DGU DANMARKS GEOLOGISKE UNDERSØGELSE • SERIE C • NR. 12
GEOLOGICAL SURVEY OF DENMARK • SERIES C • NO. 12

Proceedings of the 2nd Symposium on: Marine Geology

Geology of the North Sea and Skagerrak, Aarhus University, 1993

EDITOR

OLAF MICHELSEN

Miljø- og Energiministeriet • København 1995
Ministry of Environment and Energy • Copenhagen 1995

DGU DANMARKS GEOLOGISKE UNDERSØGELSE • SERIE C • NR. 12
GEOLOGICAL SURVEY OF DENMARK • SERIES C NO. 12

Proceedings of the 2nd Symposium on Marine Geology:

Geology of the North Sea and Skagerrak, Aarhus Universitet, 1993

REDAKTØR / EDITOR
OLAF MICHELSEN

Miljø- og Energiministeriet • København 1995
Ministry of Environment and Energy • Copenhagen 1995

DGU DANMARKS GEOLOGISKE UNDERSØGELSE • SERIE C • NR. 12
GEOLOGICAL SURVEY OF DENMARK • SERIES C NO. 12

Proceedings of the 2nd Symposium on Marine Geology:

Geology of the North Sea and Skagerrak, Aarhus Universitet, 1993

REDAKTØR / EDITOR
OLAF MICHELSEN

Miljø- og Energiministeriet • København 1995
Ministry of Environment and Energy • Copenhagen 1995

Proceedings of the 2nd Symposium on Marine Geology:

Geology of the North Sea and Skagerrak

Aarhus Universitet, 1993

Editor: Olaf Michelsen

Contents

Preface

The Marine Geology Unit of the Department of Earth Sciences organized the second Marine Geology Symposium at Aarhus University, 7-8 October 1993. The intention was to bring together people working with especially the geology of the North Sea and Skagerrak.

Approximately 60 people from different Danish and Norwegian institutions attended the symposium. 28 oral presentations were given and 2 posters presented. A large range of geological topics was covered, embracing biostratigraphy, sequence stratigraphy, sedimentology and structural geology. The majority of the presentations dealt with Quaternary geology and Cenozoic sequence stratigraphy, but also Jurassic and Lower Cretaceous stratigraphy was treated. Studies from the major part of the Danish sector were presented, spanning from Bornholm to the central North Sea, and further into the Norwegian North Sea sector.

The symposium was planned as an informal meeting, giving especially younger scientists an opportunity to present new results or ongoing marine geology projects. The present proceedings volume includes short papers or extended abstracts of some of the presentations given at the symposium. Some of the papers include preliminary results of research projects, which have not yet been finished.

The organizers thank all participants for presentations and contributions to the discussion. We also should like to thank persons who assisted with preparation of the abstract volume, reservation of lecture rooms etc.

Århus, March, 1994 Olaf Michelsen

Authors addresses

Ole R. Clausen, Department of Earth Sciences, Aarhus University, DK-8000 Århus C, Denmark.

Ulrik Gregersen, Department of Earth Sciences, Aarhus University, DK-8000 Århus C, Denmark.

H.C.S. Hansen, Geological Survey of Denmark, Thoravej 8, DK-2400 København NV, Denmark.

Henrik Jordt, Institutt for Geologi, Universitetet i Oslo, PB. 1047, Blindern, N-0316 Oslo, Norway.

Peter B. Konradi, Geological Survey of Denmark, Thoravej 8, DK-2400 København NV, Denmark.

Eva B. Koppelhus, Geological Survey of Greenland, Øster Voldgade 10, DK-1350 København K.

John A. Korstgård, Department of Earth Sciences, Aarhus University, DK-8000 Århus C, Denmark.

Finn N. Kristoffersen, Geological Survey of Denmark, Thoravej 8, DK-2400 København NV, Denmark.

Gitte V. Laursen, Department of Earth Sciences, Aarhus University, DK-8000 Århus C, Denmark.

Henrik Madsen, Department of Earth Sciences, Aarhus University, DK-8000 Århus C, Denmark.

Olaf Michelsen, Department of Earth Sciences, Aarhus University, DK-8000 Århus C, Denmark.

Søren A. V. Nielsen, Geological Survey of Denmark, Thoravej 8, DK-2400 København NV, Denmark.

Lars H. Nielsen, Geological Survey of Denmark, Thoravej 8, DK-2400 København NV, Denmark.

Kenneth Petersen, Department of Geological Sciences, University of South Carolina, Columbia, S.C 29208, USA.

Inger Salomonsen, Geological Survey of Denmark, Thoravej 8, DK-2400 København NV, Denmark.

Origin of a deep buried valley system in Pleistocene deposits of the eastern central North Sea

Inger Salomonsen

Abstract

In the North Sea, the sedimentary development of the late Tertiary and early Quaternary was dominated by deltaic sedimentation in a fast subsiding basin. During the Pleistocene, pronounced climatic changes affected the sedimentation of the area and progradation of the delta systems ceased. The Middle and Upper Pleistocene sedimentary successions consists of alternations of marine and fluvial deposits, partly reworked during glacial periods. Seismic records from the Danish sector of the North Sea reveal numerous deep incisions cut down from various levels of the Middle and Upper Pleistocene successions. These incisions are concluded to form a pattern of buried valleys. Detailed seismic stratigraphic analysis shows the occurrence of various internal unconformities within these buried valleys. It is concluded that the valleys originate from a river system developed in periods of repeated sea-level changes. Fluvial erosion during glacial sea-level lowstand and glacial meltwater action is proposed to have been responsible for the origin of the valley system. Thus, in Middle and Upper Pleistocene glacial periods drainage and associated sediment transport occurred from Northwest and Central European land areas via a presently buried river system in the southeastern North Sea towards a depositional basin north and northwest of the Danish North Sea sector.

Introduction

During the Miocene, Pliocene and the Early Pleistocene, deltas from northwest European rivers prograded towards the west and northwest from present-day North European land areas towards the North Sea. Here they formed one large delta system. The drainage from the North German and the Baltic areas took place through a Baltic river system. In connection to these rivers a well developed delta was build (Kay, 1993). During the upper Miocene the depocentre moved northwards from the Dutch land area to the southern North Sea area. Sediments transported by the Palaeo-Rhine were deposited in another delta, south of the Baltic river delta. During the Pliocene the depocentre for this delta moved northwestwards following the axis of the Central Trough (Cameron et al., 1987; Zagwijn, 1989; Kay, 1993).

In the eastern North Sea area, the supply of sediment came mainly by the Baltic rivers (Gibbard, 1988). In the beginning of the Early Pleistocene, in the Praetiglian, the delta developed in front of these rivers prograded further westwards. Sedimentation in shallow marine environment was prevalent at that time in the easternmost area.

Deposits from the Baltic rivers can be traced in the North Sea up to the Tiglian stage by virtue of their mineralogical composition (Gibbard et al., 1991). In the same period, a Proto-Baltic basin developed, causing drainage of the southeastern part of the Scandinavian and Baltic areas into this basin in stead of into the North Sea basin. From then on the North German and Central European rivers were the major agents of sediment transport to the North Sea (Gibbard, 1988).

During the Quaternary, significant changes occurred in the southern North Sea. The depocentre which in Pliocene moved towards the North to the Central Trough area, continued northward to the present-day position. The sedimentation rate increased during the Quaternary to ten times the rates of the Early Tertiary, yielding a Quaternary sedimentary sequence with a thickness of more than 900 m in the centre part of the North Sea (Zagwijn & Doppert, 1978; Zagwijn, 1989).

Climatic changes with extreme fluctuations in temperature characterized the Quaternary period. During glacial periods northwest Europe was north of the tree limit and the area was affected by severe permafrost. Under these conditions erosion of the hinterland occurred and the supply of sediment to the basin increased. In the warm periods, trees and other vegetation covered the area again. This pattern of changing cold and warm periods started at 2.3 m.a. with the first cold stage, the Praetiglian, and persisted during the entire Quaternary (Gibbard et al., 1991).

Study area

The area in which the occurrence of buried valleys has been studied covers almost the entire Danish North Sea sector (Fig. 1).

The latitude of 56°45'N defines the northern boundary for this investigation. South of this boundary, the available seismic lines form a relatively dense grid. The quality of the data, permits to resolve details in the seismic profiles, required for the interpretation of the valley structures. North of 56°45' N, only a relatively thin cover of Quaternary deposits are preserved and the late Tertiary and Quaternary deposits are intensively disturbed by halokinesis and associated fault structures.

Detailed interpretation has been carried out in the area west of 4°45'E. The valley described here is situated in this westernmost part of the Danish area. In this area the Cenozoic sedimentary succession is among the most complete seen in the basin, and data of very high quality is available.

Data and Methods

For the seismic interpretation, the regional mapping and the analyses of the valley systems, both conventional and high-resolution seismic data have been used.

The conventional seismic profiles are multichannel airgun seismic data from regional 2-D seismic surveys, made for the exploration of oil and gas. In the western and southeastern part of the study area, a high density seismic grid is available, while a more open grid is found in the rest of the study area. The interpretation was mainly performed at 10-cm migrated profiles. For some few surveys only 5-cm profiles were available. The unmigrated (filtered) profiles were used when no migrated version existed. For this type of study the character of most profiles, with the lack of resolution in the very top part, enables a interpretation of the profiles only for the section below 200 msec TWT and deeper.

Additional multichannel sleeve-gun seismic data have been used. These data were collected particularly in order to obtain information on the Quaternary succession. At this type of profiles interpretation is possible between 50 and 900 msec TWT. One survey has been made especially to investigate the buried valley further described here.

Shallow seismic and high-resolution multichannel sleeve-gun profiles permit to trace regional unconformities representing the erosive subsurfaces from which the valleys are incised (Salomonsen & Jensen, unpublished data).

Several unconformable surfaces can be detected in the uppermost part of the seismic sections. On the seismic records the outline of the valleys appears from reflector terminations seen as erosional truncations. The valleys intersected by two ore more seismic profiles have been marked, and dimensions as depth and width have been measured. The basal erosion surface of the deep incisions is very well defined on the seismic profiles, though it may be masked by multiples. The surface expresses the deepest position of the erosional level in combination with later subsidence and tectonic movements in the area.

In the study area, several geotechnical boreholes are drilled in the Holocene and Pleistocene sedimentary succession in connection to the deep oil wells. Additional, two stratigraphical boreholes are available from a multidisciplinary study of the Quaternary in the Southern North Sea. Foraminiferal analyses from some of these boreholes have established the stratigraphy of the area (Knudsen, 1985; Salomonsen & Jensen, unpublished data).

Case study of a buried valley

The valley located in the western part of the Danish North Sea sector, is the most prominent seen in the area (Fig. 2). The valley has been studied in detail by including conventional profiles from other surveys to the regional seismic data base, resulting in a grid of profiles with intervals of approximately 500-1000 m perpendicular to the structure and approximately 1750 m parallel to its strike direction. In addition, two high-resolution profiles, one cross-section and one parallel section were used.

The SSE-NNW orientated valley is seen as part of a group of valleys of similar orientation recognized in the central part of the North Sea basin. The valley is an elongated structure, 2-4 km wide. The structure is mapped from the seismic sections over a distance of 35 km. The depth to the lowermost unconformity is in general 400-500 msec TWT corresponding to 360-450 m below present sea level. Maximum depths at 550 msec TWT (500 m) are found locally in the centre and northern part of the valley. The bottom of the valley gradually deepens towards the north. Towards SE, minor valleys observed in the southern part of the area join the main valley. In the northern part of the area, the main valley branches out in several small valleys. The acoustic character of these valleys is below the seismic resolution level. It is therefore not possible to follow the continuation of the valleys north of the area mapped in this study on the conventional seismic records.

In conventional seismic profiles cross sections of the valley show at least two, occasionally three, unconformable internal reflections, indicating several generations of incision within the main valley structure. When using the high-resolution seismic profiles, it is evident that more internal unconformities are present. At least five erosional surfaces are seen, and it is obvious that the valley has been generated during repetitive cycles of erosion and deposition (Fig. 3). With only one cross-section of high-resolution quality available, the regional mapping is based on the conventional profiles. Downlaps in the lower part of the infill of the valley have been observed on a record from near the main axis of the valley. The unconformity of the first generation of incision is only seen in the northern part of the valley, the second generation unconformity is observed in part of the valley, whereas the third generation unconformity is seen in the entire valley.

Interpretation

The mapped structure is interpreted to be part of a fluvial system, which is responsible for repeated erosion in the area. Each of the unconformities showing the shape of a valley represents a river flowing through the area. The unconformities may be separated by a body of sediment deposited as infill of the valley in periods between the erosive phases. The orientation of the downlaps in the lower part of the valley indicate directional deposition by water running from the drainage area SE of the structure towards NW to a depositional basin. Signs of the first generation of erosion in the area which is only preserved in a small area in the northern part of the valley, indicate an initial northward inclination of the thalweg. The minor valleys in the southern part of the area are thus tribu-

taries to the main river, which basinwards changes into a braided river system in a deltaic environment.
The composite valley detected from conventional and high-resolution seismic profiles is shown in Fig. 4. In the southern part of the valley only one 'second-generation' inlet to the river is preserved. The unconformity of the second generation is not preserved from this inlet until a position more to the northwest. Along the northern part of the main valley this generation is preserved.
Two inlets from the third erosional generation are seen. During this third phase the erosion in the southern part of the valley may have been more intensive than previously, as the infill and outline of the older valley is not preserved. Towards the northwest the discharge current forces decreased. The two erosional levels, indicating the bottom of the respective valleys, split and are preserved here as separate unconformities. In the northernmost part a transition into a braided river system occur. The causes of braiding may be found in specific climatic conditions, affecting the discharge, water flow speed and sediment load.
The unconformable boundaries are interpreted as 'Type-1-sequence boundaries' characterized by stream rejuvenation and fluvial incision. The shelf was an area of sedimentary bypass and an abrupt basinward shift of facies and coastal onlap occurred. A eustatic fall of sea-level and low rates of subsidence may characterize the shelf margin (Vail & Todd, 1981).

Regional pattern of buried valleys
A network of deep buried valleys recognized in the entire study area has been mapped and the outline of the valley pattern is shown in Fig. 5. The dimensions of the mapped valleys vary from 0.5 to 5 km in cross-section width and 5 to 40 km in length. The depth of the valley floor is usual between 150 and 400 m, but in the northwestern part of the area, the bottom of valleys are detected below 540 m b.s.l. (600 msec TWT). This represents the deepest level of erosion seen in connection to valley formation. The distance between the valleys varies, a high number of valleys is seen in the western part of the area, while a more open pattern is observed in the eastern area. However, it should be noted, that the seismic grid in the latter part of the area is less dense.
The orientation of the valleys is in the eastern part of the area dominated by a E-W and NE-SW orientation, while a SSE-NNW to SE-NW orientation is prevalent in the area close to the British North Sea sector.
The distribution of the valleys in the area may reflect the older structural elements affecting the subsidence and thereby the Pleistocene surfaces. High density of valleys are seen in the areas of the Central Trough and Horn Graben, while no valleys are seen in the area of the Ringkøbing-Fyn High. The latter area may have been a highland during most of the Pleistocene.

Geological model
Seismic studies at the eastern North Sea basin have demonstrated that progradation of a delta complex took place during the Miocene, Pliocene and Early Pleistocene (Kay, 1993; Salomonsen, in press). Delta top and fluvio-deltaic sediments were deposited during the Pliocene to Middle Pleistocene in the eastern part of the basin, while the deposition was delayed until Early Middle Pleistocene in the western part of the basin. The sedimentary succession of this delta complex has been described in terms of a shallowing upwards basin fill.
A drainage system in the southern and central North Sea as indicated by river valleys points to a drainage basin in the area of the present Denmark, the Baltic area and the North German area. Discharge from these regions caused fluviatile sediment transport through the present southern North Sea. The rivers followed the gradient of the palaeosurface towards a depositional basin situated north or northwest of the Danish area, pre-

ferably in the central North Sea. Several generations of valley incision may be related to glacial periods. It has been possible to date some of the younger erosive surfaces to the Saalian and Weichselian glacial epochs by foraminiferal stratigraphy (Salomonsen & Jensen, unpublished data).

Thus, during sea-level fall and lowstand in relation to Pleistocene glacial periods, incised valleys were cut in the shelf as extensions of existing river valleys. The valleys seen on-shore in present-day Jutland are part of this drainage system.

In the beginning of a cooling period the landscape was exposed and periglacial conditions occurred. The erosion of land areas increased and sediment was transported by rivers towards the depositional basin, where sedimentation rates increased. When the source areas were covered by ice, a decrease of sedimentation occurred. During the cooling phase and establishing of the ice sheet a lowstand situation was developed. The sea-level was lowered in an order of 100-130 m below present sea-level during the Weichselian glacial stades (Jelgersma, 1979). The weight of the ice cap oppressed the underlying part of the shelf, causing the development of a peripheral bulge in front of the ice covered area. Some sediment must have been transported from the ice covered area towards the depositional basin by subglacial streams as indicated by glaciomarine sedimentation in the Central North Sea.

Networks of braided river systems developed at an alluvial plain, the alluvial fans had their apex at the front of the glacier. Locally the valleys and incisions may have been eroded further by the ice itself, by 'jökulhlaups' or other ice front related processes, and thus indicate the extension of the ice cap (Ehlers & Linke, 1989; Ehlers & Wingfield, 1991; Wingfield, 1989; 1990).

The change to warmer climatic conditions in the interglacial periods caused melting of ice. At initial ice cap melting, these incisions and river valleys were further deepened by excessive meltwater discharge. Contemporary to an isostatic uplift of the continent, the sea-level also rose due to ice melting. Further erosion was possible in the elevated area and increased sediment supply to the basin occurred. With rising sea-level, the coastline moved landward and a highstand situation developed. The valleys were filled during the late lowstand period by fluvial sediments and by marine sediments during the succeeding transgressive phase. A different character of the infill of the valleys is evident on seismic amplitude studies indicating different lithologies of the fill deposits. Some of the valleys were not filled totally before covered by the Holocene sediments and thus cause depressions at the sea floor.

Thus, lateral movement of the environments on the shelf during the climatic changes, resulted in a stacked pattern of sediments and erosional valleys. More generations of valleys in the same main trace represents the development of the same environment several times in the area during the Late Quaternary.

Conclusions

The regional pattern of deep buried valleys seen in the North Sea is interpreted to be the result of intermittent fluvial erosion in relation to glacial periods as part of the drainage system in Northwest Europe. Discharge took place through rivers through the present North Sea area, following the gradient of the palaeosurface towards a depositional basin. This basin was situated north or northwest of the Danish North Sea area, preferably in the central and northern North Sea. The valleys seen on-shore in present-day western Jutland are part of this system.

The two mappable generations of valleys are results of changes in the hydrographical regime in the area. Erosion of the river floor are expressed as reflectors defined by

erosional truncations at the seismic profiles. These are separated by a body of sediments representing intermediate periods of deposition.
The valleys were filled during the lowstand period, when accommodation space in the coastal area decreased. During the following transgressive phase, the valleys were buried and a very low relief surface was formed.
The erosive valleys observed in seismic records from the Danish North Sea area are thus indicative of a larger system of river valleys. The distal part of the rivers, at the transition to the depositional basin, are not visible on the seismic profiles due to low resolution. The valleys have not been generated as local incisions due to subglacial erosion solely.
The few high-resolution data available in the Danish area has confirmed the interpretation based upon the conventional seismic data. The study has evidently shown that high-resolution seismic data are a prerequisite for a detailed reconstruction of the Quaternary environment of the North Sea area.

Acknowledgements

This study was carried out at the Geological Survey of Denmark and University of Copenhagen during a Ph.D. study supported by the Carlsberg Foundation. The acquisition of the regional high-resolution seismic data and drilling of stratigraphic boreholes were made during the Southern North Sea Project funded by the CEC-Science programme. Collaboration with the University of Aarhus and the Oceanographic Institute in Kaliningrad made it possible to acquire additional high-resolution seismic lines. Antoon Kuijpers is thanked for reviewing the manuscript.

References

Cameron, T.D.J., M.S. Stoker & D. Long, 1987: The history of Quaternary sedimentation in the UK sector of the North Sea Basin. Journal of the Geological Society, London, vol. 144, 43-58.

Ehlers, J. & G. Linke, 1989: The origin of deep buried channels of Elsterian age in Northwest Germany. Journal of Quaternary Science, 4 (3), 255-265.

Ehlers, J. & R. Wingfield, 1991: The extension of the Late Weichselian/Late Devensian ice sheets in the North Sea Basin. Journal of Quaternary Science, vol. 6 (4), 313-326.

Gibbard, P.L., 1988: The history of the great northwest European rivers during the past three million years. Phil. Trans. R. Soc. London, B 318, 559-602.

Gibbard, P.L., R.G. West, W.H. Zagwijn, P.S. Balson, A.W. Burger, B.M. Funnel, D.H. Jeffery, J. de Jong, T. van Kolfschoten, A.M. Lister, T. Meijer, P.E.P. Norton, R.C. Preece, J. Rose, A.J. Stuart, C.A. Whiteman & J.A. Zalasiewicz, 1991: Early and early Middle Pleistocene correlations in the southern North Sea Basin - Quaternary Science Reviews 10: 23-52.

Jelgersma, S., 1979: Sea-level changes in the North Sea basin. In: E. Oele, R.T.E. Schütten-helm & A.J. Wiggers (eds.): The Quaternary History of the North Sea, 233-248. Acta Univ. Ups. Symp. Univ. Ups. Annum Quingentesimum Celebrantis : 2, Uppsala.

Kay, C., 1993: A regional depositional model for the southern North Sea during the Late Tertiary and Quaternary. Abstract Supplement No. 1 Terra nova 5: 605.

Knudsen, K.L., 1985: Foraminiferal stratigraphy of Quaternary deposits in the Roar, Skjold and Dan fields, central North Sea. Boreas 14, 311-324.

Salomonsen, I, in press: A seismic stratigrahic analysis of Lower Pleistocene deposits in the western Danish sector of the North Sea. Geologie en Mijnbouw.

Salomonsen, I. & K.A. Jensen, in prep.: Quaternary erosional surfaces in the Danish North Sea. Submitted to Boreas.

Vail, P.R. & R.G. Todd, 1981: North Sea Jurassic unconformities, chronostratigraphy and sea-level changes from siesmic stratigraphy. Petroleum Geology of the Continental Shelf of Northwest Europe, Proceedings, 216-235.

Wingfield, R.T.R., 1989: Glacial incisions indicating Middle and Upper Pleistocene ice limits off Britain. Terra Nova 1, 538-548.

Wingfield, R.T.R., 1990: The origin of Major Incisions Within the Pleistocene Deposits of the North Sea. Marine Geology, 91, 31-52.

Zagwijn, W.H. & J.W.C. Doppert, 1978: Upper Cenozoic ofthe Southern North Sea Basin: Palaeoclimatic and Palaeogeographic evolution. Geologie en Mijnbouw, vol. 57, 577-588.

Zagwijn, W.H., 1989: The Netherlands during the Tertiary and the Quaternary: A case history of Coastal Lowland evolution. Geologie en Mijnbouw, vol. 68, 107-120.

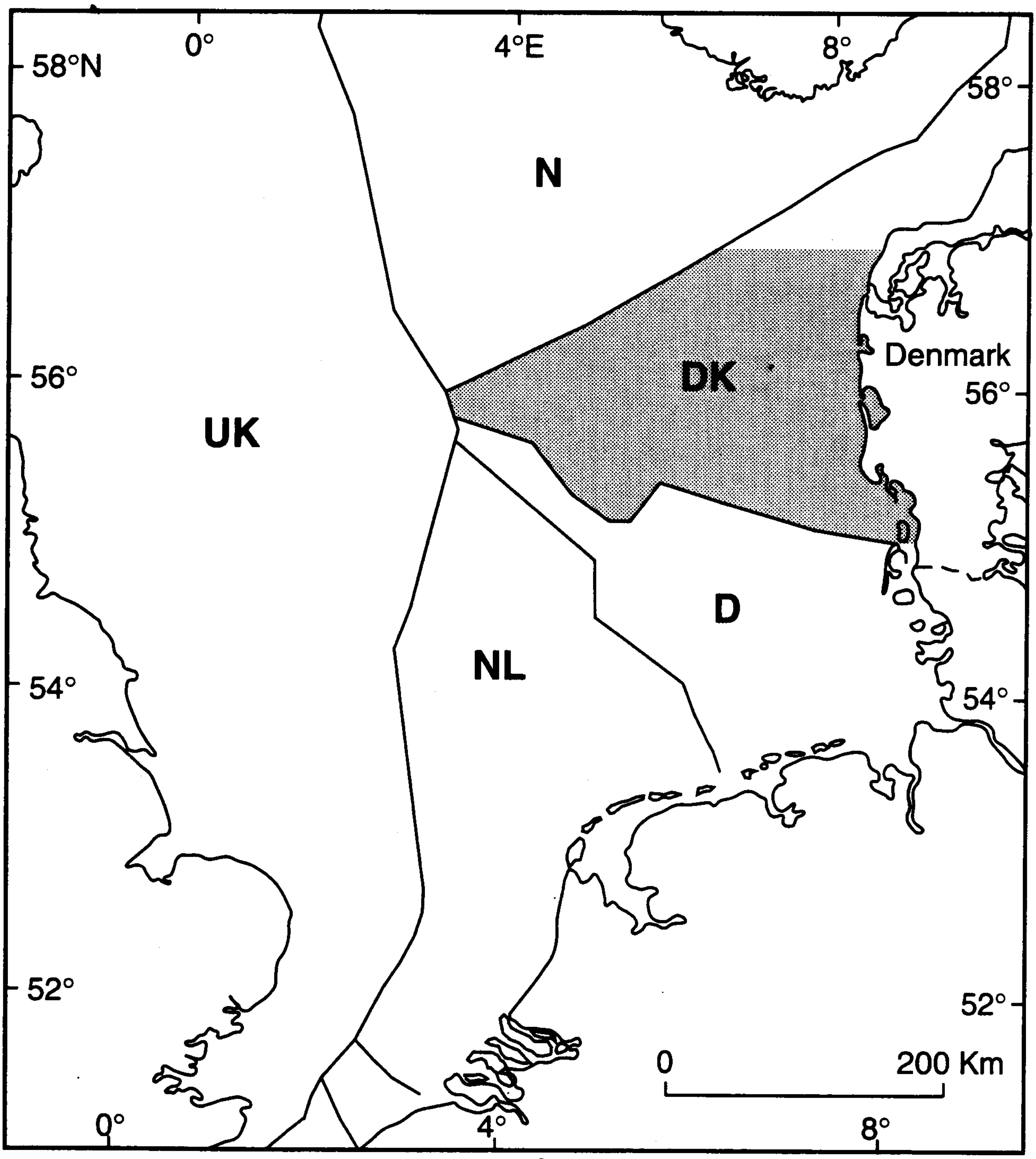
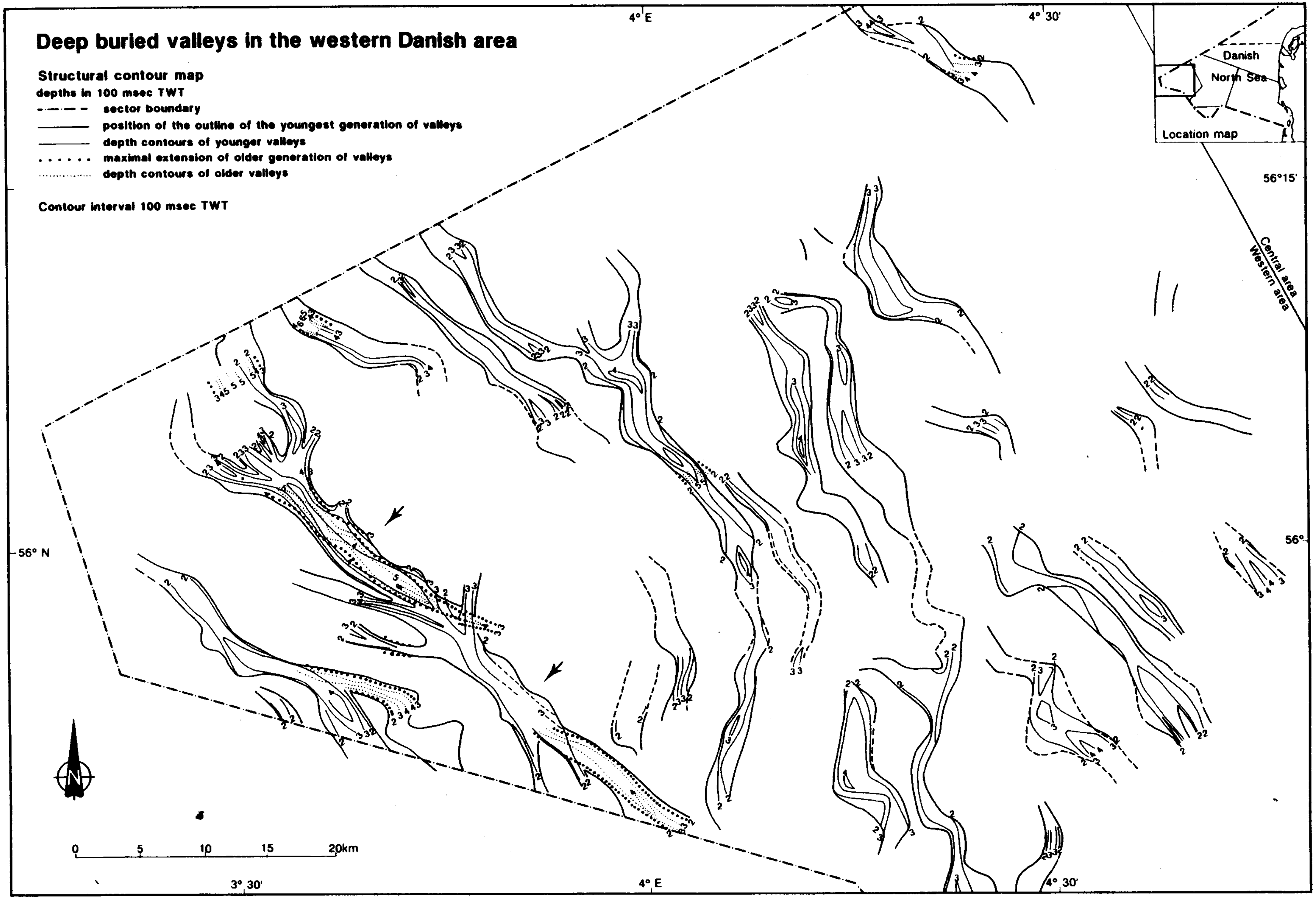


Fig. 1 Position of the study area in the North Sea region.


Deep buried valleys in the western Danish area
Structural contour map
depths in 100 msec TWT
sector boundary
position of the outline of the youngest generation of valleys
depth contours of younger valleys
maximal extension of older generation of valleys
depth contours of older valleys
Contour interval 100 msec TWT
4° E
4° 30'
3° 30'
56° N
56°
56°15'
Central area
Western area
Danish
North Sea
Location map
0
5
10
15
20km

◀ Fig. 2 Structural contour map (msec TWT) showing the outline and depths to the deepest erosional surfaces indicating the buried valleys in the western part of the study area. The valley analyzed in detail is marked by arrows.

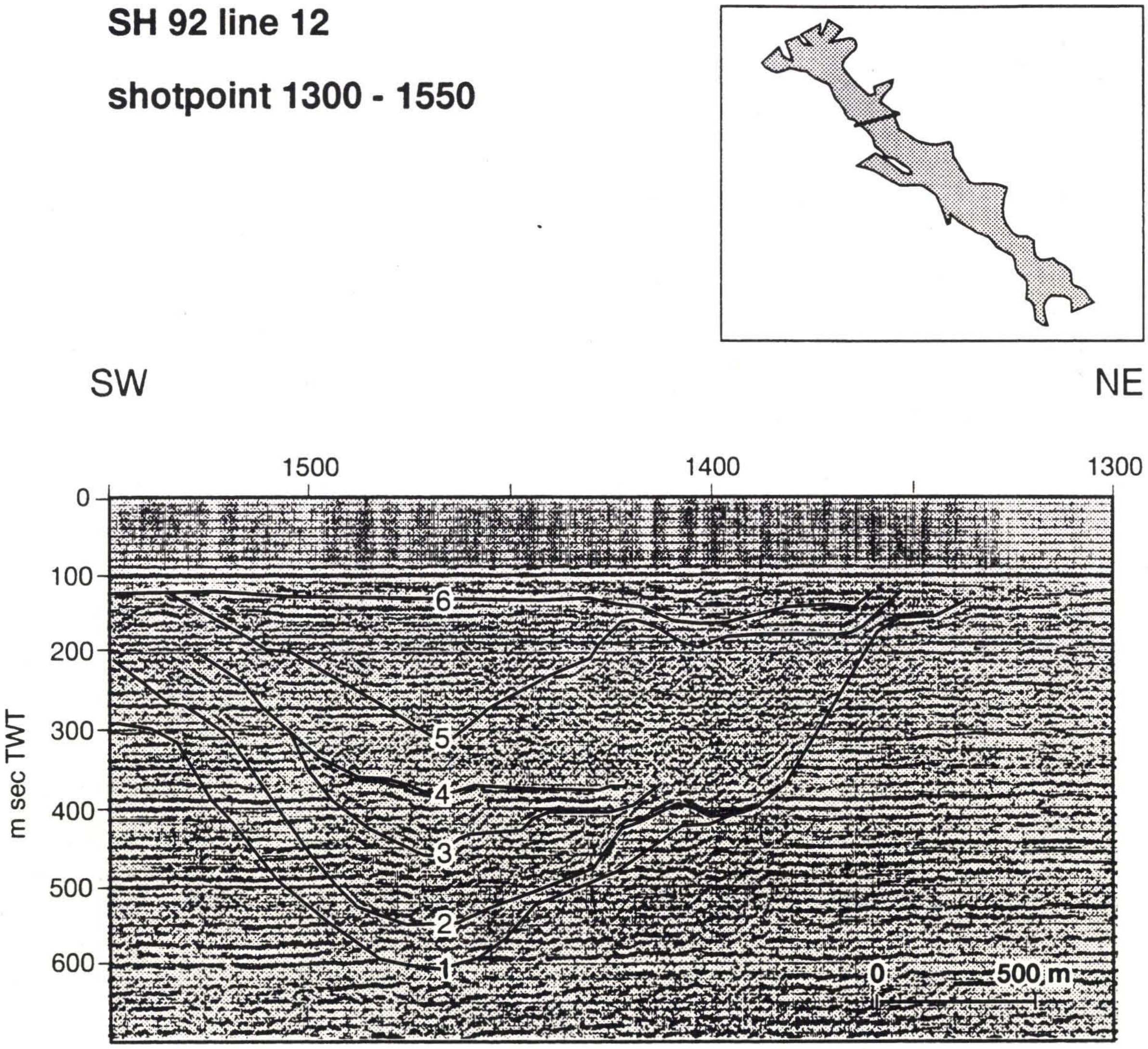


Fig. 3 High-resolution seismic section showing a cross-section through the valley. The five unconformable surfaces in the valley are indicated.

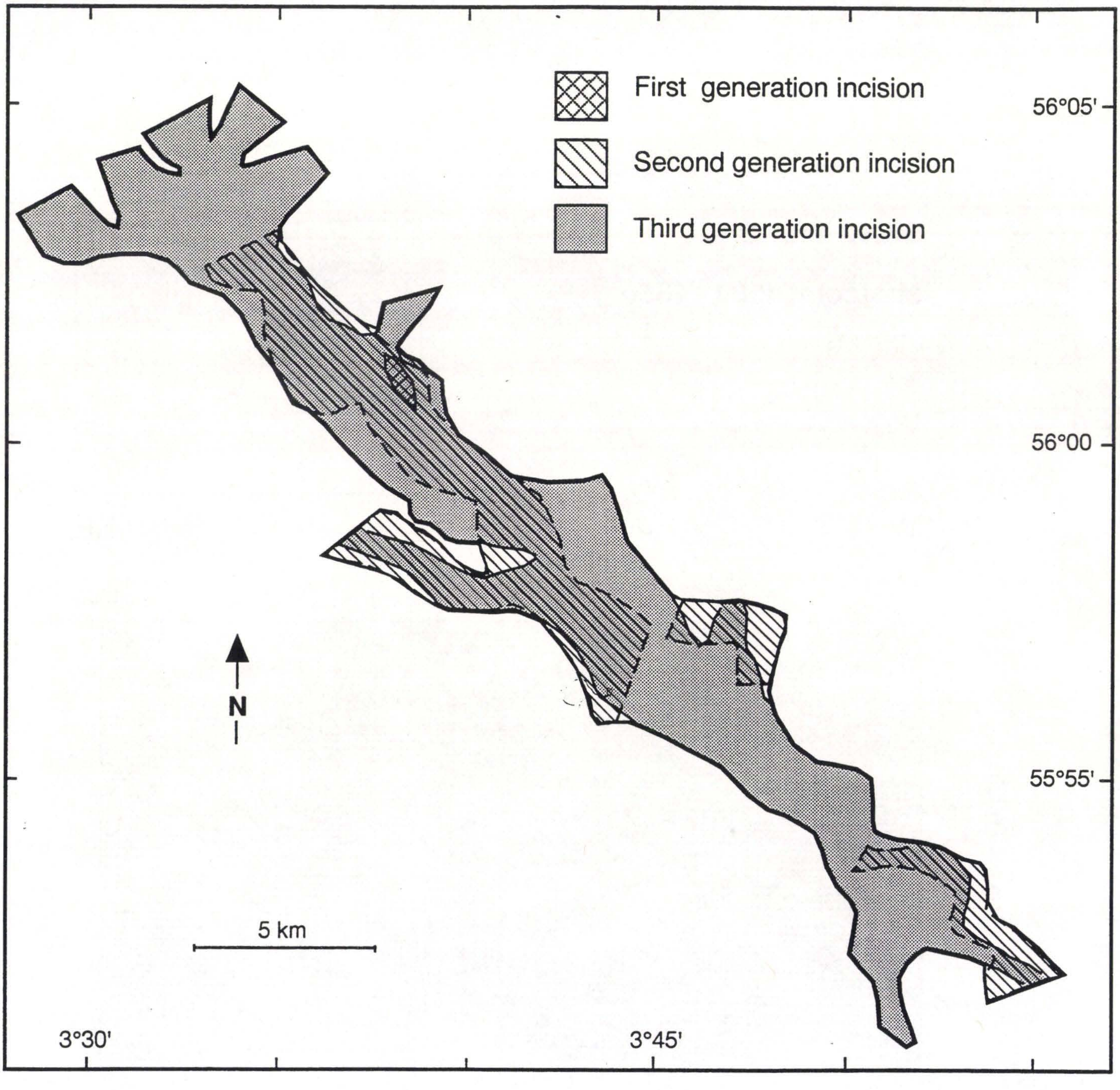


Fig. 4 The extension of the various unconformities representing three phases of incision, based on both conventional and high-resolution seismic data.

