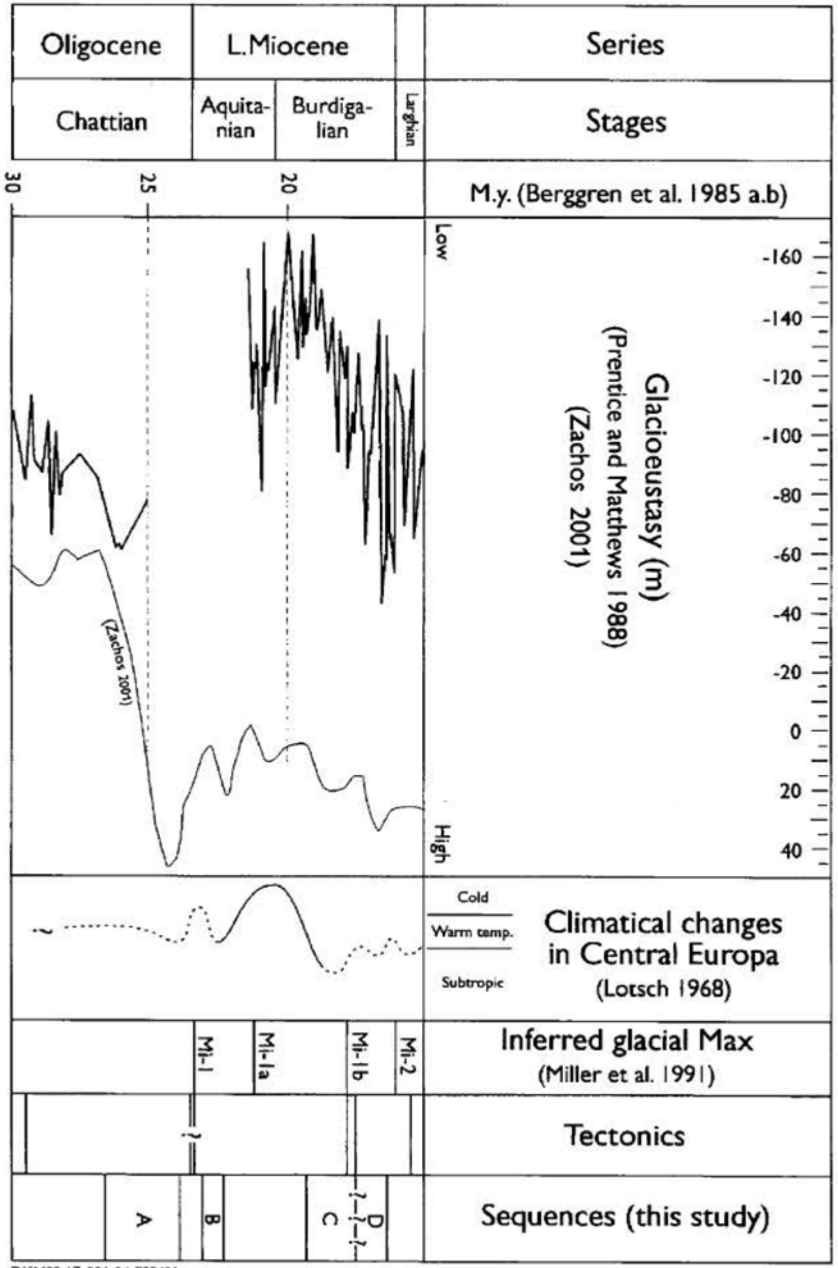
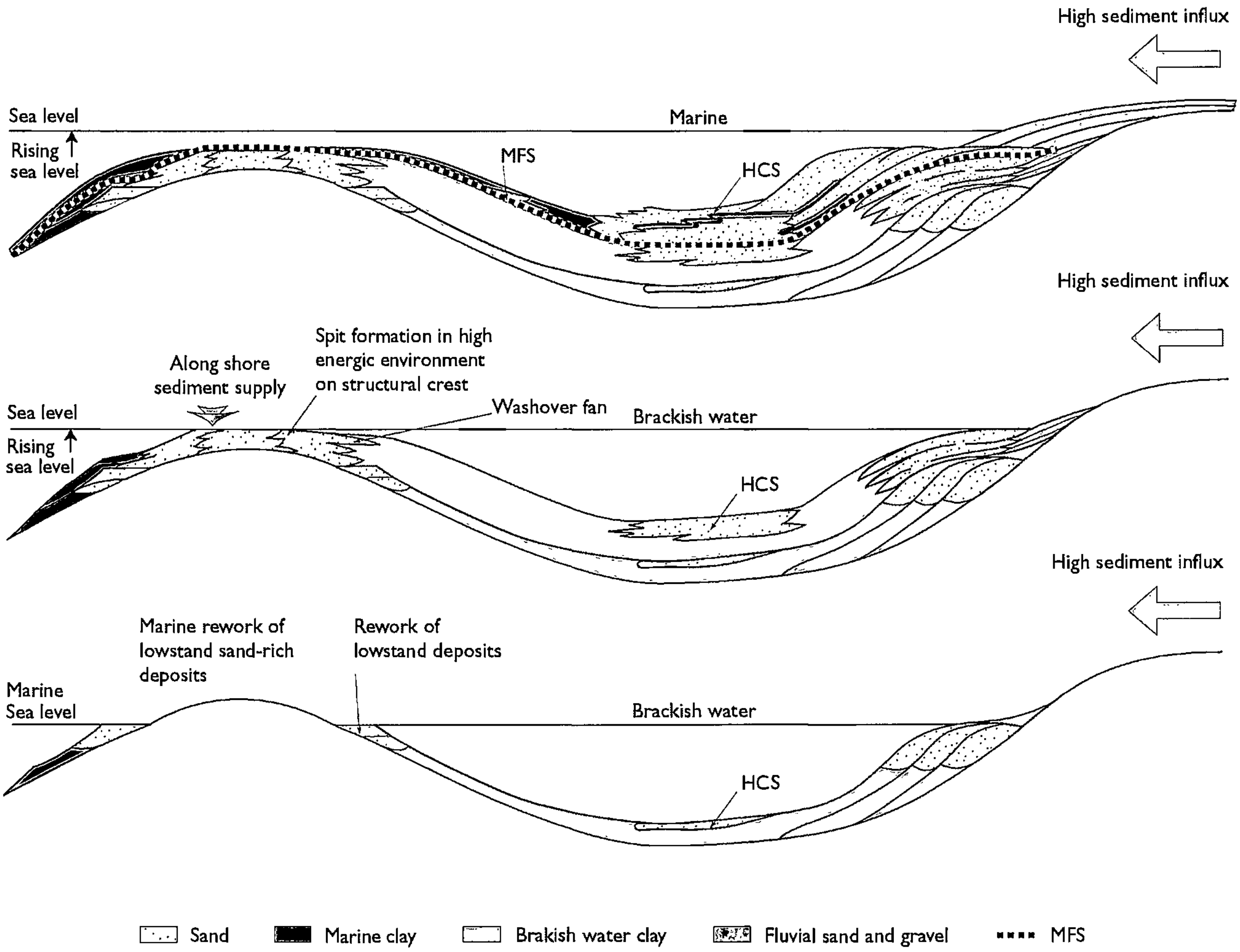


Fig 16



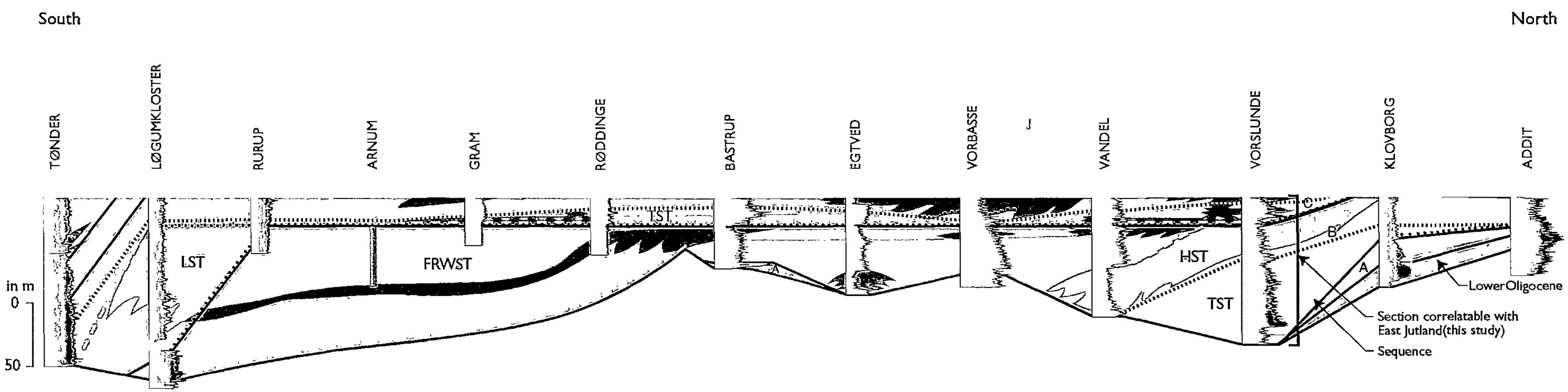
DKM02.17-001.04 ESR/01

Fig 17



High sediment influx
Sea level
Marine
Rising sea level
MFS
HCS
High sediment influx
Spit formation in high energic environment on structural crest
Along shore sediment supply
Washover fan
Sea level
Brackish water
Rising sea level
HCS
High sediment influx
Marine rework of lowstand sand-rich deposits
Rework of lowstand deposits
Marine
Sea level
Brackish water
HCS
Sand
Marine clay
Brakish water clay
Fluvial sand and gravel
MFS

Fig 18



LEGENDE

- Marine silt and clay
- Shallow marine sand
- Fluvial - deltaic sand
- Brakish water silt and clay
- Boundarytowards the Quaternary
- Sequence Boundary
- Maximun flooding surface
- Flooding surface
- HM Heavy Mineral
- Sequence Boundary
- Flooding surface
- Maximum flooding surface
- Gravel

LST = Lowstand System Tract
TST = Transgressive System Tract
HST = Highstand System Tract
FRWST = Forced Regressive Wedge System Tract

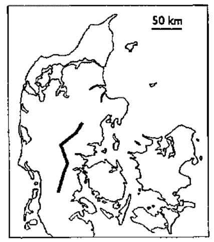


Fig 19

DKM02.14.025 ESR /01

The interplay between true eustatic sea-level changes, tectonics, and climatical changes: What is the dominating factor in sequence formation of the Upper Oligocene-Miocene succession in the eastern North Sea Basin, Denmark?