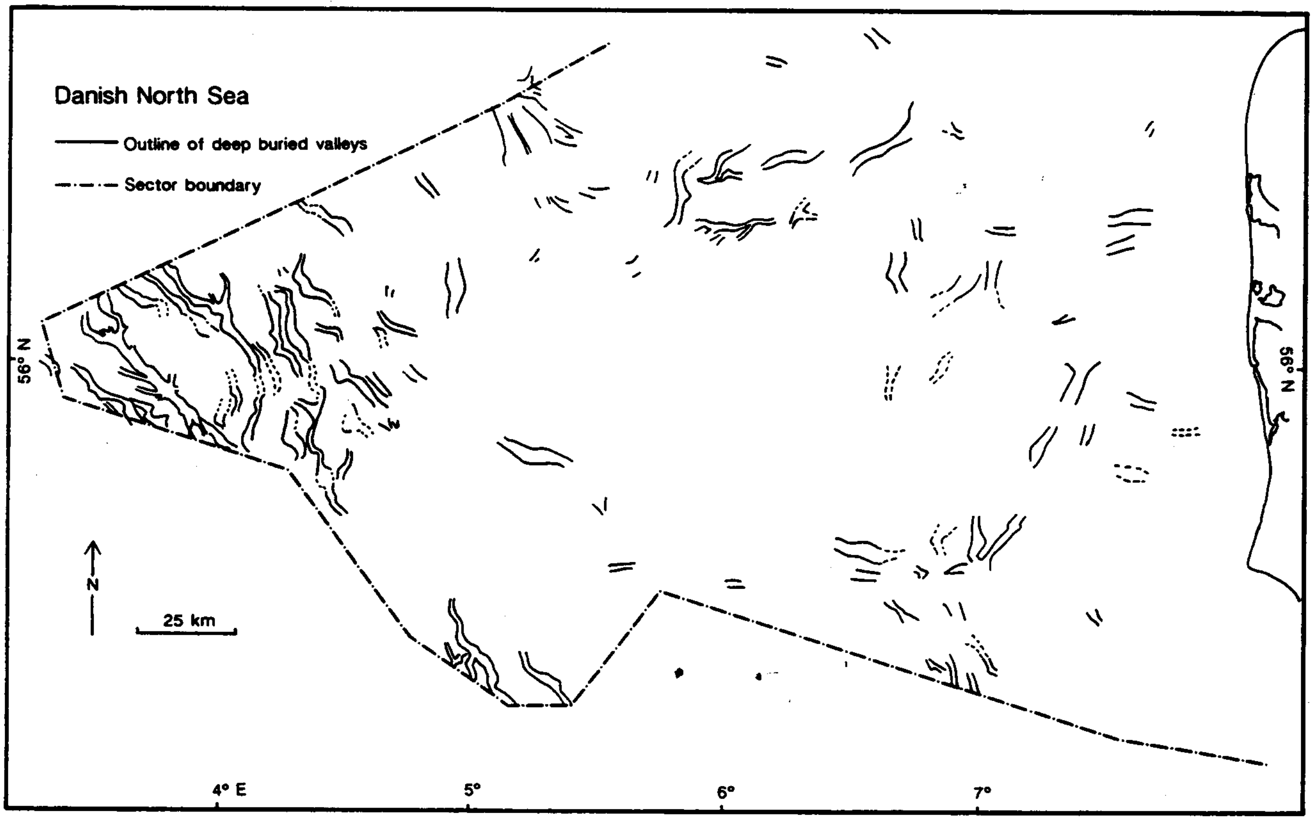


Fig. 5 The regional pattern of deep buried valleys in the eastern North Sea basin.

Mid-Miocene progradational barrier island and back-barrier deposits, central Jylland, Denmark

Søren A.V. Nielsen & Lars H. Nielsen

Abstract

This paper reports on a c. 15 m thick section of marine, coastal sand, that combine a hitherto less described facies sucession transitional to the Miocene fluvio-deltaic and open marine deposits. The section is exposed in a pit located 10 km northeast of the sandy fluvio-deltaic brown coal bearing strata of the Søby-Fasterholt area, known as the Odderup Formation (Middle Miocene). The section comprises more than 6 m of trough cross-stratified, low-angle cross-stratified and parallel-laminated, sand and gravel, deposited on the foreshore and backshore of a barrier island. Locally these deposits are eroded by a steep-sided washover channel with a sandy fill. The overlying back-barrier deposits are up to 9 m thick, and are initiated by a thin bituminous mud bed with a mixture of terrigeneous and marine organic matter. Above, a series of 0.2-2 m thick beds of tangential to sigmoidal cross-stratified sand, often with well preserved topsets, are deposited. These beds are interbedded with ripple-laminated and parallel-laminated sand. Burrows of *Ophiomorpha*, possibly *Skolithos* and *Arenicolithes* occur in the back-barrier deposits and in the top of the washover channel-fill.
The succession of well-preserved coastal facies-belts indicates that the depositional area was characterized by a large sediment supply in combination with a rising sea-level. The section was probably formed fairly rapidly during a coastal progradation more or less contemporaneously with the general transgression that led to the deposition of the brackish-marine Hodde Formation and later the fully marine Gram Formation.

Introduction

Tertiary deposits in Denmark have been studied by several workers, and the investigations have provided a good understanding of the main features of the Tertiary stratigraphy and depositional environments (e.g. Sorgenfrei 1958, Larsen & Dinesen 1959, Rasmussen 1961, 1966, Kristoffersen 1972, Radwanski et al. 1975, Friis 1976, 1978, Heilmann-Clausen 1988, Koch 1989). The Miocene, sandy Ribe and Odderup Formations are interpreted as fluvio-deltaic deposits whereas the Arnum, Hodde and Gram Formations, mainly consisting of mud, are interpreted as marine. The Vejle Fjord Formation consisting of muddy and sandy deposits are interpreted as a prograding barrier island and lagoonal succession. Many details about the spatial distribution of the formations, and the transition between the marine and non-marine depositional units have yet to be resolved.
This paper presents a preliminary interpretation of a section of marine coastal sand exposed in a sand-pit situated 4 km south of Ikast at the Toftlund Møllebakke. Here an erosional remnant of Miocene sand forms a small hill surrounded by Quaternary glacio-fluvial sand and gravel (Fig. 1). The location is only 10 km northeast of the Søby-Fasterholt area with thick brown coal bearing fluvio-deltaic strata of the Odderup Formation (Koch 1989). The deposits in the Toftlund Møllebakke are found in 75 - 91 m a.s.l. which is 15 - 40 m higher than the general topographical level of the Søby-Fasterholt area. As the tectonic dip of the Neogene deposits in the area is close to zero it is suggested that the deposits studied here are relatively younger than the deposits in the Søby Fasterholt area. The locality thus shows a hitherto less described sandy coastal facies, transitional to the sandy fluvio-deltaic deposits and the muddy marine deposits. The paper is an extended version of a presentation given at "Maringeologisk Møde i Århus, 7.-8. oktober 1993" (Nielsen & Nielsen, 1993).

FACIES AND SEDIMENTARY UNITS

The investigated section consists of three sedimentary units that can be traced over a distance of more than 600 m in a northeast-southwest direction (Fig. 1). They are defined by their bounding surfaces, geometry, facies composition and genetic relations, and are subdivided into five sub-units: Unit 1A, foreshore and backshore; Unit 1B, aeolian dunes; Unit 2, washover channel-fill; Unit 3A, bituminous mud; Unit 3B, back barrier sand. They are described in ascending order.

Unit 1A: Foreshore and backshore

Description

Unit 1A consists of a fining upward succession of gravel and coarse to medium-grained sand, that makes up the lower 5.8-6.7 m of the section (Fig. 2, loc. A). The lower part consists of trough cross-stratified sets, 5-10 cm thick and 0.5-1.0 m long, of coarse-grained sand and gravel (Fig. 3). The foreset inclination is dominantly towards the southwest while the set boundaries dip 7-10° to the northeast. Upwards, the foreset dip directions change to a highly variable pattern.

These strata are overlain by a 15-20 cm thick layer of well sorted gravel with a pebble content of c. 5 % representing the coarsest grain size found in the section. The layer shows thick sets of climbing cross-stratification. It has strong yellowish-brown and black colours due to post-depositional precipitation of ferri and mangano-oxides. The sets are 5-15 cm thick and the set-boundaries dip rather steeply, 20-30° to the southwest while the concave-upward foresets dip northeastward. The set boundaries can be traced into the overlying plane laminated sand as they change from steep dip to low angle dip. At the same point the sets thin to 0,5-1,5 cm.

The upper 1.8-2.7 m are dominated by irregular parallel-stratified and low angle cross-stratified, coarse-grained sand and gravel in beds 0.2-0.4 m thick. Subtle internal discordances and small scour-fills occur.

Interpretation

The trough cross-stratified beds were formed by accretion of 3-D dunes moving towards the south-west, driven by strong mostly unidirectional currents. The dipping set-boundaries indicate a high supply of sediment and sufficient vertical accretion space.

The variable dip of the foresets in the overlying trough cross-beds indicate that the current direction changed frequently. The gravelly cross-strata that can be followed up-dip into parallel-laminated layers reflect southwestern progradation of an inclined accretion surface in a powerful depositional regime. The overlying parallel-laminated and low angle cross-stratified gravelly sand is interpreted as deposited during upper plane bed regime.

Unit 1A was thus deposited in a very energetic environment. The sequence of structures is very similar to those found on recent sandy to gravelly coasts and a detailed comparison is possible. The lower trough cross beds were probably formed by wave-generated currents in the "inner rough zone" of Clifton et al. (1971) or the "swash-trough transition zone" described by Davidson-Arnott & Greenwood (1976). The climbing, gravelly cross-strata were formed at the toe of the beach where the surf zone passes into the swash zone; the overlying parallel-stratified sand represents beach lamination formed by the swash-backwash on the berm and at the gently sloping backshore. Unit 1A, therefore, represents a progradation of an inner nearshore zone (c.f. Clifton et al. 1971) with a northwest-southeast orientation facing the sea to the southwest.

Unit 1B: Aeolian dunes
Description

The unit is poorly exposed and the original structures are masked by Quaternary cryoturbation processes that affect minimum 3 m of the section at locality A. It consists of two gently inclined trough-stratified sets of well-sorted, coarse-grained sand, 0.5-0.8 m thick, laterally passing into horizontally laminated sand. Foresets dip to the west and to the east.

Interpretation

Due to the lack of sufficient data the interpretation of the unit is uncertain. The well-sorted sand and the trough shaped and relatively low angle foresets resemble structures produced by aeolian dunes and may have been formed on the backshore of the coast. This interpretation implies a continued progradation of the shore.

Unit 2: Washover channel
Description

In the northern part of the southern pit a 0.5-3.8 m thick channel-unit of well-sorted, medium-grained sand, is exposed for more than 60 m (Fig. 4a). Only the uppermost part is exposed in the northern pit. The channel base shows a relief of 3.3 m with steep sides sloping 10-40°. At the base, scattered pebbles and a patchy silty layer, 1-2 cm thick, occur. The lowermost meter of the unit consists of medium-grained, parallel-laminated or low-angle cross-stratified sand beds, 5-15 cm thick, conformably overlying the erosional base (Fig. 5). The upper part of the channel-fill is characterized by laterally consistent sets, 10-20 cm thick, of parallel laminated sand. Eastward dipping set boundaries downlap on internal erosion surfaces. *Ophiomorpha* burrows, cemented by iron oxides, are abundant in the top part of the channel fill (Fig. 6a). The topmost 5 cm below the overlying bituminous mud bed fines upwards and possess an upward transition from flaser to lenticular bedded heterolithic sand with a slightly bio-mottled appearance (Fig. 6b).

Interpretation

The large relief and the pebbles occurring on the erosional base of the unit show that the process cutting the basal surface was very forceful. The fill was formed during less energetic conditions, but occurred rather quick, and shortly after the erosional event as the steep sides of the channel would have been levelled out during longer term exposure. The sets seem to follow the concave channel base but laterally accreted fill is suggeted by the dipping set boundaries. The internal discordances of the channel-fill, indicate that it was formed by multiple events. The *Ophiomorpha* burrows indicate marine conditions, and were formed before the deposition of unit 3A, because no mud has been transported down from the bituminous mud bed to unit 2 by the organisms. The lack of well developed cross-bedding probably precludes a tidal inlet or a fluvial channel origin. Instead, the unit is interpreted as a storm generated erosion of a barrier island with a subsequent fair-weather fill.

Unit 3A: Bituminous mud
Description

The back barrier sequence (units 3A and 3B) is initiated by a thin layer of bituminous mud that occur at locality B and C overlying unit 2 (Fig. 2). It varies in thickness from 10 cm in the southern pit to 2-4 cm in the northern pit. The boundary to the overlying cross bed of unit 3B is sharp and accentuated by a cemented sand layer, 1 cm thick (Fig. 6b). Where the unit is thickest, the lower 4 cm consist of sticky, bituminous, black clay with plant fragments. The upper 6 cm consist of bituminous mud with sandy lenses. A LECO-ROCK-EVAL combustion analysis from the lower 4 cm indicates a total organic carbon content of c. 25 % and a hydrogen index of 210. The main component is amorphous organic matter, with fragments of brown coal as a minor constituent. It is barren of microfossils and contains few pollen grains and dinoflagellate cysts (pers. com. D. Jutson & N.P. Poulsen). Dry samples are brown and show a very thin lamination.

Interpretation

The unit was deposited in a protected environment that received both mud and organic material. The sandy lenses show that sand was supplied occasionally. Roots have not been seen which suggests that the organic matter is allochtonous. The fairly high hydrocarbon index may suggest a marine origin of some of the organic matter. The unit overlies the channel-fill and may be restricted to the depression of the washover channel. It is thus suggested that unit 3A was deposited in a small pond formed in the residual topographical low of the washower channel on the backside of the barrier island, where organic matter (such as seaweed) accumulated.

Unit 3B: Back barrier sand
Description

This unit is exposed at locality B and C. It is up to 7,5 m thick and comprises cross-bedded and low-angle cross-bedded, medium to coarse-grained sand separated by beds of parallel-laminated and ripple-laminated fine to medium-grained sand (Fig. 2). It is coloured by oxides, especially in the upper 5 m, and the sedimentary features in the upper 2 m are intensely disturbed by Quaternary cryoturbation.
The horizontally-laminated and ripple-laminated sand exhibit weakly developed bedding recognized either by small grain size variations or by patchy lamination of black, organic detritus. The cross-stratified sand beds are mostly 0.2-0.5 m thick. Some show an overall coarsening upward, others are normal graded with tangential to sigmoidal foresets where topsets are preserved. The dip directions are uniform to the northwest or south within a single bed.
One cross-stratified set, with a thickness varying from nearly 2 meters at loc. B to 0.2 m at loc. C make up the lower part of the unit (Fig. 4b). The lower contact of the cross-bed is slightly erosive. The upper limit is arbitrary at loc. B as no distinct surface exists between the topsets and the overlying diffusely laminated sand (Fig. 7). At loc. C the upper surface is plane and erosive. The bed shows an overall fining upwards from coarse to medium-grained sand. The lowermost 0.1 m of the bed shows sub-horizontal lamination which continues upward into foresets with a thickness of 1-7 cm. Systematic variations in foreset thicknesses have not been observed. The foresets dip 20-28° to the south-southwest at loc. B and to the south at loc. C. Foresets are sigmoidal where the topsets are preserved (Fig. 8). Reactivation surfaces occur regularly at intervals of 1.0-3.0 m. The upper half of the bed contains *Ophiomorpha* burrows, c. 10 cm long and 1.0-1.5 cm thick (Fig. 6c).
The upper part of unit 3B contains muddy sand with 0.2-0.3 cm thick and 5 cm long, vertical to sub-vertical burrows that bifurcate and sometimes occur in clusters c. 5 cm wide (Fig. 6d). *Ophiomorpha* burrows, 1.0 - 1.5 cm thick and up to 8 cm long occur together with vertical burrows, up to 8 cm long and 0.4 - 1.0 cm thick, possibly of *Skolithos* or *Arenicolithes*-type.

Interpretation

The cross-bedding was formed by southward and northwestward migrating dunes. The uniform dip directions of the foreset and the well preserved topset indicate that the dunes were relatively straight crested, 0,5 - 2.0 m high. The burrows indicate marine conditions. The sigmoidal foresets and the reactivation surfaces may suggest a tidal origin (Kreisa & Moiola, 1986), but further support is missing. The well preserved topsets and the gradual transition to overlying plane and ripple-laminated sand indicate a large sediment supply. This, and the lack of scours, suggest that the bedforms were protected from direct influence of large waves. The ripple-laminated sand was deposited by small ripples during calm periods or between the larger bedforms. The large difference in thickness of the lower cross-bed may reflect a topographic relief of the depositional area or erosion of the bed. The unit is thus suggested to have been formed behind a barrier island protected from the North Sea waves.

WELL DATA

The regional extension of these marine deposits is not known. However, data from boreholes in the nearby Nørlund Plantage, 2.5 km south of the pit, suggest that the deposits are present here as well.

Conclusions

A barrier-coast environment is suggested for the section studied here. The deposits consist of wave-formed, trough cross-stratified, coarse-grained sand of the inner rough zone, gravel deposited at the beach toe, and parallel-laminated and low angle cross-stratified sand of the swash-backwash zone and the backshore (unit 1A) overlain by aeolian sand (unit 1B). It is erosively overlain by a sandy washover channel-fill (unit 2) formed by a storm induced break-through of the barrier, whereby the dune field and backshore were eroded. The channel-fill is overlain by back-barrier deposits initiated by a thin, bituminous mud bed (unit 3A) deposited in a pond in the residual topographical low of the washover channel on the leeward side of the barrier. The mud is overlain by the back barrier sand with an up to 2.0 m thick cross-stratified bed formed by a bedform migrating south-southwestward. The protected back-barrier environment persisted through the deposition of the overlying ripple-laminated and cross-bedded sand.
The well preserved sedimentary structures indicate that the deposits were formed in an area characterized by a high sediment influx during a period of rising sea-level. The section represents a coastal progradation during a phase of rising sea level. We suggest that it is younger than the brown coal bearing fluvio-deltaic sequence of the upper Odderup Formation in the Søby - Fasterholt area. The section may thus have formed during the general transgression that flooded the deltaic coast, leading to the deposition of the brackish-marine Hodde Formation, and the fully marine Gram Formation.

References

Clifton, H.E.: Hunter, R.E. & Phillips, R.L., 1971: Depositional structures and processes in the non-barred high-energy nearshore. J.sedim.Petrol., 41, 3, 651-670.

Davidson-Arnott, R.G.D. & Greenwood, B., 1976: Facies relationships on a barred coast. Kouchibouguac Bay, New Brunswick, Canada. In: R.A. Davis Jr. & R.L. Ethington (eds): Beach and Nearshore Sedimentation. Spec. Publs. Soc. Econ. Paleont. Miner. Tulsa 24, 149-168.

Friis, H., 1976: Weathering of a Neogene fluviatile fining-upwards sequence at Voervadsbro, Denmark. Bull. geol. Soc. Denmark, vol. 25, 99-105.

Friis, H., 1978: Heavy mineral variability in Miocene marine sediments in Denmark: a combined effect of weathering and reworking. Sedim. Geol., 21, 169-188.

Heilmann-Clausen, C., 1988: The Danish subbasin, Palaeogene dinoflagellates, neogene dinoflagellates. In: Vinken, R., compiler, The Northwest European Tertiary basin: Geologisches Jahrbuch, Reihe A, 100, 339-343.

Koch, B.E., 1989: Geology of the Søby-Fasterholt area. Danm. geol. Unders. Ser. A 22. 167 pp.

Kreisa, R.D. & Moiola, R.J., 1986: sigmoidal tidal bundles and other tide-generated sedimentary structures of the Curtis Formation, Utah. Geol. Soc. Am. Bull., 97, p 381-387.

Kristoffersen, F.N., 1972: Foraminiferzonering i det jyske miocæn. Dansk geol. Foren. Årsskr. for 1971, 70-85.

Larsen, G. & Dinesen, A.,1959: Vejle Fjord Formationen ved Brejning; sedimenterne og foraminiferfaunaen (oligocæn - miocæn). Danm. geol. Unders. II Række 82, 114 pp.

Nielsen, S.A.V. & Nielsen, L.H., 1993: Miocene sandy shore deposits, Isenvad, central Jylland, Denmark. In: Abstract Volume p. 17, Maringeologisk Møde: Nordsøens og Skagerraks geologi. Aarhus Universitet 7.-8. oktober 1993.

Radwanski, A., Friis, H. & Larsen, G., 1975: The Miocene Hagenør-Børup sequence at Lillebælt, Denmark; its biogenic structures and depositional environment. Bull. geol. Soc. Denmark, 24, 3-4, 229-260.

Rasmussen, L.B., 1961: De Miocæne aflejringer i Danmark. Danm. geol. Unders. IV Række 4, (5), 45 pp.

Rasmussen, L.B., 1966: Molluscan Faunas and Biostratigraphy of the Marine Younger Miocene Formations in Denmark. Part I: Geology and Biostratigraphy. Danm. geol. Unders. II Række 88. 359 pp.

Sorgenfrei, Th., 1958: Molluscan assemblages from the marine middle Miocene of South Jutland and their environments. Danm. geol. Unders. II Række 79., vol. 1, 355 pp.

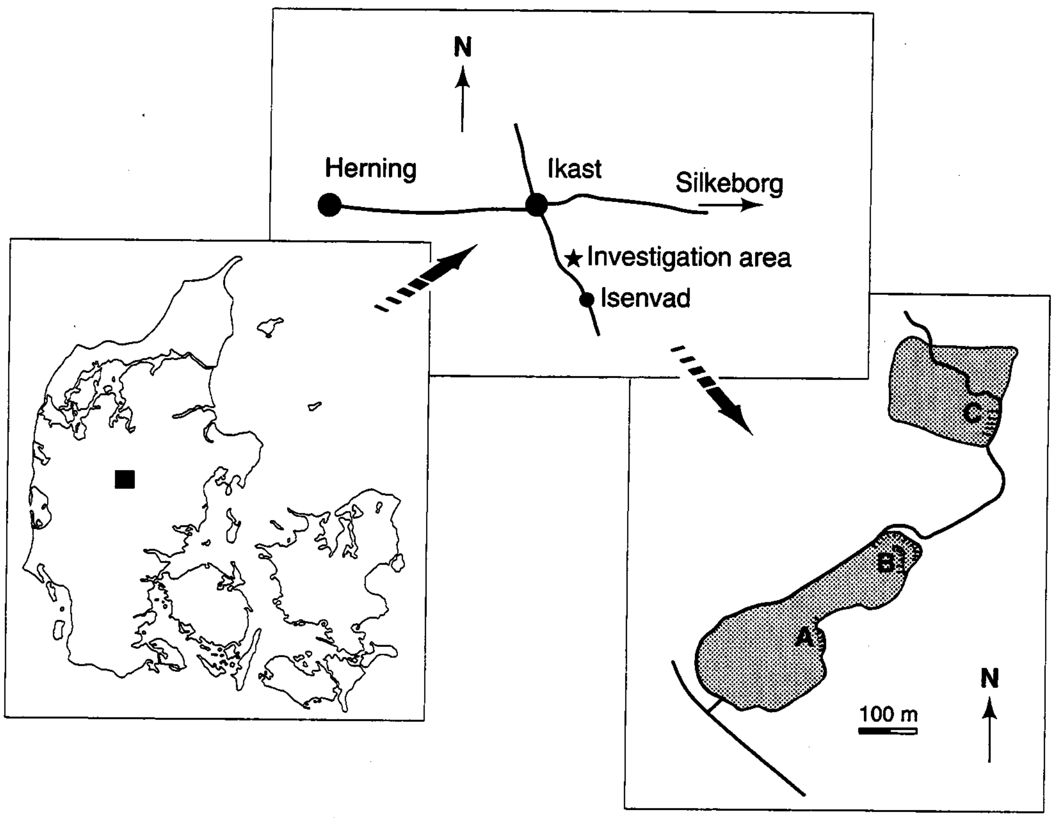


Fig. 1 Location map, localities in the sand pit are indicated by the letters A,B & C.

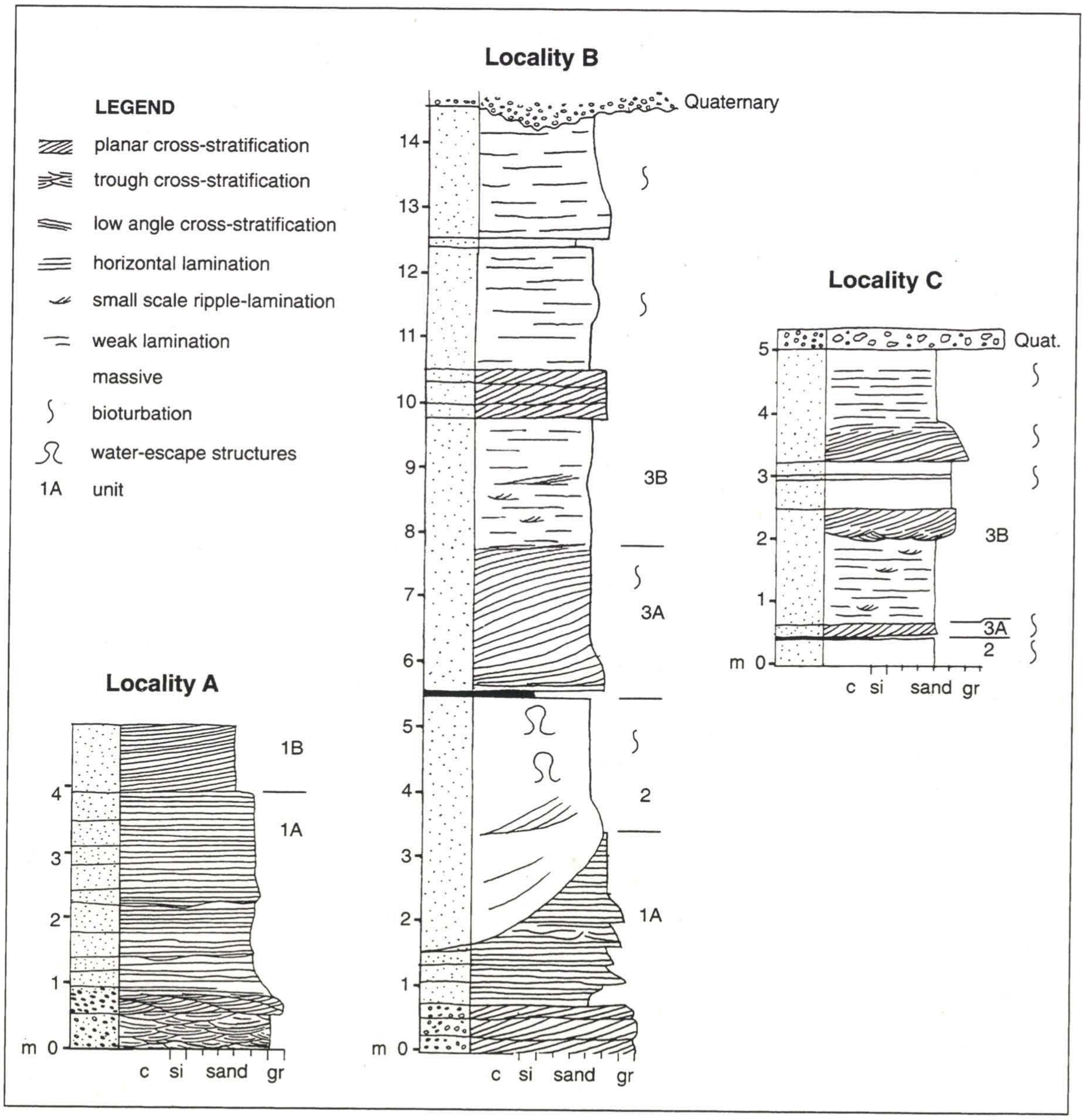


Fig. 2 Sedimentological logs from locality A, B and C.

Fig. 3 Wave-formed trough cross-bedding of the inner rough zone/swash-trough transition zone, gravelly cross-stratification of the beach toe overlain by plane laminated and low angle cross-stratified sand of the swash-backwash zone and back shore (unit 1A). Northeast to the left. Height of the section shown is 2 m.

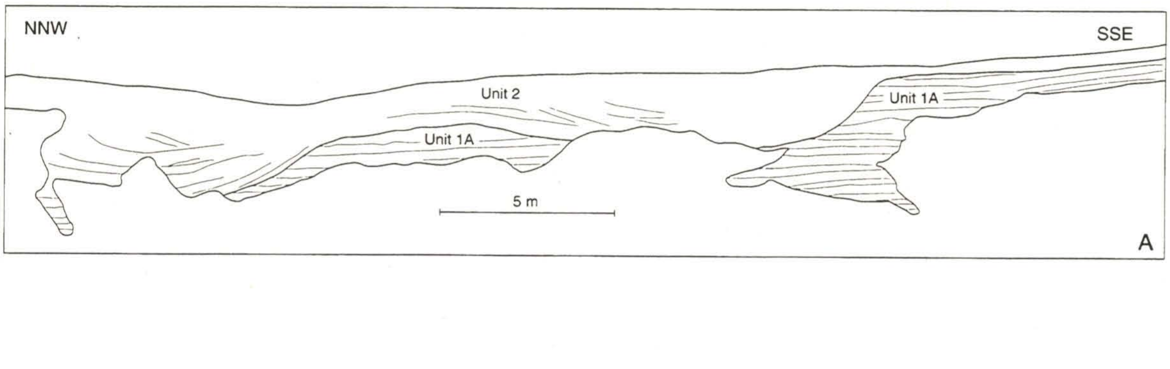


Fig. 4A Line drawing from photo mosaic of the washover channel-fill (unit 2) and underlying plane-laminated sand of unit 1A. Loc. B.

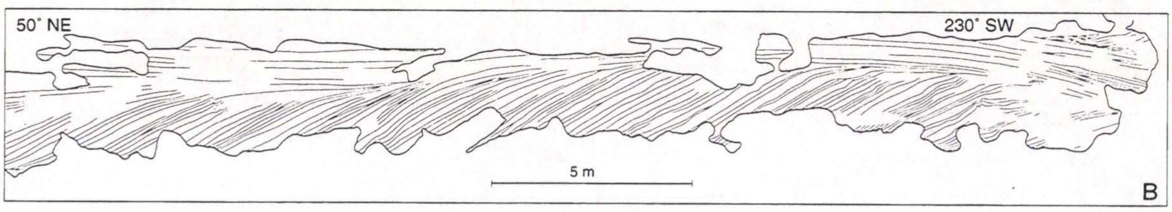


Fig. 4B Line drawing from photo mosaic of the lower cross-bed of unit 3 (Loc. B). Note the tangential to sigmoidal foresets, reactivation-surfaces and the relief of approximately 1 m over a distance of only 10 m (from 29 m to 19 m).

Fig. 5 Oblique photo of the erosional contact between unit 1A and unit 2. The true maximum dip of the surface is 40°. Lamination in the plane-laminated sand is accentuated by heavy minerals. Note irregular stratification in the middle of unit 1A. Bag is 60 cm high. NNW is to the left.

Fig. 6A *Ophiomorpha* burrows cemented by iron-oxides, in the top of the channel-fill.

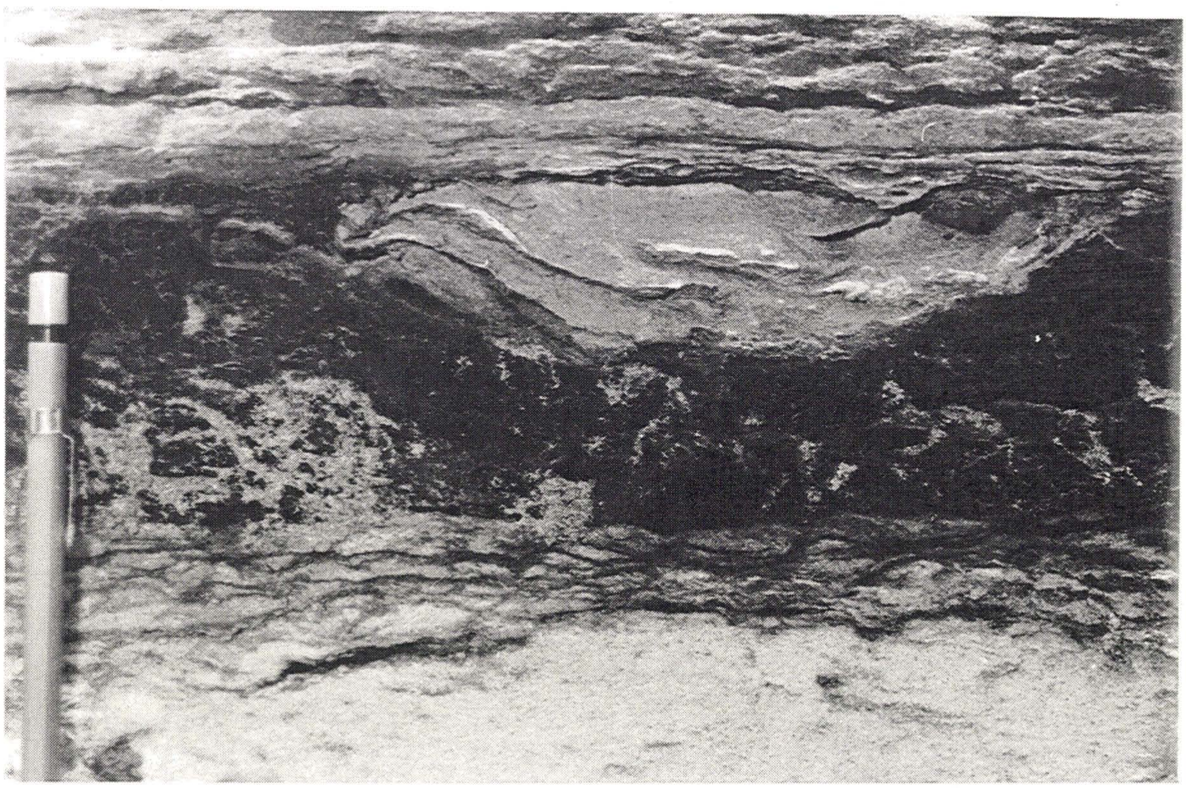


Fig. 6B Bituminous mud bed (Unit 3A, loc. B). The lower boundary is gradual and the upper is sharp to slightly erosive. A sand-filled scour is seen. Note the fining-upward of the underlying unit 2. Photo taken by H.C.S. Hansen.

Fig. 6C *Ophiomorpha* burrows, cemented by ferri-oxides penetrating the foresets of the bedform seen in fig. 9.

Fig. 6D Muddy, bioturbated sand of unit 3B (Loc. B). Vertical 2-3 mm thick burrows occurring solitary or gathered in clusters, and *Ophiomorpha* burrows. Photo taken by H.C.S. Hansen.

Fig. 7 The thick cross-bed in the lower part of unit 3B. Note the well preserved topsets and the toesets to the lower left. Foresets dip south-southwest. Southwest is to the left.

Tertiary fluvial deposits of Jylland, Addit area.

H.C.S. Hansen

Abstract

Sandy fluvial deposits of Tertiary age are described from three sand pits in the Addit area with up to 28 metres high outcrops. The deposits form up to 20 metres thick fining-upwards successions of mainly large-scale tabular cross-sets of medium and coarse sand interpreted as fluvial bars. Individual successions are capped by thinly interbedded sands and silts and occasionally completed with a coal bed. Concave-up bounding surfaces separate the fining-upwards successions. Channel switching, breaks in active channel aggradation, rapid scour- and filling events and chute activity created bounding surfaces described as a 4-tier hierarchy. The palaeocurrents derived from trough foresets suggest that the channel course was straight rather than sinuous. The current directions were generally to the south and southwest.

Introduction

Miocene deposits consisting of interfingering marine and non-marine sands and clays are found throughout mid and southern Jylland in Denmark. They are generally covered by a Quaternary overburden consisting of glacial outwash sands and diamictons. The Miocene deposits were grouped into formations by several authors (Sorgenfrei, 1958; Rasmussen, 1961a, 1961b, 1966; Kristoffersen, 1972). The deposits described in the present study probably belong to the non-marine Middle Miocene Odderup Formation (B.E. Koch, 1993, personal communication). This formation mainly consists of medium to coarse-grained sand with occasional silt, clay and lignite beds. The Odderup Formation was deposited in a fluvio-deltaic environment near Søby and Fasterholt, some 40 km west of the present study area (Rasmussen, 1961; Larsen and Friis, 1973; Friis, 1978; Koch, 1989). Vegetational studies around Fasterholt show (Friis, 1985), that the climate was warm, temperate to subtropical and that the plant communities corresponded to wetland communities of the Atlantic Coastal Plain of North America. Petrographic studies of heavy minerals and the presence of fossiliferous Palaeozoic chert suggest a provenance from the Scandinavian shield to the east and northeast of Denmark (Friis, 1973, 1974). The present study describes the Odderup Formation in three pits along the sides of the Gudenå valley near Addit and Voervadsbro (fig. 1). The Voervadsbro locality was previously interpreted to be of fluvial origin and tentatively referred to the Odderup Formation (Larsen and Friis, 1973; Friis, 1976). The location is only 29 km east-southeast of the locality of Toftlund Møllebakke. The latter locality is interpreted as marine, Middle Miocene sand deposited in the foreshore and backshore of a barrier island (Nielsen & Nielsen, 1993). This paper is an extended version of a presentation given on 8th October 1993 at "Maringeologisk Møde i Århus" (Hansen & Nielsen, 1993).