Erik S. Rasmussen

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Abstract

The Upper Oligocene-Miocene succession of the eastern North Sea is subdivided into six sequences on the basis of an integrated study of outcrops, boreholes, and seismic data. Consequently all available data, methodologies/criteria for the definition of sequences have been used. The datings of the sequences is based on palynology, micropalaeontology, and macropalaeontolgy, which give a high confidence of the datings. The numbers of six sequences, defined in this study, do not correlate either to the 8 marked changes in true eustatic sea-level variation as indicated from oxygene isotope curves or the 9 glacial maximum, which have been recognised within the Miocene. The development of the individual sequence and stacking pattern of sequences is both depended on true eustatic sea-level changes, relative sea-level changes (tectonics) and sediment supply. A true eustatic sea-level fall as well as uplift may result in major progradation of a siliciclastic wedge. In the Miocene succession studied here, a distinct progradation in the lower Aquitanian was a result of a true eustatic sea-level fall. This resulted in deposition of a clean and widespread sand-rich clastic wedge. Marked progradation associated with an uplift of the hinterland in the Langhian resulted in sand-rich deposits alternating with coals. The interbedded coal-seams were a result of a rising ground water table within the basin partly due to stable or even rising sea level and partly due to local subsidence around old fault trends. Similarly, a major transgression may be a result of a true sea-level rise or accelerated subsidence of a basin. In the case of the eastern North Sea Basin accelerated subsidence was responsible for the major transgression in the Serravallian and Tortonian times which is a period with a general climatic cooling. The frequency of true eustatic sea-level changes and relative sea-level changes (tectonic pulses) in the Miocene is in the order of 2.9 - 2.0 m.y. to 4 m.y. respectively. Both of these intervals are within the time range of the studied sequences, which spans 2 - 4 m.y. Consequently, but not surprisingly, neither of the two processes responsible for changes in sea level can solely be attributed to glaciations nor tectonics. The climatic changes during the Late Oligocene – Miocene, which changed from cool temperate to sub tropical with several reversals, did not influence the sediment yield.

Introduction

The architecture of a sedimentary succession is dependent on the changes in relative sea level and sediment supply. The cause of sea-level changes is either attributed to true eustatic sea-level variation, basically due to climatic changes and growth of ice caps at the poles (e.g. Vail 1991; Abreu 1998) or changing morphology of the basin due to tectonics (Cloetingh 1988; van Balen et al. 1998). The tectonic forces effecting the shape of a sedimentary basin is numerous, e.g. interplate stess, rifting, underplating, delamination, and phase transformation. The frequency of these tectonic episodes are debatable, but interplate stresses and rift pulses are believed to be of relatively high frequency (Cloetingh 1985; van Balen et al 1998; Nøttvedt et al. 1995). Recently a number of studies related high frequency unconformity bounded sequences to tectonic movements. For instance the turbidites in the Terbernas Basin can be related to tectonic pulses of the Miocene Betic Event (Pickering et al. 2001). Paleocene mass flow deposits in the North Sea are also associated with tectonic event (Galloway 1993).

The Miocene succession of the eastern North Sea provide a good example to test the interrelationship between climatically caused sea-level changes and interplate stresses. This is due to the high knowledge about climatic changes during the Miocene is detailed compared to other periods and can be tested by independently methodologies, e.g. global sea-level curves based on oxygene isotope measurements (Prentice and Matthews 1988; Zachos 2001), variation in atsmopheric carbon dioxide (Pagani et al. 1999), and floristic changes in Central Europe (Mai 1967; Utscher et al. 2000). The conclusions about the structural evolution are on the other hand more subjective. However, on the basis of a detailed seismic study of data from the North Sea combined with a sedimentological study of the Miocene succession onshore Denmark, many tectonic pulses within the North Sea area can be unravelled.

The aim of the study is to investigate the interrelationship between true eustatic sea-level changes, tectonics, and climatic changes and its consequence for the infill of the eastern North Sea Basin (Fig. 1).

Geological framwork

The formation of the North Sea Basin was a result of several tectonic events (Ziegler 1990; Vejbæk and Andersen 1987; Vejbæk 1992; Underhill and Partington 1993; Clausen et al. 1999; Møller and Rasmusen in press). Vulcanism and rifting occurred already during the Permian and Triassic times (Ziegler 1982) and during the Early Jurassic regional subsidence occurred due to thermal sagging after the Permo- Triassic tectonic event . In the Middle Jurassic a major dome was formed in the central part of the North Sea region due to the mid North Sea plume (Ziegler 1982; Ziegler 1990; Partington and Underhill 1993). Following the Middle Jurassic dome intensive rifting occurred in Late Jurassic to Early Cretaceous. The latter formed a major part of the structural elements which is known from the Central Graben area. From the Early Cretaceous subsidence had occurred due to thermal contraction after rifting. The North Sea Basin undervent inversion during the Late Cretaceous and Early Paleocene. This is considered to be a result of the collision between Africa and Europe, the Alpine Orogen. The North Sea area was further effected by the Alpine Orogeny in the Late Eocene and fault controlled subsidence and movements of salt structures are renown in the mid Oligocene (Sarvische Phase). In the late Neogene and quaternary erosion and uplift of the margins and accelerated deposition and subsidence of the central part of the North Sea Basin took place (Kooi et al. 1991; Vejbæk 1992; Japsen and Bidstrup 2000; Japsen et al. in press).

During the Cenozoic the North Sea Basin was filled from the margins as a result of the elevation and erosion of the hinterland during the Cretaceous and Early Paleocene. Very huge amounts of sediments was supplied from the Shetland Platform and Norway in the Paleocene and Eocene (Galloway 1993; Martinsen et al. 1999). The progradation of major siliciclastic wedges from the Fennoscandian Shield can be recognised in the eastern North Sea from the Oligocene (Michelsen et al. 1998; Clausen et al. 1999). In the southern and Central part of the North Sea huge sediment influx has been recognised from the Late Miocene (Cameron et al. 1993).

The overall architecture of the Upper Oligocene and Miocene succession in the study area is characterised by progradation of three sand-rich sedimentary wedges in the Lower to early Middle Miocene (Rasmussen 2001). The sand was deposited in shallow marine and terrestrial depositional environments and these deposits dominated in the eastern part of the area (Larsen and Dinesen 1959; Rasmussen 1961; Rasmussen 1996; 1998; Friis et al. 1998), the western part is dominated by clayey shelf to deep-marine deposits. Following the early Middle Miocene sand-rich sediments clay-rich fully marine deposits characterised the middle- and Upper Miocene succession in the whole study area. These deposits were laid down in outer shelf to littoral depositional environments representing an overall shallowing upward pattern (Konradi 1996). Resumed major progradation in the eastern North Sea is first recognised in Pliocene (Gregersen et al. 1998).

Data

A total of 11 outcrops and 25 borings onshore and offshore has been investigated (Rasmussen and Dybkjær 1999; Dybkjær et al. 2001). Most of these have been described lithologically and dated by dinoflagelattes (Dybkjær et al. 1999; Dybkjær and Rasmussen 2000; Dybkjær et al. 2001). Other biostratigraphic datings included in the study are: Sorgenfrei (1958), Larsen and Dinesen (1959), Rasmussen 1961), Piasecki (1980), Konradi (1996), and Laursen and Kristoffersen (1999)
9 seismic surveys distributed both onshore and offshore Denmark have been available for the study (Fig. 2).

Sequence stratigraphy of the Upper Oligocene – Miocene succession

The upper Oligocene – Miocene succession in the Danish area is subdivided into 6 sequences A to F (Fig. 3)(Dybkjær and Rasmussen 2000; Rasmussen 2001). In the following a brief description of the sequence will be performed.

The base of the lowermost sequence is in most of the onshore area formed by a major hiatus separating Eocene marly sediments from Chattian glaucony rich clay. In the North Sea area this boundary correlates to a seismic unconformity (Fig. 3b and c). The lower part of sequence A consists of greenish, glacony-rich clay. Upwards there is an increase in silt and interbedded sand layers and lenses. Beds of iron ooids may occur in the uppermost part. The upper boundary is placed at the top of a oolitic sand layer forming the roof of the sequence (Van Houten and ...) and locally a thin gravel layer marks the sequence boundary. At the boundary, there is a change in depositional environment from marine to brackish water (Larsen and Dinesen 1959; Rasmussen and Dybkjær 1999). The change in depositional environment is seen throughout the study area and was a result of a global sea-level fall in the Aquitanian (Dybkjær and Rasmussen 2000; Rasmussen and Dybkjær submitted). In the North Sea area the sequence boundary correlates to a major unconformity (Fig. 3b and c). At this sequence boundary slope failure occurred locally (Huuse and Clausen 2001).

Sequence B is composed of organic-rich silty clay. Upwards the content of sand increases and locally major sand-rich deltaic deposits occurs (Fig. 3a). In the late stage of the development of Sequence B, massive fluvial sand was deposited in the basinal setting and the displacement of the shoreline was in order of 100 km (Rasmussen 1998). The upper boundary of Sequence B is formed by a major erosional surface. In the northeastern part a hiatus of ca. 3.5 m.y. separates Sequence B from Sequence C (Dybkjær and Rasmussen 2000). On seismic panels the sequence boundary is elusidated as a regional unconformity (Fig. 3b and c).

Sequence C consists of organic-rich silty clay in the lower part. Locally sandy sediments deposited in transgressive barrier complexes can be found (Fig. 3a). Upwards the sequence becomes sandy and the overall evolution of the sequence is a progradation of a shoreline towards the southwest. The upper boundary is marked by a change from sandy deposits to more fine-grained sediments. Locally the boundary is characterised by incision. Here the boundary is very sharp and marine sediments is overlain by fluvial deposists (Fig. 3a). On seismic panels the boundary corresponds to a regional seismic unconformity (Fig. 3b and c).

Sequence D is composed of organic-rich sediments in the lower part. Upwards the sequence gets more sand-rich and some times gravelly. Sequence D is different from B and C in having a very high content of heavy minerals (high gamma peaks in log pattern in Fig. 3a). In the upper part of the sequence up to 3 layers of brown coal occurs (Koch 1989). The upper boundary is characterised by a transition from fluvial deposits to marine organic-rich sediments. At the boundary a transgressive gravel layer occurs. On seismic panel the sequence boundary corresponds to the so-called mid Miocene unconformity (Jordt et al 1995; Michelsen et al. 1998; Huuse and Clausen 2001) and locally slope failure is associated with this boundary.

Sequence E consists of marine silty clay. In the lower part a very high content of organic matter occurs. Upwards the sequence becomes clayey and rich in glaucony. The upper part of the sequence contains of goethite deposited in shallow water (Dinesen 1976). The sequence boundary towards Sequence F is defined where goethite-rich deposits is overlain by marine clay. Due to no datings of the Upper Miocene succession within the North Sea this sequence boundary is only tentatively indicated on the seismic panel (Fig 3b and c).

Sequence F is composed of marine shell-rich clay. Upwards the sequence becomes silty and sandy. The sand-rich sediments were deposited as storm sand layers (Rasmussen and Larsen 1989). In the North Sea area the boundary is correlated to a regional unconformity close to the Tortonian – Messinian boundary (Jordt et al. 1995; Michelsen et al. 1998). In the North Sea area this sequence is up to 400 m, which is considerble more than in the onshore area where normally ca. 25 m have been penetrated.

Evidence for tectonics in the eastern North Sea Basin.

On seismic lines from the study area fault movements and flexuring can be recognised at the base of the Upper Oligocene succession (Fig. 3). In Central Europe fault controlled subsidence and a formation of a major unconformity occurred at this boundary (Hager et al. 1999; Ziegler 1982; 1990). This tectonic phase is renown as the Savishe Phase in Central Europe and seems to have effected the North Sea region too. Huge amounts of coarse-grained sediments from the Fenoscandian Shield were supplied to the North Sea basin in the Upper Oligocene time (Michelsen et al. 1998). This indirectly indicates an uplift of the hinterland, especially, because it follows the Savishe tectonic phase.

A detailed study of the Miocene sediments reveals that at certain levels within the succession changes had occurred in the hinterland such as uplift or earthquakes. Within the early Aquitanian nearshore deposits in East Jutland slumping and listric growth faults occurs at a well defined level (Mikkelsen 1983; Rasmussen and Dybkjær 1999). These sedimentary structures (secondary structures) may have been triggered by an earthquake shock. Similar sedimentary structures (slumping of washover fans and listric faults in tidal deposits) are, however, also common without any connection with earthquakes. What is interesting here is that it only occurs at a well defined stratigraphic level and not at other levels where these types of sediments are widely distributed within the succession. In the mid Burdigalian a distinct increase of reworked Paleocene and Eocene, and to some extent Jurassic spores, pollen and dinoflagellates occurred (Dybkjær et al. 1999; Dybkjær et al. 2001). In association with this phase a high supply of heavy minerals dominates the remaining part of the Miocene lower shoreface and beach deposits (Fig. 3a). In the mid Langhian (Early Middle Miocene) a thick pile of coal deposits were laid down in association with old fault trends in Central Jutland (Koch 1989) indicating renewed tectonic activity at this time. The fluvial deposits laid down in the Central Jutland were deposited in braided river systems, which most likely reflect a topography in the area e.g. growth of nearby salt structures (Miall 1996). It is under any circumstances unlikely that braided river systems should dominate in an area, which has been tectonically quiet for a long geological period, here meandring- and anastomosing river systems are most common. The two tectonic phases, late Burdigalian and mid Langhian, which is recognised from the study of the sedimentary succession can be correlated to two distinct phases in the growth of salt structures in the North Sea (Fig. 4). In this figure two phases in the growth of the salt structure can be recognised; one in the late Burdigarlian and one in the mid Langhian. The mid Langhian phase also marked a change in direction of the sediments influx to the North Sea from a dominantly northerly and north-easterly supply to a dominantly easterly influx of sediments Clausen et al. 1999). **The extreme thickness of the Serravallian-Tortonian succession in the North Sea (Fig. 3b-c) occurred actually during a period of falling global sea level (see below). This indicate an increased subsidence of the North Sea Basin in the late Miocene times and this subsidence was not only concentrated to the central North Sea basin, but included also the onshore area (Japsen and Bidstrup; Japsen et al. 2002). Due to late Cenezoic tilting of the North Sea strong erosion took place in the eastern part of the basin.**

As argued above up to 4 tectonic pulses occurred during the Late Oligocene–Miocene times. The frequency of the tectonic pulses is in the order of 2.5 to 5 m.y.

Evidence for climatic changes and true eustatic sea-level variations

During the Late Oligocene - Miocene the climate changes between subtropical to cool temperate in Central Europe. The climate was humid dominated by wet summers (Mai 1967; Lotsch 1968; Utescher et al. 2000).

In the Late Oligocene the climate was warm temperate (Fig. 5). The sea-level curves, based on oxygen isotope indicate a general rise in sea level during the latest Oligocene. At the boundary to the Miocene a climatic cooling occurred and a period with ice growth on antarctic took place (Miller et al. 1991). This resulted in lowering of the sea level and a cooler period in Central Europe. In the Early Miocene, in the Aquitanian, a minor rise in sea level followed the period indicated by the ice growth maximum (Mi-1) (Fig. 5). This is succeeded by a dramatically lowering in temperature in the late Aquitanian and early Burdigalian, which also resulted in lowering of the sea-level. This period correlate to the glacial maximum of Mi- 1a (Miller et al. 1991). During the middle and late Burdigalian a general sea-level rise took place as indicated by the oxygen isotope curve (Fig. 5). In Central Europe the Burdigarlian was relatively warm (subtropical-warm temperate), however, the overall trend of the climate in the Burdigarlian was a slightly decreasing temperature (Mai 1967; Lotsch 1968), which is different from the global trend indicated from the oxygene isotope curves (Prentice and Mathews 1988; Zachos 2001)(Fig. 5). In the early Middle Miocene (Langhian) a distinct sea-level rise occurred. This period, late part of the Langhian, is also referred to as the mid-Miocene climatic optimum (Zachos 2001). On the climatic curve of Central Europe a subtropical climate correlates to this period (Lotsch 1968; Utescher et al. 2000). Following this mid-Miocene climatic optimum a general lowering in the temperature for Central Europe occurred through out the rest of the Miocene. This is also indicated by the overall fall in eustatic sea level and in the high frequency of glacial maximums (Mi-3 – Mi-7).

The above mentioned changes in climate both in Europe and globally clearly indicate that variation in the sea level have occurred during the Late Oligocene and Miocene times. The frequency of sea-level changes if using the simplified curve of Zachos (2001) is 2.9 m.y.

Discussion and conclusion

In the formation of sequences three variables are important: eustatic sea-level changes; tectonics, and sediment yield. The origin and influence of these parameters on the formation of the Upper Oligocene – Miocene succession in the eastern North Sea basin is discussed in the following.

Absolute sea-level changes during the Late Oligocene and Miocene

The most important cause for eustatic sea-level changes is the fixation of water masses at the poles by growth of ice-caps. In the geological past several periods with increased fixation of water at the poles have occurred, the so-called "ice-house Earth". In the Cenozoic such an icehouse Earth has exsisted since the latest Eocene (Abreu 1998). Thus the Upper Oligocene – Miocene succession studied here was laid down within an icehouse period. The method to study the changing volume of ice at the poles is the oxygene isotope record, which has been preformed by a number of researcher (Buchart 1978; Miller et al. 1991; Printice and Mattews 1988; 1993; Zachors et al. 2001). Two of these studies, that of Printice and Mattews (1988) and Zarchos et al. (2001), are shown in figure X. These curves are further compared with studies indicating climatic changes globaly (Pagani et al. 1999) using variation in the content of atmospheric CO2. In addition local climatic changes based on floristic changes in Central Europe is also shown in (Fig. 5)(Mai 1967; Lotsch 1968; Utscher et al. 2000). The correlation of these results is good, all though there are minor discrepancies in the timing and variations in the changes. Therefore it can be concluded that the Late Oligocene – Miocene was a period with true glacio-eustatic sea-level changes. These glacio-eustaticc sea-level change strongly superposed any other processes causing global sea-level variations, e.g. swelling and shrinking of mid ocean ridges, eruption of basalt from mantel plumes, breakup of continental super plates, and sublithospheric mantle convection and advection (Pitman 1978; Heller et al. 1996; Gurnis 1993; Burgess et al. 1997).

Tectonic pulses

During the evolution of a basin a number of processes are involved, e.g. thermal relaxation, streching/rifting, delamination, underplating, phase transformation, sediment loading, unroofing, and interplate stress. These processes acting on a variable time scale. The low frequency processes are those of thermal relaxation, delamination, underplating, phase transformation. Differential subsidence associated with sediment loading and unroofing at the margins may be both long - and short termed depending on the climatical conditions and changes. High frequency tectonics may be related to rifting and interplate stress (Nøttvedt et al 1995; Cloetingh 1988; van Balen et al. 1998).

The evolution of the North Sea Basin during the Cenozoic has been interpreted to be caused by several factors. Basically the subsidence of the basin is related to thermal relaxation following the Jurassic – early Cretaceous rift event (Møller and Rasmussen in press). However, due to the fact that accelerated subsidence occurs during the Cenozoic additional processes as phase transformation and interplate stress have been proposed (Vejbæk 1992; Kooi et al. 1991; van Balen et al. 1998). From the study of the Upper Oligocene and Miocene succession of this study it is revealed that the tectonics was partly frequential and therefore interplate stresses is a likely process in the development of the North Sea basin.

The collision between the African Plate and European Plate during the Cretaceous and Paleogene is well known and the effects can be traced in northwest Europe. In the North Sea the major inversion during the Cretaceous and Paleocene was a consequence of the collision (Ziegler 1982; 1991; Vejbæk and Andersen 1987). Tectonic movements in the latest Eocene is known to have effected the southern part of the North Sea, e.g. in Belgium (Ziegler 1982) and probably also the northeastern part of the North Sea

(Clausen et al. 1999). This effect of the Alpine tectonics is very evident from folding and tilting of areas and have caused distinct formation of unconformities in northwest Europe. The timing of the unconformities and pulses in the Alpine Orogeny is evident and not to any debate for the Paleocene-Eocene period. During the Neogene the effects of the Alpine orogeny is less evident, because no marked tilting or folding can be recognised. However, the collision between Eureasia and Africa continued during the Neogene and especially the Betic event is renown from the Iberian peninsula (Ribeiro 1990). The timing of tectonic pulses during the Betic event can, however, still be traced in the studied succession. It is unlikely that the affects of the collision between the African Plate and the European Plate totally stopped in the Neogene. The changes in the development of the succession correlates to the phases in the Alpine orogeny and consequently it must be considered as a mechanism influencing the evolution of the North Sea Basin also in the Neogene.

In addition to the collision between the African Plate and the European Plate, tectonics of the North Atlantic possibly also played a roll. However, the datings of compressional phases in the North Atlantic is not well constrained (Boldreel and Andersen 1993). Therefore a direct comparison cannot be done, but a Middle Miocene compressional event has been suggested e.g. by Boldreel and Andersen (1999). The change in rift systems in Iceland at 15 m.y. fairly correlate to the Langhian tectonic phase found in this study.

Sediment yield

The sediment yield from the hinterland and into the basin is one of the controlling factors resulting in progradation of sedimentary wedges. The sediment yield is dependent on tectonic uplift, sea-level changes, climate, and type of source rock.