Facies description and interpretation

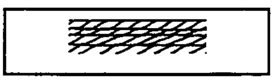
Logs were recorded in the field and later redrawn from photographs of outcrops to provide a photorealistic rendering of facies of a scale of 1:50. Symbols represent structures too small to be recorded naturalistically at 1:50. The description and interpretation of facies follow the well established lithofacies classification of Miall (1977, 1978). This facies classification is subdivided further according to the size and geometry of beds, foreset features, grain-size and coset development (McKee et al., 1953, Bridge, 1993). Bridge (1993) has pointed to the danger of oversimplifying the classification and interpretation of facies through the use of acronyms. To remedy this situation, representative sections of logs have been included in the text to provide both an enhanced legend and a visual link from facies descriptions to logs and outcrop.

Facies Sp: planar cross-bedded sand.

Planar cross-beds are predominant in most of the recorded logs (figs. 2, 4-6). The excellent lateral continuity of this facies group is shown on fig. 7. Sets comprising cosets usually maintain their thickness for some tens of metres normal to the progradation direction. The lower bounding surface eventually becomes concave-up and wedges out against the upper bounding surface of a coset or group of cosets (fig. 7). The bounding surfaces may be parallel throughout sections parallel to bedform progradation within the extent of an outcrop (100 metres). Facies Sp is arranged into three main groups according to set thickness: simple dune bedding less than one metre thick, simple dune bedding from 1 to 2 metres thick and large, composite cosets, 1 to 3 metres thick.

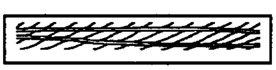
Simple dune bedding less than one m thick:

This facies is divided into three facies based on set geometry and foreset style.



Cosets of tabular cross-bedded, medium-grained sand with steep foresets with angular foreset terminations. Each set is non-erosive. Sets may stack into uniform intervals some 5 metres thick (fig. 4). This facies is interpreted as having formed by 2-dimensional dunes (Harms et al., 1982) migrating under low to intermediate flow-stage in the shallower parts of a river channel. They may be similar to transverse bedforms described by Smith, 1971.

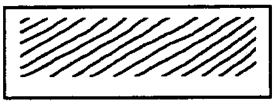
Tabular cosets composed of groups of planar, wedge-shaped sets. The individual sets are angular to tangential cross-bedded with occasional deformed foresets and composed of medium to coarse-grained sand. Set bases may be erosional in places. This facies may be associated with intervals of near-massive sand, e.g. at 2 metres on fig. 4. During high stage a high traction-transported sediment load may induce a shear stress on the bedform thereby causing it to deform (McKee et al. 1962a, 1962b, Allen & Banks, 1972). High sediment concentrations are expected in the deeper parts of a river channel during rising stage as a result of increasing competence of the river to transport sediment (McKee et al, 1967). The supply of sediment is often augmented by sediment released by riverbank collapse during rising stage. Banks tend to become unstable during rising stage because of river scouring in combination with an increased weight and decreased shear strength of bank material due to absorption of water (Laury, 1971; Wells et al. 1993). The sets are therefore interpreted as formed by 2-dimensional dunes migrating under high flow stage in the deeper part of a river channel.



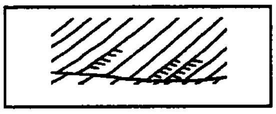
Tabular cosets of tapering sets of angular cross-bedded, medium to coarse-grained sand with distinct, massive bottomsets. Interpreted as 2-dimensional dunes transitory to 3-dimensional dunes migrating under high river flow stage promoting a high rate of suspended load versus bedload in the deeper parts of a river channel (Harms et al. 1982).

Simple dune bedding from 1 to 2 metres thick :

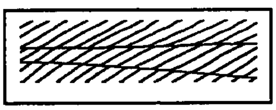
This facies is subdivided into three facies according to set geometry and the presence or absence of backflow ripples. The sets may combine to form cosets which share a constant, total thickness although some sets may increase in thickness at the expense of others. Fig. 6 and 8 show 2nd order bounding surfaces of this nature.



Tabular sets of angular cross-bedded, fine, medium or coarse sand. Interpreted as formed by 2-dimensional, simple bars migrating slowly under low to intermediate flow stage conditions in deeper parts of a river channel.



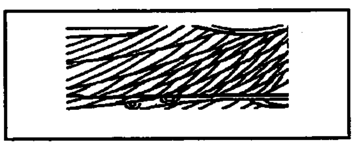
Tabular sets of angular cross-bedded, medium or coarse sand with occasional backflow ripples climbing up the lower third of the foresets. The base is often erosive. Interpreted as formed by 2-dimensional, simple bars migrating under intermediate to high stage, stable flow conditions in deeper parts of a river channel. Thicker sets are seen in the bottom half of fig. 6, thinner sets higher up in the succession.



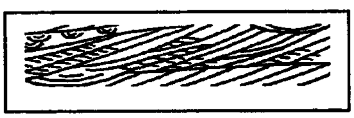
Tabular cosets composed of wedge-shaped, angular cross-bedded sets of medium sand. Interpreted as formed by 2-dimensional bars transitory to 3-dimensional bars. The bars were migrating slowly with downstream bars being frequently eroded by upstream bars. This facies was probably deposited in a shallower part of the channel than the above two facies and therefore subject to more varying flow conditions (fig.5, at 5-7 metres).

Large, composite cosets, 1 to 3 metres thick :

This facies is subdivided into two facies according to the geometry of the sets forming the cosets.



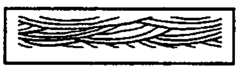
Tabular cosets constructed of wedge-shaped sets of medium to coarse sand building down large, low-angle concave-up foresets. Often with erosive top and base. Interpreted as formed by the migration of 3-dimensional bars. The large thickness of the bars is a result of their migration into the deeper parts of a channel under intermediate to high flow stage conditions. The partial erosion of the bar crest and front and the many reactivation surfaces are interpreted as a result of the 3-dimensionality of the bedform rather than numerous flow-stage variations (fig.6).



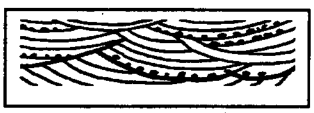
Tabular cosets made of cross-bedded sets with angular foreset terminations or foresets with asymptotic terminations. Numerous ripples are seen on the lower half of foresets and rarely on the upper half. They are interpreted as having formed by strong eddy currents in the lee of the bedform (Simons et al. 1965). Reactivation surfaces are found occasionally. Ripple lamination in the top half of cosets may display current directions normal to the direction of progradation of the large foresets. The base is strongly erosive with tangential-based foresets grading into bottomsets, that are occasionally deposited in cut- and fill structures. Interpreted as formed by the migration of 2-dimensional bars into shallower water than the above facies giving rise to strong separation eddies and cross-current phenomena in the lee side of a transverse bar (fig. 6).

Facies St: trough cross-bedded sand.
This facies is subdivided into four facies according to the grain-size and scale of the sets. The large scale St facies are found close above the deeper parts of concave-upwards 2nd order bounding surfaces (figs 2, 4 and 5). The small scale St facies occur in a somewhat higher position (fig.2 at 17 metres, fig. 5 at 14 metres).

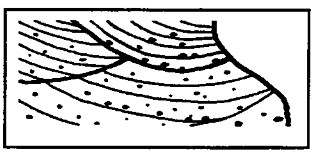
Small scale trough cross-bedded sand, fine-grained, occasionally medium to coarse sand. Interpreted as formed by the migration of 3-dimensional ripples in deeper parts of the river channel under high flow stage.



Medium scale trough cross-bedded medium to coarse-grained sand. Interpreted as formed by the migration of strongly 3-dimensional dunes under high flow stage in the deeper parts of river channels.



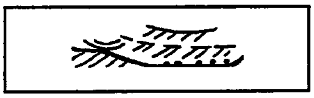
Large scale trough cross-bedded medium and coarse sand with granule and pebble lags in troughs. Interpreted as formed by the migration of strongly 3-dimensional dunes under very high flow stage in the deepest parts of river channels.



Large to giant scale trough cross-bedded coarse-grained pebbly sand fining to medium-grained sand. Interpreted as formed by the migration of strongly 3-dimensional dunes under very high and waning flow stages in the deepest parts of river channels.

Facies Ss : scour-fill sand.
This facies is subdivided into three facies according to grain-size, bed geometry., the nature and conspicuousness of laminae.

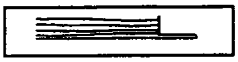
Medium to coarse, pebbly sand bedded conformably to the bottom and sides of scours several metres wide. Eroded into the top of simple, 2-dimensional bars. Interpreted as formed by chutes eroding into the top of bars situated in topographically high positions within the river channel. Chutes filled during waning flow stage (fig. 2 at 19 metres, fig. 5 at 13 metres) (McGowen and Garner, 1970).



Medium and coarse-grained sand, partly vaguely ripple laminated and partly massive, with decimeter-wide cut- and fill structures and granule lags at the base. This facies fills several meter wide, shallow scours. It is interpreted as having formed as a result of relatively rapid deposition during high flow stage in the deeper parts of the river channel (fig. 6 at 1 meter).

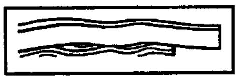
Diffusely laminated to massive, medium to coarse sand displaying shallow scour- and fill structures and deposited in 5 - 10 m wide channel features. This facies may be found immediately above a 1st order bounding surface (fig. 4 at 1 meter). It is interpreted as having formed during very high stage as a result of erosion and rapid deposition in the deepest part of the river channel.

Facies Sh : plane-bedded sand.



Plane-bed laminated, medium-grained sand with coarse sand and granules at the base (fig. 6 at 6 metres). This facies may form the top of cosets otherwise consisting of large scale Sp facies. They are grouped by 2nd order bounding surfaces. This facies is interpreted as having formed on the top of bars during a large increase in current velocity. This increase created the lag and the plane bedded facies was deposited subsequently during slightly waning flow.

Facies Sm : massive sand.

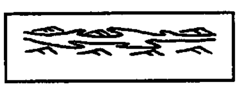


Sand, massive. Drapes existing topography, which may be erosive. Interpreted as having formed during rapid stage variations in parts of the river channel carrying a high sediment load or due to rapid deposition of surplus sediment load following a collapse of the river bank (fig. 2 at 12, 14 and 18 metres).

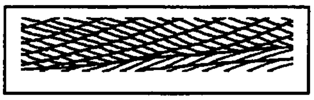
Facies Sr: ripple cross-laminated sand.

This facies is subdivided into three facies according to grain-size, the presence of interbeds of draped lamination , convoluted bedding or climbing ripple lamination. It is predominant in the upper part of fining upwards successions (fig. 4 at 12-16 metres).

Rippled sand, fine to medium, rarely coarse-grained, interbedded with thin drapes of massive sand. Interpreted as deposited by relatively slow moving water in a very shallow part of the river channel, e.g. during the formation of passive channel fill in a partly abandoned river channel.



Rippled sand, fine to medium-grained, interbedded with layers of massive, convoluted sand. Interpreted as passive channel fill that formed due to an alternation of relatively slow moving water in a shallow part of the river channel and sediment saturated pulses of water flowing into this partly abandoned river channel. The subsequent deposits of clays, silts and muds on top of this facies retarded the expelling of pore water. High pore water pressures led to convolution of the massive interbeds of sand.



Sand, medium to coarse, climbing ripple laminated. The base is erosive. Interpreted as having formed during intermediate to high stage as a result of rapid sediment deposition in depressions between large bars in the deeper parts of the river channel.

Architecture of the deposits

To fully understand the deposits, it is necessary to first consider the organization of the succession i.e. the architecture of the deposits. A hierarchy of four orders of bounding surfaces has been interpreted on figs. 2-7 according to their relative position and the hierarchy of their mutual intersection. The bounding surfaces have been described and interpreted as follows:

1st order : Low-curvature bounding surface, defining a '50 metres plus' channel width. This surface forms the base of a 10-20 metres thick fining-upwards succession. Interpreted to record channel switching. See figs. 3-6.

2nd order : Low-curvature bounding surface , defining a '50 metres plus' channel width. This surface forms the base of 2-5 metres thick successions, which may be fining upwards. Interpreted to record stages in active channel aggradation brought about by lateral movement of the channel on a more frequent basis than the 1st order surface.

3rd order : High-curvature bounding surface, defining a 5-10 metres scour/channel width. Position: lower part of a fining-upwards succession. Interpreted to record rapid scour and fill events within the lowest level of a channel during high stage flow. See figs. 5 and 7.

4th order : High-curvature bounding surface, defining 5-10 metres scour/channel width. Position: middle to upper part of a fining-upwards succession. Interpreted to record rising stage chute activity or the dissection of large bars during falling stage. See figs. 5 and 7.

Paleocurrents

Paleocurrents have been measured in outcrop on unconsolidated sediments. Trough axes and foreset dip directions are plotted on fig. 10. Separate plots were made for each of the three localities and facies groups.

Large scale Sp facies is dominant in the Sønder Vissing Sand (A) locality. The foreset dip azimuths towards the south-southeast are very consistent with a low spread (fig. 6). No St facies were available for measurement.

The Silkeborg Kvartssand (B) locality is divided into many sediment packets separated by bounding surfaces (fig. 7). Trough axis dip directions towards 210-230 degrees were measured on St facies immediately above the presumably central, planar part of the lower 1st order bounding surface shown on fig. 9. In contrast to this, directions towards 150-180 degrees were measured in large scale St facies above the slightly concave, upper 1st order bounding surface (fig. 5 and 9). It may be assumed, that the measurements above the lower 1st order bounding surface is more central to a channel axis than the measurements above the sloping, upper 1st order bounding surface and should yield a better estimate of channel axis direction. The large scale Sp facies yield foreset azimuths towards the southeast (fig. 5) and south-southwest (fig. 2) respectively for the same two intervals. There is a tendency for the Sp foreset azimuths to diverge some 60 degrees from St trough axes dip directions measured above the same 1st order bounding surface.

At the Voervadsbro (C) locality a single, large trough axis yielded 202 degrees dip direction immediately above a more than 100 m wide 1st order bounding surface. Abundant large scale Sp facies showed consistent progradation directions towards the west and southwest (fig. 4). Accordingly, the same tendency of diverging St and Sp foreset dip directions is seen both at locality B and C.

It can be concluded, that the paleocurrent measurements are consistent between locality C and the lower 1st order succession in locality B. The difference in measurements between the upper and lower 1st order successions in locality B confirm the distinction between stacked 1st order successions.

The consistent difference in foreset dip directions between St and Sp facies support the interpretation of a type of river with complex bar forms, cross-channel bars, which may migrate at an angle to the river trend as described from the South Saskatchewan by Cant and Walker (1978) and from the Brahmaputra by Coleman (1969) and Bristow (1987).

Facies associations

One fining upwards succession has been identified in pit C (fig. 4) and three, stacked, 10 to 20 metres thick, fining-upwards facies successions have been identified in pit "B" (fig. 9). Two incomplete successions were identified on the basis of an analysis of the hierarchy of bounding surfaces in outcrop (fig. 7) and the trend of facies transitions from large scale to small scale structures and from large scale, sandy, gravelly St facies via small scale Sp facies to sandy, silty Sr facies (fig. 2 at 12 metres). A third, 15 metres thick succession was identified immediately below these in a borehole (fig. 3) on the basis of a fining upwards trend from coarse sand to silt and clay with roots (fig. 3). The facies associations comprising these successions are described and interpreted below.

A. Massive and weakly laminated sand association

A typical succession may start with a several metres thick set of massive to weakly laminated, medium to coarse-grained sand immediately overlying the first order bounding surface. The massive aspect is interpreted to be the result of a very high rate of deposition. Deformed and transported megaripple sets are interpreted as caused by shear exerted by high sediment loads, perhaps induced by bank collapse (McKee et al., 1962a, 1962b, Allen and Banks, 1972; Wells et al., 1993). Large scour and fill structures (on bounding surface # 3) are due to erosion in the lowest part of a channel during high stage.

B. Tabular sand association

Large tabular sets occur on top of or laterally to facies association A, and constitute most of the active channel fill. The sets are 1 to 3 metres thick and are often capped by several, smaller sets. Sp facies are dominant with large scale St facies occurring at the base of fining-upwards successions. This structure represents sinuous crested dunes (Harms et al., 1982). Backflow ripples up to 10 cm thick are commonly associated with solitary, large scale Sp facies. Backflow ripples were formed by strong separation currents developed in front of the large bar slipfaces (Jopling, 1965, Boersma et al., 1968). Palaeocurrent measurements show that some of the ripples migrated at right angles to the progradation direction of the Sp facies foresets indicating that flow was diverted around bars. These facies are grouped into 2-5 metres thick, fining-upwards successions and separated by second order bounding surfaces. The Sp facies association is interpreted to represent straight to sinuous crested bars. The migration of the bars was frequently interrupted by flow stage variations as shown by numerous reactivation surfaces and the almost complete erosion of bars in places (fig. 8). The bars were capped by megaripples. The bars migrated oblique to the channel trend as defined by St facies progradation directions. The migration of slip faces of bar complexes obliquely to channel trend was documented by Coleman (1969) and Bristow (1987) from the braided reach of the Brahmaputra, Smith (1970, 1971) from the Platte River and Cant and Walker (1978) from the South Saskatchewan River.

C. Rippled and draped sand, clay and coal association
The top of the fining-upwards succession is formed by 1-2 metres of cosets of fine to medium-grained, rippled sand interbedded with thin drapes of massive, fine-grained sand and grading up into silty sand, silt and a metre of clay, occasionally with coal. The clay in the borehole contained roots in the clay interval (fig.3). The facies association is interpreted as a vertical-accretion deposit passing gradually into floodplain clays and swamp coals. Similar deposits are described from the Mississippi by Farrell (1987).

Depositional environments

The complete fining-upwards succession within associations A+B is interpreted to represent the establishment of a fluvial channel in a new position on the floodplain, thereby eroding 10-20 metres into the previous, mainly sandy succession and obliterating the overbank silt, clay and coal deposits. The slight decrease in set thickness and grain size upwards within associations A+B is interpreted to be due to the gradual infilling of an active channel. The topmost, fine-grained facies association C is interpreted as passive channel fill or overbank deposits, occasionally punctuated by pulses of sand deposited in massive, later convoluted, beds. The 1st order and 2nd order bounding surfaces (fig. 9) are interpreted as the result of channel switching on different time scales resulting in a nesting of channels within channels as described by Bristow (1987) from the Brahmaputra. According to Bristow, the movement of his 1st order channels, which encompass the entire river, determines the geometry of the entire sand body, whereas the movement of 2nd and 3rd order channels rework any structures left by 1st order channel movements and determines the internal structure of the preserved sand body. First order channel movements are by avulsion. Second order channels migrate laterally and third order channels dissect bars during falling stage and are subject to sudden and irregular switching. If an analogy is drawn to the present study area, the 1st and 2nd order bounding surfaces would probably correspond to the 2nd and 3rd order channels of the Brahmaputra. The 2nd order channels form 40 m thick sand bodies in the Brahmaputra. This corresponds to the 20 metres thick fining upwards succession deposited on a 1st order bounding surface in the present study area.

Conclusions

The following conclusions are based on both the geometry of bounding surfaces and the facies :

1. The dominance of sandy, active channel fill over passive channel fill and the confinement of possible lateral accretion surfaces to fronts of large, composite bars suggest that this succession does not represent a meandering river.

2. The uniform azimuth directions of trough sets towards the south and southwest indicate that the channel course was straight rather than sinuous. The azimuth directions may vary, if a different 1st order sand body is considered.

3. The foreset dip directions of tabular sets interpreted as 2-D and 3-D bars are often at a steep angle to the azimuths of immediately associated trough sets, indicating that bars migrated at an angle to the general direction of the river.

4. A possible interpretation of river style would be that of a very slightly sinuous river with bars migrating across the river channel in the style of lateral bars. Such fluvial systems are typical of the upper delta plain suggesting that the fluvial system described here might be related to a deltaic system to the south or west, where it was described by previous authors (Sorgenfrei, 1958; Rasmussen, 1961a, 1961b; Koch, 1989).

Acknowledgements

I thank Dr. Lars H. Nielsen for constructive discussions and Dr. Jon R. Ineson for critical reading of the manuscript.

References

Allen, J.R.L & Banks, N.L., 1972 : An interpretation and analysis of recumbent-folded deformed cross-bedding. Sedimentology, 19, p. 257-283.

Bluck, B. J., 1980 : Structure, generation and preservation of upward fining, braided stream cycles in the Old Red Sandstone of Scotland. Trans R. Soc. Edinburgh, v. 71, p. 29-46.

Boersma, J. R., Van de Meene, E. A. and Tjalsma, R.C., 1968 : Intricated Cross-Stratification due to interactions of a Mega Ripple with its Lee-Side System of Backflow Ripples (Upper Point Bar Deposits, Lower Rhine). Sedimentology, 11, p. 147-162.

Boothroyd, Jon C. and Ashley, Gail M., 1975 : Process, Bar Morphology, and Sedimentary Structures on Braided Outwash Fans, Northeastern Gulf of Alaska; in A.V. Jopling and B.C. McDonald, eds., Glaciofluvial and Glaciolacustrine Sedimentation: Soc. Econ. Paleont. Mineral. Spec. Pub. 23, p. 193-222.

Bristow, C.S., 1987 : Brahmaputra River: channel migration and deposition. In: F.G. Ethridge, R.M. Flores and M.D. Harvey (Editors), Recent Developments in Fluvial Sedimentology. Soc. Econ. Paleont. Mineral. Spec. Pub. 39, p.63-74.

Cant, D.J. and Walker, R.G., 1978 : Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada. Sedimentology, 25, p. 625-648.

Coleman, J.M., 1969 : Brahmaputra River, channel processes and sedimentation. Sedimentary Geology, v. 3, p.131-239.

Collinson, J.D., 1970 : Bedforms of the Tana River, Norway. Geogr. Ann. 52A, 31-56.

Farrell, K.M., 1987 : Sedimentology and facies architecture of overbank deposits of the Mississippi River, False River region, Louisiana. In: F.G. Ethridge, R.M. Flores and M.D. Harvey (Editors), Recent Developments in Fluvial Sedimentology. Soc. Econ. Paleont. Mineral. Spec. Pub. 39, p.111-120..

Friis, E. M., 1985 : Angiosperm Fruits and Seeds from the Middle Miocene of Jutland (Denmark). Det Kongelige Danske Videnskaberne Selskab Biologiske Skrifter. 24:3, 102 pp.

Friis, H., 1973 : Om silicifikater i danske ung-Tertiære aflejringer. Dansk Geol. Foren. Årsskrift for 1972. p.85-86..

Friis, H., 1974 : Weathered heavy-mineral associations from the Young-Tertiary deposits of Jutland, Denmark. Sedimentary Geology, v.12, p.199-213.

Friis, H., 1976 : Weathering of a Neogene fluviatile fining-upwards sequence at Voervadsbro, Denmark. Bull. Geol. Soc. Denmark, v. 25, p.99-105.

Friis, H., 1978 : Heavy mineral variability in Miocene marine sediments in Denmark: a combined effect of weathering and reworking. Sedim. Geol., v.21, p.169-188.

Hansen, H.C. Steen and Nielsen, Lars H., 1993 : Tertiary Fluvial Deposits of Jylland, Addit area. In: Abstract Volume, Maringeologisk Møde: Nordsøens og Skagerraks geologi. Geologisk Institut, Århus Universitet, 7.-8. oktober 1993.

Harms, J.C., Southard, J.B. and Walker, R.G., 1982 : Structures and Sequences in Clastic Rocks : Soc. of Econ. Paleo and Mineral. Short Course No. 9, 249 pp.

Haszeldine, R.S., 1983 : Fluvial bars reconstructed from a deep, straight channel, Upper Carboniferous coalfield of northeast England. Journal of Sedimentary Petrology, v. 53, p. 1233-1248.

Laury, R.L., 1971 : Stream Bank Failure and Rotational Slumping: Preservation and Significance in the Geological Record. Geological Society of America Bulletin, v. 82, p. 1251-1266.

Jopling, A.V., 1965 : Hydraulic factors controlling the shape of laminae in laboratory deltas. Journal of Sedimentary Petrology, v. 35, p. 777-791.

Koch, B.E., 1989 : Geology of the Søby-Fasterholt area. Danm. Geol. Unders. Ser. A, 22. 167 pp.

Kristoffersen, F. N., 1972 : Foraminiferzonering i det jyske Miocæn. Dansk Geol. Foren. Årsskrift for 1971. p.79-85.

Larsen, G. & Friis, H., 1973 : Sedimentologiske undersøgelser af det jyske ung-Tertiær. Dansk Geol. Foren. Årsskrift for 1972. p.119-128.

McGowen, J.H. and Garner, L.E., 1970 : Physiographic features and stratification types in coarse-grained point bars : modern and ancient examples. Sedimentology, v.14, p.77-111.

McKee, E.D. and Weir, G.W., 1953 : Terminology for stratification and cross-stratification of sedimentary rocks. Bull. Geol. Soc. Am., 64, 381-390.

McKee, E.D., Reynolds, M.A. and Baker, C.H., 1962a. Laboratory studies on deformation in unconsolidated sediment. U.S. Geol. Surv., Profess. Pap.,450D, p.151-155.

McKee, E.D., Reynolds, M.A. and Baker, C.H., 1962b. Experiments on intraformational recumbent folds in cross-bedded sand. U.S. Geol. Surv., Profess. Pap.,450D, p.155-160.

McKee, E.D.,Crosby, E.J. and Berryhill, Jr., 1967 : Flood Deposits, Bijou Creek, Colorado, June 1965. Journal of Sedimentary Petrology, v. 37, p. 829-851.

Miall, A.D., 1977 : A Review of the Braided-River Depositional Environment. Earth Sci. Rev., v.13, p.1-62.

Miall, A.D., 1978, ed., Fluvial Sedimentology : Calgary, Canadian Society of Petroleum Geologists, Memoir 5, 859 pp.

Miall, A.D., 1985 : Architectural-Element Analysis: A new Method of Facies Analysis applied to Fluvial Deposits, in : Flores, R.M., Ethridge, F.G., Miall, A.D., Galloway, W.E. & Fouch, T.D., eds., Recognition of Fluvial Depositional Systems and their Resource Potential. Soc. Econ. Paleo and Mineral. Short Course No. 19, p. 33-81.

Nielsen, Søren A.V. and Nielsen, Lars H., 1993 : A Mid-Miocene progradational, sandy barrier island and backbarrier section, central Jylland, Denmark. Geological Survey of Denmark, Ser. C. "in press."

Rasmussen, L.B., 1961a : De miocæne Formationer i Danmark. Danm. Geol. Unders. IV.rk., 4, p.1-45.

Rasmussen, L.B., 1961b : Mittel- und Ober-Miozän von Dänemark. Meyniana, 10, p.59-62.

Rasmussen, L.B., 1966 : Molluscan Faunas and Biostratigraphy of the Marine Younger Miocene Formations in Denmark. Part I: Geology and Biostratigraphy. Danm. Geol. Unders. II.rk.,88, p.1-358.

Simons, D.B., Richardson, E.V. and Nordin, C.F., 1965 : Sedimentary Structures generated by flow in alluvial channels. In: Middleton, G.V., ed., Primary sedimentary structures and their hydrodynamic interpretation. Soc. Econ. Paleo and Mineral., Spec. Publ. 12, 34-52.

Smith, Norman D., 1970 : The Braided Stream Depositional Environment: Comparison of the Platte River with Some Silurian Clastic Rocks, North-Central Appalachians. Geological Society of America Bulletin, v. 81, p. 2993-3014.

Smith, Norman D., 1971 : Transverse Bars and Braiding in the Lower Platte River, Nebraska. Geological Society of America Bulletin, v. 82, p. 3407-3420.

Smith, Norman D., 1972 : Some Sedimentological Aspects of Planar Cross-Stratification in a Sandy Braided River. Journal of Sedimentary Petrology, v. 42, p. 624-634.

Sorgenfrei, T., 1958 : Molluscan assemblages from the marine Middle Miocene of South Jutland and their environments. Dan. Geol. Unders., rk. 2, 79, 503 pp.

Wells, N.A, Richards, S.S., Peng, S., Keattch, S.E., Hudson, J.A. and Copsey, C.J., 1993 : Fluvial processes and recumbently folded crossbeds in the Pennsylvanian Sharon Conglomerate in Summit County, Ohio, U.S.A. Sedimentary Geology, v. 85, p. 63-83.

Williams, G.E., 1966 : Planar Cross-Stratification formed by the Lateral Migration of Shallow Streams. Journal of Sedimentary Petrology, v. 36, p. 742-746.

Williams, G.E., 1971 : Flood Deposits of the Sand-Bed Ephemeral Streams of Central Australia. Sedimentology, v. 17, p. 1-40.

Williams, Peter F. and Rust, Brian R., 1969 : The Sedimentology of a Braided River. Journal of Sedimentary Petrology, v. 39, p. 649-679.

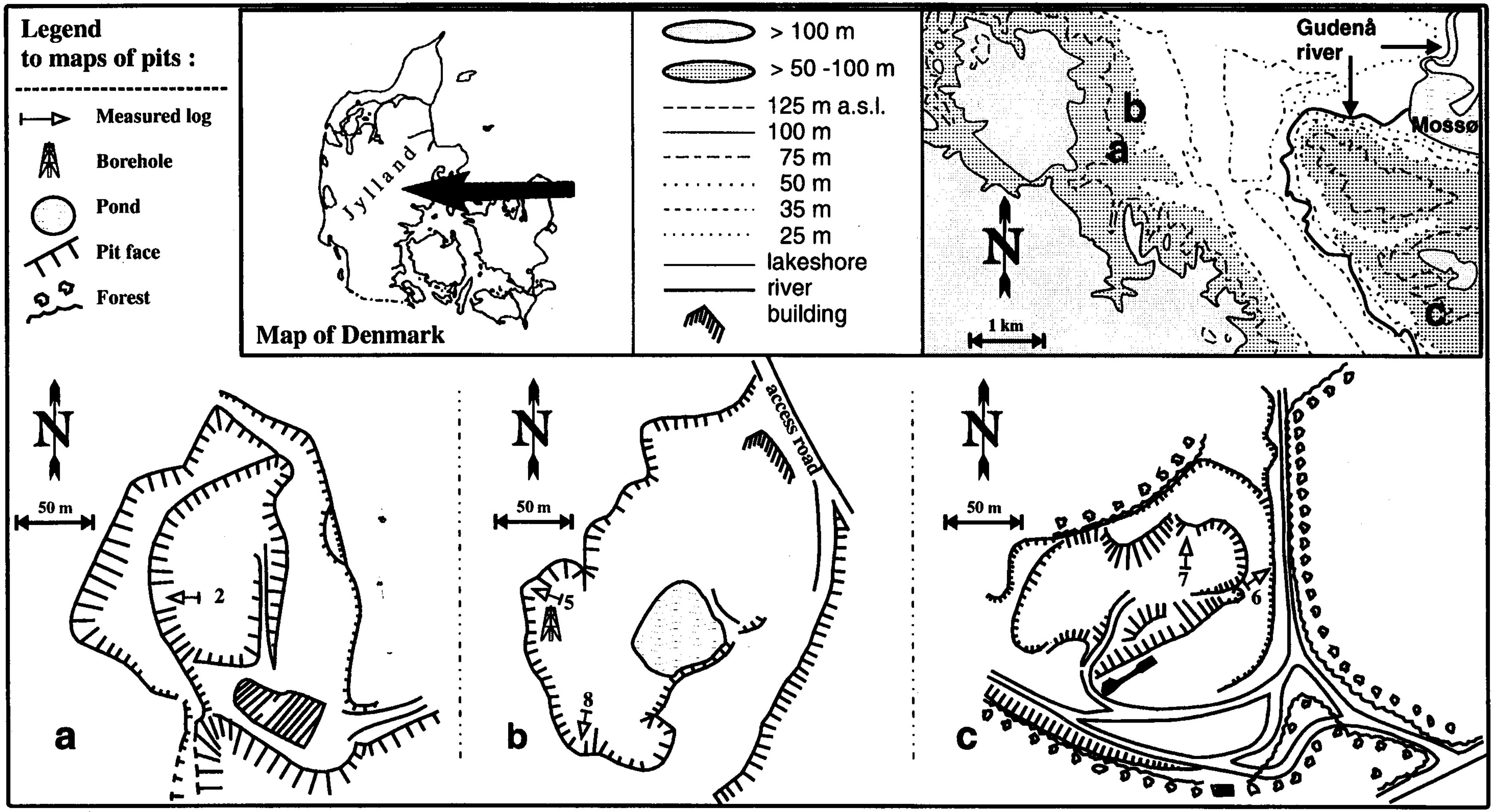


Fig.1 : Maps of quartz-sand pits in the the Addit - Voervadsbro area in central Jylland :
a: Sønder Vissing Sand A/S; b: Silkeborg Kvartssand A/S; c: pit north of Voervadsbro.

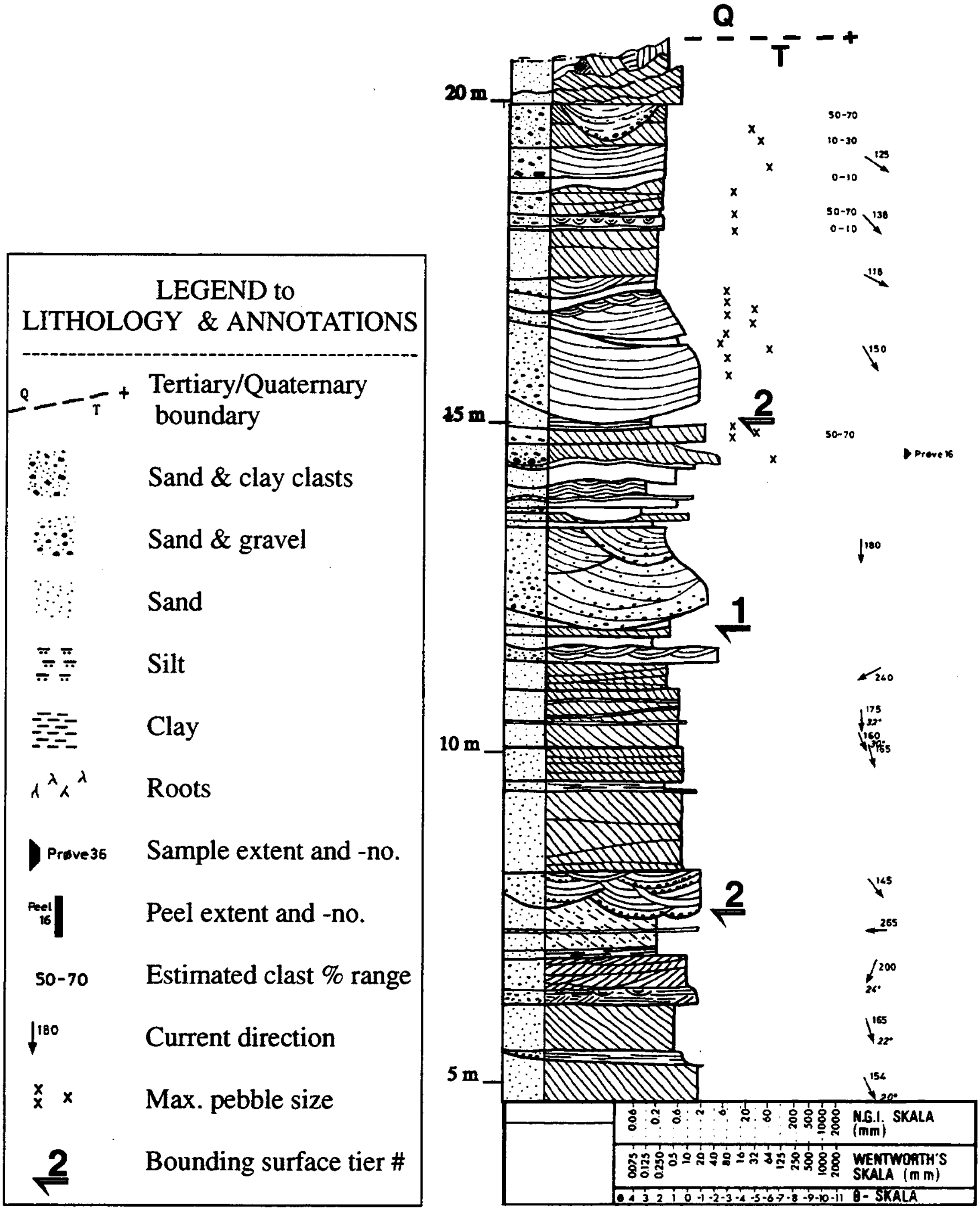
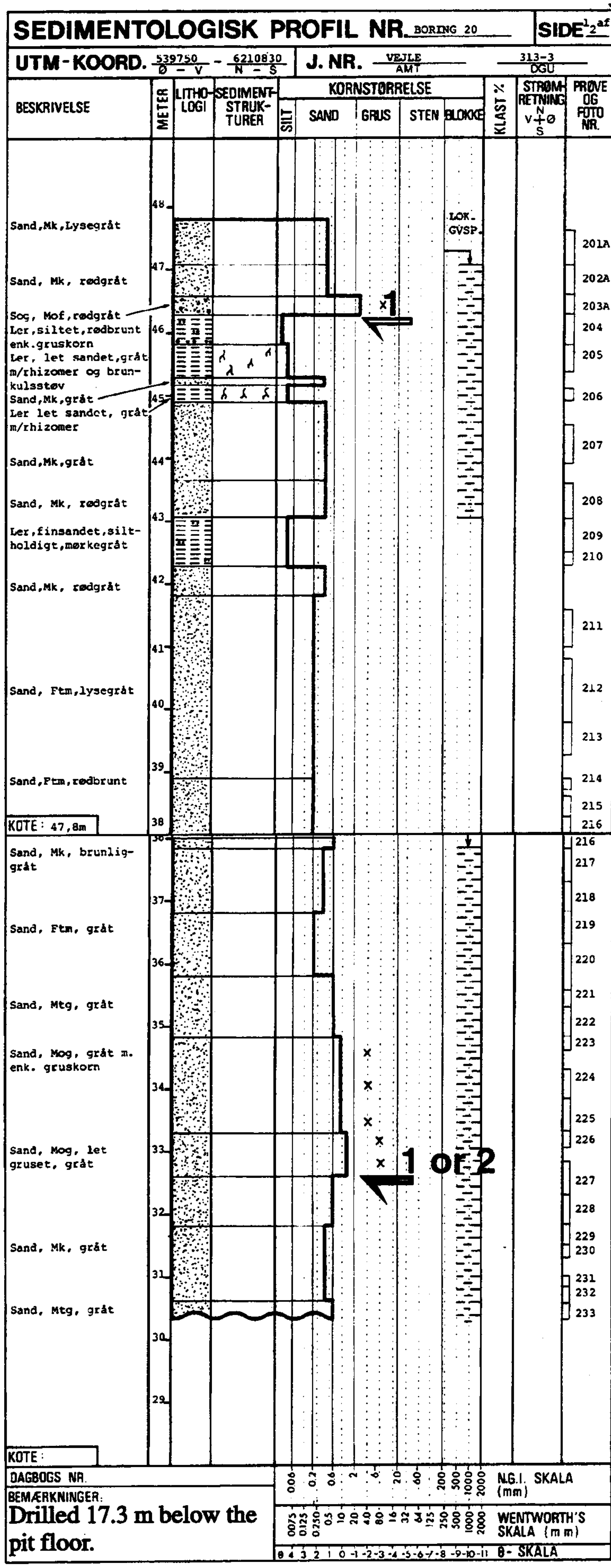


Fig. 2 :
Log no. 5 recorded at pit "b", Silkeborg Kvartssand A/S.
Several fining-upwards successions are seen. Each succession starts with a gravel lag, massive beds and St-type facies, e.g. at 7.5m, 12m and 15m. They are separated by level # 1 and 2 bounding surfaces as indicated. The interval 5-12m is the incomplete, upper part of one level # 1 fining upwards succession. The level #1 succession above 12m is truncated by quaternary erosion in this log, but fines into silty sand Sr facies elsewhere in pit "b".

Fig 3:
Borehole drilled 17 m below the pit floor near log no. 5 in the sand pit "b" of Silkeborg Kvartssand A/S. The borehole was drilled with steel casing driven in front of the auger and the sand -filled casing was bailed out successively.
A 1st order fining upwards succession begins at 46.2m with a gravel lag and extends up into log no. 5, fig. 2
A local groundwater table is found at 47m and it is concluded that the clays underneath and at 42.2-43m therefore possess a significant lateral extension and are floodplain deposits. Roots found in the top clay interval indicate the floodplain was vegetated. These clays form the top of another 1st order succession which displays a 1st or 2nd order bounding surface at 32.5m.



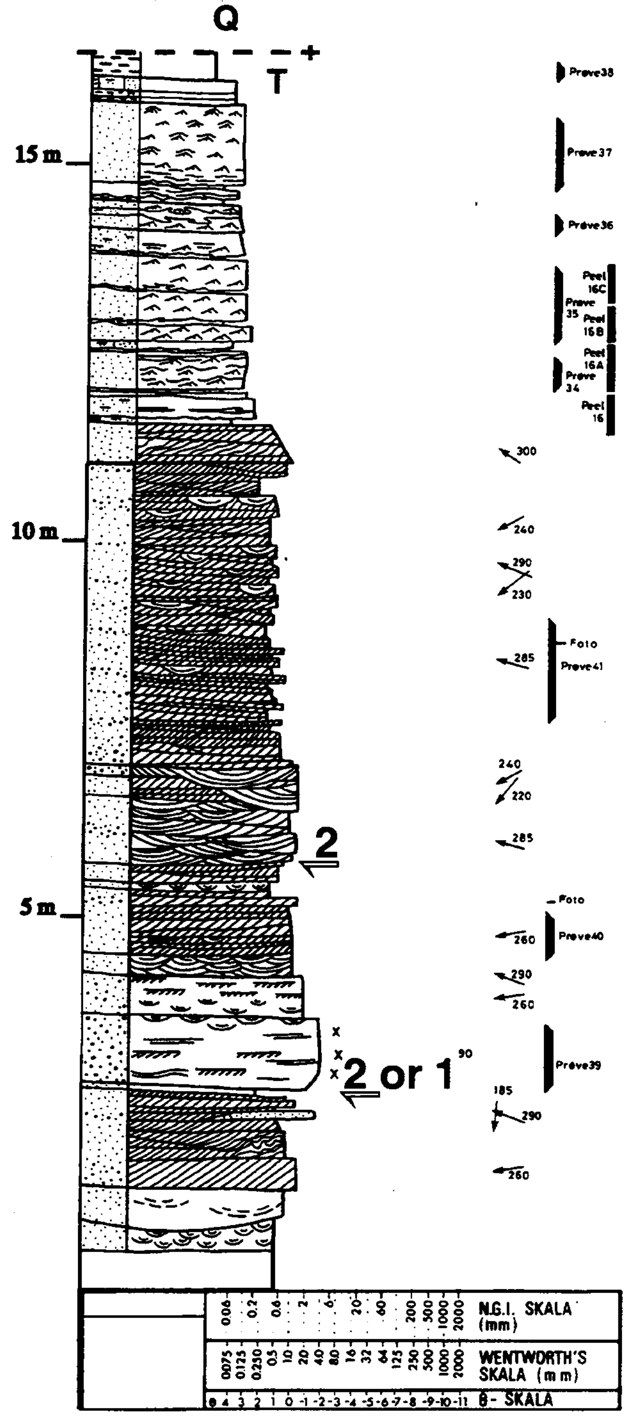


Fig. 4:

Logs no. 6 and 7 combined from pit "c", Voervadsbro. Logs were recorded below and above a terrace at 11m. A fining upwards succession begins at 2.5m, marked "2 or 1" on the log, i.e., this may be a 1st or 2nd order bounding surface. This typical succession begins with massive to wispy laminated sand with pebbles and extends through St and Sp facies to Sr facies and finally clay. Further excavations have demonstrated the presence of coal at a level corresponding to approximately 18 m on the log. Another 2nd order bounding surface is found at 6m, where the St facies reappears.

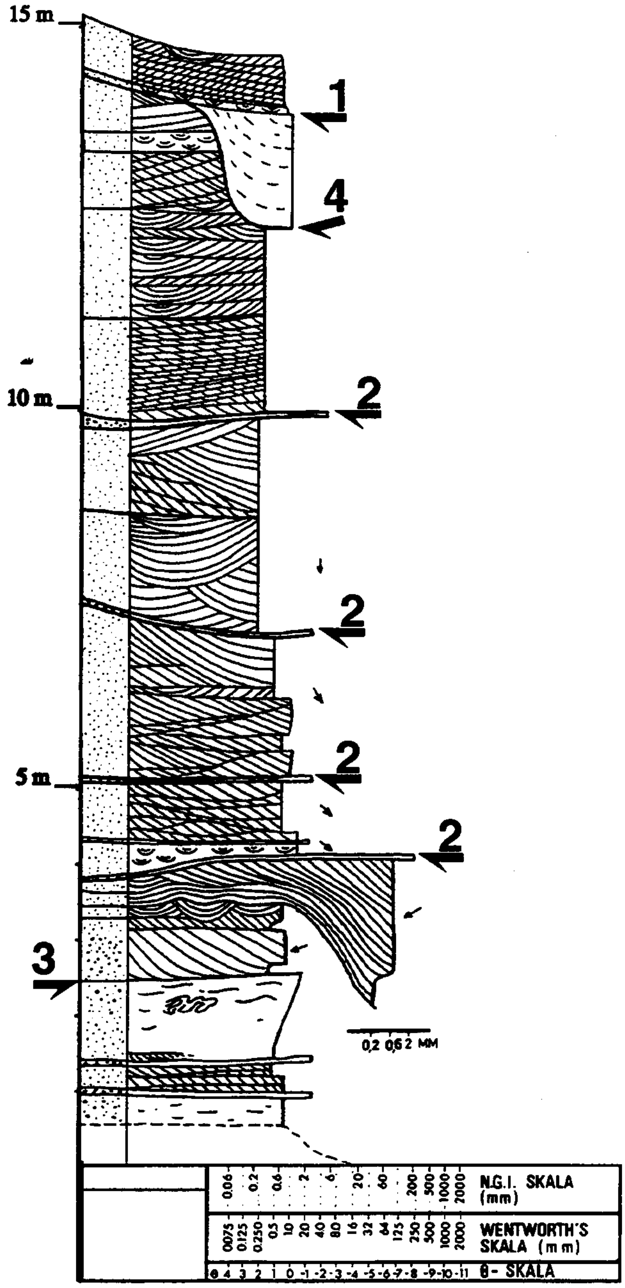


Fig. 5 :
Log no. 8 from pit "b", Silkeborg Kvartssand A/S. 1st, 2nd and 3rd order bounding surfaces correspond to bounding surfaces on fig. 7 recorded from the same pit outcrop. A several m wide scour and fill structure above surface 2b is a chute. Another scour, 20m wide, is interpreted to have formed in a deeper part of the river channel. It is found at 4m on the log. A massive to wispy laminated facies with deformed, transported megaripples is found below the set boundary at "3". It formed during very high stage flow and rapid deposition, perhaps as a result of sediment oversaturated flow after a bank collapse.

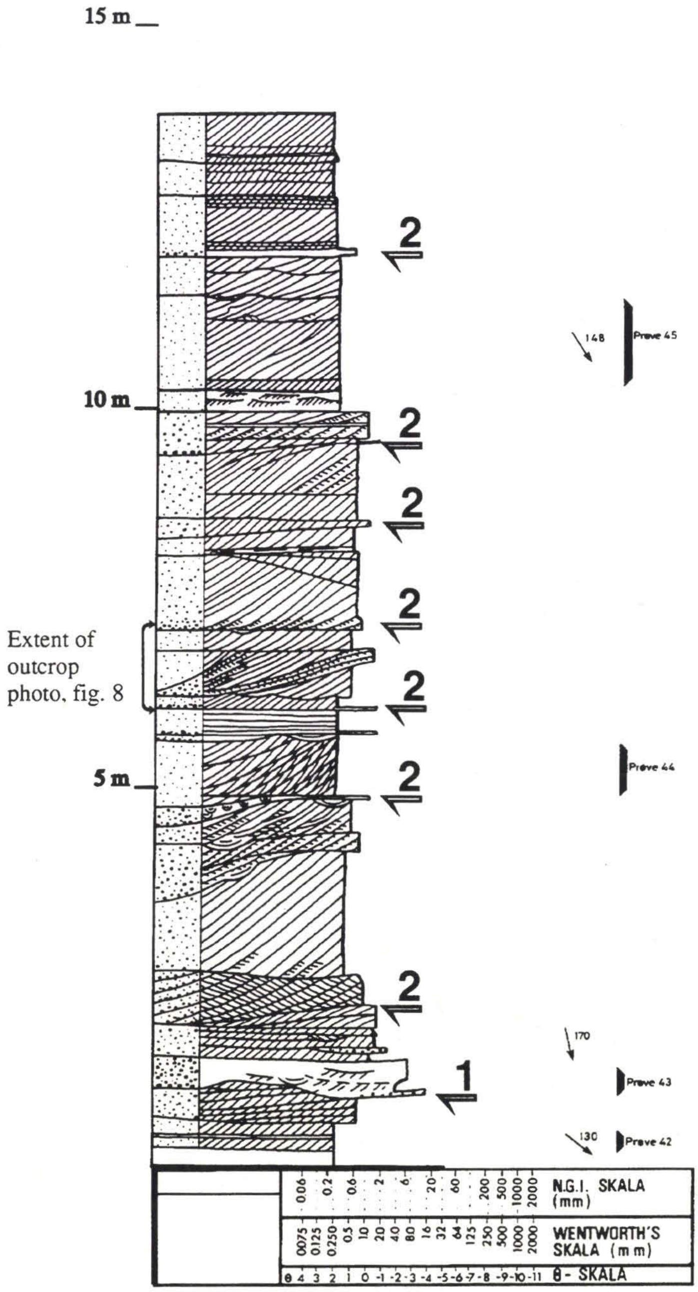


Fig. 6 :
Log no. 2 from pit "a" of Sønder Vissing Sand A/S. The base of an incomplete 1st order succession or another amalgamated 2nd order association is seen at 1m. Amalgamated Sp facies association bar deposits are found above several 2nd order bounding surfaces. The level of detail available for analysis is demonstrated by the detailed photo on fig. 8.

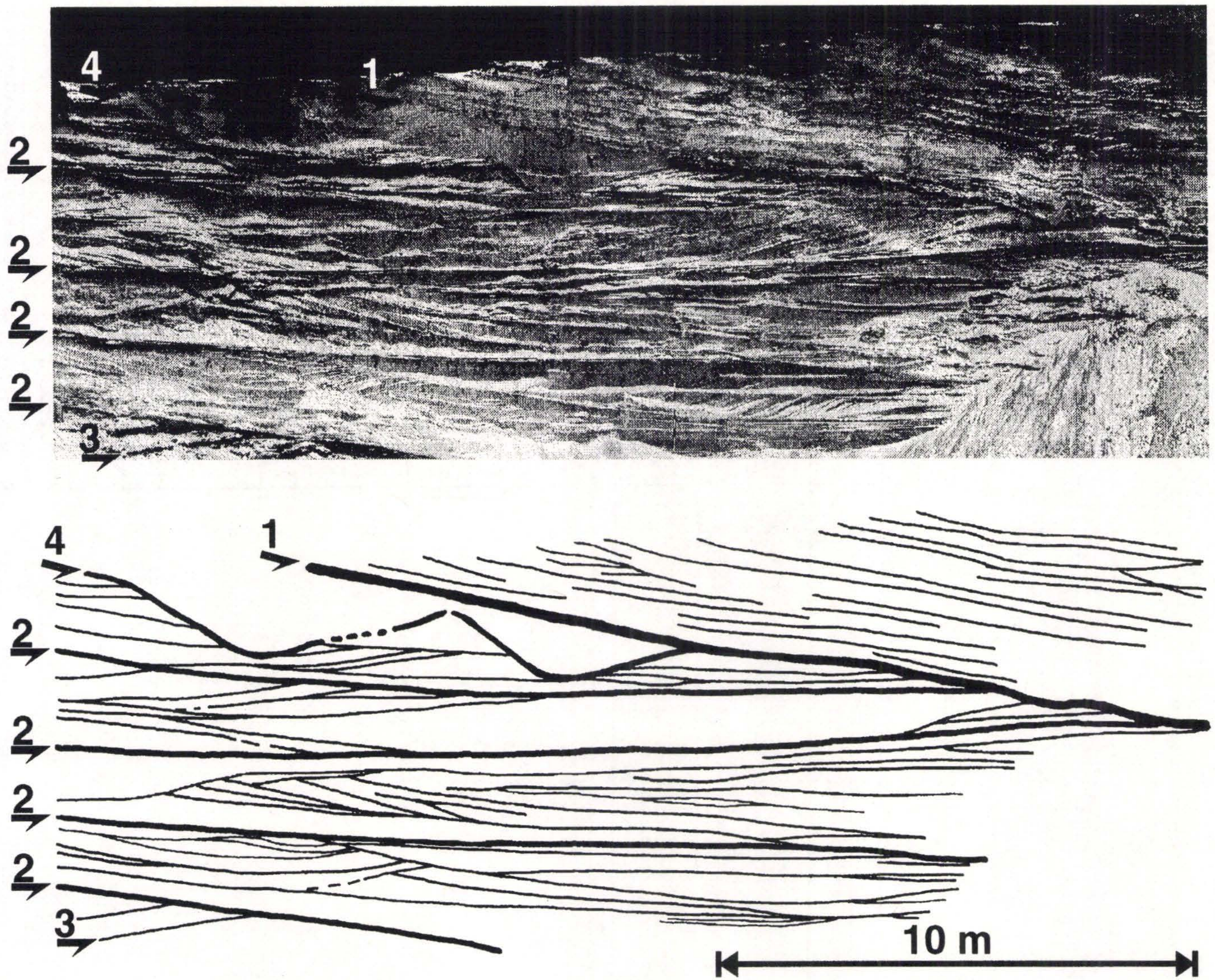
Fig.7 :
The sand pit "b" of Silkeborg Kvartssand A/S at the site of log no. 8. Bounding surfaces have been interpreted in the following hierarchy :

1) Major channel scour level, base of 1st order fining upwards successions.

2) Coset boundaries, , base of 2nd order successions, entirely Sp-facies types on this exposure. Other exposures display St-facies types at the base of 2nd order successions (fig. 2 and 5).

3) Major scour, about 20m wide. Positioned very low in a river channel.

4) Minor scour, usually 3 or 5 m wide. Interpreted as chutes.



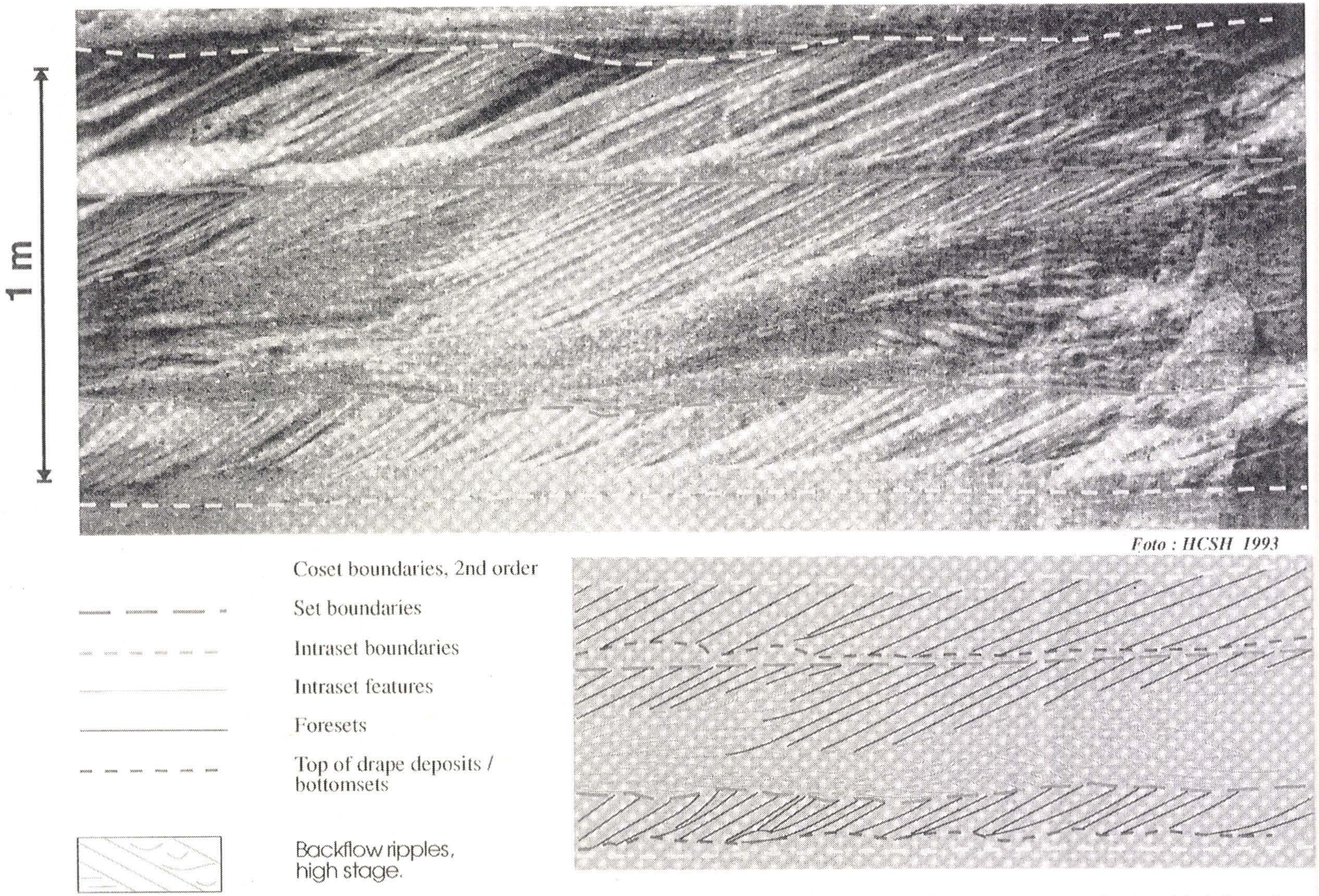


Fig. 8 : Pit "a": 3 Sp bar facies associations separated by green set boundaries: The lowest unit is a remnant of a 1m high bar. It was eroded by the passage of no. 2. The progradation of no. 2 was punctuated by development of bar lee intraset features, including backflow ripples..

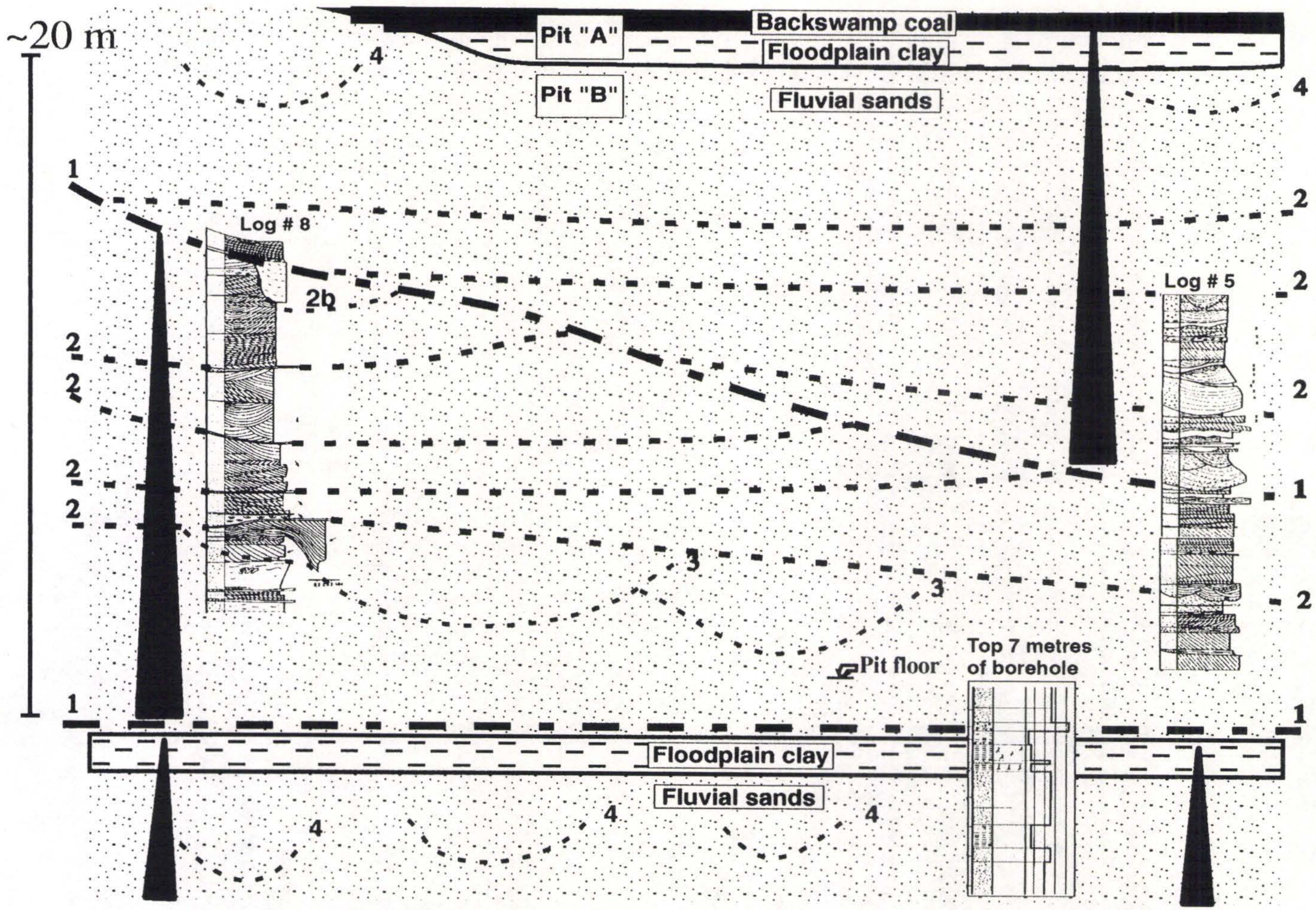


Fig. 9: Model of fluvial architecture, pit "B", Silkeborg Kvartssand. The model is based on logs, a borehole and the outcrop sketch in fig. 7. Two fining-upward successions are identified in outcrop and a third, lower one in a borehole (fig. 3). The lower succession is 13.5 metres thick and fines from coarse sand with granules (not shown) to clay with roots. The middle succession is represented by 9 metres of slightly fining coarse- to medium-grained sand (log # 8).The base of log # 8 is not recorded due to talus. The top is missing due to erosion. The third and top succession is also incomplete, lacking the lowermost, channel-bottom facies. The floodplain silt, clay and coal were recorded from pit "A", 500 metres distant.

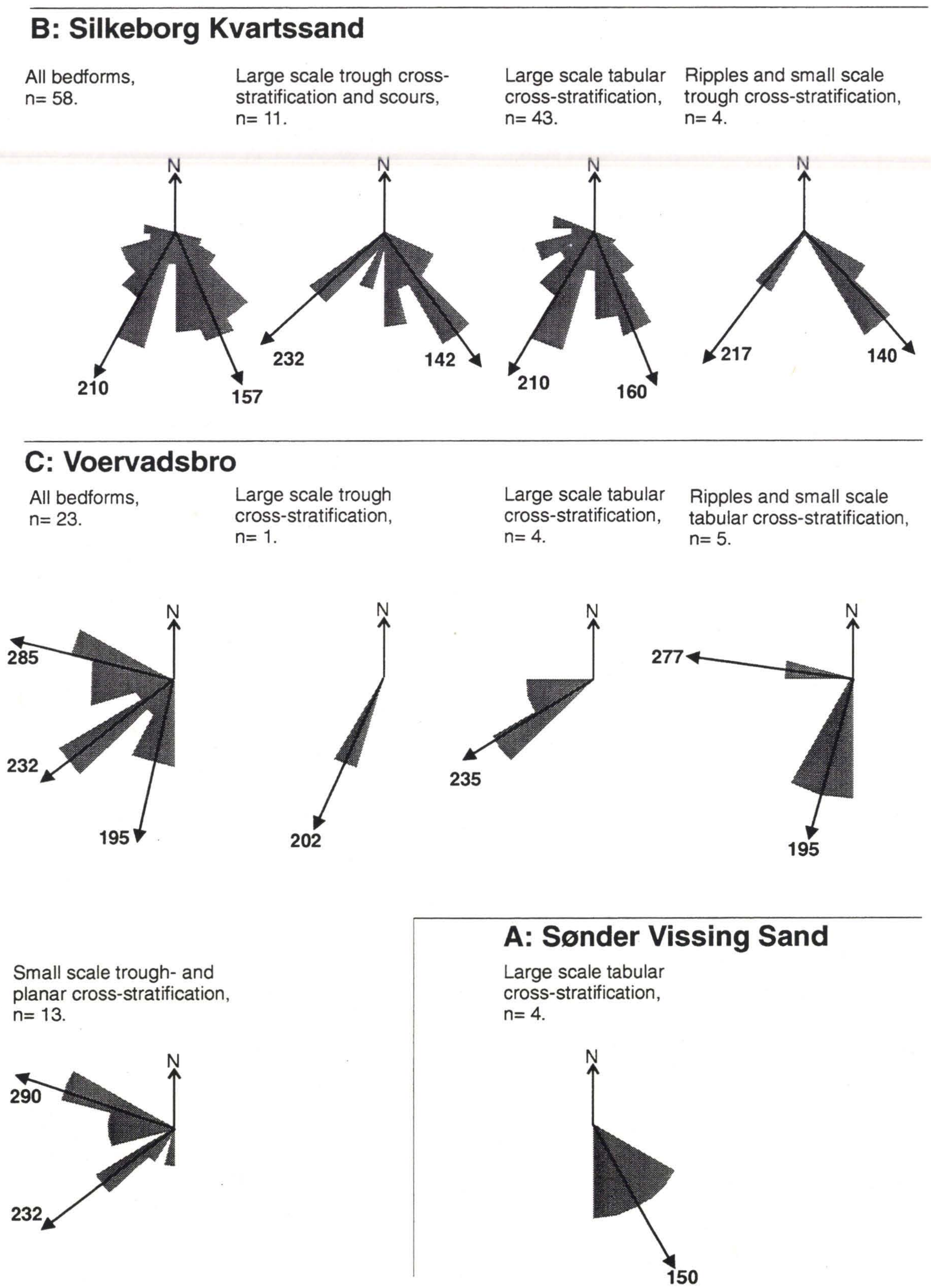


Fig. 10: Estimated mean progradation directions of bedforms in 3 sand pits: Silkeborg Kvartssand, Voervadsbro and Sønder Vissing Sand. Classification ntervals are 15 degrees.

Regional Cenozoic uplift and subsidence events in the southeastern North Sea

Henrik Jordt

Abstract

The Paleocene topography of the Fennoscandian Shield is indicated by outbuilding towards the Central Trough and the Ringkøbing-Fyn High. From Eocene until Pliocene time three events of relative vertical movements are indicated by changes in outbuilding directions and reflection termination patterns in the central North Sea. The first event of uplift was in the Eocene and resulted in relative uplift of the Mid North Sea High and contemporary subsidence east of it, indicated by a change in outbuilding from north to west. A second event of uplift is indicated to the north of the study area at the Eocene-Oligocene boundary by renewed southward outbuilding in the Norwegian-Danish Basin. In Miocene until Early Pliocene time a relatively stationary, almost east-west striking, basin margin was probably located to the north along the Tornquist Zone as indicated by the continued outbuilding towards the Ringkøbing Fyn High . A third event of relative uplift is indicated east of the study area by changes in the Pliocene outbuilding pattern. After the first event of uplift it appears that the deepest parts of the Eocene North Sea Basin was located more easterly than the deepest parts are today. Apparantly the two latest uplift events north and east of the study area were related to movements of, or along the Tornquist Zone or to regional uplift of the Fennoscandian Shield finally resulting in the present-day configuration of the North Sea.

Introduction

This study focus on Tertiary outbuilding directions and subsidence/uplift patterns in the Danish North Sea and adjacent areas. The results are based on seismic interpretation carried out during the Cenos Project[1] (Michelsen et al., in prep). The database comprises more than 20000 km of multichannel reflection profiles (Fig. 1). The results of the seismic interpretation is documented in Jordt (in prep.).

Several structural elements within the study area (Fig. 1) are of importance for the Tertiary outbuilding. Among these are: the Norwegian-Danish Basin, the Central Trough, the Mid North Sea High and the Ringkøbing-Fyn High.

Sequences are defined relative to a full cycle of relative change of onlap, and internally by a backstepping and a forestepping system. Progradation is used to indicate outbuilding directions. Seismic reflection termination maps are used to indicate the palaeo-geometry of the basin and events of vertical movements.

Sequence stratigraphic method

The sequence definition is related to a full cycle of the controlling parameter (Surlyk et al., 1993). This sequence definition focus on observations in the seismic sections and is therefore, of greater relevance than sequence definitions based on different types of hiatal surfaces. The controlling parameters are reflection terminations against the sequence boundaries and internal reflection geometry. Thus, a sequence is present if onlap on the lower sequence boundary can be followed from the basin towards the margins and fol-

---

[1]Cenozoic North Sea Study, Aarhus University, Denmark

lowed back to the basin again along the upper sequence boundary. Often such a sequence is comprised of a backstepping and a forestepping system, characterized by the internal reflection geometry (Fig. 2).

In the Norwegian-Danish Basin, we have mapped a lowermost Oligocene sequence that can be subdivided into a backstepping and a forestepping system separated by a maximum flooding surface (Fig. 2). The lower sequence boundary is characterised by parallel reflections with onlap indicated farther northward. The upper sequence boundary is characterised by truncation below and by onlap above. Also a topographic low, comparable to the erosional valley cf. Vail (1987), is seen at the top of the sequence. A full cycle of relative change of onlap, defining this sequence, is indicated by internal reflection geometry and by reflection terminations against lower and upper sequence boundary.

A more typical North Sea sequence from the lowermost Miocene is shown in Fig. 3. It is charaterized by onlap against the upper and lower sequence boundaries and by subtle toplap. The progradation of the sequence appears as basinward migration of subunits outlined by internal reflections. In this case the sequence definiton is based on the recognition of a full cycle of relative change of onlap. Although different, both sequences are adequately defined by the sequence definition proposed by Surlyk et al., (1993)

Near the limit of the seismic resolution it may be impossible to distinguish between interference patterns that look like reflection terminations and geologically significant reflection terminations. To overcome this problem, reflection terminations against the lower sequence boundaries are mapped regionally to find a consistent pattern. In this way we found for all boundaries regionally coherent areas characterized by either onlap, downlap or reflections parallel to the boundary. In all cases outbuilding was from the onlap area towards the downlap area.

The sediment supply may have been perpendicular or parallel to the coast during deposition. Sediment supply in a fluvial dominated delta is mainly perpendicular to the coast, whereas, coast parallel sediment transport is the dominant process between deltas. In both cases, if the supply of sediment along the coast is greater than the erosion rate, then the coastline will move seaward (Bjørlykke, 1989). Thus outbuilding observed on seismic data does not directly indicate source or provenance areas.

Downlap and onlap reflect the palaeo-topography of the basin floor during deposition (Mitchum et al., 1977). On a regional scale, it is suggested that coherent regions with onlap are located landwards and updip relative to downlap areas. Therefore, it is assumed that the boundary separating these areas shows the approximate strike direction of the basin margin from which outbuildning of the overlying sequence took place. This means that reflection-termination maps combined with outbuilding directions can be used to indicate the palaeo-geometry of the basin.

The coherent areas with onlap or downlap are generally defined in the entire study area for the mapped sequences. It is therefore suggested, that the observed regional changes in the reflection termination configuration and the suggested strike of the basin margin were caused by regional changes in the geometry of the basin, and probably indicate variations in the pattern of relative vertical movements.

Outbuilding patterns

Isopach and seismic reflection termination maps for seven sequences representing the time from Late Paleocene to the Quarternary are used to indicate outbuilding patterns. The dating of the sequences (Fig. 4) are from Michelsen et al., (in prep).

The Cenozoic sediment distribution in the eastern North Sea appears related to older structural elements (Fig. 1). It is shown below that events of vertical movements influenced the Norwegian-Danish Basin to the north and the Ringkøbing-Fyn High to the east. The Tornquist Zone (Pegrum, 1984) separates these structural elements from Fennoscandia To the west the Mid North Sea High was also affected by uplift. The Northwest German Basin to the south appears to be continuously subsiding in the entire Cenozoic era. The Central Trough to the west influenced the sediment dispersal for several sequences.

In the Late Paleocene and Early Eocene outbuilding took place in the Norwegian-Danish Basin mainly towards the south and southwest (Fig.5). In the later part of this period, sediments probably also built out from the Mid North Sea High as Late Paleocene uplift and eastward tilting of the Shetland Platform resulted in development of an eastward-directed drainage pattern (Ziegler, 1982). The seismic facies map shows that the areas to the north and northeast and later also the areas to the west comprised topographic highs relative to the Central Trough and the Ringkøbing-Fyn High.

From Middle Eocene times outbuilding from the west dominated (Fig. 6A). The Lower Eocene outbuilding in the Norwegian-Danish Basin is followed by starved sedimentation indicated by pinch out of overlying sequence. This marked change in reflection stacking pattern and outbuilding direction may indicate uplift to the west and relative subsidence of the Norwegian-Danish Basin and probably also the Ringkøbing-Fyn High.

A major shift in the outbuilding directions again took place at the Eocene-Oligocene transition (Fig. 6B). The two Lower Oligocene sequences shows outbuilding from north. Onlap against the lower sequence boundary shows that the Oligocene sediments were deposited on a southward inclined surface indicating that subsidence in the Norwegian-Danish Basin was succeeded by uplift. It is suggested that the pronounced progradation of the Lower Rupelian sequence may indicate that the sediments was deposited near a prograding shoreline possibly established by uplift along the Tornquist Zone. The two overlying Chattian sequences show weak progradation from northeast.

In the latest Oligocene and Early Miocene outbuilding was from the Norwegian-Danish Basin towards the Central Trough and the Ringkøbing-Fyn High (Fig. 7). The location of the depocenter is highly influenced by the underlying Oligocene deposits. The northeast- and eastward thinning and pinchout of the two Lower Miocene sequences in the Norwegian-Danish Basin is probably due to sediment starvation or bypass.

The seismic facies map indicates that the Middle Miocene - Quarternary sequence progrades towards the Central Trough and towards south across the Ringkøbing-Fyn High (Fig. 8). This reflection termination pattern shows south- and southeast-ward inclination of the basin margin north of the study area, and indicates the presence of an uplifted Fennoscandian Shield. In the German and Dutch areas only westward progradation is observed. The integrated study of sequence 7.0 shows that the two Middle -Upper Miocene and Lower Pleistocene sequences (i.e. sequence 7.1 & 7.2) prograde to the south, while the overlying sequences show westward progradation (Michelsen et al., in prep.). This change from southward to westward outbuilding probably took place in Early Pliocene times. It is suggested that this shift in outbuilding directions from south to west was caused by a change in the basin geometry to the east as a result of uplift. Possibly the Ringkøbing-Fyn High was affected by this uplift event, as indicated by the direction of Late Pliocene and Quarternary progradation.

History of relative vertical motion.

Three main events of relative vertical motion during Eocene until Pliocene time is indicated by outbuilding directions and reflection termination patterns (Fig. 9). These events probably resulted in marked changes in the basin geometry.

- A topographically high area was present north of the study area in Late Paleocene - Early Eocene and in Oligocene - Late Miocene times.
- The Mid North Sea High was uplifted contemporary with relative subsidence of the areas to the east in Middle - Late Eocene times. This probably resulted in an eastward movement of the deepest parts of the basin relative to the present-day situation. It appears also that the North Sea Basin was extended to the northeast, as no marginal facies of these sequences has been found to the North and East
- A marked shift in the pattern of vertical motions took place at the Eocene-Oligocene transition due to uplift north and northeast of the study area. Possibly this event resulted a basin-margin striking parallel to the Tornquist Zone
- A new episode of uplift probably took place east of the study area in the Late Miocene - Early Pliocene, resulting in change from southward to westward progradation across the Ringkøbing-Fyn High. It appears that this event may have resulted in a basin configuration very similar to the present-day North Sea.

The Tornquist Zone and the Mid North Sea High may have been among the most important structural elements during the Cenozoic era in relation to the history of vetical motions in the study area. The western margin of the North Sea Basin was probably located along the Central Trough in Middle - Late Eocene, and possibly the Mid North Sea High constituted a prominant high even in Pliocene times. To the north and east the location of the basin-margin may have been controlled by movements along the Tornquist Zone as indicated by the reflection terminations. Possibly the two latest uplift events were focused along the Tornquist Zone (Fig. 9), as it is a fundamental structural lineation representing the southwestern margin of the Fennoscandian Precambrian basement platform, and characterised by complex, often rejuvenated faulting and frequently by tectonic inversion (Pegrum, 1984).