Elevation due to tectonics creates a relief, which under the right climatic condition results in an increase in sediment supply to the basin. This may lead to regression even during a sea-level rise if the influx is high. This is a well known phenoma from rift basins (Prosser 1993; Rasmussen et al. 1998) and in collision zones (Summerfield and Hulton 1994). The above discussion about tectonics, where certain tectonic pulses have been recognised and resulted in marked changes in the composition of the sediments, e.g. sudden increase in heavy minerals and reworked dinoflagellates indicate that movements had occurred within the hinterland and thus a potential factor for increasing sediment supply.

The changes in base-level due to sea-level changes, however, also influences the hinterland by creating a new equilibrium profile. Thus enhanced erosion occur during a sea-level fall due to lowering of the base level (Posamentier et al. 1988). The latter, however, is believed to be of minor importance compared to relief formed during structural uplift and cannot fully explain the marked change in mineral composition of the sediments and sudden increase of reworked dinoflagellates as have been observed in the studied succession.

The climate during the Late Oligocene – Miocene changes from cold temperate to subtropical with several reversals during the period. The precipitation was relatively high and concentrated to the summer period (Utesche 2000). However, there has been no report on any distinct changes in humidity during the changing climatical conditions. Therefore it is not likely that the fluctuation in the climate have had any major consequences for the sediment yield because high sediment supply has been found both under cool temperate climate, e.g. early Aquitanian and under subtropical climate, e.g. early Langhian.

In conclusion a comparison between climatical caused processes; eustatic sea-level changes, climate variation including precipitation and tectonic pulses is listed in (Fig. 5).

The transgression in the uppermost part of the Oligocene seems to be a result of an eustatic sea-level rise and marine deposits were laid down in the onshore area for the first time in ca. 10 m.y. The sequence boundary at the Oligocene/Miocene boundary correlates to glacial maximum: Mi-1(Miller et al. 1991), which has resulted in a sea-level fall. This change is also recorded in the floristic changes in Central Europe and consequently there is a strong indication of a climatic control of this sequence boundary. The sediments, however, indicate some activity of earthquakes close to the boundary, but the conclusion is uncertain. The succeeding rise in eustatic sea level in the early Aquitanian is recorded by the deposition of sequence B. The development of Sequence B during the Aquitanian, where a displacement of the shoreline of 100 km has been recorded, was a result of a true eustatic sea-level fall in the late Aquitanian and early Burdigalian. This is clearly indicated by isotope data, floristic changes and timing of the glacial maximum Mi-1a. During this period there is no evidences of tectonics (Fig. 5). The succeeding transgression in the Burdigarlian resulted in deposition of Sequence C. The development of Sequence C occurred in between two glacial maximums; Mi-1a and MI-1b. The upper boundary can also be correlated to a climatical cooling in Central Europe and a sea-level fall. The upper boundary of Sequence C also correlates to an abrupt change in mineral composition of the sediments within the sequence by having a distinct higher concentration of heavy minerals. Furthermore, marked reworked of Paleocene and Eocene deposits have been recorded too. At this level salt movements also occurred in the North Sea Basin. Therefore it is most likely that tectonics played a part in the formation of the sequence boundary between Sequences C and D. The development of Sequence D seems to be a result of high sediment influx, and perhaps a minor sea-level fall, e.g. indicated by the isotope data, glacial maximum Mi-2 and a minor cooling in Central Europe. However, the high content of coal beds within this sequence clearly indicate that the ground water table was rising during deposition. Consequently, uplift of the hinterland followed by high sediment supply is a likely explanation of the development of Sequence D. A tectonic pulse in the Langhian is additionally documented by thick coal beds along older fault in Central Jutland and on seismic data from the North Sea, where movements of salt structures occurred in the late Langhian. The deposition of a relative thick package of late Serravallian and Tortonian marine deposits (sequences E and F) above continental sediments strongly indicate a regional increased subsidence rate of the eastern North Sea Basin. The initial transgression recorded by deposition of sequence E correlates remarkable to the distinct rise in sea level in the late Langhian and to the so-called mid Miocene climatic optimum, but the succeeding cooling of the climate and general fall in eustatic sea level is not inline with the observed development of the Upper Miocene succession both onshore and offshore. Consequently, increased subsidence of the eastern North Sea basin occurred in the late Miocene due to tectonics.

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Figures

Figure 1. *Study area. Boreholes and seismic key-lines are indicated.*

Figure 2. *Density of seismic lines in the study area.*

Figure 3. *Seismic sections and a correlation panel shows the overall architecture of the uppermost Oligocene – Miocene sequences from west to east. The location of the seismic lines and correlation panel area indicated in figure 1 and on the inserted section to the lower right.*

Figure 4. *Seismic section from the North Sea showing tectonic movements of a salt structure. Note the truncation of Sequence C. The timing of this tectonic movement correspond to the abrupt increase in the content of heavy minerals. Note also the onlap of Middle Miocene deposits on the dome. This phase correlate to the onset of Late Miocene subsidence.*

Figure 5. *Comparison of glacio-eustatic sea-level changes, climatical changes, timing of maximum glaciations, and tectonic pulses with the timing of sequences identified within the study area.*

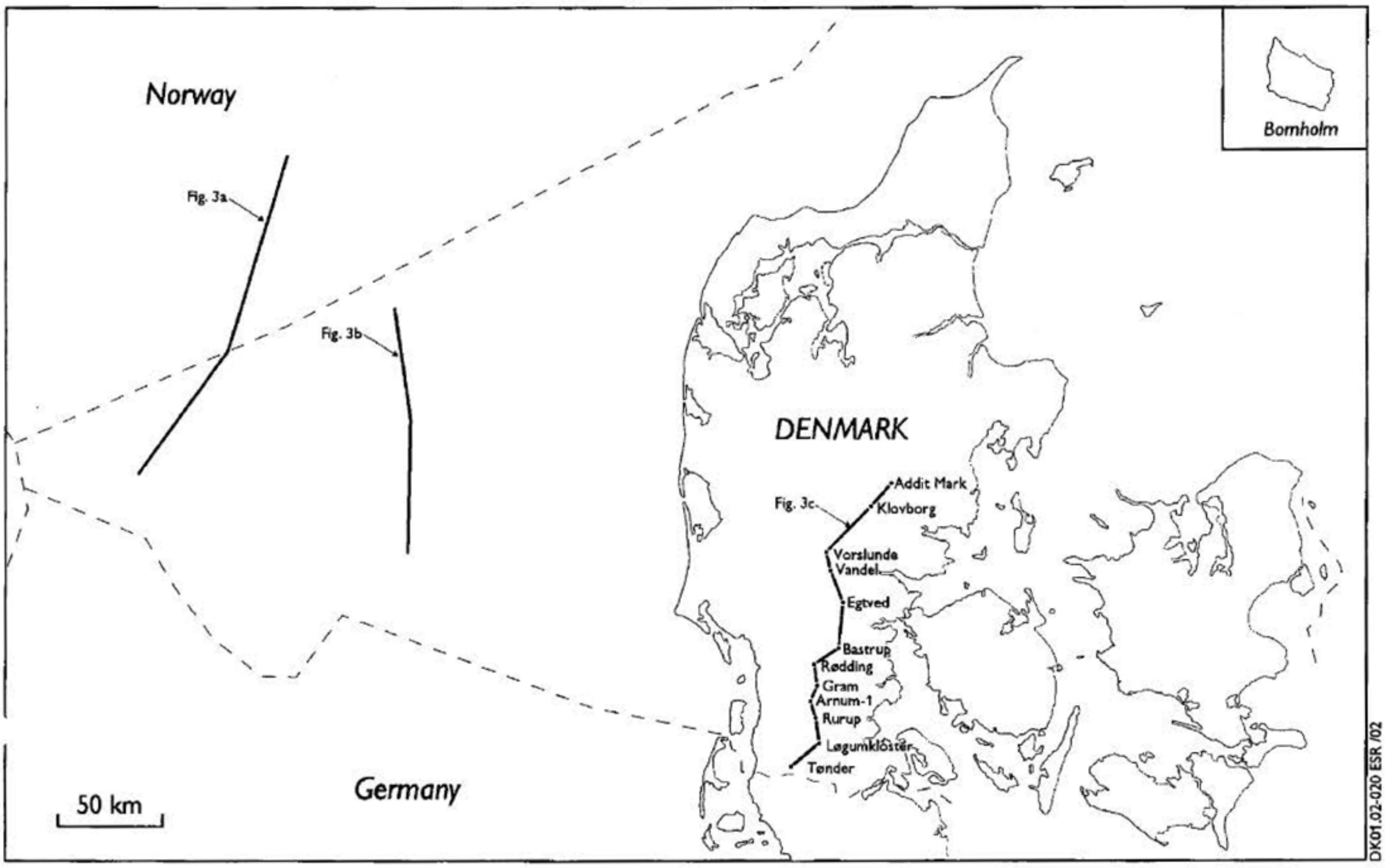
Norway
Fig. 3a
Fig. 3b
DENMARK
Fig. 3c
Addit Mark
Klovborg
Vorslunde
Vandel
Egtved
Bastrup
Rødding
Gram
Arnum-1
Rurup
Løgumkloster
Tønder
Germany
50 km
Bornholm
DK01.02-020 ESR /02

Fig 1

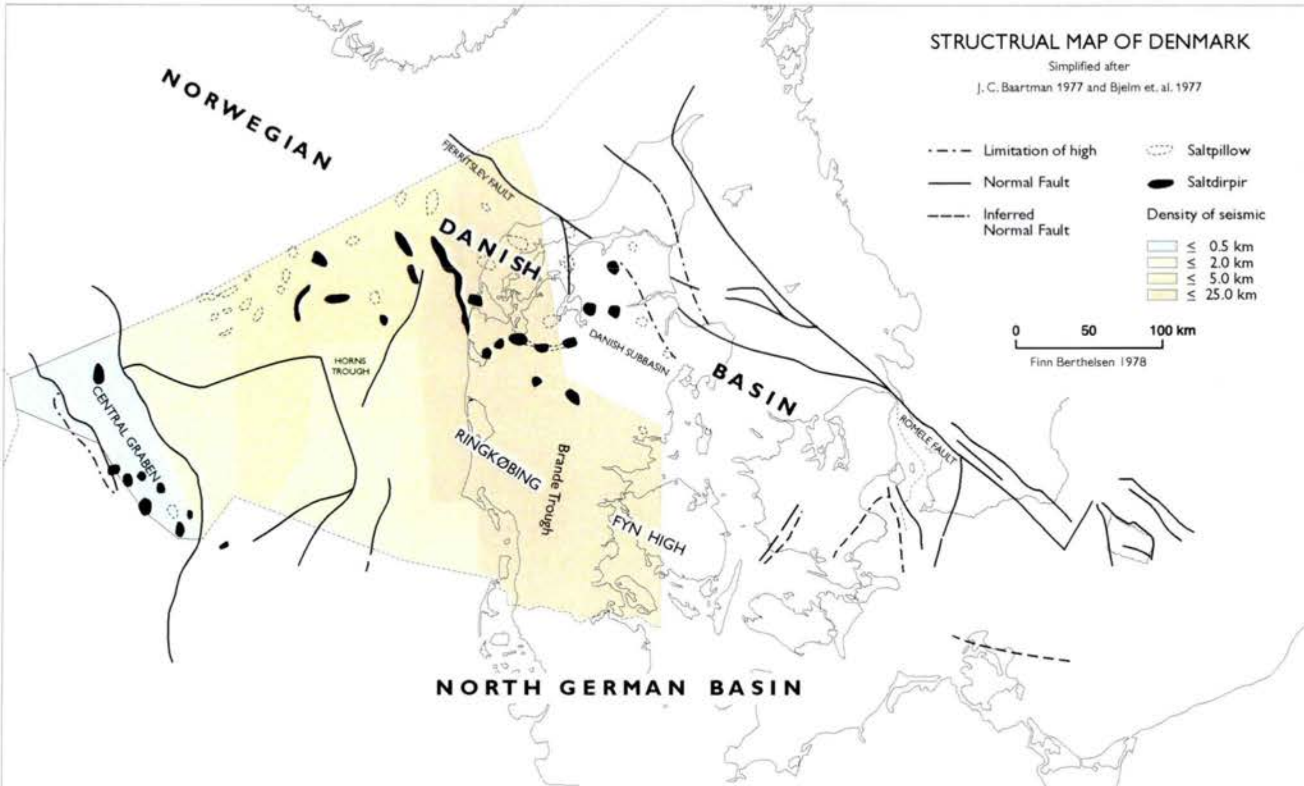

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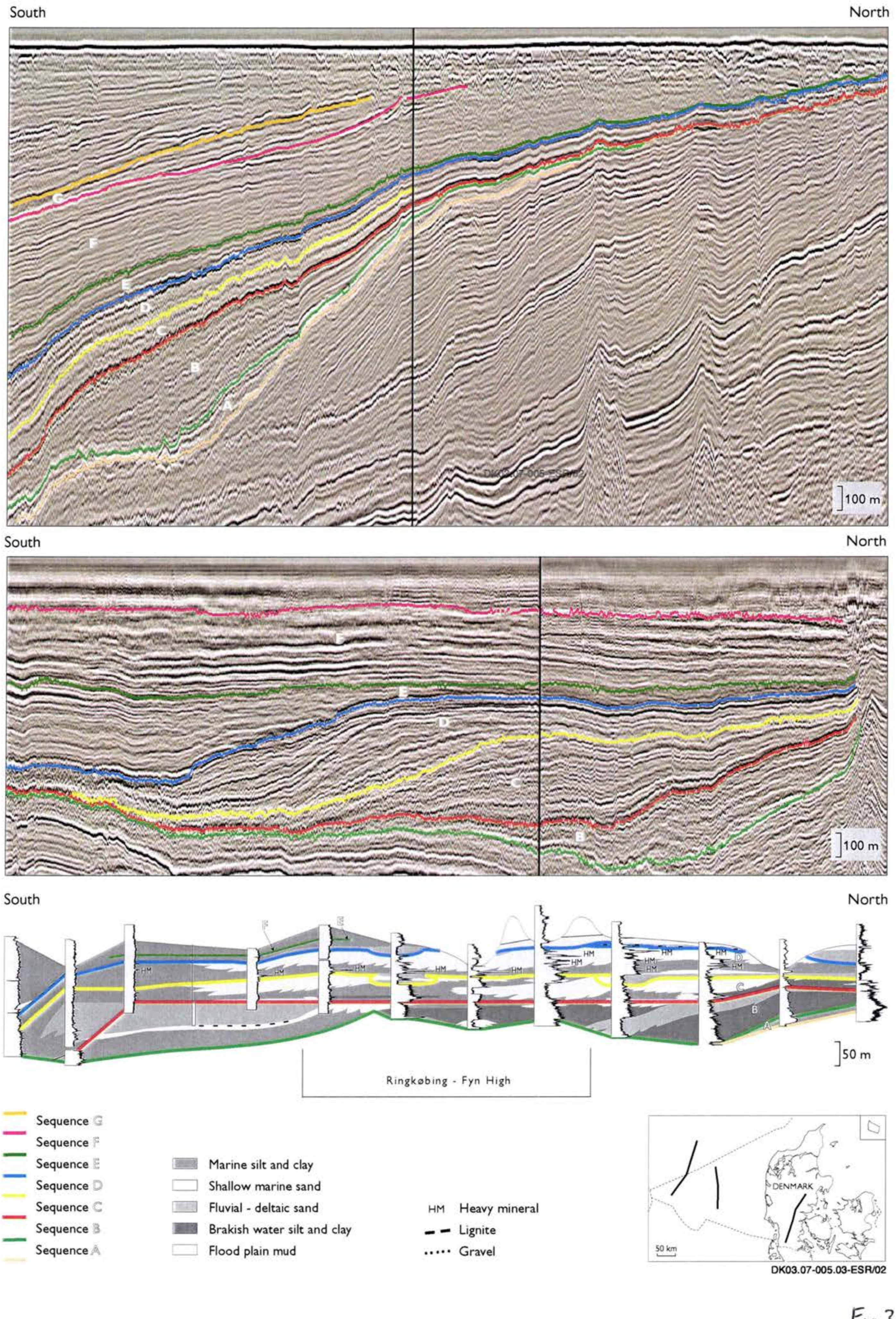
Fig 2


South
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South
North
F
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D
C
B
100 m
South
North
F
E
HM
D
C
B
A
50 m
Ringkøbing - Fyn High
Sequence G
Sequence F
Sequence E
Sequence D
Sequence C
Sequence B
Sequence A
Marine silt and clay
Shallow marine sand
Fluvial - deltaic sand
Brakish water silt and clay
Flood plain mud
HM Heavy mineral
Lignite
Gravel
DENMARK
50 km
DK03.07-005.03-ESR/02