Acknowledgement

The study was financially supported by the Statoil-Group, Denmark (Statoil Efterforskning og Produktion A/S, BHP Petroleum (Denmark) Inc., TOTAL Marine Denmark, DENERCO K/S, LD Energi A/S, EAC Energi A/S, and Dansk Olie- og Gasproduktion A/S). Prof. Jan Inge Faleide read the manuscript.

References

Bjørlykke, K. (1989). Sedimentology and petroleum geology. Springer-Verlag Berlin,

Jordt, H., (in prep); Seismic documentation of the Cenozoic sequence stratigraphy in the eastern North Sea (Cenos).

Michelsen, O., M. Danielsen, C. Heilmann-Clausen, H. Jordt, G. V. Laursen and E. Thomsen. (in prep.). Cenozoic sequence stratigraphy in the eastern North Sea, pp. 70 + 26 figs + 2 tables

Mitchum, R. M., P. R. Vail and S. Thompson. (1977). Seismic stratigraphy and global changes of sea level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis. In: C. E. Payton (ed.): Seismic Stratigraphy - applications to hydrocarbon exploration, AAPG, pp. 53-62

Pegrum, R. M. (1984). The extension of the Tornquist Zone in the Norwegian North Sea. Norsk Geologisk Tidsskrift. 64: pp. 39-68.

Surlyk, F., N. Noe-Nygaard and G. Dam. (1993). High and low resolution sequence stratigraphy in lithological prediction - examples from the Mesozoic around the North Atlantic. In: J. R. Parker (ed.): Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, The Geological Society, pp. 199-214

Vail, P. R. (1987). Seismic stratigraphic interpretation using sequence statigraphy. In: A. W. Bally (ed.): Atlas of seismic stratigraphy, The American Association of Petroleum Geologist, pp. 1-10

Ziegler, P. A. (1982). Geological atlas of Western and Central Europe. Elsevier.

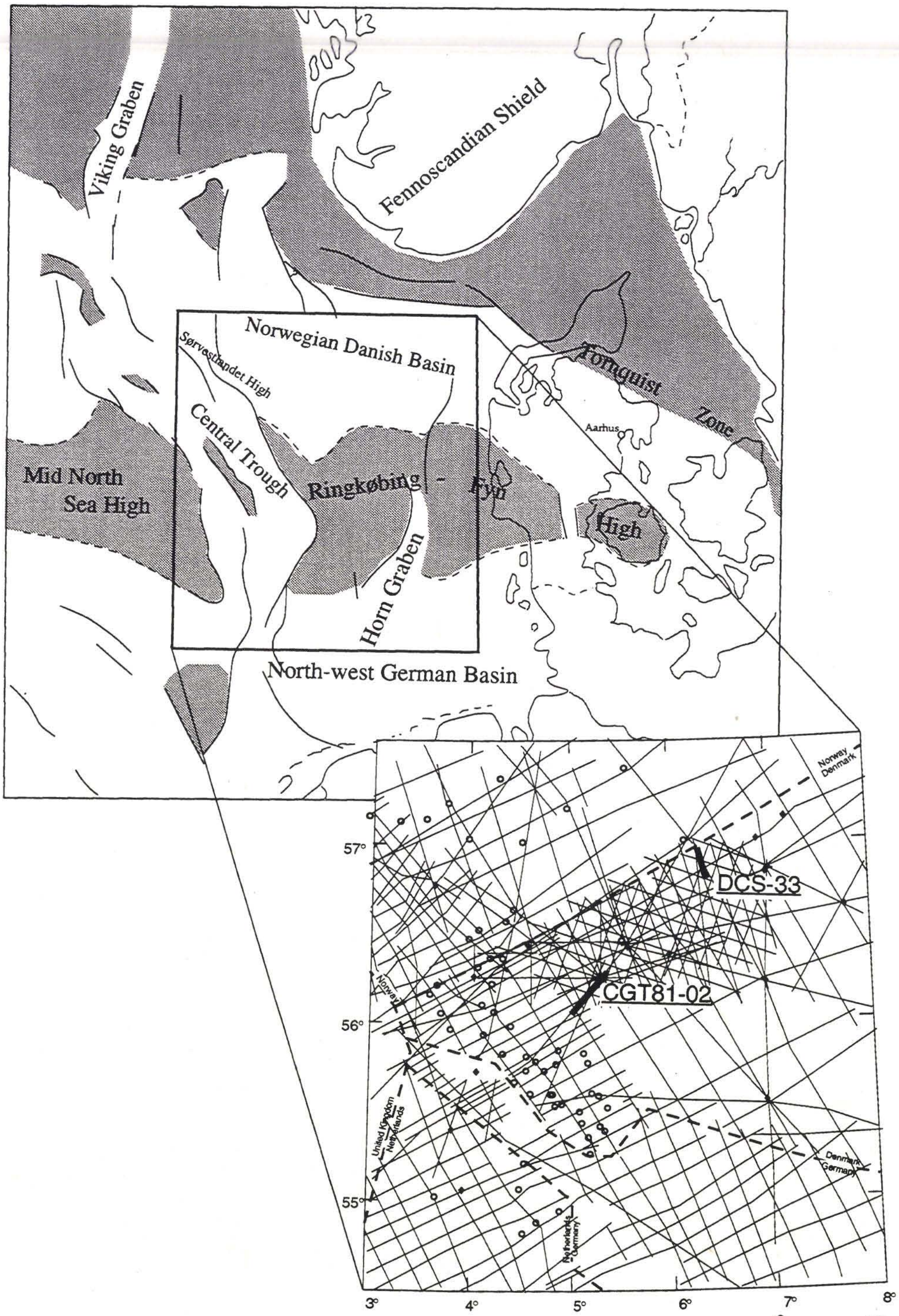


Fig. 1 Regional map showing the main pre-Cenozoic strutural elements in the North Sea and the location of the study area. Platform areas and highs are shaded. The location map shows the seismic database and the wells used in the Cenos study. Bold lines indicate locations of the seismic examples in Figs 2 and 3.

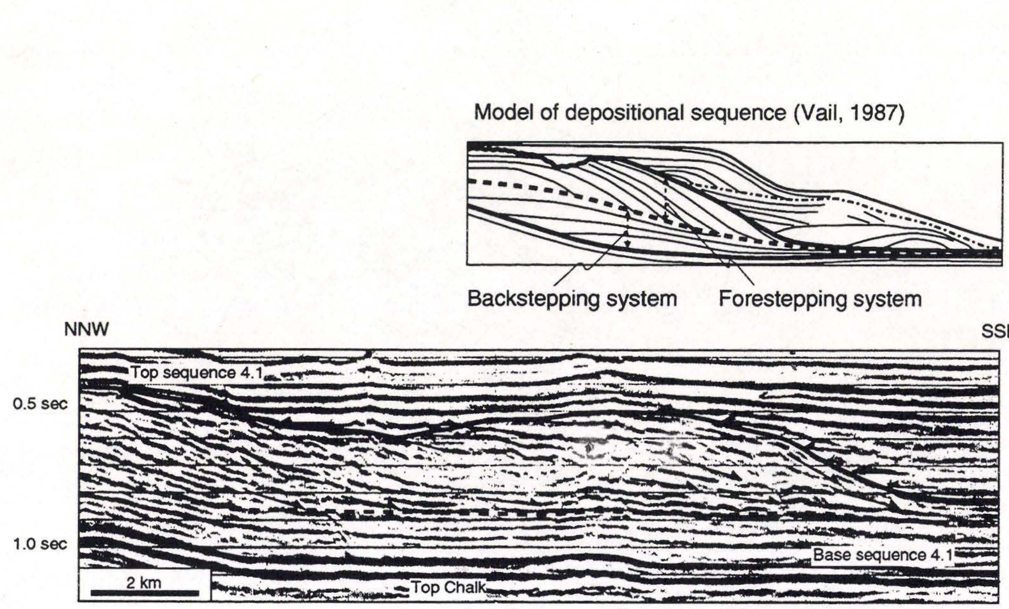


Fig. 2 Sequence 4.1, Lower Rupelian, shown on the seismic section DCS-33. The location of the profile is indicated in Fig. 1.

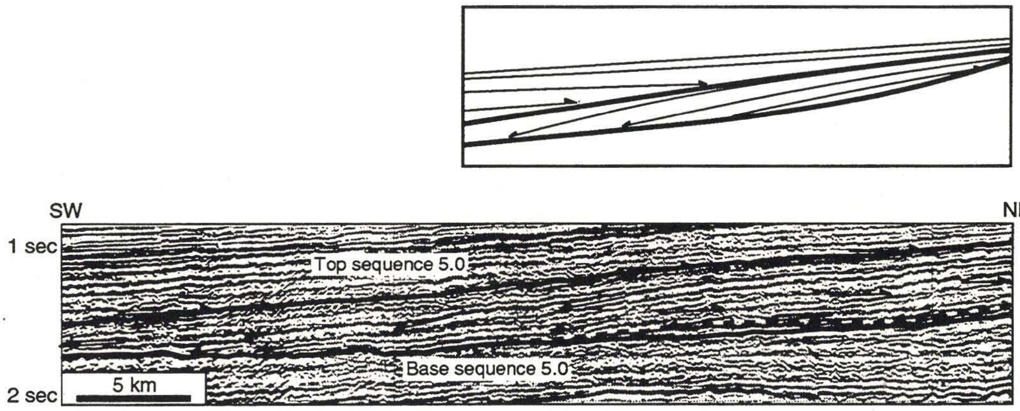


Fig. 3 Sequence 5.0, uppermost Oligocene- Lower Miocene, shown on the seismic section CGT81-02. The location of the profile is indicated in Fig. 1.

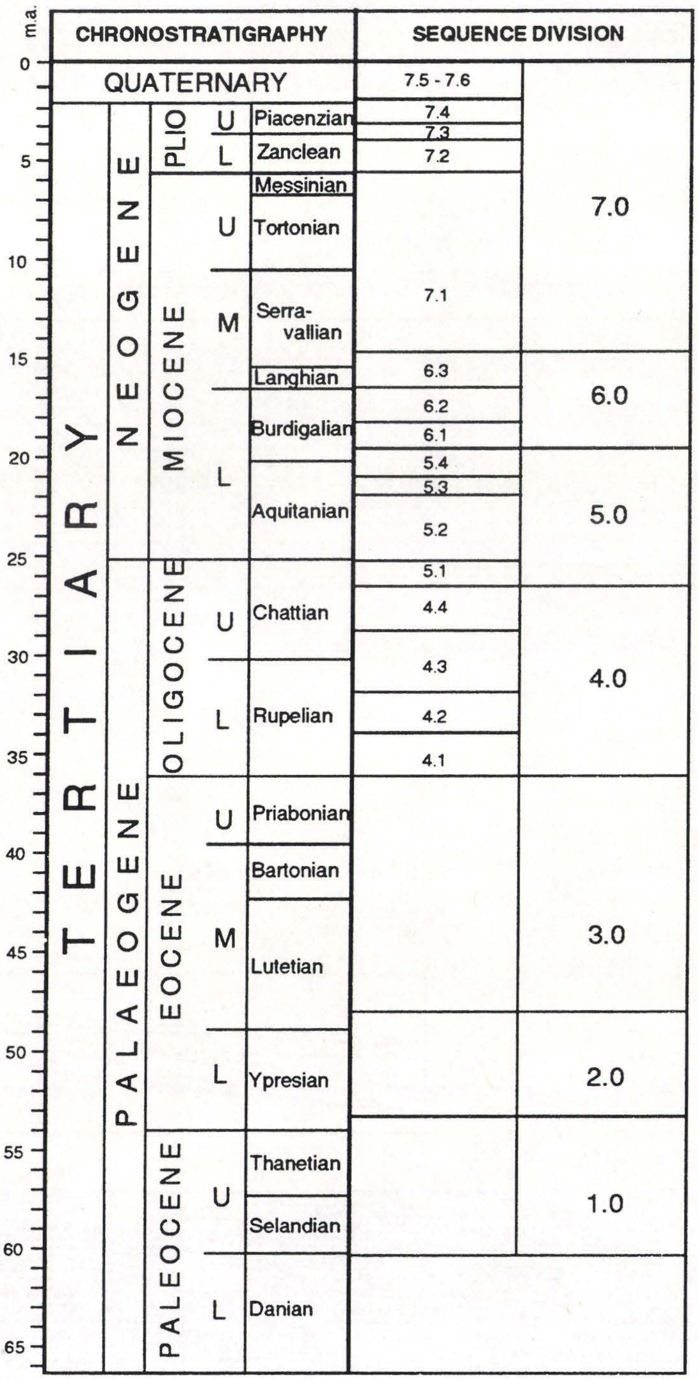


Fig. 4 Chronostratigraphic correlation of all the sequences mapped in the Cenos study. Isopach and reflection termination maps are shown for the sequences 1.0 - 7.0 in Figs 5-8.

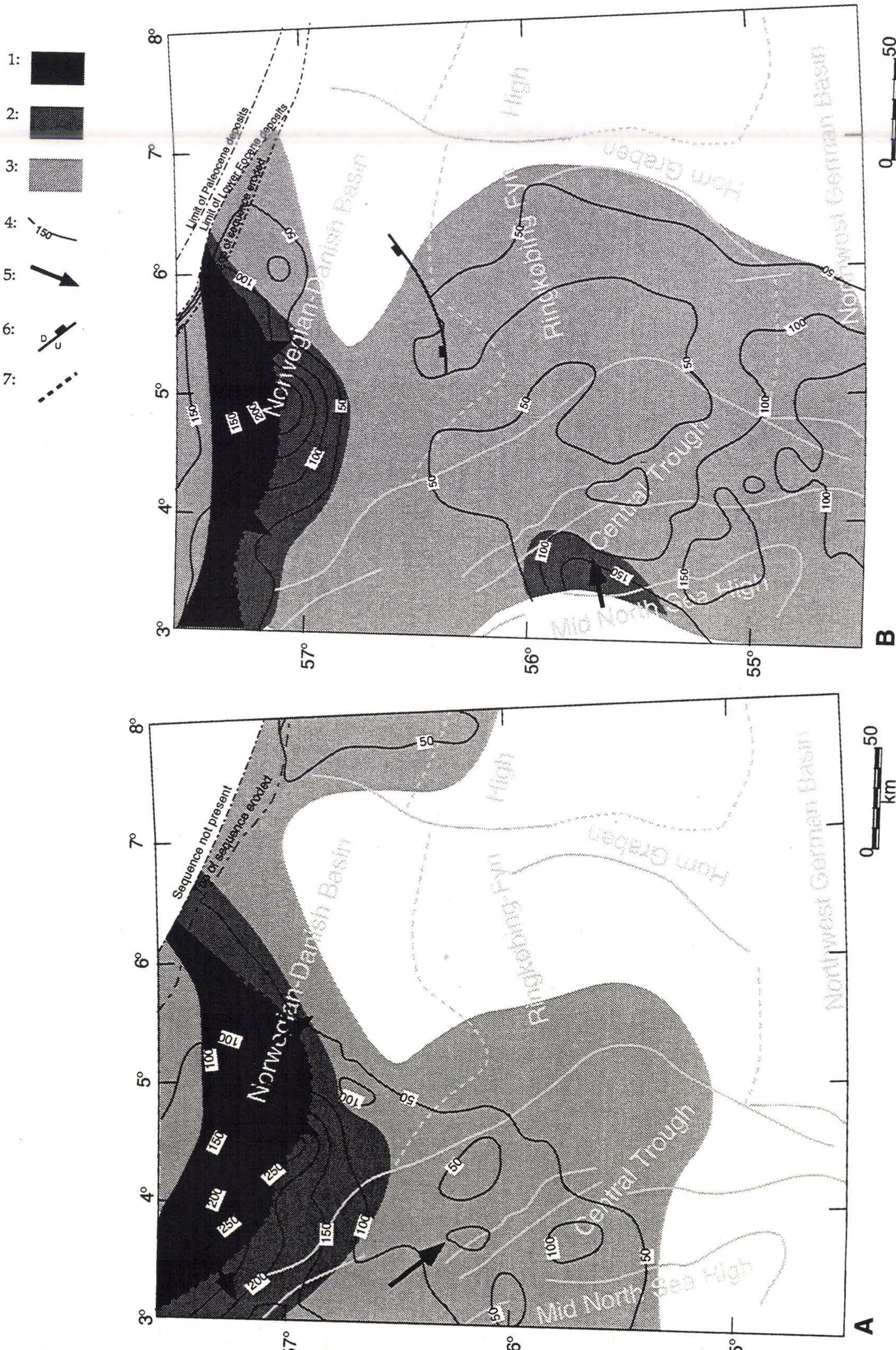


Fig. 5 Isopach and reflection termination maps of (A) Sequence 1.0, Upper Paleocene, and (B) Sequence 2.0, Lower Eocene. 1: area with observed onlap; 2: area with observed downlap; 3: area with reflections parallel to lower sequence boundary; 4: contour line in ms, contour interval 50 ms; 5: direction of progradation; 6: fault trace at lower boundary; 7: observed boundary between areas of onlap and downlap.

Fig. 6 Isopach and reflection termination maps of (A) Sequence 3.0, Middle-Upper Eocene, and (B) Sequence 4.0, Oligocene. 1: area with observed onlap; 2: area with observed downlap; 3: contour line in ms, contour interval 50 ms; 4: direction of progradation; 5: fault trace at lower boundary.

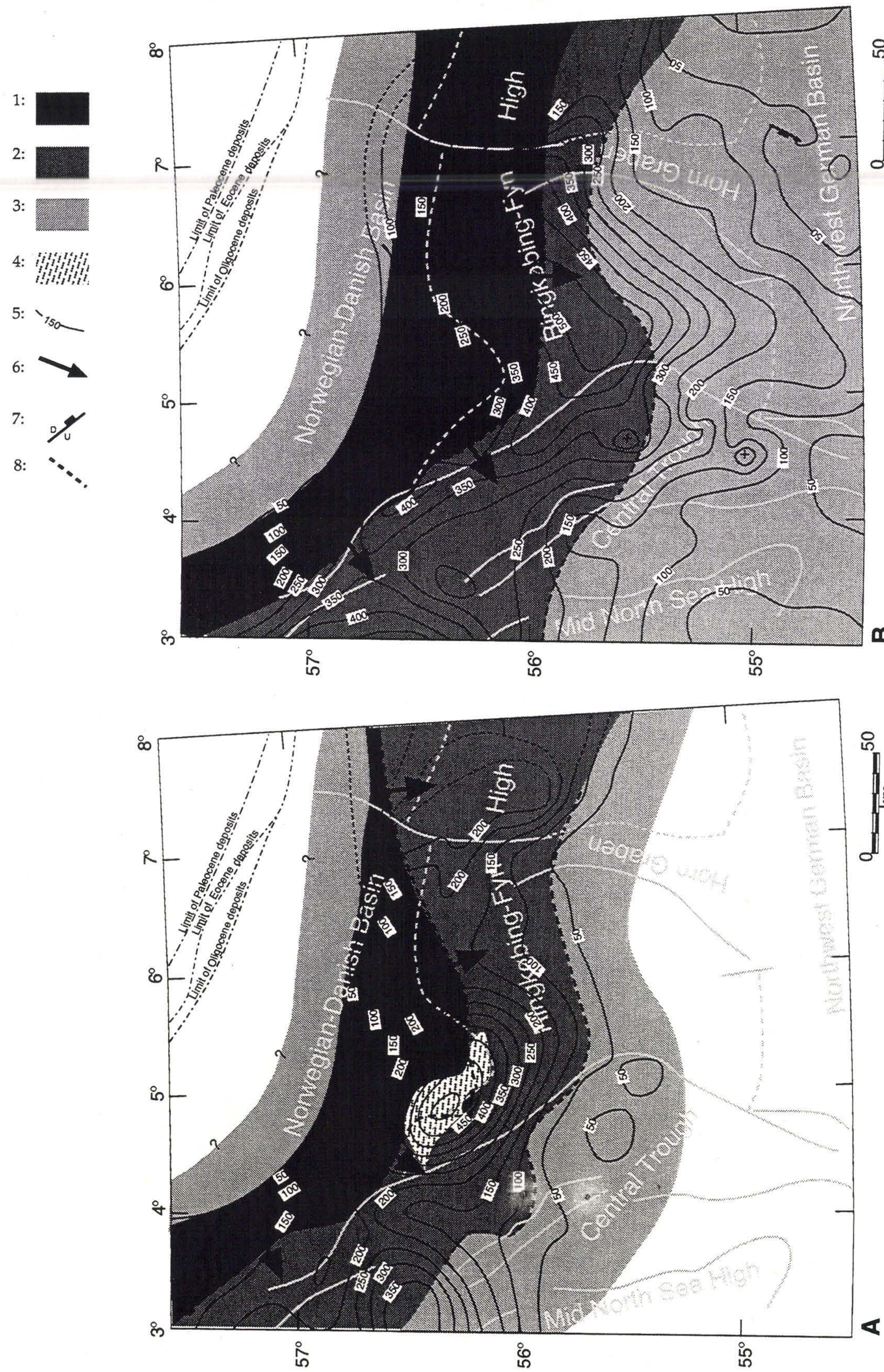


Fig. 7 Isopach and reflection termination maps of (A) Sequence 5.0, Lower-Middle Miocene and (B) Sequence 6.0, upper Lower- lower Middle Miocene. 1: area with observed onlap; 2: area with observed downlap; 3: area with reflections parallel to lower sequence boundary; 4: mounded seimic unit; 5: contour line in ms, contour interval 50 ms; 6: direction of progradation; 7: fault trace at lower boundary; 8: observed boundary between areas of onlap, downlap and parallel reflections.

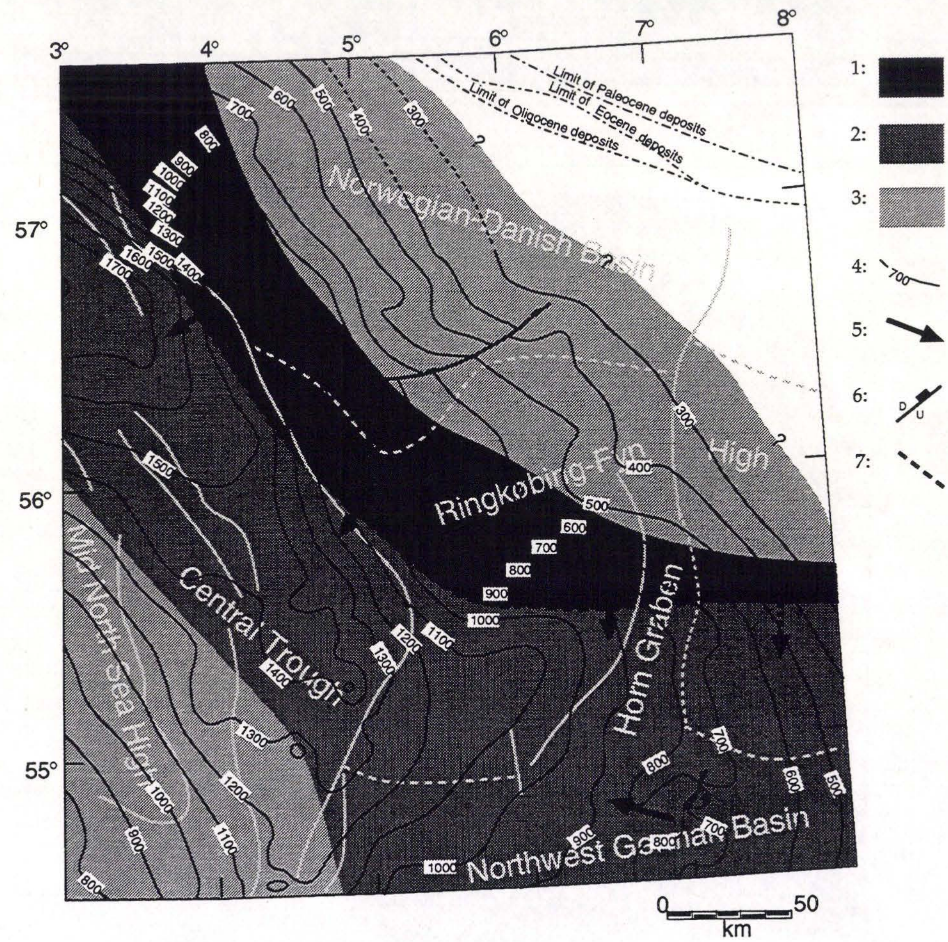


Fig. 8 Isopach and reflection termination map of Sequence 7.0, upper Middle Miocene - Quarternay. 1: area with observed onlap; 2: area with observed downlap; 3: area with reflections parallel to lower sequence boundary; 4: contour line in ms, contour interval 100 ms; 5: direction of progradation; 6: fault trace at lower boundary; 7: observed boundary between areas of onlap, downlap and parallel reflections.

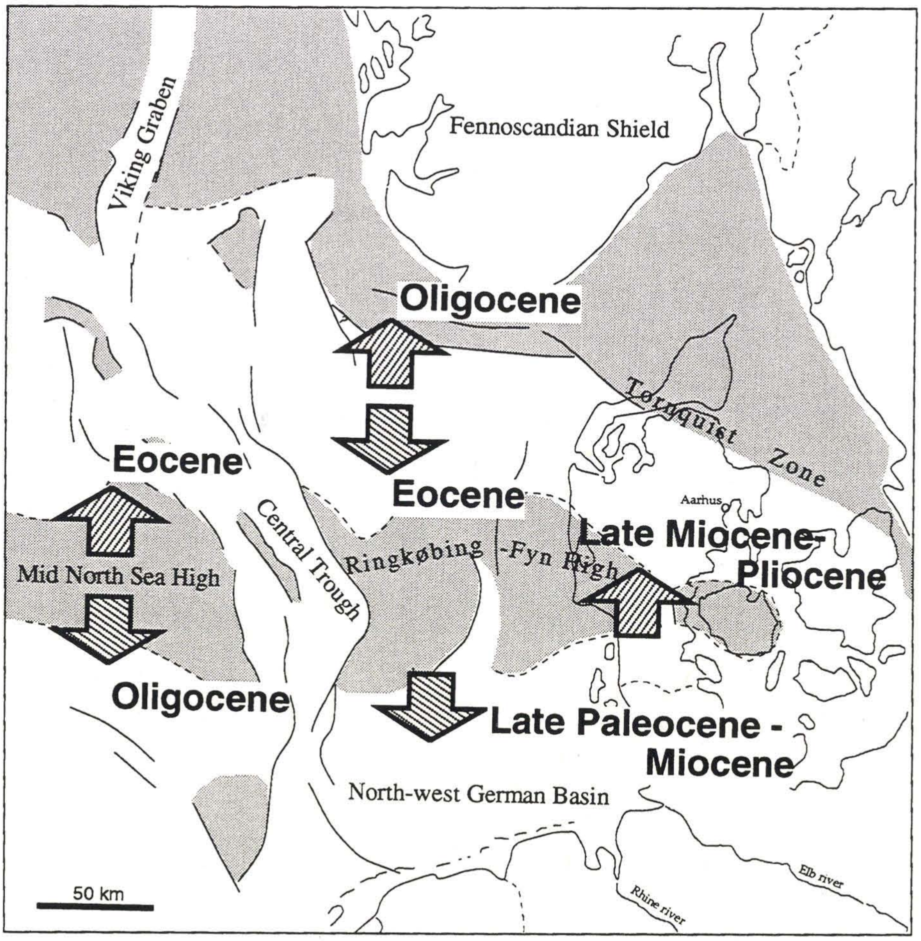


Fig. 9 Regional map indicating timing and location of uplift/subsidence during the Tertiary. Arrows indicate direction of relative vertical movement.

Generation of accommodation space around the D-1 fault during the Oligocene , Danish North Sea

Henrik Madsen and Ole Rønø Clausen

Abstract

Implications of a sequence stratigraphic study of the Oligocene sediments in the Norwegian-Danish Basin around the D-1 well are presented. The study is based on seismic mapping, log interpretations and detailed dating. This paper focuses on the evolution of the accommodation space along and across the D-1 fault since the fault generated deviations in the available accommodation space and has a significant influence on the depositional geometry of the sequences. The results show that displacement across the D-1 is fairly constant along strike during deposition of the older Oligocene sequences. This is in contrast to the youngest Oligocene sequence which has a higher displacement rate and thus significant variations along strike. This emphasises, that the understanding of the structural evolution of local faults in a basin dominated by clastic sediment infill as the Tertiary North Sea has to be as detailed as the sequence stratigraphy, because the fault may have had a significant influence on the depositional geometry, and hence the complete sequence stratigraphic interpretation.

Introduction

The general objective of this sequence stratigraphic study was to map the Oligocene succession in order to create a reliable stratigraphic framework for a future modelling of the parametres controlling the Oligocene sequence development in the Norwegian-Danish Basin (fig. 1). The present paper describes the sequence development controlled by the D-1 fault, which throw affect the entire Tertiary succession. The D-1 fault is a NNE-SSW striking listric fault dipping to the north and detaching along a Zechstein salt surface (Petersen et al., 1992, 1993, Clausen et al., 1993). Displacement of the D-1 fault creates deviations in the subsidence pattern by generating a local accommodation space in the hangingwall of the D-1 fault. Control on the displacement history of the D-1 fault is of great importance as an input to the future sequence stratigraphic modelling of the evolution in the Norwegian Danish Basin, since generation of the accommodation space has influence on the sequence geometry. A detailed seismic mapping of sequences is performed to describe variation in sequence geometry. Decompaction and backstripping of selected profiles are carried out to describe the displacement history of the D-1 fault.

Materials

The PH-n85, DCS and RDT81 surveys were used to map the sequences. The seismic interpretation was tied to the L-1, Inez-1, Ibenholt-1 and F-1 wells (fig. 2), enabling dating of the sequence boundaries (fig. 3). The dating in these wells is based on the coccolith zonation by Erik Thomsen (pers. com.), which gives a very detailed chronostratigraphic subdivision of the Oligocene sediments. Biostratigraphic dating in the D-1 well was avoided since the Oligocene deposits in this well are affected by the faulting.

Regional geology

During the late Palaeozoic and Mesozoic, the North Sea region (fig. 1), was dominated by two east-west trending basins, the Northern Permian Basin (including the Norwegian-

Danish Basin) and the Southern Permian Basin, separated by the Ringkøbing-Fyn High and the Mid North Sea High trend. This trend was cut by the north-south oriented Central Trough and the Horn Graben.
During the Cenozoic time, the North Sea region constituted a large epicontinental basin with a north-south axis above the older Central Trough structures (Nielsen et al., 1986). The Cenozoic deposits in the central part of the North Sea Basin reach a thickness of more than 3000 m, representing most of the erathem. The Upper Palaeocene and Eocene deposits comprise clays, deposited in a distal position. The sediment transport seems to have been from the north and the west. The depocentres of the Upper Palaeocene and lower Eocene are located north of the Danish sector, and the depocenter of the Middle to Upper Eocene section is found at the western border of the Danish Central Trough. The Oligocene and Miocene sediments consist of clay with an upward increasing amount of silt and mica, and sand bodies are present in the eastern part of the study area. The sediment transport was mainly from the north and northeast. The depocentres of the Oligocene to Middle Miocene sequences are located in the Norwegian-Danish Basin and on the Ringkøbing-Fyn High, and the depocenter of the Middle to Upper Miocene deposits in the Norwegian Central Trough (Michelsen et al., in press).
The D-1 fault is located at the northern flank of the Ringkøbing-Fyn High (fig. 2), in the distal part of the Oligocene depocenter. The base of the Zechstein salt is here dipping to the north, whereas the Upper Cretaceous - Lower Palaeocene Chalk Group has a westward dipping surface. The fault is located above a Zechstein salt structure, which was initiated during the Triassic and was an active diapir during the Tertiary. Salt migration from the hangingwall to the footwall controlled the shape of the fault and the displacement along the fault (Petersen et al., 1992, 1993, Clausen et al., 1993).

Sequence stratigraphy

The sequence stratigraphic subdivision

The Cenozoic succession in the southeastern North Sea has recently been subdivided into 7 major sequence stratigraphic units, which are further subdivided into sequences. In total, twenty-one sequences were identified in the Danish offshore area (Michelsen et al., in press.). The major sequence stratigraphic unit 4 comprises four sequences, 4.1 to 4.4, and represent the main part of the Oligocene deposits.
Additional sequence stratigraphic studies of unit 4, carried out by the present authors, have indicated that eight seismic sequences, O.1 to O.8, can be identified whith in the depocenter (fig. 3). The studies are based on the principle of Vail et al. (1977), and the eight sequences are defined as unconformity bounded units, which have a chronostratigraphic significans. Basinwards shift of onlaps occurs at the lower seqence boundarie. The uppermost sequence, O.8, is furthermore characterised by distinct erosional features at the lower and upper boundaries. These features occur approximately 2-3 km west to northwest of the D-1 fault, but there is not recognised erosive feature at the crest of the footwall.

Location of depocentres

Variation in thicknesses of the sequences are illustrated by the seismic section DCS 27 and DCS 31 (figs 4a and 4b). The two sections crosses the central and eastern marginal parts of the fault, respectively (fig. 3).
Sequences O.1-O.5 are represented by distal deposits in the area around the D-1 fault, and the corresponding sequence depocentres are located east-northeast of the fault. The thick-

ness of each of these sequences is very small, and the five sequences are, therefore, treated as one stratigraphic unit in the area close to the fault.

The depocentres of sequences O.6, O.7, and O.8 migrate successively westwards into the area north of the D-1 fault. The depocenter of sequence O.8 is located just northwest of the seismic section DCS 27, which explain the larger thickness of sequence O.8, seen on this section compared to that seen on the seismic section DCS 31 (see figs 4a and 4b).

Each of the sequences O.1 to O.7 shows a minor individual thickness variation across the fault. A pronounced and consistent change in thicknesses along the fault is evident for sequence O.8 (figs 4a and 4b). On the hangingwall, sequence O.8 shows a reflection pattern typical of a normal growth fault with maximum subsidence at the fault (fig. 4b). 1-2 km in front of the fault zone, there is a small synform, indicating that salt has migrated from the hangingwall into the fault plane. On the seismic section DCS 27, the reflectors suggest the presence of a roll-over anticline on the hangingwall, resulting from salt migration into a small dome under the D-1 fault plane, which also amplifies the footwall crest.

Since the goal of the present paper is to analyse the difference in rate of displacements at the central and the marginal parts of the fault, we have decided to treat sequences O.1 - O.7 as one group and sequence O.8 as another group. By doing so, the differences in displacement between the two parts of the fault and the change in displacement rates during the main part of Oligocene are emphasised.

Fault displacement

Methods

Estimates of the displacement rates of the D-1 fault are based on rather simple geometric considerations assuming that the top of a sequence was continuous across the fault during deposition. The thickness variations across the fault, therefore, reflect the displacement which took place during deposition of the sequence. The depth and isopach values at several location on the hangingwall and the footwall were measured in order to construct backstripped and decompacted sections. The reference point for the depth during the backstripping is located at the sea floor assuming that the palaeo-depth of the Oligocene North Sea Basin was constant in the area around the D-1 fault. The depth conversion is based on a simple depth-dependency velocity, based on a simple linear regression through the Tertiary succession. The decompaction is based on the algorithm given by Allen and Allen (1990). This algorithm is a mathematical attempt of sliding the sedimentary layer up along an "exponential porosity - depth" curve, the solution to which is found by forward numerical iteration. The principle is based on Sclater and Christie (1980). Values for the sedimentary composition taking into account surface porosity and porosity/depth ratios are from Sørensen (1986).

The backstripped and decompacted sequences are then related to geological time so that the displacement during deposition of each sequence can be calculated. The displacement rate (v) is determined by the following relation:

$$v = \frac{\Delta Z_{decom}}{Time}$$

where ΔZ_{decom} is the decompacted thickness after backstripping to the relevant horizon and *Time* is the geological time interval (fig. 3) for deposition of the decompacted sequence. The unit for is thus metres/1000 years.

Displacement variations along the D-1 fault

The seismic sections DCS 27 and DCS 31 have been depth converted using an interval velocity of approximate 1900 m/sec for the sediments on top of sequence O.8 and approximate 1950 m/sec for sequences O.1 to O.8. This relative low velocity gradient is partly derived from the sonic log of wells in the study area (L-1, Inez-1, Ibenholt-1 and F-1) and partly from the sedimentary composition. The gamma ray logs of the wells indicate, that the older Oligocene sediments are dominated by fine-grained sediments but there is an upward increase in the relative amount of coarse-grained clastic sediments.

The depth conversion and the subsequent backstripping/decompaction was performed at 10 pseudo-wells along each seismic section. The decompacted sections show the Oligocene evolution of the D-1 fault across the centre of the fault (fig. 5a) and across the more eastern marginal section (fig. 5b). The decompacted sections emphasize that the compaction of the underlying sequences constitutes a major part of the differential subsidence across the fault as argued by Petersen et al. (1993).

The true decompacted displacement across the D-1 fault on the seismic sections DCS 27 and DCS 31, during the periods represented by sequences O.1 - O.7 and O.8, is shown in figure 6. The uncompacted thicknesses in the footwall and in the hangingwall indicates the size of the displacement at the time when the upper sequence boundary was horizontal. The displacement was smaller at section DCS 31, than at DCS 27, during both periods examined here, and the difference is more pronounced during the deposition of sequence O.8.

Figure 7 shows the fraction of the accommodation space generated by displacement across the D-1 fault in relation to the total accommodation space generated during the Oligocene. It is evident that the D-1 fault has large influence on the accommodation space at the centre of the fault.

The dating of the sequence boundaries (fig. 3) gives the following ages: base O.1 - 36 Ma; top O.7 - 28.8 Ma and top O.8 - 26.5 Ma. These values are used to calculate the displacement rate across the fault on the given sections, and the values are shown in figrue 8. It shows that the displacement rates were higher at the centre of the fault during both periods, represented by O.1 - O.7 and O.8, and the displacement rate was highest during deposition of O.8.

Discussion

The total displacement and therefore also displacement rate are minimum values since the generated accommodation space is assumed to be filled continuously during deposition of the actual sequence. However, if erosion of the sequence in the footwall took place the displacement and thus displacement rate achieved would be overestimated. In the study area there is no seismic evidence indicating that the area was suffering from sediment starvation and the assumption of continuous sediment infill in the fault-generated accommodation space seems to be valid. Furthermore, if the sedimentary input direction (north to northeast) is taken into to account, the presence of sequences O.1-O.7 and O.8 on both the footwall and the hangingwall of the D-1 fault indicates that there was enough clastic material available for keeping pace with the fault-controlled generation of accommodation space. The erosion on the footwall, described earlier, does not influence the estimates of displacement since the thicknesses measured are at locations where there is no seismic indication of erosion.

This analysis does not take into account the compaction of the underlying sequences. This means that the displacement and displacement rate includes both the tectonic and compactional differential subsidence across the D-1 fault. To differentiate between these two,

causes of subsidence, would require a complex decompaction including the sediments in the footwall (Petersen et al., 1993), which is beyond the scope of this study.
The location of the depocentres north of the D-1 fault may have enhanced the movement of salt from the hangingwall into the footwall of the D-1 fault. This would have a major influence on the evolution of the D-1 fault since salt movement is the major cause for faulting along the D-1 fault (Petersen et al., 1992, 1993). However, the removal of salt from beneath the hangingwall would create local accommodation space, which with enough sediment available would enhance the removal of salt from the hangingwall to the footwall and so on. The location of the depocentres may thus be controlled by the salt removal, but the salt removal is also enhanced by the deposition in the hangingwall.

Conclusion

The preliminary results of this study shows that :

i: The fault-generated accommodation space at the D-1 fault varies systematically both in time and space. The major generation, of space, is at the centre of the fault where it constitutes up to 25 % of the available accommodation space in contrast to the more marginal sections where it constitutes less than 20%.

ii: The displacement rate varies only a little along the strike of the fault during the deposition of sequence O.1-O.7 whereas the displacement rate is significantly higher and has higher lateral variation during the deposition of O.8.

iii: The location of depocentres seems to be related to the displacement on the D-1 fault, since the depocentres are located at the hangingwall of the D-1 fault and occur contemporaneously with an acceleration in displacement rate.

iv: A detailed sequence stratigraphic mapping is valuable as a basis for a detailed geometrical analysis of faulting and displacement rates.

References

Allen, P. A. and Allen, J. R., 1990. Basin Analysis. Principles and Applications. Blackwell, Oxford. 451 pp.

Clausen, O. R., Petersen, K. and Korstgård, J. A., 1993. Analysis of the fault geometry of a Cenozoic salt related fault close to the D-1 well, Danish North Sea. In this volume.

Haq, B. U., Hardenbol, J. and Vail, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C. K., Posamentier, H., Roos, C. A. and Kendall, C. G. S. C. (ed.) Sea-Level Changes - An Integrated Approach. Society of Economic Paleontologists and Mineralogists, Special Publication, 42, 71-109.

Nielsen, O.B., Sørensen, S. Thiede, J. and Skarbø, O., 1986. Cenozoic Differential Subsidence of North Sea. The American Association of petroleum Geologists Bulletin, 70 (3), 276-298.

Michelsen, O., Danielsen, M., Heilmann-Clausen, C., Jordt, H., Laursen, G V. and Thomsen, E. (in press). Cenozoic sequence stratigraphy in the eastern North Sea. In de Graciansky, P.Ch., Jacquin, T. and Vail, P. R. (eds) Mesozoic-Cenozoic Sequence Stratigraphy of Western European Basins, 2. Society of Economic Paleontologists and Mineralogists (SEPM).

Petersen, K., Clausen, O. R. and Korstgård, J. A., 1992. Evolution of a salt-related listric growth fault near the D-1 well, block 5605, Danish North Sea: displacement history and salt kinematics. Journal of Structural Geology, 14, 565-577.

Petersen, K., Clausen, O. R. and Korstgård, J. A., 1993. Evolution of a Salt-Related Tertiary Growth Fault in the Danish North Sea. In Spencer, A M. (ed.). Generation, Accumulation and Production of Europe's Hydrocarbons III. Special Publication of the European Association of Petroleum Geoscientists No 3, pp. 69-78.

Sclater, J. G. and Christie, P. A. F., 1980. Continental stretching: an explanation of the post-Mid-Cretaceous subsidence of the Central North Sea Basin. Journal of Geophysical Research, 85, 3711-3739.

Sørensen, K., 1986. Rim syncline volume estimation and salt diapirism. Nature, 319, 23-27.

Vail, P. R., Mitchum, K. G., Jr., Todd, R. J., Widmier, J. M., Thompson III, S., Sangree, J. B., Bubb, J. N. and Hatlelid, W. G., 1977. Seismic stratigraphy and global changes of sea level. In: Payton, C. E. (ed.), Seismic Stratigraphy: Applications to Hydrocarbon Exploration, American Association of Petroleum Geologists Memoir, 26, 49-212.

Ziegler, P. A., 1982. Geological atlas of Central and Northern Europe. Elsevier, Amsterdam. 130 pp.

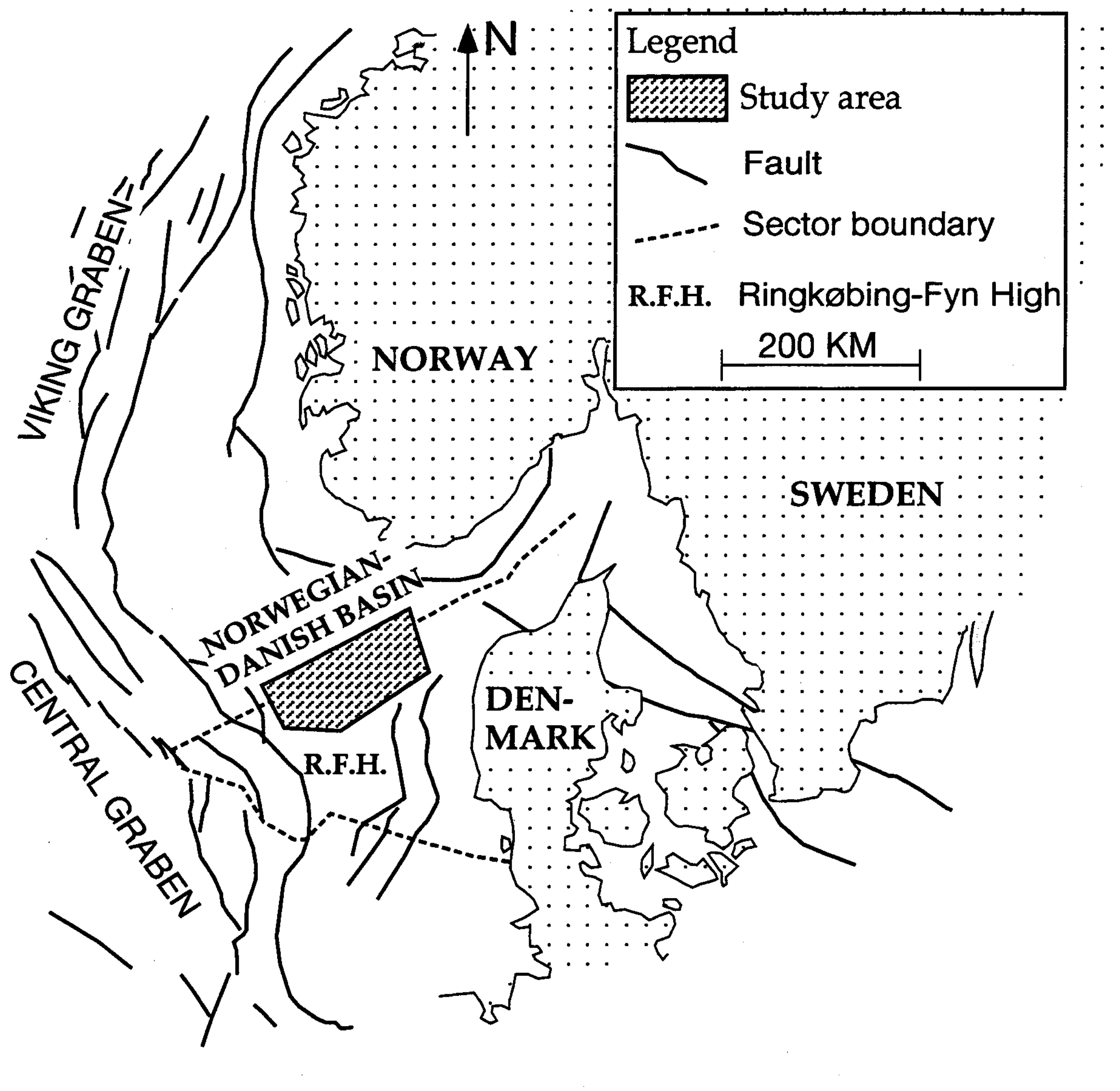


Fig. 1 Tectonic framework and location of the study area (after Ziegler 1982).

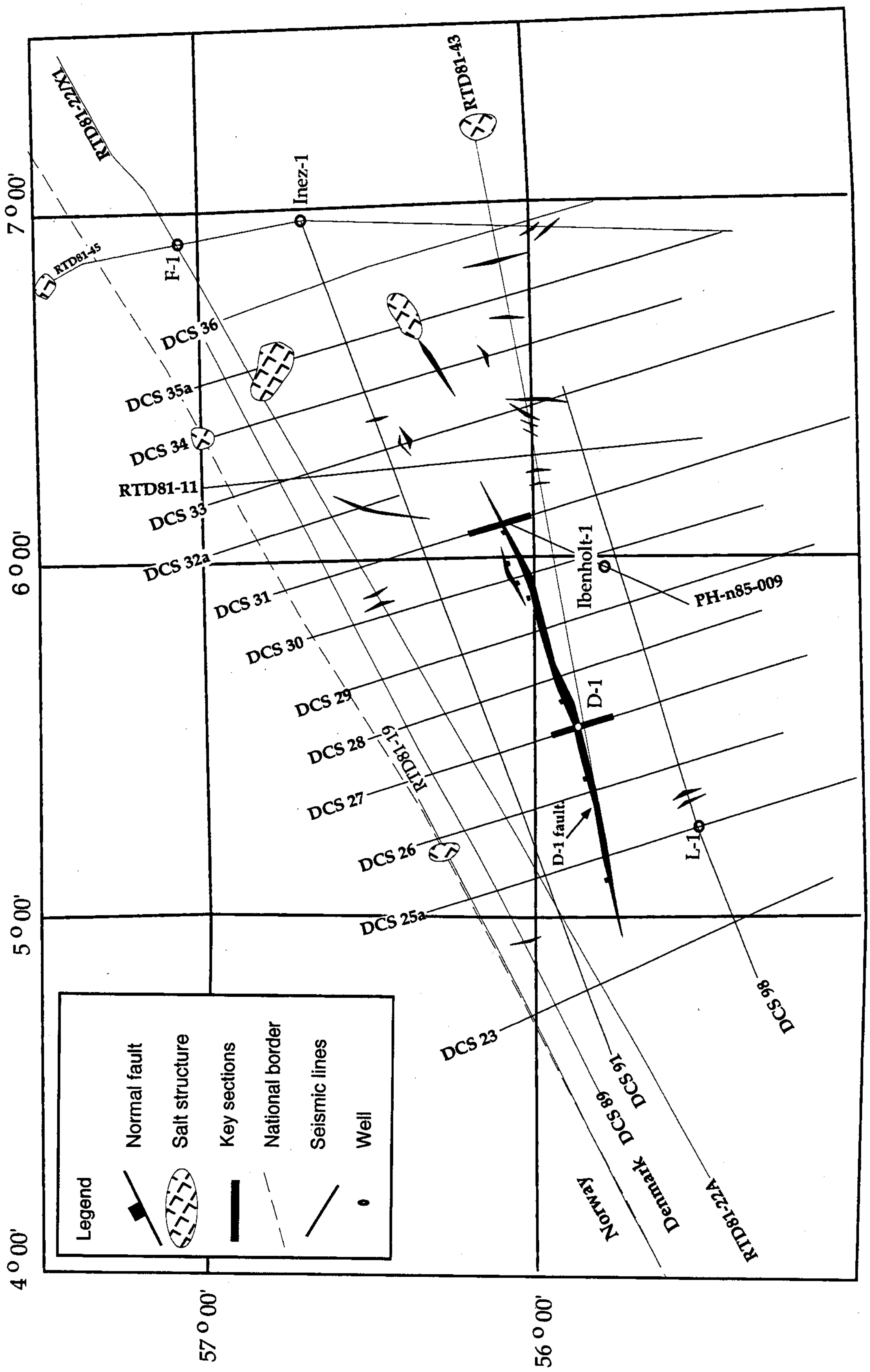


Fig. 2 Location of the seismic sections and the wells used in this study. The key sections DCS 27 and DCS 31 are emphasised by a bold line.

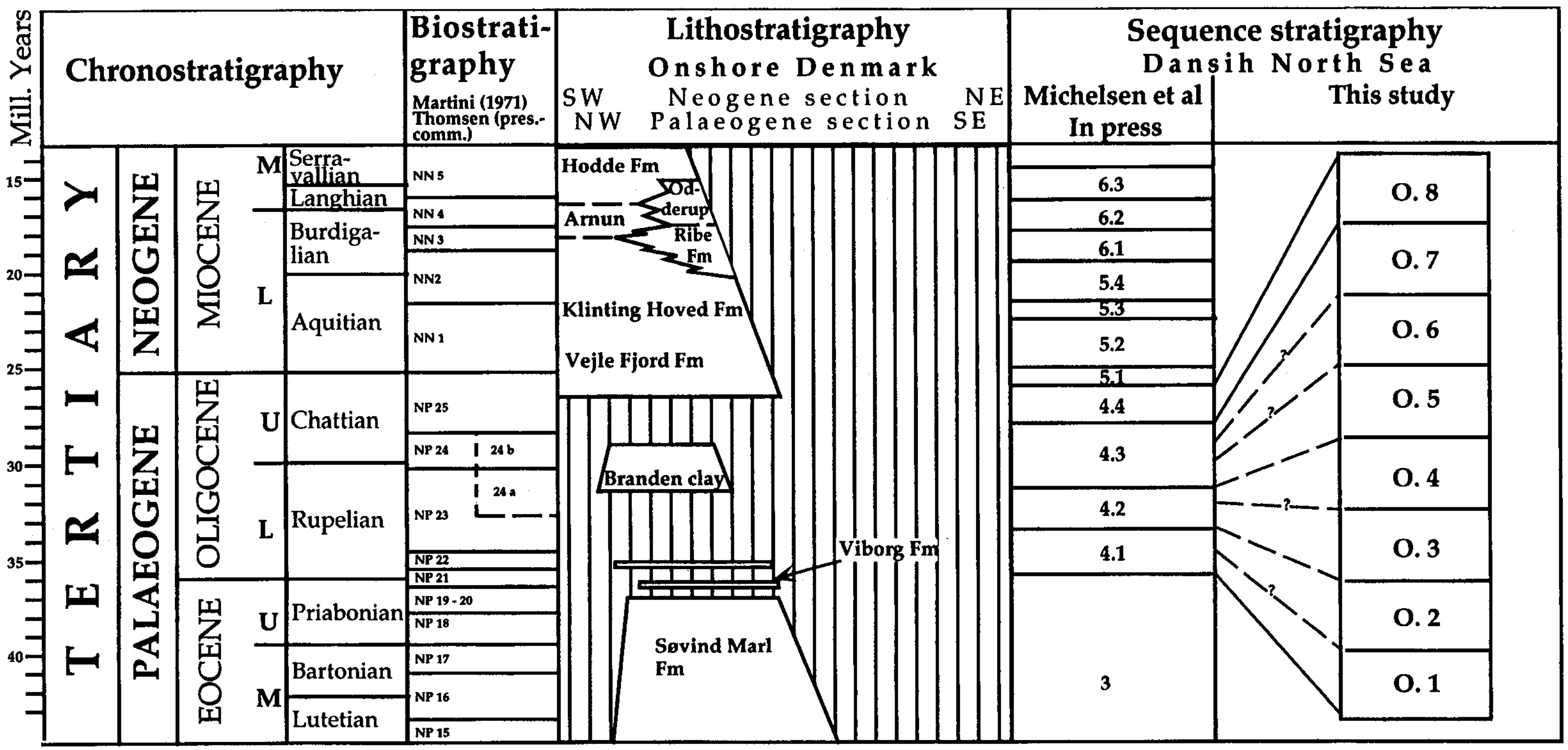


Fig. 3 The interpreted sequence stratigraphic subdivision related to the chronostratigraphy and to the Tertiary lithostratigraphy in the North Sea and the Danish onshore area (from Michelsen et al., 1993).

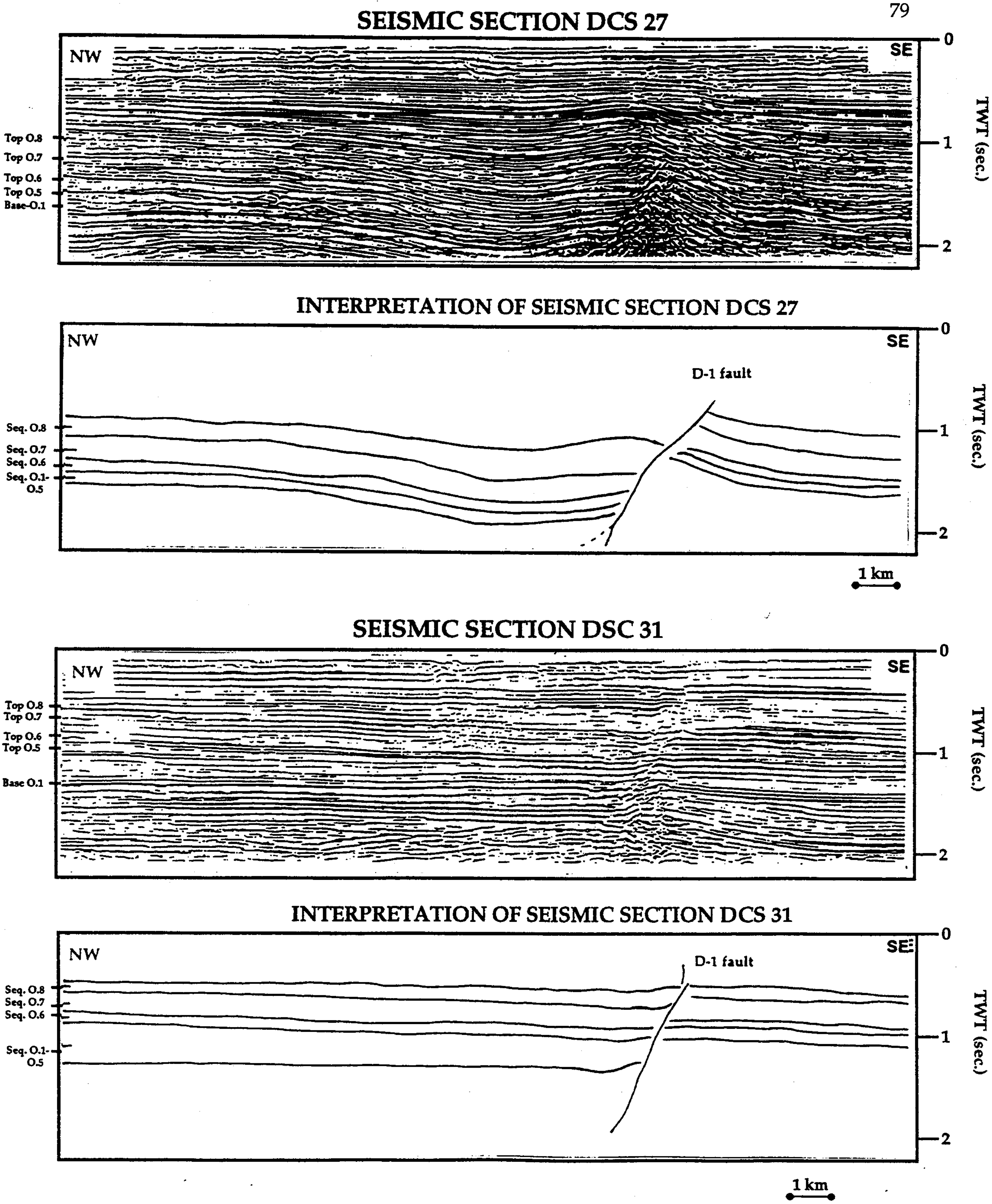


Fig. 4 Seismic sections DCS 27 (a) and DCS 31 (b) and corresponding line drawing of the interpreted sequence boundaries. For location of the sections see figure 2.

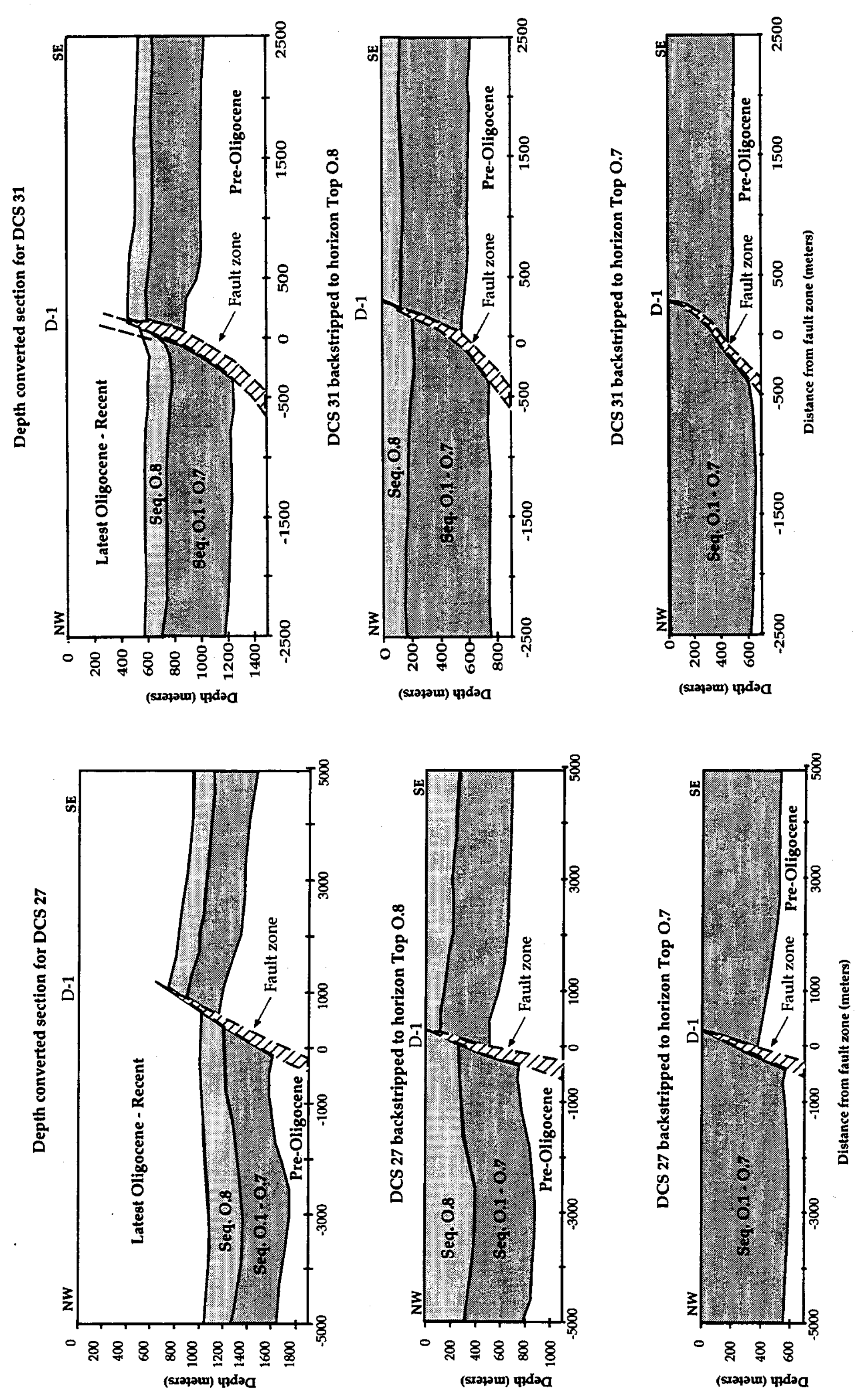
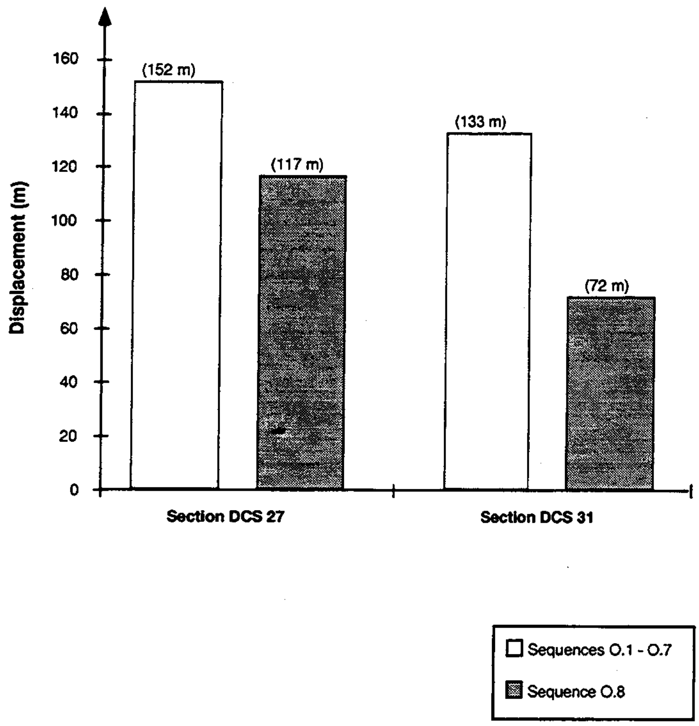


Fig. 5 Decompaction and reconstruction of Oligocene sequences on the sections DCS 27 (a) and DCS 31 (b). The evolution of the accommodation space across the D-1 fault is clearly indicated. The fault is regarded as a fault zone and thus not represented as a single plane.



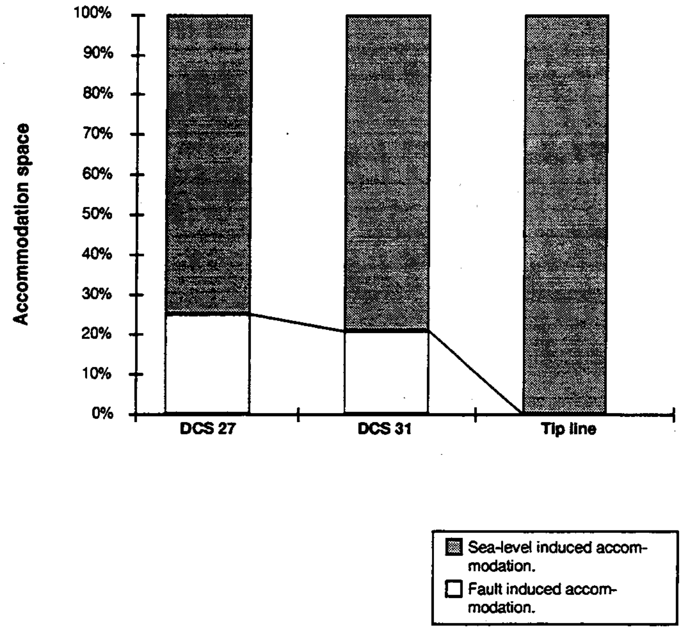


Fig. 6 Graph showing the uncompacted thickness difference (at two seismic sections) between the footwall and hangingwall (= displacement) across the D-1 fault at the time where the top of the sequence was continuos and nearly horizontal.

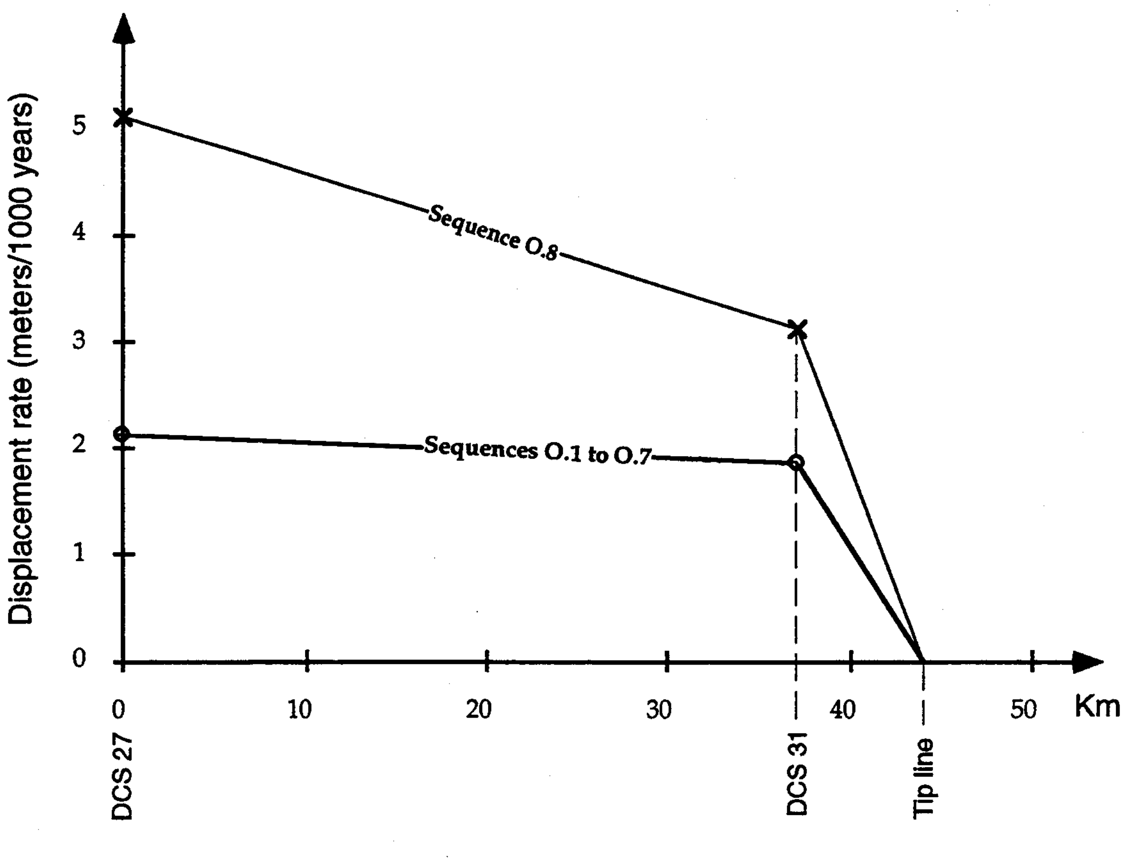


Fig. 7 The fault-generated accommodation space as a normalised fraction of the total accommodation space along strike of the D-1 fault (at relative locations along the fault).

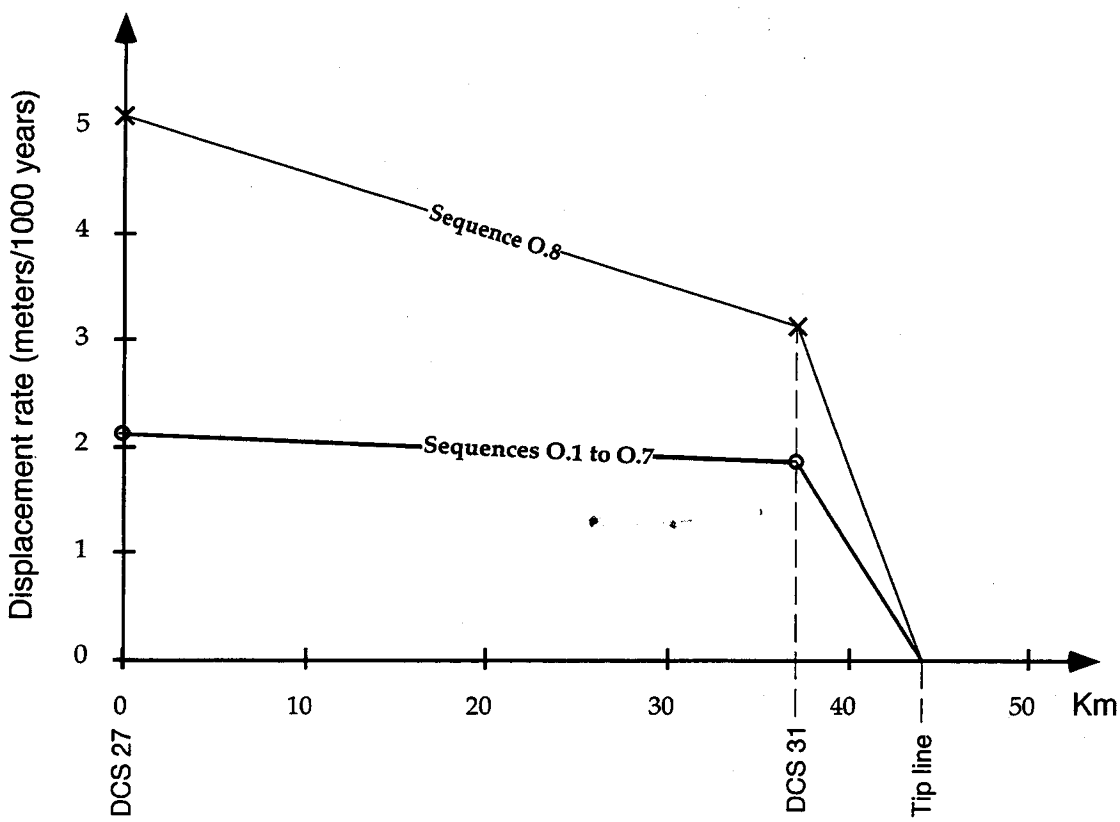


Fig. 8 The variations in displacement rate along the strike of the D-1 fault.

Analysis of the fault geometry of a Cenozoic salt-related fault close to the D-1 well, Danish North Sea

Ole Rønø Clausen, Kenneth Petersen and John A. Korstgård

Abstract

A normal detaching fault in the Norwegian-Danish Basin around the D-1 well (the D-1 fault) has been mapped using seismic sections. The fault has been analysed in detail by constructing backstripped-decompacted sections across the fault, contoured displacement diagrams along the fault, and vertical displacement maps. The result shows that the listric D-1 fault follows the displacement patterns for blind normal faults. Deviations from the ideal displacement pattern is suggested to be caused by salt-movements, which is the main driving mechanism for the faulting. Zechstein salt moves primarily from the hangingwall to the footwall and is superposed by later minor lateral flow beneath the footwall. Back-stripping of depth-converted and decompacted sections results in an estimation of the salt-surface and the shape of the fault through time. This procedure then enables a simple modelling of the hangingwall deformation using a Chevron model with hangingwall collapse along dipping surfaces. The modelling indicates that the fault follows the salt surface until the Middle Miocene after which the offset on the fault also may be accommodated along the Top Chalk surface.

Introduction

Structural hydrocarbon traps in a broad sense represent the habitat of the bulk of the already discovered petroleum reserves in the world. The cause for generation of the structural trap may vary from halokinesis, major faulting of the crust due to change in the regional horizontal stresses, differential compaction across former active faults and gravitationally introduced local changes in horizontal stresses. The latter involves not the faulting of the entire crust but only down to a dipping detachment surface of low viscosity material (most often undercompacted clays, or salt). The shape of the faults may vary from planar to listric the latter generating a roll-over anticline in the hangingwall sediments reflecting the shape of the fault plane (Crans and Mandl, 1980, Hamblin, 1965, Waltham, 1989, White et al., 1986). However, deformation of the volume of rock containing a fault (even a planar fault) will introduce a reverse drag on both the footwall and hangingwall of the fault (Barnett et al., 1987, Walsh and Watterson, 1987, Watterson, 1986) and the reverse drag may resemble the roll-over anticline. It is with respect to hydrocarbon prospectivity in the hangingwall roll-over anticlines of major importance to evaluate the generation of the anticline in time and space and compare it to the generation and migration of hydrocarbons. The fault investigated here is located in the Norwegian-Danish Basin (Fig. 1) is penetrated by the D-1 well, and will be called the D-1 fault hereafter. A number of different methods have been used to unravel the geological history of the D-1 fault. The methods and the results will be briefly described here with a focus on modelling of the hangingwall deformation through time.

Geological setting

The D-1 fault has a horizontal length of approximately 70 km, strikes ENE-WSW and down throws the Triassic to Late Tertiary sediments down to the NNW along a listric fault surface. The D-1 well (Fig. 2) has penetrated of Rotligendes volcanics, Zechstein evaporites (hereafter called Zechstein salt), Triassic, Jurassic, Cretaceous and Tertiary sediments. The Chalk Group (including the Late Cretaceous and Danian) constitutes a fairly thick layer compared to the Jurassic and Lower Cretaceous. However, it is striking that almost half of the total sedimentary succession consists of Tertiary sediments of Late Paleocene to Late

Miocene age. The pre-Oligocene Tertiary sediments are clay dominated whereas the Oligocene and younger sediments are dominated by cyclic input of clastic sediments of varying clay-sand ratio (Kristoffersen and Bang 1982). The Zechstein salt has periodically been mobile since Middle Triassic (Glennie, 1990, Ziegler, 1990).

Data

The mapping of the fault is based on the seismic surveys RTD-81, SP-82, DCS-81 and CGT-81 which cover the area in a dense grid and thus give control on the tie of horizons across the D-1 fault. The lithostratigraphic subdivision and dating for the pre-Tertiary sediments has been adopted from Nielsen and Japsen (1991) whereas the dating of the Tertiary horizons is taken from wells in the adjacent Central Trough area dated by Stouge (1988) and correlated to seismic section by Clausen (1991).

Fault analysis

The following horizons have been mapped and used in the fault analysis : Top pre-Zechstein (TPZ), Top Zechstein (TZ), Top Triassic (TTR), Base Upper Cretaceous (BUC), Top Chalk (TC), Intra Lower Miocene I (C1) Intra Lower Miocene 2 (C2) and Base Middle Miocene (C3). Fig. 3 shows the seismic appearance of the fault and the mapped horizons.

Displacement analysis

Displacement on a fault can be examined by analyzing the variations of throw along the fault plane and/or by analyzing the deformation introduced by a fault onto a given horizon.

The throw on a fault at given points tends to vary systematically with respect to the maximum throw at the fault center, fault width and distance from the fault center (Barnett et al., 1987, Walsh and Watterson, 1987, Watterson, 1986). One way to show the variations is a contoured displacement diagram where the throw values obtained from the seismic sections are projected onto a vertical plane parallel with fault strike (Fig. 4). The projected throw values are contoured and the contour pattern is a unique description of the throw variations along the fault plane. The ideal theoretical contour pattern is a full ellipse where the zero contour shows the location of the tip-line of the fault and the center of the contours shows the location of the fault center. Since the D-1 fault is a detaching listric fault the contours will be open downwards which however does not indicate that the fault continues downwards. The diagrams at C2-time, C3-time and present-day are shown in Fig. 5 and analyzed in detail in Petersen et al. (1992, 1993).