Fig 3

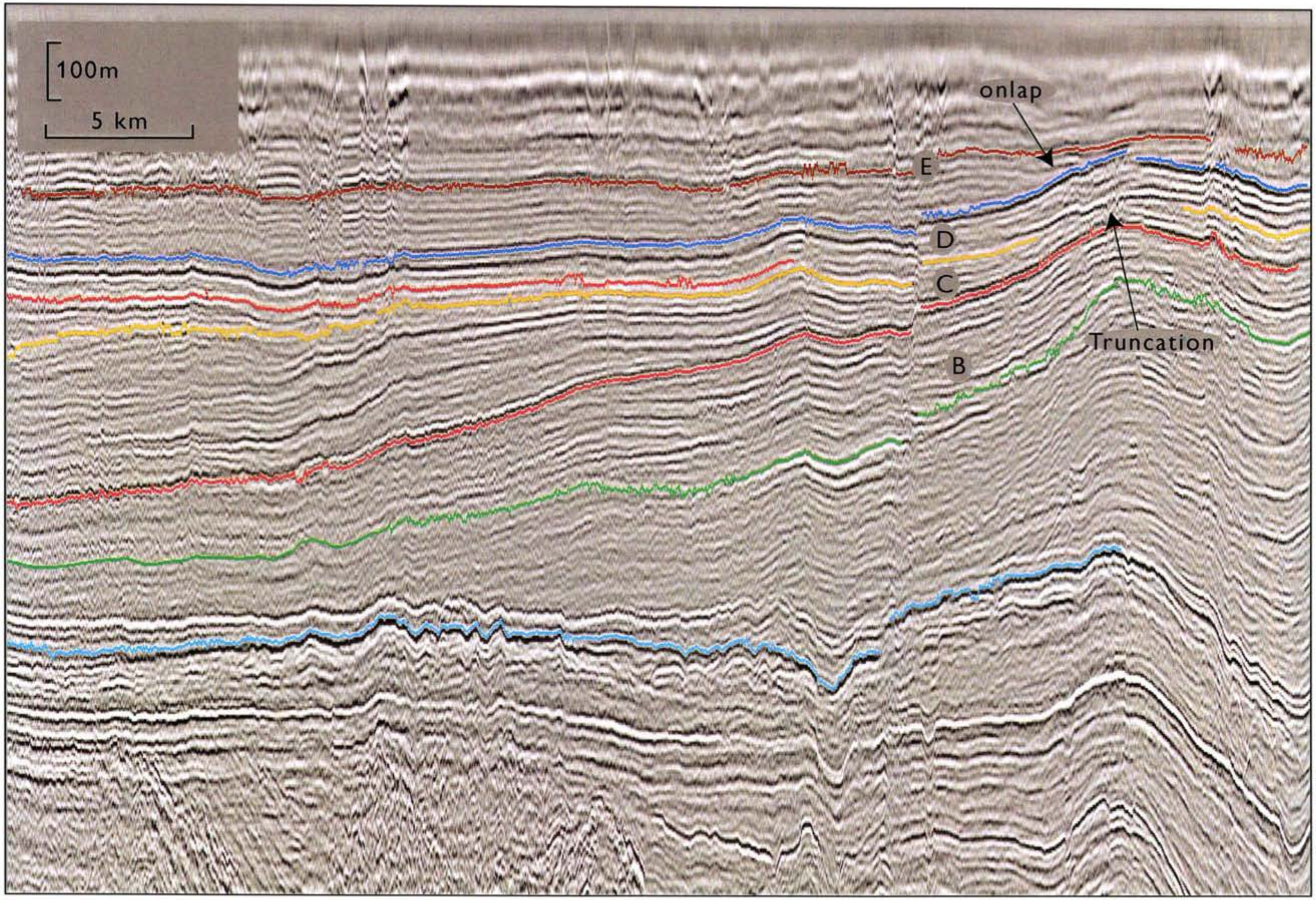

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Fig 4

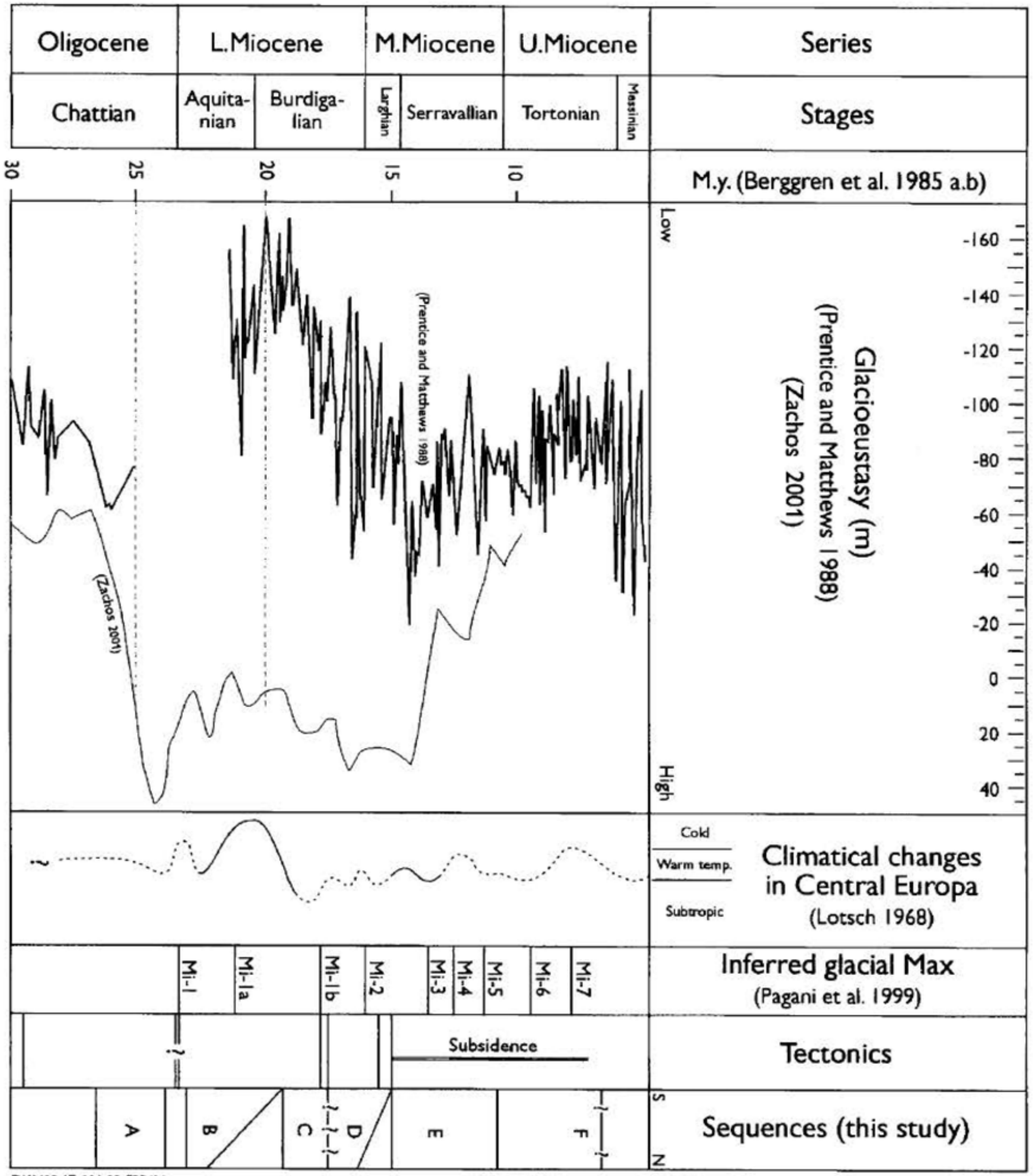

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Fig 5

Upper Oligocene – Miocene shallow marine siliciclastic deposits in East Jylland: A possible analogue for Jurassic oil fields in the Central and Viking grabens

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Introduction

During the last three years intensive studies of the Upper Oligocene – Miocene succession in Central and South Jylland has been undertaken by GEUS in co-operation with the counties. Originally, the aim of the study was to use the Danish Miocene as an analogue for siliciclastic reservoir, e.g. prediction of reservoir sand and architecture. However, the study also turned out to be very useful in mapping of water aquifers and are now use intensively in the search for drinking water in Jylland. These studies include detailed sedimentological descriptions of outcrops, sedimentological and log interpretations of new stratigraphic borings and interpretation of new high resolution seismic data. A number of outcrops and borings have been studied palynologically resulting in a detailed dinoflagellate cyst stratigraphy and palynofacies interpretations. The results of these studies have been integrated in a quite robust regional geological model using the sequence stratigraphic method.

The Upper Oligocene – Miocene succession provides good examples of spit systems formed during highstand systems tracts and sand-rich delta systems deposited during forced regressive and lowstand systems tracts. The studied succession also shows an extremely good example of how to predict reservoir sands in a basinal setting from a systematical study of outcrops located at the basin margin.

The study is of interest for both the oil industry and counties. The oil industry may use the Danish Upper Oligocene – Miocene succession as an analogue for siliciclastic oil fields. To enhance the oil recovery it is thus necessary to understand the architecture of the reservoir sand and distribution of clay layers associated with distinct depositional facies. Furthermore, in exploration for stratigraphic traps it is also necessary to understand the interrelationship between sand reservoirs and the sealing rock. Therefore analogue studies are important and Upper Oligocene – Miocene succession in East Jylland, Denmark may provide such an analogue for Jurassic oil fields in the Central and Viking grabens. In search for drinking water, a 3-D model of the reservoir sand and mapping of impermeable clay layers are necessary in the planing of future water recovery.

Geological setting

The eastern North Sea basin formed as a result of Paleozoic – Mesozoic rifting and late Mesozoic – Cenozoic inversion tectonics (Vejbæk 1997; Clausen *et al.* 1999; Møller & Rasmussen in press). This generated a topographic complex basin floor which strongly influenced the depositional systems even during the late Cenozoic time. Major structural elements are the Sorgenfrei-Tornquist Zone, the Norwegian-Danish Basin, the Ringkøbing-Fyn High, and the North German Basin (Fig. 1). Additionally, minor structures formed due to halogenetic movements also influenced the depositional setting within the Norwegian-Danish and North German basins (Fig. 1).

During the Late Oligocene – Middle Miocene major progradational wedges build out from the margin of the Fenno-Scandia Shield, especially from the present day Norway. Coarse-grained sediments were deposited in connection with progradation of the shoreline. These deposits were laid down in spit-complexes, coastal-plains, and fluvial systems. The coarse-grained sediments alternates with fine-grained clay and silt deposited in shelf environments. Regressive and transgressive events were strongly controlled by eustatic sea-level changes whereas changes in sediment supply is inferred to have a tectonic origin. Therefore the northern flank of the eastern North Sea in the Late Oligocene – Miocene fluctuated across Jylland several times (Rasmussen 1996).

The Upper Oligocene – Miocene climatical conditions as revealed from floristic changes in Central Europe and brown coal pits in Jylland, indicate a humid, warm-temperate to subtropical climate with a cool period within the Aquitanian (Mai 1967; Koch 1989).

Regional distribution of reservoir sand and seals

The distribution of reservoir sand and mud seals of the Upper Oligocene – Miocene succession is shown in a profile through East- and South Jylland (Fig. 2). There are four levels of reservoir sands. The lower reservoir sand is the Hvidbjerg sand which is outcropping in East and Northwest Jylland. The thickness of the Hvidbjerg sand is up to 26 m. The succeeding reservoir unit, the is best developed in the southern and western part of Jylland where it is up to 50 m thick. The main part of this sand was deposited in a lobe approximately 50 km wide and 75 km long. This sand is known as the Ribe Formation (Rasmussen 1961; Dybkjær *et al.* 1999; Rasmussen 2001). The sand unit is superposed by marine clay of the Arnum Formation which provides a seal for the reservoir sand. Above the marine clay a new sand interval prograded out into the basin. This sand interval is up to 40 m thick. The distribution of this sand is more regional. The sand is informally named the Bastrup sand (Rasmussen 2001). This is again overlain by marine clay of the Arnum Formation, which provide a seal for the reservoir interval. Resumed progradation of the shoreline resulted in deposition of a third sand interval, which is generally thinner than the two lower intervals, rarely thicker than 30 m. The distribution of this sand interval is also regional. The third sand is referred to as the Odderup Formation (Rasmussen 1961; Rasmussen 2001). This is succeeded by marine clay of the Hodde and Gram Formations, which has excellent and regional sealing properties.

High quality reservoir sand

Spit systems

The Hvidbjerg sand outcrops as a 25 m thick spitsystem on the south coast of Vejle Fjord. Associated depositional complexes can be seen in the adjacent area (Fig. 3). This is informally called the Hvidbjerg sand (Rasmussen 2001)(Fig. 2). North of the spit system organic-rich silty clay deposited in a lagoon crops out at several localities and has been drilled in a number of borings (Fig. 3). Close to the spit system washover fans dominates the back-barrier facies. Channel complexes cross cutting the spit system are found in both outcrops and pits and when excavation is done perpendicular to the paleocurrent direction, good examples of tidal bundles are exposed. South of the spit system the development of lower and upper shoreface sediments are demonstrated at a number of localities around the strait of Lille Bælt (Fig. 3). Here various types of storm deposits outcrop, e.g. hummocky cross stratified beds, homogenous to plan-laminated thick sand beds with wave rippled top and coarse-grained ripples.

The spit system consists of medium to coarse-grained sand with scattered gravel horizons and occasionally thin silty beds occur. Within the inlets extremly well rounded and clean sand was deposited. This sand is used as castings in the nearby Iron Factory, which illustrates the quality. The sand deposited in the upper shoreface constitutes also good reservoir sand, but the thickness decreases distinctively from 25 m to ca. 10 –15 m in thickness (Fig. 3).

The formation of spit systems is associated with highstand systems tracts. The occurence of the spit systems is often associated with structural highs on the Ringkøbing-Fyn High, as for example is known from Lower Cretaceous deposits from Bornholm (Noe-Nygaard and Surlyk 1988).

Fluvial-deltaic systems

Fluvial-deltaic systems deposited in Denmark obtained the best reservoir quality when the sediments were deposited during falling sea level. The Ribe Formation was deposited during a major sea-level fall in the Early Miocene. This resulted in deposition of up to 50 m of sand and gravel deposits without intercalation of coal layers (Fig. 2). The sediment grains are generally subangular to well rounded, and well to poorly sorted.

Fluvial-deltaic systems of the Bastrup and Odderup formations are petrologically very similar to the Ribe Formation, but they are normally thinner, 20 – 30 m in thickness (Fig. 2). The fluvial deposits of the odderup Formation can be studied in pits in Central Jutland. Here they were laid down in braided river systems (Hansen 1985) and deposited during a general sea-level rise.

Prediction of lithology

At outcrops and pits in East Jylland an excellent example of a sequence boundary is exposed. This sequence boundary and the facies change across the boundary indicate a displacement of the shoreline (Fig. 4).