The depth maps (in TWT) of the Top Chalk Group and C2 (Fig. 6) show that the D-1 fault introduces systematic deviations from the regional trend of the horizons. The regional surface topography is interpreted across the deformed zone for each horizon and vertical displacement maps are constructed by subtracting the interpreted regional map from the depth map. The vertical displacement map thus shows the deformation of the hangingwall and the footwall introduced by the faulting without the disturbing effects of a palaeotopography or later differential basement subsidence (Fig. 7).

The displacement analysis shows that there are deviations from ideal displacements along the D-1 fault. This observation is interpreted to be a consequence of complex salt flow beneath the fault. The Zechstein salt, which became concentrated in a salt pillow during the Triassic, was reactivated during the Late Cretaceous (Petersen et al. 1992). The reconstructed salt-surface on the backstripped and decompacted sections (Fig. 8) indicate a flow of salt from the NNW to the SSE during the Late Cretaceous and the Tertiary controlling the displacement along the D-1 fault. The relative topographic low at the footwall of the

D-1 fault (east of the fault center) and the distorted contours on the contoured displacement diagrams indicates subsequent movements of salt from the ENE to the WSW beneath the footwall. The salt movements caused the very steep closure on the footwall at the center of the D-1 fault as indicated on both the depth maps and the vertical displacement maps.

Shape of the fault-plane

The shape of the fault plane is controlling the hangingwall geometry (Waltham, 1989, White et al., 1986). The variations of the fault plane geometry in time and space is examined by depth-converting, decompacting and backstripping the sections oriented at approximately 90° to the strike of the D-1 fault (Fig 8). During the backstripping the fault beneath the Zechstein salt has been regarded as inactive, and the regional topography of the basement is used as reference level (details in the backstripping and decompaction procedure are given in Petersen et al. (1993)). This procedure enables the construction of the salt surface and the fault geometry through time (Petersen et al. 1993). The salt movements inferred from this approach confirm the interpretations from the displacement analysis. The analysis also shows that the fault shape is both a consequence of compaction across the fault and of the location of the salt structure since the salt is regarded as non-compacting. In addition to the deformation of the horizons the upward movements of the salt have also affected the fault plane geometry.

The fault shape at different times obtained from the backstripping and decompaction have been used in a simple forward modelling of the hangingwall deformation. The modelling of the hangingwall deformation on a horizon uses a simple Chevron model with hangingwall collapse along inclined shear surfaces.

To minimize the influence of the salt movements beneath the hangingwall the effect of a given fault plane geometry is only examined onto the latest deposited horizon. This procedure implies that the geometry of the Top Chalk horizon is modelled using the geometry of the fault plane at C1 time, the geometry of the C1 horizon is modelled using the geometry of the fault plane at C2 time, etc. (Fig. 9).

The modelled geometries of the pre-C3 horizons approximate those obtained by backstripping the seismic sections when assuming a fault plane that detaches approximately along the top of the Zechstein salt structure (Fig. 9). However, using a fault detaching along the northern flank of the salt structure does not provide a geometry of the C3-horizon similar to the one obtained during the backstripping. A satisfactorily predicted geometry of the C3-horizon may instead be obtained by selecting a fault detachment along the present Top Chalk surface. The extension across the D-1 fault may thus be accommodated along two detachments, since it is impossible to exclude slip along the top of the Zechstein. The Late Paleocene and Eocene siliciclastic sediments deposited on the Top Chalk surface are dominated by clays, which in large areas are undercompacted. The shear strength of the clay may thus be reduced significantly. Furthermore, the dip of the Top Chalk surface is also to the NNW indicating that a generally northward movement along the Top Chalk surface is possible. The internal structures of the Late Paleocene-Eocene sediments in the hangingwall also show thinning close to the fault and thickening away from the fault associated with internal deformation of the sediments supporting a detachment along the Top Chalk surface (Petersen et al. 1993).

Conclusions

The geometrical analysis of the D-1 fault shows that
i. Although the fault differs fundamentally from the ideal blind normal fault of Watterson (1986) many of the geometrical relationships are similar giving good constraints on the lateral tie of detaching faults.

ii. Reactivation of a Zechstein salt pillow generated in the Triassic controlled the evolution of the D-1 fault geometry.

iii. Salt below the fault moved primarily from the hangingwall area into the footwall area, and secondarily laterally below the footwall generating a steep northern slope along which the D-1 fault detached during the period when the main offset took place.

iv. A combination of compaction and salt-induced deformation of the overburden changes the shape of the fault plane making the hangingwall deformation through time complex and enabling the possible generation of an additional detachment along the Top Chalk surface. However, the introduction of this bipartition of detachment is controversial and a better modelling of the bed geometries, determination of the possible overpressure in the undercompacted clays above the Top Chalk and analysis of possible stress configurations are necessary.

References

Barnett, J. A. M., Mortimer, J., Rippon, J. H., Walsh, J. J. and Watterson, J. 1987. Displacement geometry in the volume containing a single normal fault. American Association of Petroleum Geologists Bulletin, 71, 925-937.

Clausen, O. R. 1991. Tertiary seismic stratigraphic and structural evolution of the northern Danish Central Trough. PhD thesis, Aarhus University, 320 pp.

Crans, W. and Mandl, G. 1980. On the theory of growth faulting part II(a): Genesis of the unit. Journal of Petroleum Geology, 3, 209-236.

Glennie, K. W. 1990. Introduction to the Petroleum Geology of the North Sea. 3rd edition. Blackwell, London. 402 pp.

Hamblin, W. K. 1965. Origin of "reverse drag" on the downthrown side of normal faults. Geological Society of America Bulletin, 76, 1145-1164.

Kristoffersen, F. N. and Bang, I. 1982. Cenozioc excl. Danian limestone. In: Michelsen, O. (ed.) Geology of the Danish Central Graben. Danmarks Geologiske Undersøgelse, Series B, no. 8, 61-70.

Nielsen, L. H. and Japsen, P. 1991. Deep wells in Denmark 1935-1990. Danmarks Geologiske Undersøgelse, Serie A, Nr. 31, 177 pp.

Petersen, K., Clausen, O. R. and Korstgård, J. A. 1992. Evolution of a salt-related listric growth fault near the D-1 well, block 5605, Danish North Sea: displacement history and salt kinematics. Journal of Structural Geology, 14, 565-577.

Petersen, K., Clausen, O. R. and Korstgård, J. A. 1993. Evolution of a Salt-Related Tertiary Growth Fault in the Danish North Sea. In A.M Spencer (ed): Generation, Accumulation and Production of Europe's Hydrocarbons III. Special Publication of the European Association of Petroleum Geoscientists No 3, 69-78.

Stouge, S. 1988. Biostratigraphy of selected wells from the northwestern part of the Danish Central Trough. Internal CENBAS report, 63 pp.

Sørensen, K. 1986. Danish Basin subsidence by Triassic rifting on a lithosphere cooling background. Nature 319, 660-663.

Walsh, J. J. and Watterson, J. 1987. Distributions of cumulative displacement and seismic slip on a single normal fault surface. Journal of Structural Geology, 9, 1039-1046.

Waltham, D. 1989. Finite difference modelling of hangingwall deformation. Journal of Structural Geology, 11, 433-437.

Watterson, J. 1986. Fault dimensions, displacements and growth. Pure and Applied Geophysics, 124, 365-373.

White, N. J., Jackson, J. A. and McKenzie, D. P. 1986. The relationship between the geometry of normal faults and that of the sedimentary layer in their hanging walls. Journal of Structural Geology, 8, 897-909.

Ziegler, P. A. 1990. Geological Atlas of Western and Central Europe. Elsevier, Amsterdam. 239 pp.

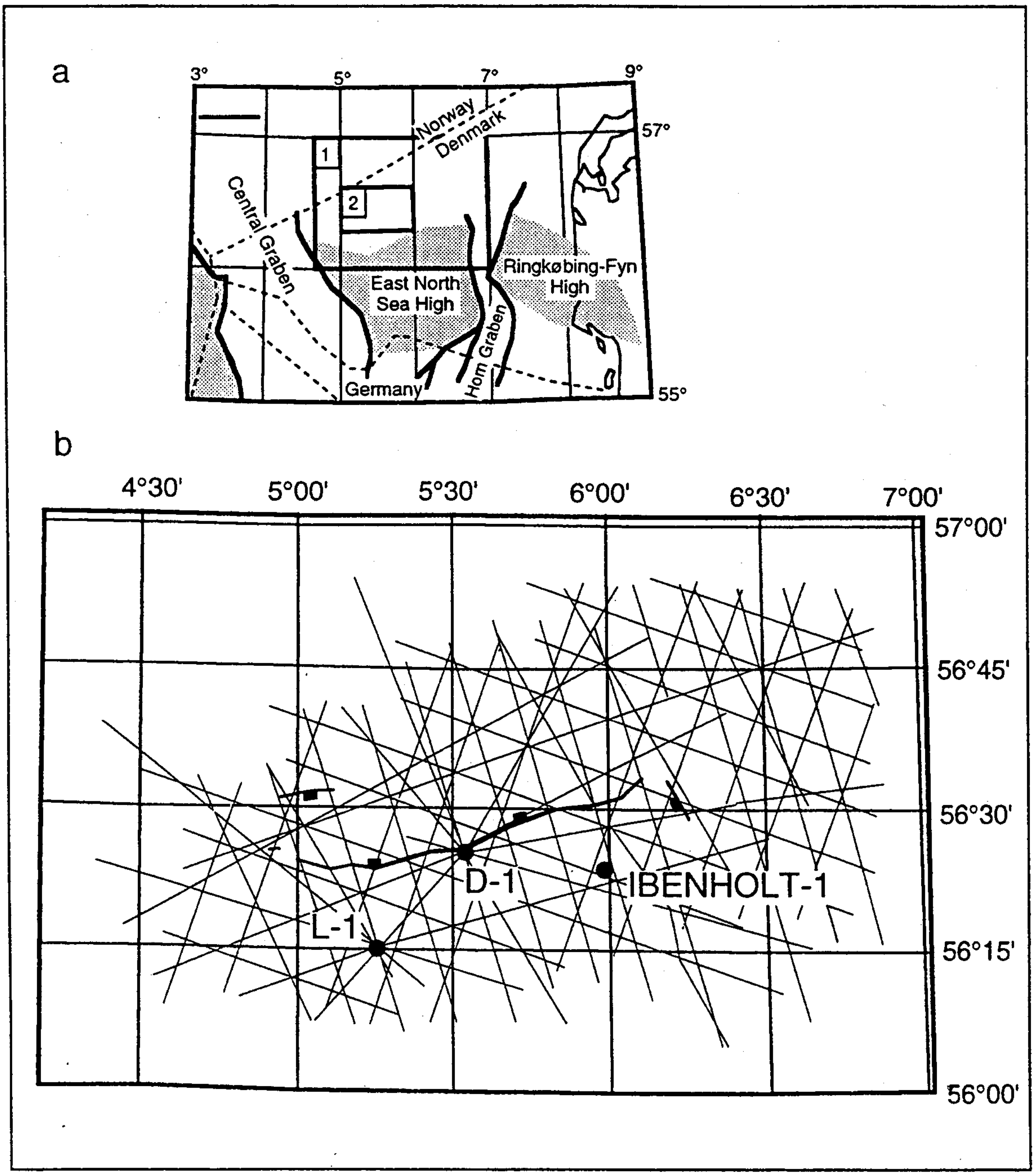


Fig. 1
a.The location of the studied area is indicated by box no. 1 which outlines the map border of Figs. 1b, 6a and 6b. Box no. 2 outlines the map border of Figs. 7a and 7b.
b. Map showing the D-1 fault cutting the Top Chalk level and the traces of the seismic lines used in the study.

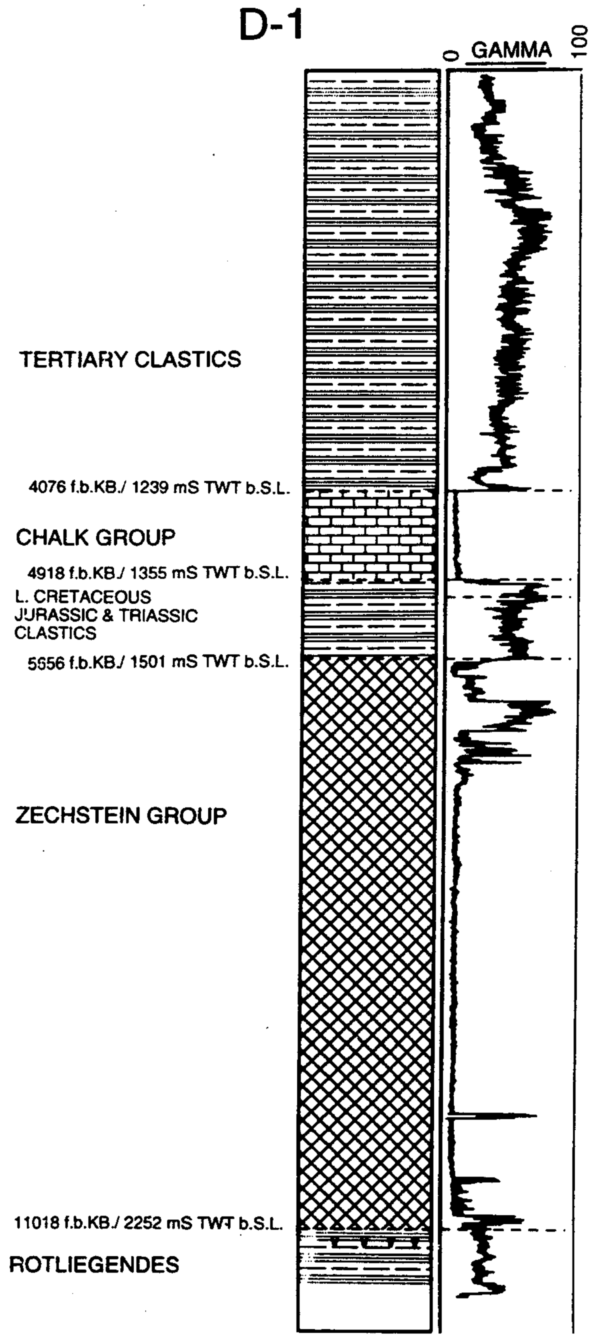


Fig. 2 Lithology and stratigraphy of the D-1 well (after Nielsen and Japsen, 1991) and associated gamma ray log curve.

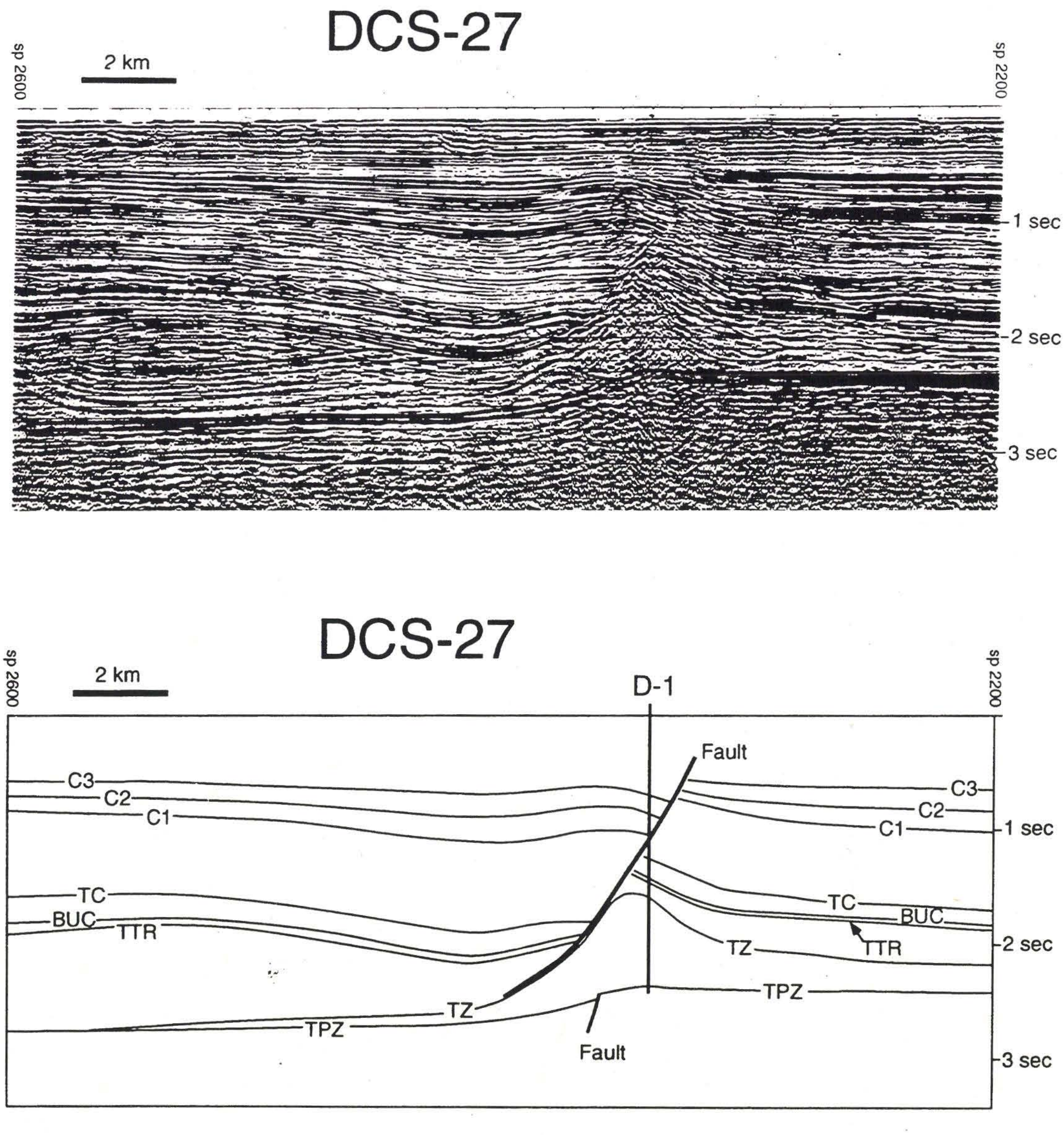


Fig. 3 Seismic line and line-drawing of DCS-27 which is cut by the D-1 well. The interpreted horizons are indicated and their ages are as follows: TPZ - Top Pre-Zechstein; TZ - Top Zechstein; TTR - Top Trias; BUC - Base Upper Cretaceous; TC - Top Chalk (top Cretaceous-top Danian); C1 - Intra Early Miocene; C2 - Intra Early Miocene and C3 - Base Middle Miocene.

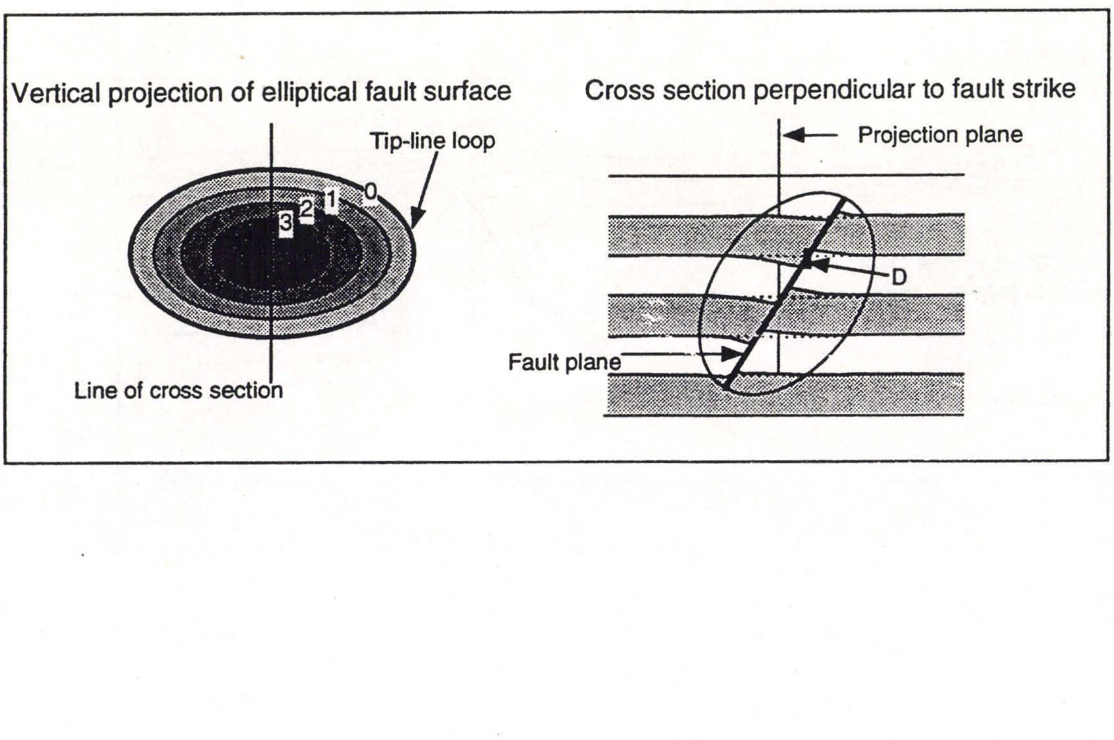


Fig. 4 Principles in determining the throw values and projecting them onto a vertical section parallel with the fault strike. The values are contoured and the result is a contoured displacement diagram, which uniquely describes the displacement on the fault (Barnett et al., 1987).

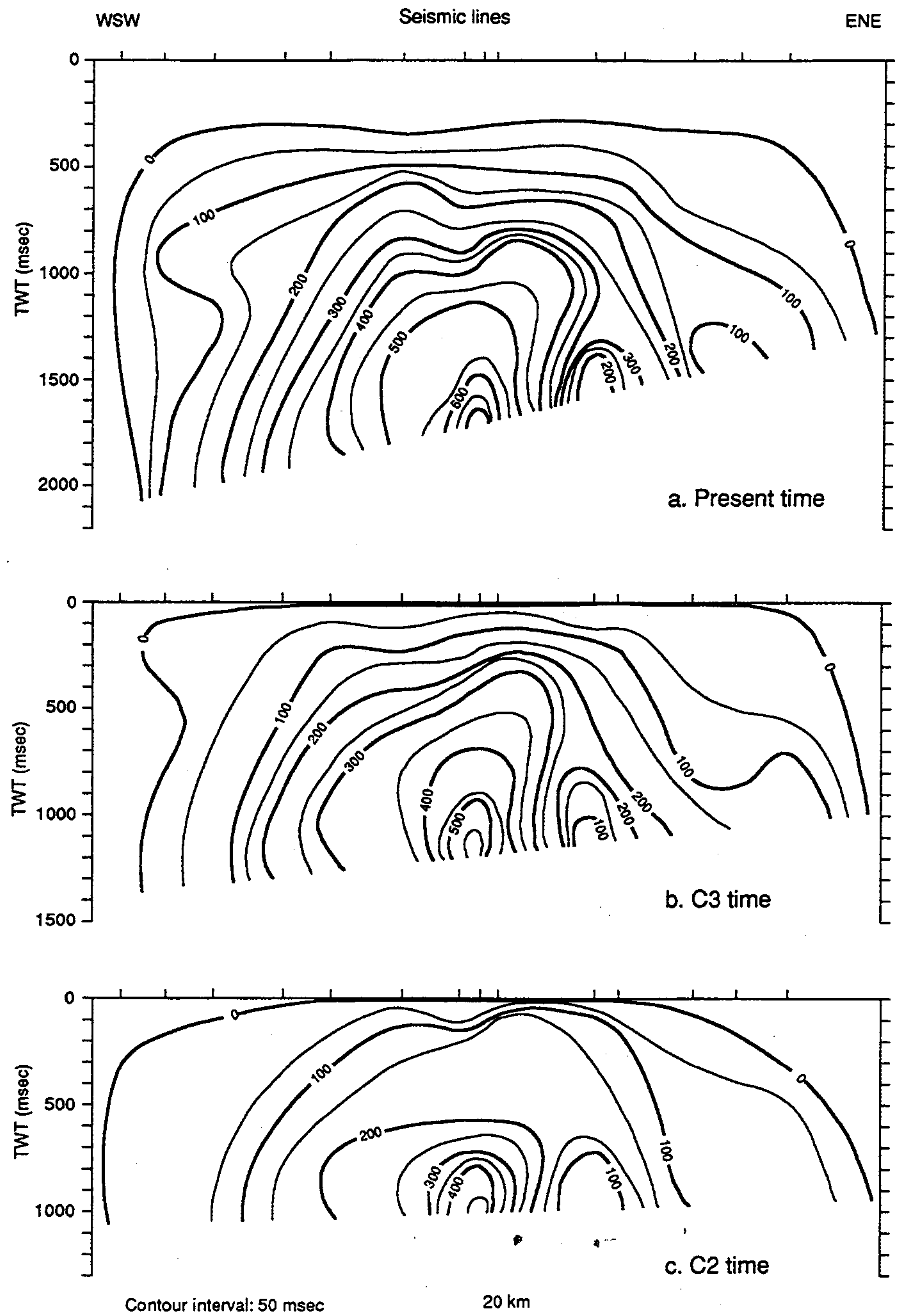
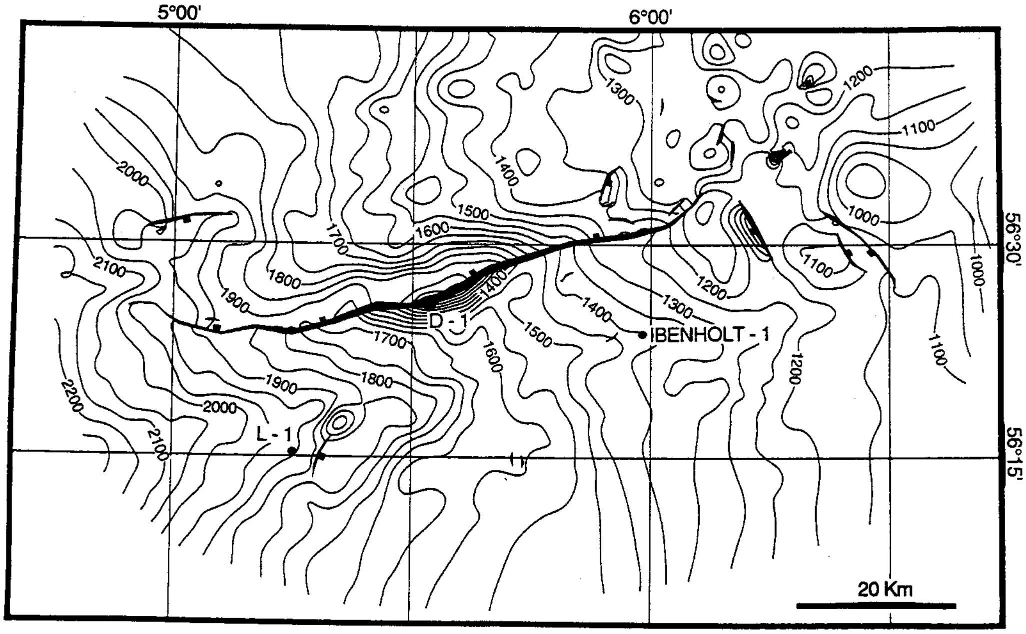


Fig. 5 Contoured displacement diagrams from the D-1 fault at present (a) and backstripped to C3 time (b) and C2 time (c). Displacement values are from 5 mapped horizons.



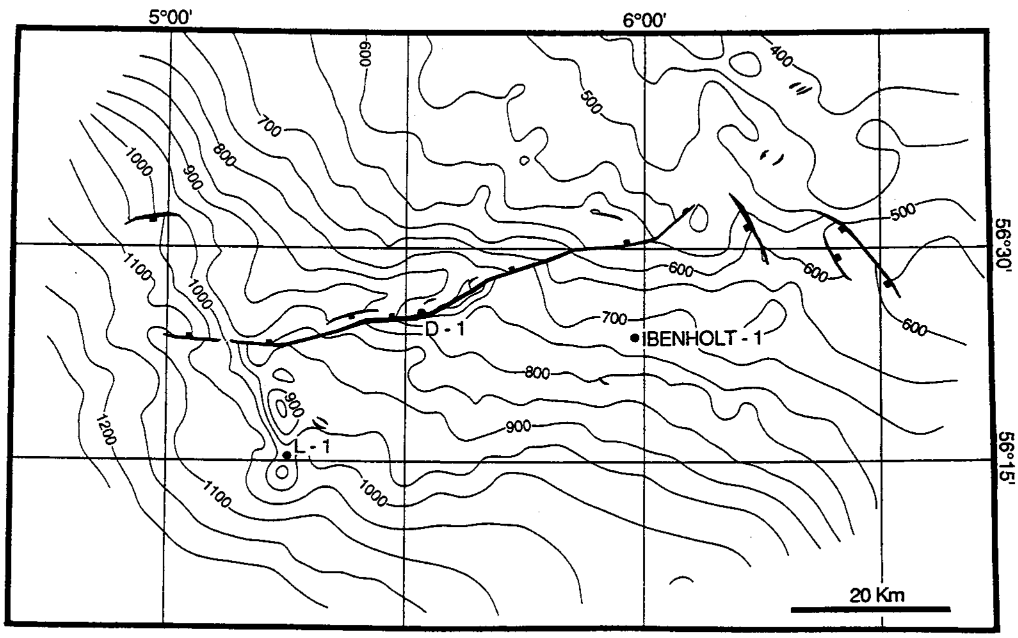


Fig. 6 Depth maps (TWT) of the Top Chalk (a) and C2 horizons (b). The regional dip on the horizons is distorted by the D-1 fault. The distortions are more prominent at the Top Chalk surface which emphasizes that the Top Chalk has suffered more deformation than the younger horizons.

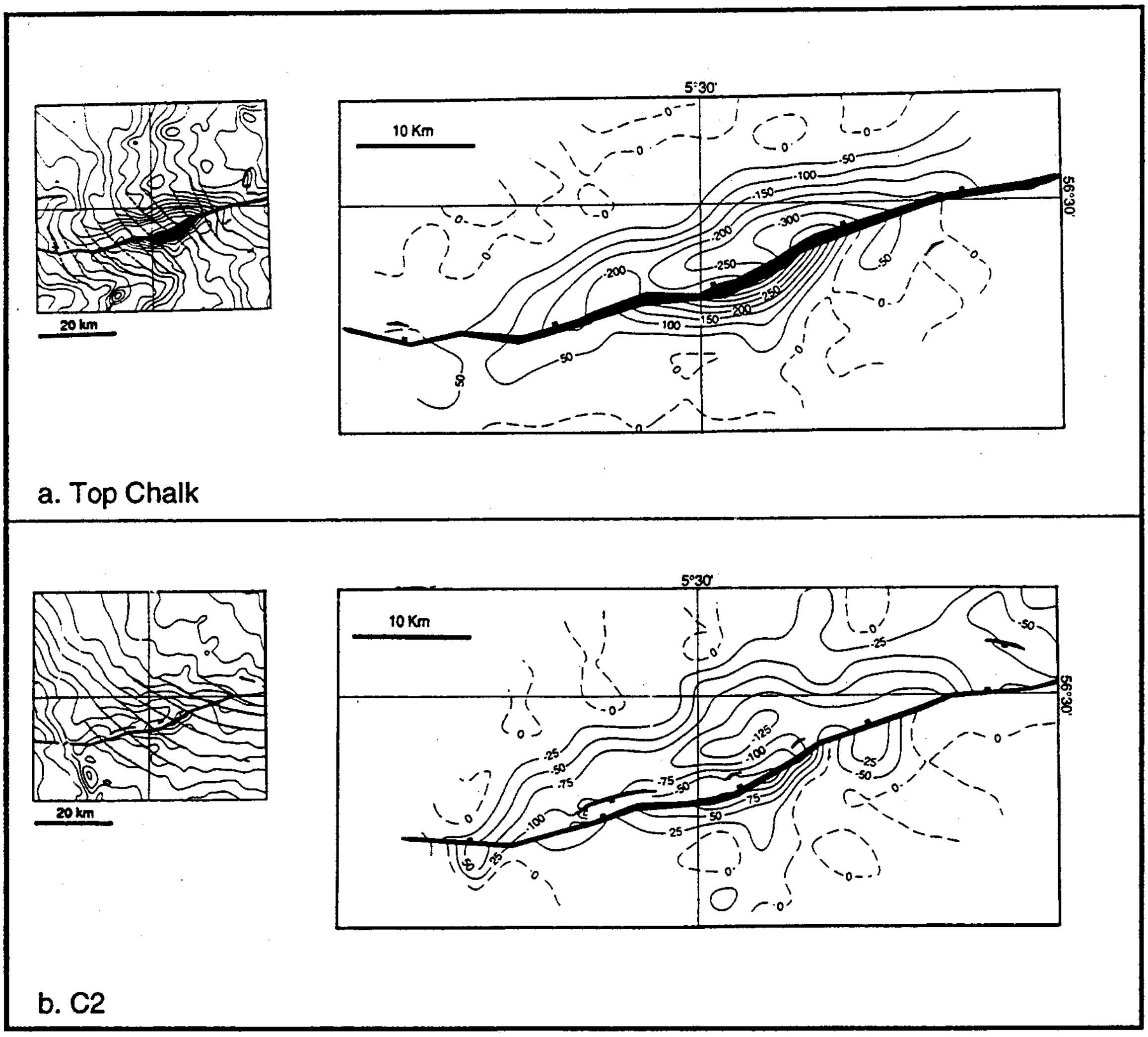


Fig. 7 Vertical displacement maps of the Top Chalk (a) and C2 (b) horizons. The inserted map shows the topography of the horizon with the interpreted regional (dashed lines). The footwall shows positive uplift except to the east, where a minor area shows subsidence with respect to the interpreted regional. The hangingwall shows subsidence but not symmetrically with respect to the footwall uplift.

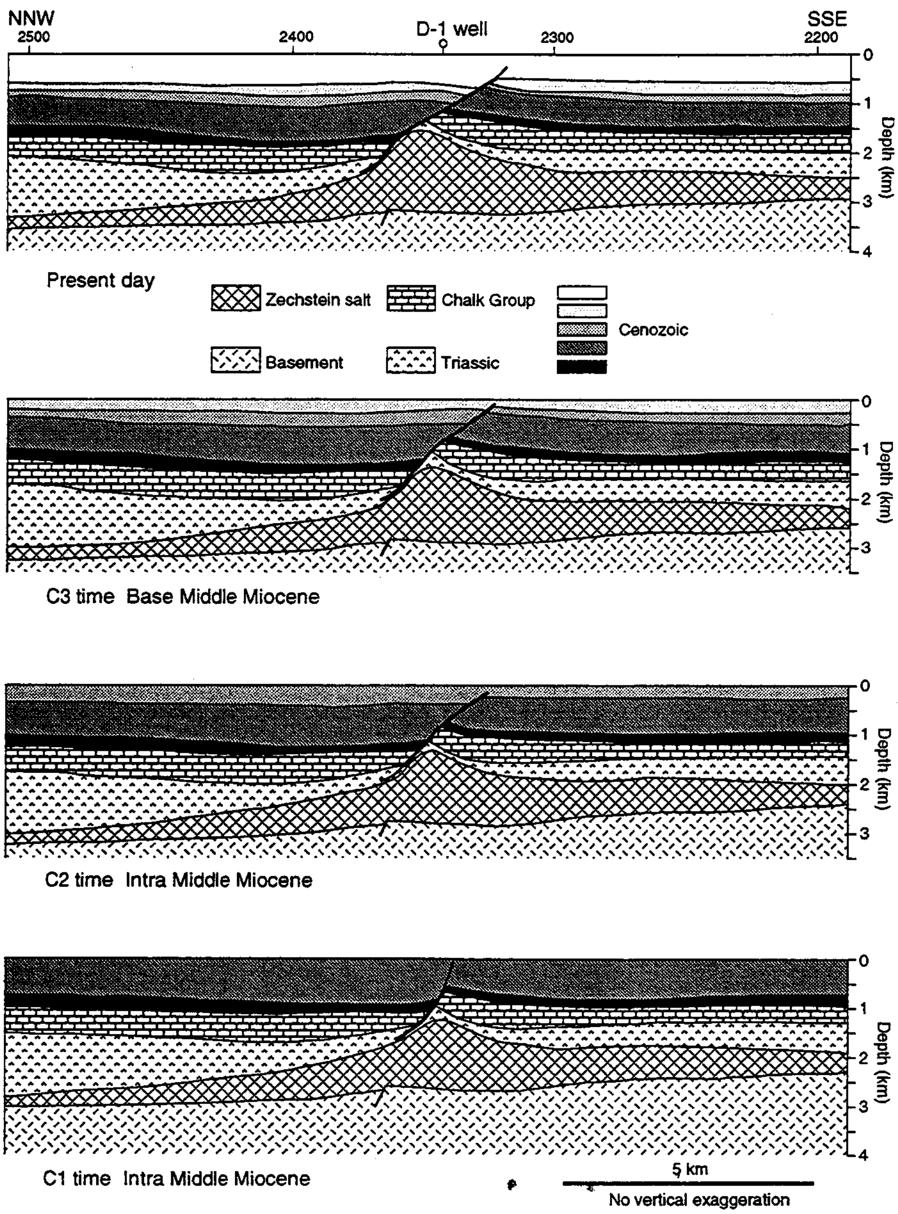


Fig. 8 Seismic section DCS-27 depth is converted and backstripped. The stratigraphicn sections are decompacted using the surface porosity and compaction parameters of Sørensen (1986). The change in shape of the D-1 fault and the salt structure is evident.