The Upper Oligocene – Lower Miocene succession, in East Jylland, shows a normal progradation of a shoreline which is illustrated through a gradual increase in grain size, from fine-grained sand to medium-/coarse-grained sand, and thickening of bed thickness upwards (Rasmussen 1998). The sedimentary structures demonstrate a development from hummocky cross-stratified beds through swaley cross-stratified beds to gently dipping cross-stratified beds characteristic for lower-upper shoreface to beach deposits. This evolution is abruptly cut by an erosional surface overlain by distinctly coarser grained sediments, e.g. gravel (Fig. 4). Biostratigraphic data indicate a hiatus of ca. 3.5 Ma equivalent to Aquitanian – early Burdigalian. During this time the shoreline was displaced up to 100 km towards the southwest (Fig. 5) and extremely good reservoir sand and gravel were deposited in the basinal setting (Ribe Formation). Such analogues are important in future exploration for hydrocarbons in the Central and Vikings Grabens especially for prediction of reservoir potential and quality.

Future studies

The investigation of the Miocene succession will continue with high activities throughout the decade. The project will result in a robust 3-D model of all reservoir intervals, which should enable counties to plan future water supply in Jylland.

An additional outcome of the studies will be a detailed biostratigraphic framework which should enable stratigraphers to make high resolution correlations and better datings of borings and wells in this part of the North Sea Basin. Detailed studies of palynofacies combined with sedimentology will result in a strong interpretation technique of boreholes samples with respect to depositional environment. The detailed knowledge of the development of the succession and relatively precise data about climatical changes during the Late Cenozoic will further result in a better understanding of the interrelationship between the response of sedimentary successions and sea-level variations.

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Figures

Figure 1. *Structural elements of the Eastern North Sea basin and borings and outcrops referred to in the text. Partly from Bertelsen (1978).*

Figure 2. *Log correlation panel of the Upper Oligocene – Miocene succession. Lithostratigraphic names are indicated on the figure. From Rasmussen (2001).*

Figure 3. *Schematic illustration of the depositional environment with inserted log- and outcrop sections.*

Figure 4. *Upper shoreface sand cut by a pebble layer at the Børup locality. The erosive base forms a ravinement surface which have replaced the sequence boundary. The hiatus at the surface represent more than 3.5 my, corresponding to Aquitanian – early Burdigalian of Early Miocene.*

Figure 5. *Schematic illustration of the development of Late Oligocene and Early Miocene succession. During the Late Oligocene (a) the area was transgressed and fine-grained, glaucony-rich marine sediments were deposited. In the marginal areas e.g. Vejle Fjord area a shoreline was formed by deposition of near-shore sand-rich deposits (b). Increased sediment supply into the area resulted in regression of the shoreline under relative sea-level rise (highstand systems tract) (c). A drop in the relative sea level resulted in a distinct shift of the shoreline towards the southwest and fluvial-deltaic sediments of the Ribe Formation were deposited in the southwestern part of Jylland (d). During the subsequent transgression, parts of the fluvial deposits were reworked and a ravinement surface was formed (e). Resumed establishment of a shoreline in East Jylland (Lille Bælt) resulted in deposition sand-rich sediments within a barrier-complexes (f, g). Rfom Rasmussen (1998).*

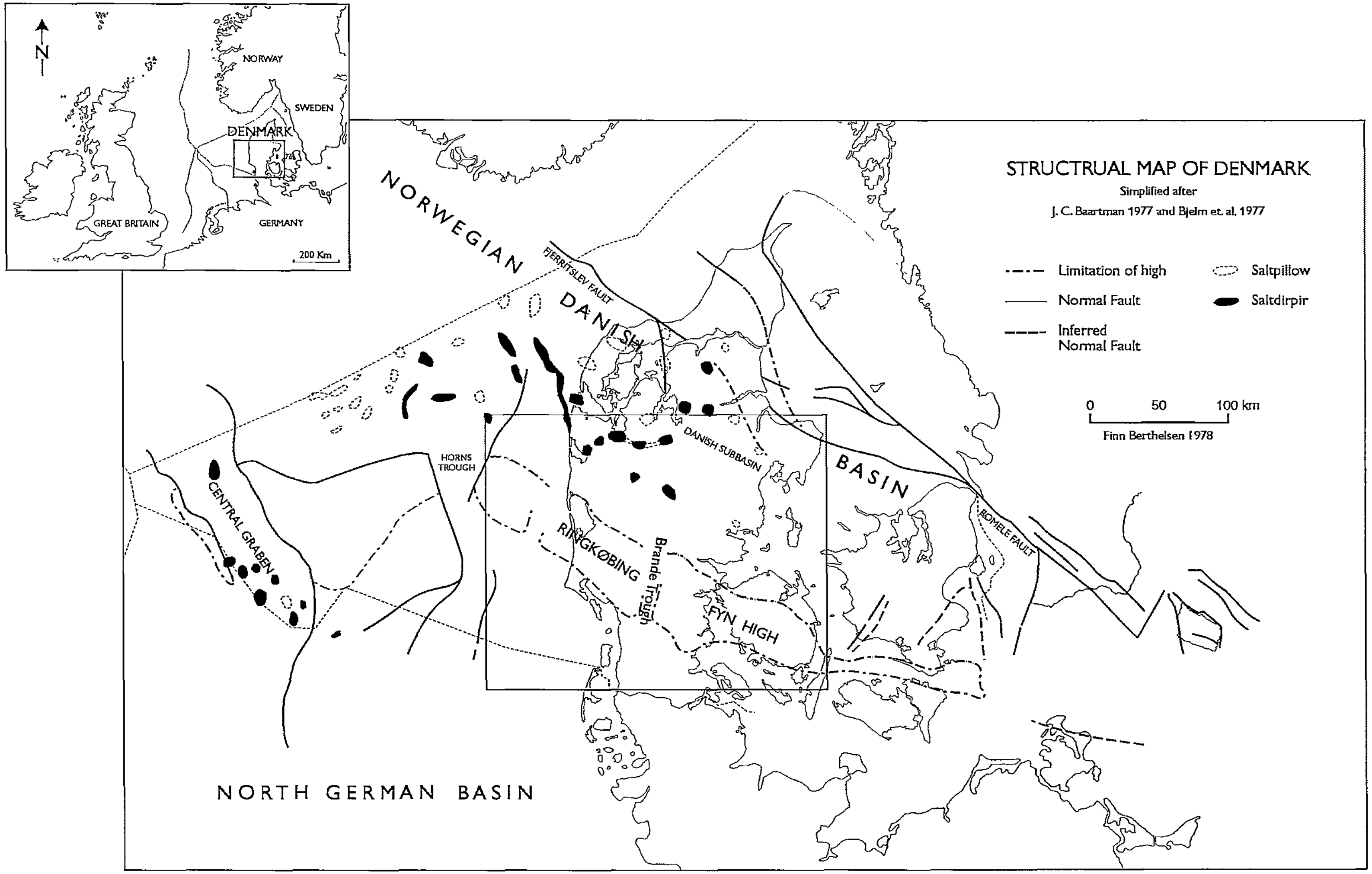
N
NORWAY
SWEDEN
DENMARK
GREAT BRITAIN
GERMANY
200 Km
STRUCTRUAL MAP OF DENMARK
Simplified after
J. C. Baartman 1977 and Bjelm et. al. 1977
Limitation of high
Normal Fault
Inferred Normal Fault
Saltpillow
Saltdirpir
0 50 100 km
Finn Berthelsen 1978
NORWEGIAN
DANISH
BASIN
FJERRITSLEV FAULT
DANISH SUBBASIN
HORNS TROUGH
CENTRAL GRABEN
RINGKØBING
Brande Trough
FYN HIGH
RØMELE FAULT
NORTH GERMAN BASIN

Fig 1

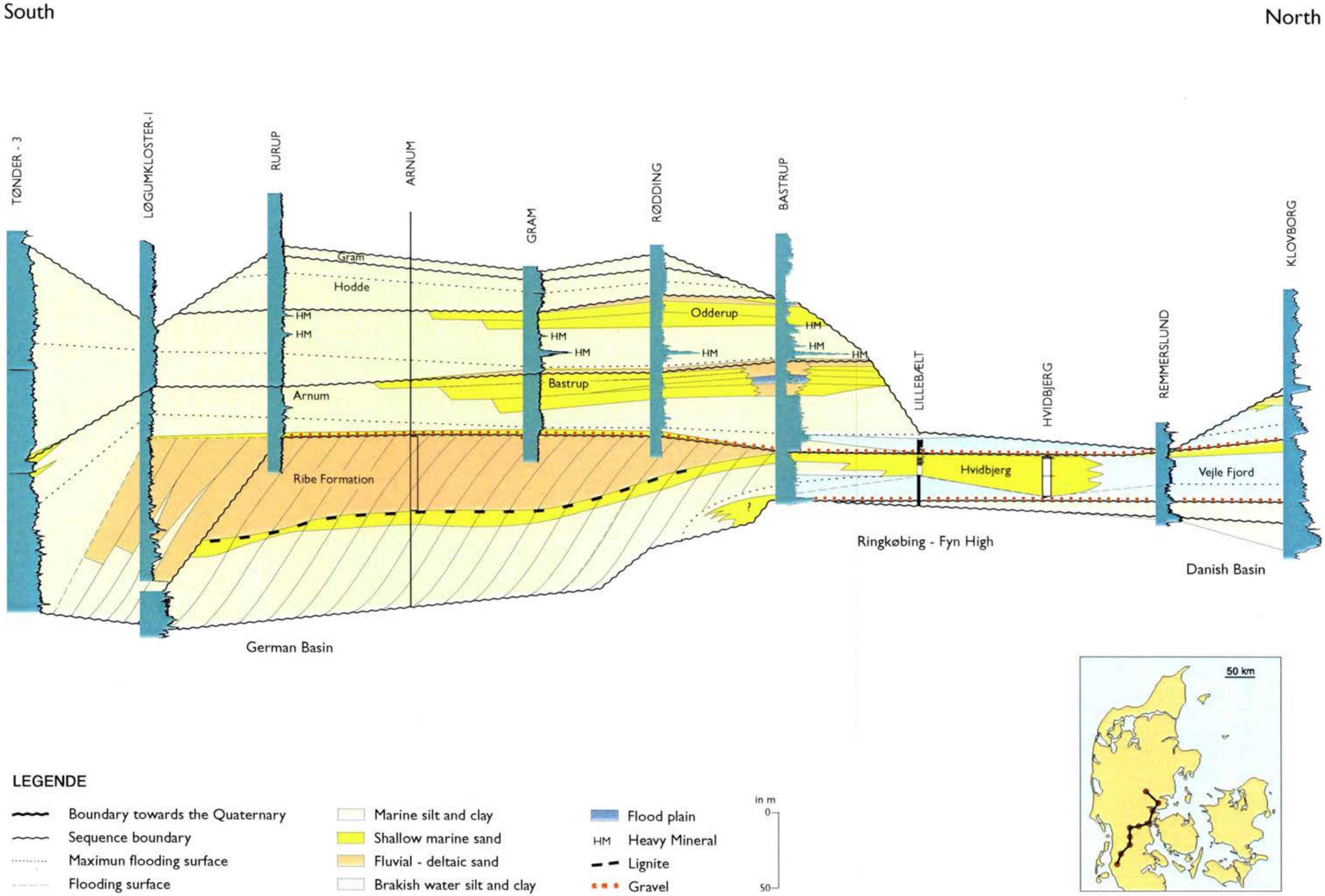

Fig 2

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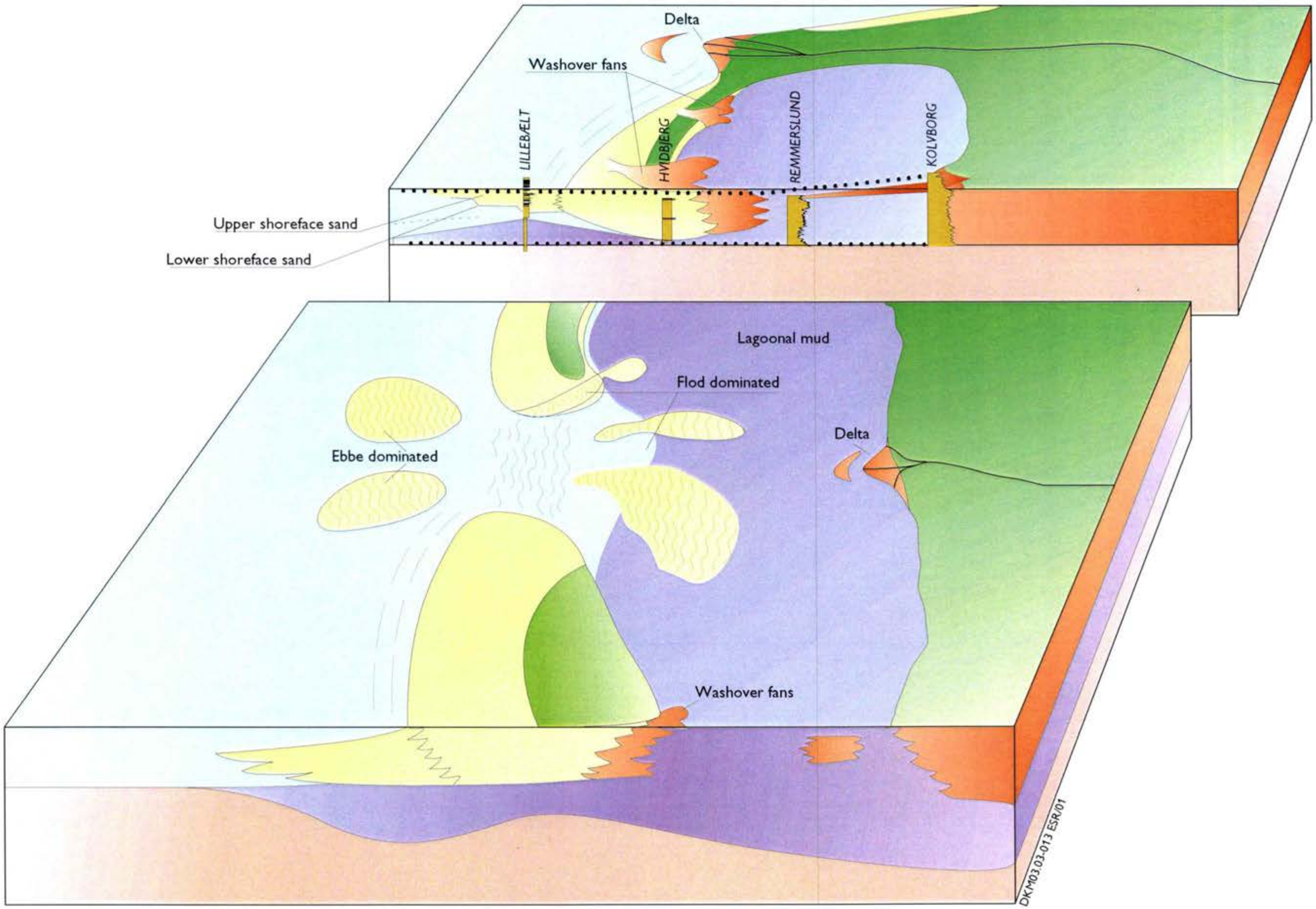

Open Marine

Brackish water

Fig 3

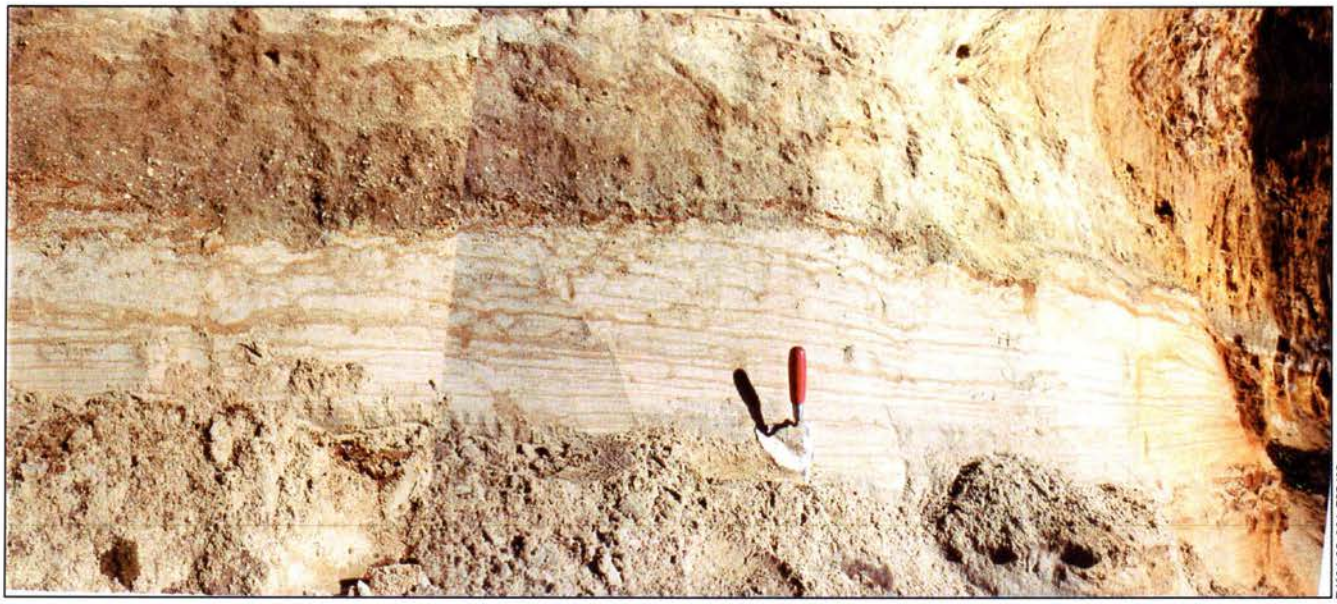

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Fig 4

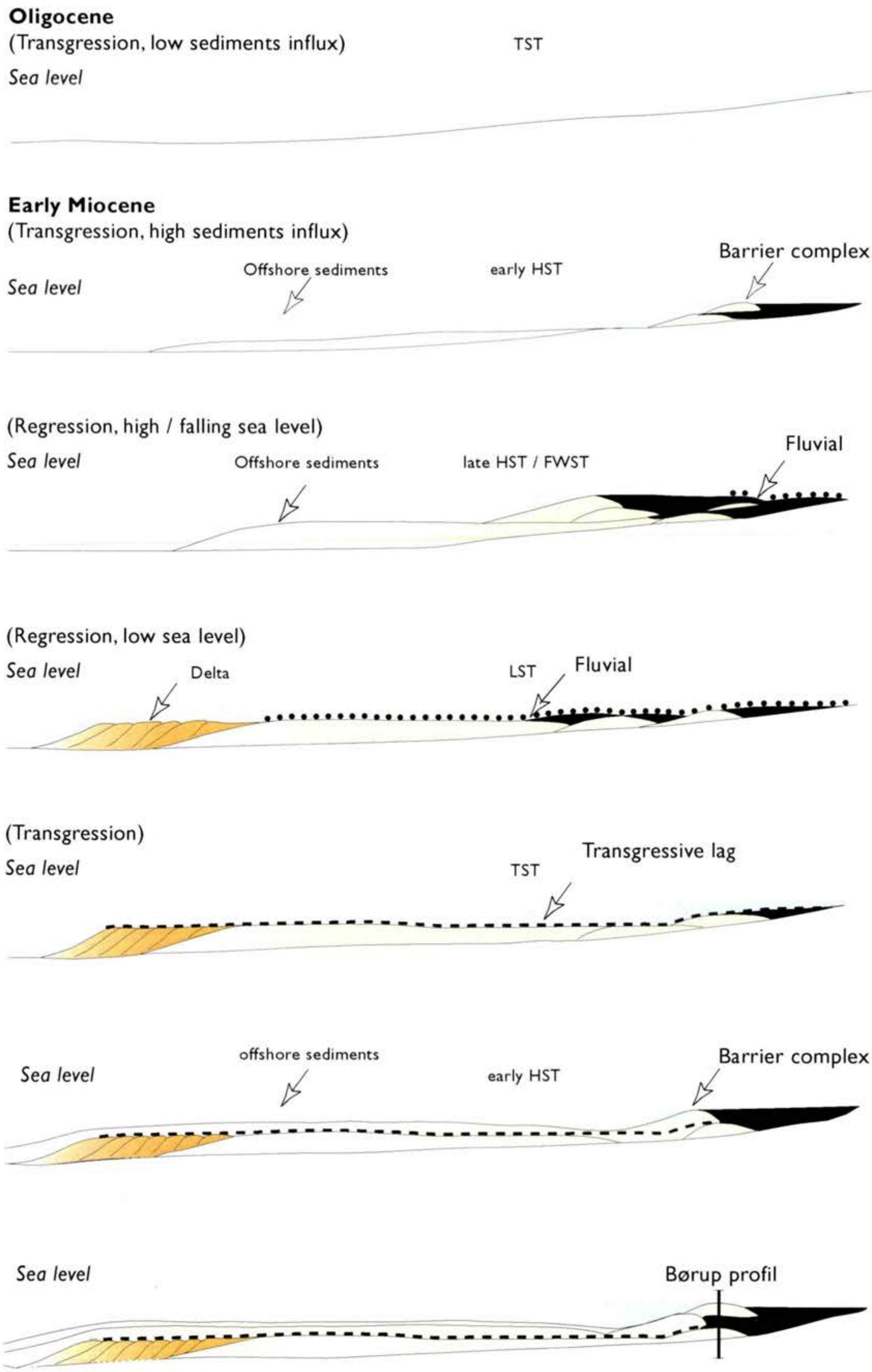

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Fig 5