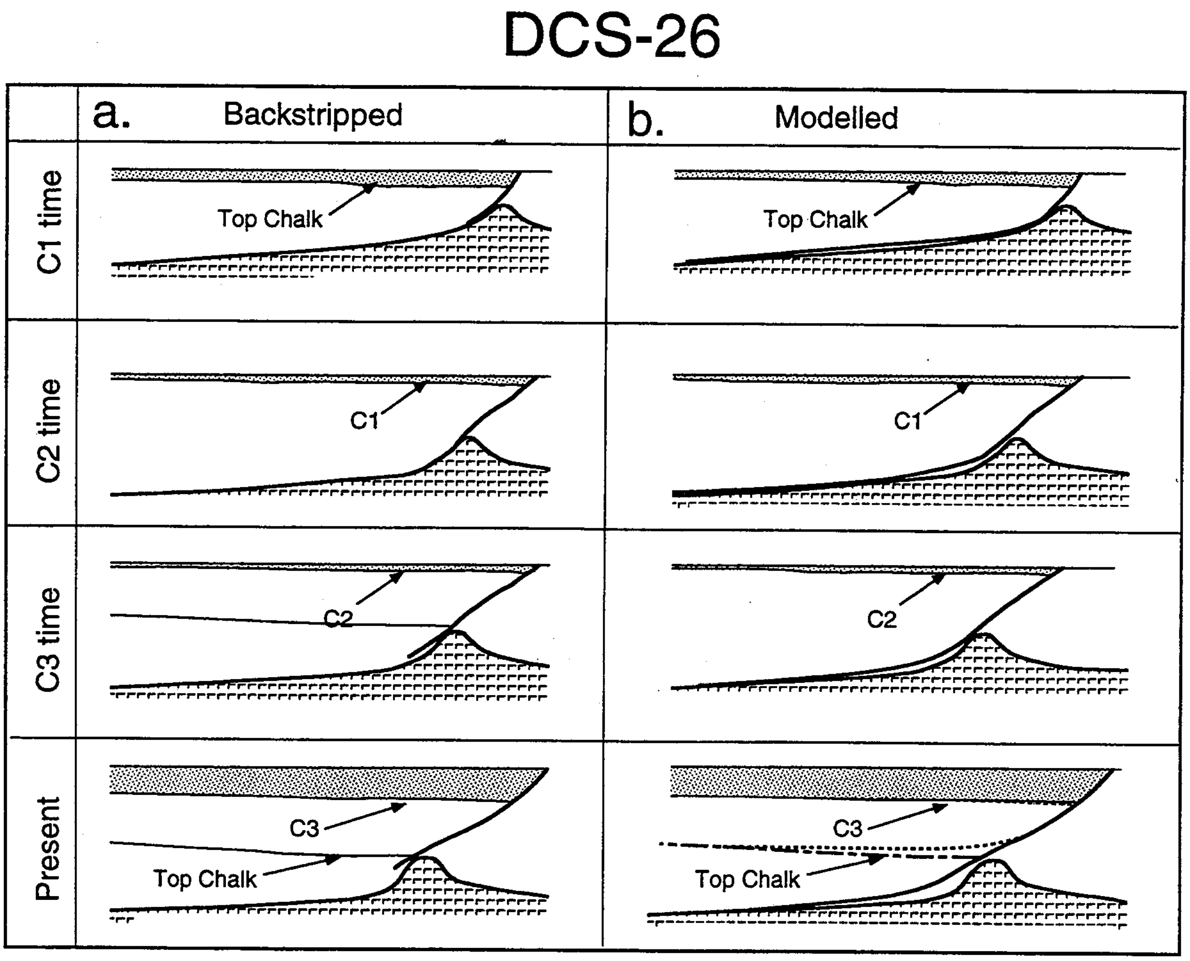


Fig. 9 The topography of the latest deposited but yet deformed horizon and the D-1 fault through time is shown in (a). The topography is derived from the backstripped section. In (b) is shown the corresponding modelled topography assuming a fault plane as shown. It is evident that the topography of the hangingwall horizons may be reproduced by a fault detaching along the Top Zechstein salt. However, the C3 horizon modelled does not fit the observed. The dashed line shows the closest fit using the dashed fault, whereas the full line shows the geometry achieved by using a fault detaching along the Top Zechstein salt surface. For further see text.

Foraminiferal biostratigraphy of the post mid-Miocene in two bore-holes in the Danish North Sea

Peter B. Konradi

Abstract

Cutting samples from two exploration wells, Cleo-1 and Kim-1, in the Central Trough area in the northwestern part of the Danish North Sea, have been investigated for foraminiferal content in the section above the prominent mid-Miocene event. Benthonic foraminifera have been used to produce a stratigraphic subdivision by reference to the standard NSB zonation of King. The NSB 12 to NSB 17 zones (Middle Miocene to Middle Pleistocene) have been identified above the event. These zones can be related to the paleo water depth zonation. Paleoenvironmental reconstruction shows that sediments from the subject interval from Cleo-1 were deposited in a shallower situation than equivalent deposits in Kim-1. A conspicuous hiatus is identified in Cleo-1 at the Pliocene-Pleistocene boundary.

Introduction

The following is an extended abstract of an ongoing research project on the foraminiferal faunas of the interval above the mid-Miocene event in the Danish sector, North Sea. The mid-Miocene event is a geological event, which is expressed in several ways. In seismic investigations in the North Sea, it is seen as a marker horizon or prominent unconformity (Cameron *et al.*, 1993). It is also registered in log sequence analyses as the base of usually two distinct gamma ray peaks (Kristoffersen & Bang, 1982). In the microfossils, the event is seen as a change in the faunas between the NSB 11 and NSB 12 zones (King, 1989, fig. 9.12), and especially evidenced by the occurrences of *Uvigerina* species (von Daniels, 1986) and of *Bolboforma* species (Spiegler and von Daniels, 1991).

The present study is concerned with the two exploration wells Cleo-1 and Kim-1 (Fig. 1) and is based on cutting samples stored at the archives of the Geological Survey of Denmark. The samples were washed on 0.1 mm and 0.063 mm screens. From the residue on the 0.1 mm screen a minimum of 300 foraminifera were picked, if possible, and counted. In samples with abundant inorganic material, the foraminifera were concentrated by means of a heavy liquid with the specific gravity of 1.8 g/ccm, and the residues were checked for remaining foraminifera.

Ditch cutting samples only allow the first downhole occurrence of species to be used in biostratigraphic interpretations (King, 1983). In this paper the term "first occurrence" is used in the sence of first downhole occurrence. Therefore "tops" of specific foraminiferal species together with *Bolboforma spp.* are used to divide the intervals into zones in accordance with the NSB zonation of King (1983,1989).

King (1989) revised the NSB 16 and NSB 17 zones of his 1983 paper into a NSB 16x zone for the North Sea north of 57 N. Apparently, he also includes his NSB 16 zone of 1983 in his NSB 15b zone of 1989. For that reason King's updated zonation of 1989 is used, except for the NSB 15b and NSB 16x zones, where the NSB 15b, NSB 16 and NSB 17 zones of 1983 are used. The Pliocene-Pleistocene boundary is placed in accordance with Thompson *et al.* (1992), which is equivalent to the base of NSB 15b subzone (King, 1989, fig. 9.7).

Ecological interpretation of the faunas is based on Murray (1991).

The investigated strata are equivalent to the major sequence stratigraphic unit 7 of Michel sen et al.(1994).

Cleo-1

The Cleo-1 well is situated at 56 23'N and 4 25'E in the Central Trough area, just west of the Ringkøbing-Fyn High to the northwest of the Danish Sector.
A total of 124 species are identified. A summary of the foraminiferal investigations are given in Fig. 2 as percentage distributions of selected species, with information about the number of species, faunal dominance and the diversity (Walton, 1964).
The correlation of the investigated strata to the NSB-zonation is based on the following.
The **NSB 17 zone** is indicated by the fauna sampled in the interval 480' to 1110'. Most faunas have low diversity and are dominated by *Elphidium excavatum* (Terquem). Other species are the cold water species *Elphidium asklundi* Brotzen and *Nonion orbiculare* (Brady) suggesting shallow water, and in one sample the presence of *Elphidium albiumbilicatum* (Weiss) indicates lowered salinity.
The **NSB 16b subzone** is found in the interval from 1170' to 1380', based on the first occurrence of *Elphidiella hannai* (Cushman and Grant). The faunas continue to have low abundances and diversity. The assemblages are dominated by *Elphidium excavatum* and other species include *Buccella tenerrima* (Bandy) and a few *Cassidulina laevigata* d'Orbigny and *Elphidium ustulatum* Todd. This fauna is indicative of a littoral and cold environment. The NSB 16b and NSB 17 zones are equivalent to the Pleistocene.
The sample at 1470' yielded a fauna with few specimens. The presence of *Ammonia beccarii* (Linne) and *Elphidium albiumbilicatum* indicate shallow water and reduced salinity. This restricted fauna could be an inner littoral facies or be reworked. It can not be referred to any zone with certaienty.
The **NSB 15 zone** is not identified in this well and a hiatus must exist at this level.
The **NSB 14b subzone** is identified in the interval from 1530' to 1740', characterized by the first occurrence of *Monspeliensina pseudotepida* (van Voorthuysen) and *Nonion crassesuturatum* van Voorthuysen from the top. The faunas have low diversities in the upper part and are dominated by *Elphidium excavatum*. Other species include *Elphidiella hannai, Cassidulina laevigata* and *Buccella spp*. The faunal dominance is high and the environment is interpreted to be outer littoral.
The **NSB 14a subzone** is represented in the interval from 1800' to 1980' based on the first occurrence of *Cassidulina pliocarinata* van Voorthuysen, *Cibicidoides limbatosuturalis* (van Voorthuysen) and *Florilus boueanus* (d'Orbigny) from the top. The faunas are dominated by *Elphidium excavatum* and *Monspeliensina pseudotepida*, and other species include *Cassidulina laevigata, Nonion affine* (Reuss) and *Buccella spp*. The dominance decreases downhole, whereas the diversity is slightly increased. These faunas indicate an outer littoral to inner shelf environment.
The top of the interval is characterized by a notable change in the fauna which probably indicates a hiatus.
The **NSB 13b subzone** is found in the interval 1980' to 2550' based on the occurrence of *Cribroelphidium vulgare* Voloshinova in the top of the zone and from 2280' *Uvigerina venusta saxonica* von Daniels and Spiegler. Other species associated are *Cassidulina laevigata, C. pliocarinata, Nonion affine, Florilus boueanus, Bulimina aculeata* d'Orbigny, *Globocassidulina subglobosa* (Brady) and *Cibicides spp*. The shallow water species *Elphidium excavatum* and *Monspeliensina pseudotepida* decrease downhole as planktonic specimens increase in number. The diversity increases strongly at the top of the interval. The fauna indicates an increasing water depth from inner to middle shelf environment downhole.
The top of the Miocene is placed at 2280' where *Valvulineria complanata* (d'Orbigny) has its first appearence (Doppert, 1980).
The **NSB 13a subzone** is indicated in the interval 2610' to 3450' based on the first occurrence of *Uvigerina pygmaea langeri* von Daniels and Spiegler at the top of the interval and *Bulimina elongata* d'Orbigny from 3180'. Other species include *Cassidulina laevigata, Nonion*

affine, Bulimina aculeata, Globocassidulina subglobosa, Hoeglundina elegans (d'Orbigny) and *Cibicides spp*. The fairly constant presence (2% to 4%) of the shallow water species *Elphidium excavatum* and *Monspeliensina pseudotepida* in all the samples from this interval may indicate reworking of shallow water sediments in the basin. The number of planktonic specimens increases downhole. The environment is considered to be middle shelf.

The **NSB 12c subzone** is not recorded in this borehole.

The **NSB 12b subzone** is identified in the interval 3510′ to 4020′ based on the occurrence of *Elphidium antoninum* (d'Orbigny) from the top. Other species in the interval are *Cassidulina laevigata, Nonion affine, Bulimina aculeata, Globocassidulina subglobosa* and *Cibicides spp*. The planktonic foraminiferal content is high, and in the samples below 3900′ *Bolboforma metzmacheri* (Clodius) is found. The diversity is high and the dominance is low, except in the lowermost sample. The environment is interpreted as open marine, middle to outer shelf.

The **NSB 12a subzone** is indicated in the samples from the interval 4020′ to 4170′ based on the first occurrence of *Elphidium ungeri* (Reuss) at the top. An additional species characteristic of this subzone is *Trifarina gracilis* (Reuss). Other common species are *Cassidulina laevigata, Nonion affine, Bulimina aculeata, Bulimina elongata, Oridorsalis umbonatus* (Reuss), *Pullenia bulloides* (d'Orbigny) and *Cibicides spp*. Furthermore, the interval is characterized by the occurrence of *Bolboforma clodiusi* von Daniels and Spiegler and abundant planktonic specimens. This faunal assemblage indicates an open marine, outer shelf environment. This subzone partly have low frequiencies in the faunas probably indicating a benthonic environment that was unfavorable for the fauna or for the preservation of tests.

The samples from 4170′ to 4230′ did not yield calcareous microfossils and represent a barren interval.

The **NSB 11 zone** is not identified in this well and a hiatus must exist at this level.

The **NSB 10 zone** is represented by the lowermost sample investigated from this borehole (4260′) situated immediately below the mid-Miocene event. The fauna is characterized by the occurrence of *Uvigerina tenuipustulata* van Voorthuysen, *Elphidium inflatum* (Reuss) and *Asterigerina guerichi staeschei* (ten Dam and Reinhold).

Kim-1

The well Kim-1 is situated at 56 07′ N and 3 30′ E in the Central Trough above the Lindesnes Ridge in the western part of the Danish sector.

A total of 144 species were identified. A summary of the foraminiferal investigations is shown in Fig. 3 as a percentage distribution of selected species together with the number of species, faunal dominance and the diversity (Walton, 1964).

The subdivision of the investigated interval into the NSB-zonation is based on the following.

The **NSB 17 zone** is found in the upper part of the borehole above 1380′. The faunas are characterized by *Elphidium ustulatum* and are dominated by *Elphidium excavatum* and high numbers of *Nonion orbiculare* indicating littoral facies. The occurrence of *Elphidium asklundi* suggests a cold water environment and *Elphidium albiumbilicatum* indicates periods with reduced salinity. The interval 1050′ to 1140′ is characterized by the presence of *Elphidium gorbunovi* Stschedrina, which has a very restricted stratigraphic range in the upper part of the Early Pleistocene in this part of the North Sea (Pedersen, 1995) where it has been found in several wells.

A **NSB 16b subzone** fauna is recognized in the samples from 1440′ to 2280′. It is indicated by the first occurrence of *Elphidiella hannai* and is dominated by *Elphidium excavatum*. In the upper part of the interval *Nonion orbiculare* reflects a shallower water depth. In the lower part *Cassidulina teretis* and *C. reniforme* constitute important components of the fauna indicating inner shelf, cold environment.

The NSB 16b and NSB 17 zones are equivalent to the Pleistocene.

The **NSB 15b subzone** is identified in the interval from 2310′ to 2880′ based on the first occurrence of common *Cibicides grossus* (ten Dam and Reinhold) from the top and the influx of *Elphidiella hannai*. The fauna is dominated by *Elphidium excavatum*. In the upper part and at the base of the interval *Cassidulina teretis* and *C. reniforme* also constitute a significant part of the fauna indicating greater water depth than in the middle of the zone. The fauna indicates fluctuation in sea level from inner shelf to littoral environment.

The **NSB 15a subzone** is represented by two samples at 2910′ and 3030′ as indicated by the first occurrence of *Cibicides pseudoungerianus* (Cushman) in the latter sample. The upper sample is included in the subzone based on the conspicuous faunal change to the next sample uphole. The fauna includes *Elphidium excavatum, Cassidulina teretis, C. laevigata, C. carinata, Nonion affine* and *Epistominella vitrea* Parker. The faunal dominance has dropped notably and the diversity increases downhole. The fauna indicates an inner to middle shelf environment.

The abrupt faunal change at the top of the zone probably indicates a hiatus.

The **NSB 14b subzone** is indicated the sample at 3150′ by the first occurrence of *Monspeliensina pseudotepida*. The fauna further includes *Elphidium excavatum, Cassidulina teretis, C. laevigata, C. carinata, Bulimina aculeata* and planktonic species. The environment is interpreted to be middle shelf.

The **NSB 14a subzone** is found in the interval 3210′ to 3330′ where the top is characterized by first occurrences of *Cassidulina pliocarinata* and *Florilus boueanus*. Other species include *Elphidium excavatum, Monspeliensina pseudotepida, Cassidulina teretis, C. laevigata, C. carinata, Bulimina aculeata, Nonion affine* and *Globocassidulina subglobosa*. The planktonic component together with the diversity increase downhole. This fauna indicates a middle shelf environment.

The **NSB 13b subzone**, in the interval 3450′ to 3870′, is characterized by the first occurrence of *Uvigerina venusta saxonica* from the top. Other species include *Elphidium excavatum, Monspeliensina pseudotepida, Cassidulina teretis, C. laevigata, C. carinata, Bulimina aculeata, Nonion affine, Globocassidulina subglobosa, Trifarina fluens* and planktonic species. The diversity is high and the fauna represents a middle to outer shelf environment.

The top of the Miocene is placed at first occurrence of common *Valvulineria complanata* at 3570′.

The **NSB 13a subzone** is recognised in the interval 3930′ to 4720′ based on the first occurrence of *Uvigerina pygmaea langeri* from the top and of *Bulimina elongata* from 4090′ depth. The fauna includes *Monspeliensina pseudotepida, Cassidulina laevigata, C. carinata, Bulimina aculeata, Nonion affine, Globocassidulina subglobosa, Uvigerina venusta saxonica* and *Cibicides spp*. The samples from 4180′ to 4600′ have impoverished faunas or are barren probably due to either unfavorable benthonic conditions or poor preservation of the tests. *Bolboforma costairregularis* (Toering and van Voorthuysen) is recorded in the uppermost part of the interval. *Bolboforma metzmacheri* and *Bolboforma laevis* von Daniels and Spiegler occur in the lowermost sample from 4720′ depth. The planktonic foraminifera are common and the diversity is generally high. This fauna indicates an open marine, middle to outer shelf environment.

The **NSB 12 zone** is identified in the interval 4780′ to 4960′ based on a characteristic high content of *Trifarina gracilis* and of *Bolboforma clodiusi*. The index species *Elphidium antoninum* is absent in this well. The faunas include *Bulimina aculeata, B. elongata, Nonion affine, Globocassidulina subglobosa, Oridorsalis umbonatus* and *Cibicides spp*. The planktonic component is high. The fauna indicates an open marine, outer shelf environment.

The **NSB 11 zone** is represented by the samples from 4980′ to 5200′ based on the first occurrence of *Asterigerina guerichi staeschei, Uvigerina acuminata* Hosius, *Uvigerina macrocarinata* Papp and Turnovsky and of *Bolboforma reticulata* von Daniels and Spiegler from the top. Other species are *Nonion affine, Bulimina elongata, Oridorsalis umbonatus, Trifarina gracilis* and *Pullenia bulloides*. The interval has a fairly large planktonic component and *Bolboforma spp.* are common. The samples in the middle part of the interval have somewhat impoverished faunas. The assemblages indicate an open marine, outer shelf environment.
The **NSB 10 zone** is identified in the lowermost sample investigated from this well, at 5280′, based on the occurrence of *Uvigerina tenuipustulata.*

Comparison between the wells

The faunal assemblages of the biostratigraphic zonation in the two investigated wells clearly reflects the depositional environmental settings related to water depth.
In both wells the NSB 10 zone is identified in the lowermost investigated sample.
The NSB 11 zone is only identified in Kim-1 with a thickness of 220′.
In Cleo-1, the NSB 12 zone has a thickness of 570′ and can be subdivided into two subzones NSB 12a and NSB 12b, whereas in Kim-1 the NSB 12 zone can not be subdivided and has a thickness of 150′. An impoverished fauna is found in the NSB 12a subzone in Cleo-1. An equivalent interval is not identified in Kim-1. The existence of *Elphidiidae* in Cleo-1 indicates a shallower water depth than at the Kim-1 site. A seismic section between the two wells shows that the major sequence stratigraphic unit is made up of several lensoid shaped sequences building out into the basin from the northeast to the southwest. At the time of the NSB 12 zone, the major sedimentation took place around the Cleo-1 site, whereas the Kim-1 site was situated further out into the basin.
The NSB 13 zone in both wells is subdivided into 13a and 13b subzones. In Cleo-1, the thicknesses of the subzones are 840′ and 570′ respectively and in Kim-1 790′ and 420′. At the time of NSB 13 zone deposition the sedimentation rate was somewhat higher at the Cleo-1 site compared to the Kim-1 site. In Kim-1, an interval with an impoverished or missing fauna is found in the lower half of the NSB 13a subzone. An equivalent interval is not identified in Cleo-1. The faunas also in this zone indicate a shallower water depth at the Cleo-1 site than at the Kim-1 site. The Miocene-Pliocene boundary is placed in the NSB 13b subzone, in Cleo-1 well at 2190′ depth and in Kim-1 well at 3480′ depth.
The thickness of the NSB 14 zone in the Cleo-1 well is 450′ and in the Kim-1 well 210′. Again, the faunas indicate a shallower water depth at the Cleo-1 site. In both wells, this zone can be subdivided into a 14a subzone and a 14b subzone. In the Cleo-1 well there is a conspicuous change in the fauna to a more littoral facies between the two subzones indicating a possible hiatus at this level. A comparable faunal change is not seen in the Kim-1 well.
At the Cleo-1 site, the NSB 15 zone is not identified indicating a hiatus here. This zone in the Kim-1 well has a thickness of 720′ and is subdivided into the NSB 15a and NSB 15b subzones. In the latter subzone the faunas suggest a fluctuation in sea level. A faunal change at the top of the NSB 15a subzone indicates a hiatus at this level.
The NSB 16b subzone is 210′ thick in Cleo-1 and is deposited in a littoral facies. In Kim-1, the subzone is 840′ thick and displays a shallowing water depth.

The NSB 17 zone is represented by 630′ of sediment in the Cleo-1 well and by 900′ in the Kim-1 well. At both sites the faunas indicate a cold environment, but in Cleo-1 they are impoverished showing a more extreme environment perhaps due to proximity to the coast.

Conclusion

Based on investigations of the foraminiferal fauna assemblages the exploraton wells Cleo-1 and Kim-1 can be subdivided according to the NSB zonation of King (1983, 1989) above the mid-Miocene. The sediments are of Miocene, Pliocene and Early to Middle Pleistocene age. The Miocene-Pliocene boundary is placed in the NSB 13b subzone and the Pliocene-Pleistocene boundary is placed at the base of the NSB 16b subzone.
At the Cleo-1 site the sediments were deposited at a shallower water depth than at the Kim-1 site, which was situated further out in the basin. Moreover, the main sedimentation took place earlier at Cleo-1 than at Kim-1, as the sediments were building out into the basin.
At Cleo-1, a considerable hiatus is identified in the Middle Miocene and at the Pliocene-Pleistocene boundary. At Kim-1, a fluctuation in water depth is seen in the latest Late Pliocene. Hiati are also indicated in Cleo-1 between the NSB 14a and 14b subzones and at Kim-1 between the NSB 15a and 15b subzones.

References

Cameron, T.D.J., Bulat, J. and Mesdag, C.S. 1993: High resolution seismic profile through a Late Cenozoic delta complex in the southern North Sea. Marine and Petroleum Geology, 10, 591-599.

Daniels, C.H. von 1986: *Uvigerina* in the NW European Neogene. Utrecht Micropal. Bull. 35, 67-119.

Doppert, J.W.C. 1980: Lithostratigraphy and Biostratigraphy of marine Neogene deposits in the Netherlands. Meded. Rijks Geol. Dinst, 32-16, 255-312.

King, C. 1983: Cainozoic micropalaeontological biostratigraphy of the North Sea. Rep. Inst. Geol. Sci., No. 82/7, 40 pp.

King, C. 1989: Cenozoic of the North Sea. *In*: Jenkins, D.G. & Murray, J.W. (Eds.): Stratigraphical atlas of fossil Foraminifera. 2nd ed., 418-489. Ellis Horwood, Chichester.

Kristoffersen, F.N. & Bang, I. 1982: Cenozoic excl. Danian limestone. *In*: Michelsen, O.: Geology of the Danish Central Graben. Danm. Geol. Unders. Ser. B, 8, 133pp.

Michelsen, O., Danielsen, M., Heilman-Clausen, C., Jordt, H., Laursen, G.V. & Thomsen, E. 1994: Cenozoic sequence stratigraphy in the eastern North Sea. *In*: S.E.P.M.: Mesozoic and Cenozoic Sequence Stratigraphy of European Basins (In press).

Murray, J.W. 1991: Ecology and Palecology of Benthic Foraminifera. 397pp. Longman Scientific & Technical, London.

Pedersen, A.M. 1995: Foraminiferal biozonation of the Lower Pleistocene in the North Sea. Danm. Geol. Unders. Ser. C, 12, 66pp.

Spiegler, D. and Daniels, C.H. von 1991: A stratigraphic and taxonomic atlas of *Bolboforma* (Protophytes, *Incertae sedis*, Tertiary). Jour. Foram. Res. 21 (2), 126-158.

Thompson, R., Cameron, T.D.J., Schwartz, C., Jensen, K.A., Maenhaut van Lemberge, V. and Sha, L.P. 1992: The magnetic properties of Quaternary and Tertiary sediments in the southern North Sea. Jour. Quat. Sci. 7 (4), 319-334.

Walton, W.R. 1964: Recent foraminiferal ecology and paleoecology. *In*: Imbrie, J. & Newell, N.D. (Eds.): Approaches to Paleoecology. 151-237. Wiley & Sons, New York.

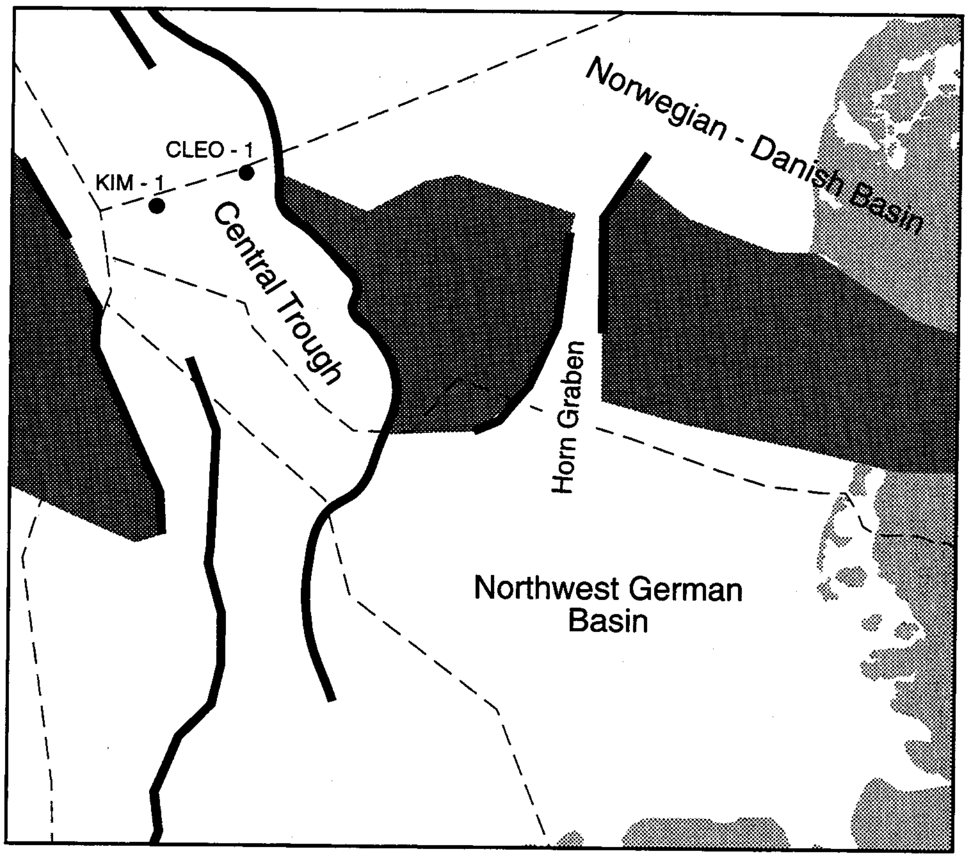


Fig. 1 Position of the wells Cleo-1 and Kim-1 in the Danish North Sea.

Fig. 2 Range chart of selected calcareous microfossils in the Cleo-1 well, Danish North Sea.

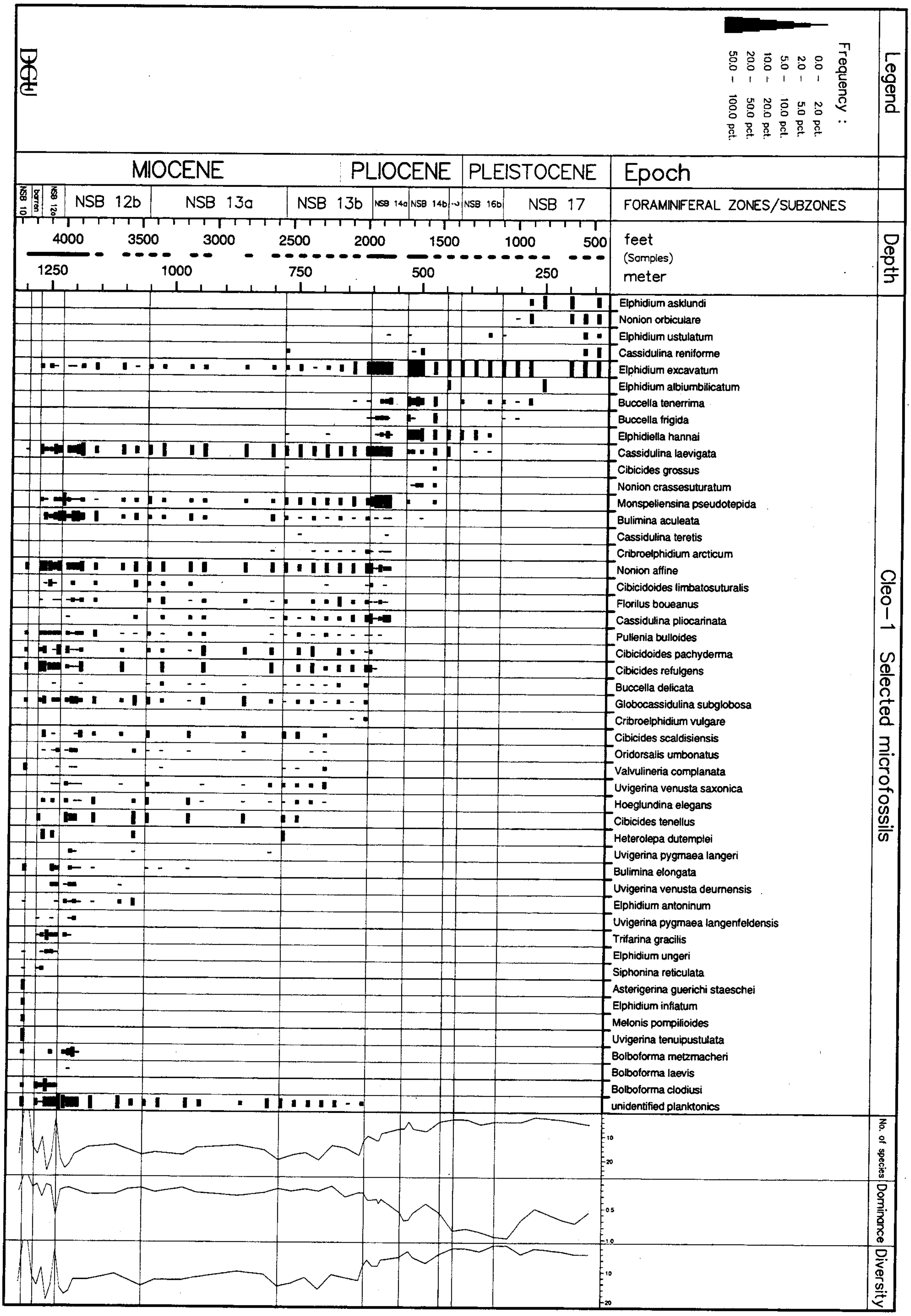
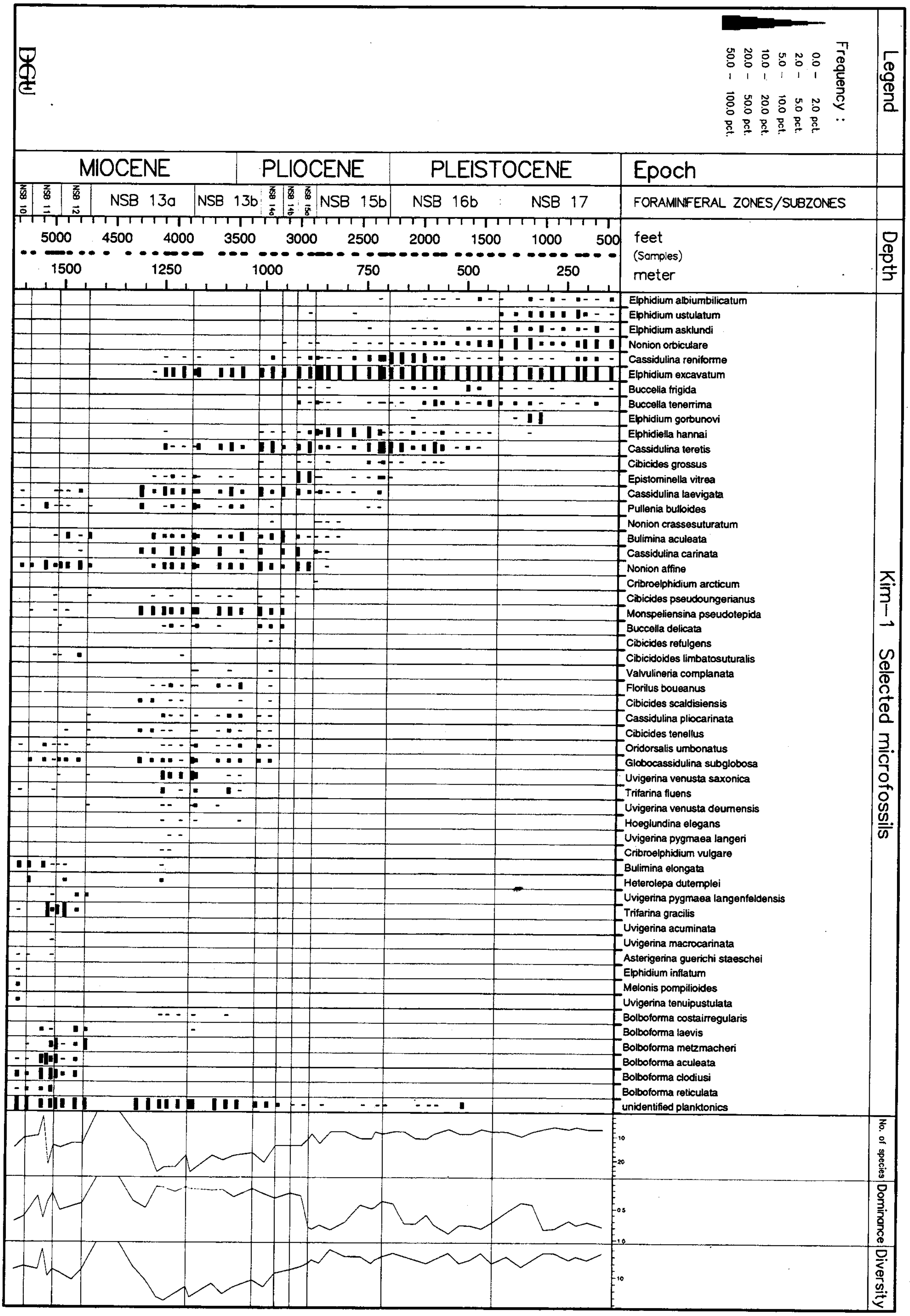


Fig. 3 Range chart of selected calcareous microfossils in the Kim-1 well, Danish North Sea.



Correlation of Miocene North Sea sequences with the Danish land area based on foraminifera

Gitte Vestergaard Laursen & Finn Nyhuus Kristoffersen

Abstract

In the present study comparisons are made between the Miocene North Sea sequences and the Danish onshore formations based on foraminiferal biostratigraphy. Foraminiferal faunas of four onshore borings previously analyzed by Kristoffersen have been reviewed. Biozones NSB 9 - NSB 13 of the offshore sequences were all found in the Danish Miocene formations, and the obtained results promise well for a future more detailed correlation between the North Sea and the Danish land area.

Introduction

A recent sequence stratigraphical study of the eastern North Sea region have revealed 21 sequences during the Cenozoic (Michelsen et al., in press). Seven of these sequences are located within the Miocene. The sequence boundaries and the maximum flooding surfaces in the Miocene interval are chronostratigraphically allocated primarily by means of foraminiferal biostratigraphy. The North Sea foraminiferal zonations of King (1989) has been applied for the Miocene.

In the present study we have re-examined the foraminiferal biostratigraphy of four onshore borings, in order to test the applicability of the offshore stratigraphy in the Miocene of Denmark, and to assess its reliability in future offshore stratigraphic investigations. As onshore seismic data and petrophysical logs are of varying quality we have chosen to correlate the North Sea sequences and the Danish onshore formations primarily on the basis of foraminiferal biostratigraphy. Emphasis has been placed on examining whether the revised version of King's (1983) North Sea foraminiferal zonation (King, 1989), can also be applied in onshore regions (of the North Sea basin) in the Miocene, and in particular, whether biozones NSB 9 to NSB 13 are present in the Danish Miocene formations. To reach this goal the foraminiferal faunas of four of the onshore borings previously analyzed by Kristoffersen (1972) were reviewed (for location see Fig. 1).

The borings

Selected details of the foraminiferal stratigraphy of four borings at Høruphav, Alkærsig, Gram and Sæd, Denmark (Fig.1) are shown in Figs. 2-5. In order to ease correlation with the biostratigraphical North Sea zonation (King, 1989) the data are presented as events (highest occurrence). The sample interval is approximately half a meter. The borings are described in ascending stratigraphical order.

Høruphav (Fig. 2):
Bolivina antiqua d'Orbigny and *Plectofrondicularia seminuda* (Reuss) were found in the Høruphav boring (DGU ref. No. 170.381). These are index species of North Sea Benthic Zones (NSB) 8c and 9 (King, 1989), respectively (Late Oligocene and Early Miocene). Between the highest occurrences of these two species a fossil poor interval with no stratigraphical important species was encountered. This interval is difficult to correlate to any established zonation. *Loxostomum sinuosum* (Cushman), substitute marker of NSB 10, had its highest occurrence approximately two metres above the highest occurrence of *P. seminuda*. In the same interval *Asterigerina staeschei* ten Dam & Reinhold was also present. The coexistence of *L. sinuosum* and *A. staeschei* has previously been shown from the Arnum

Formation (Kristoffersen, 1972). The presence of the planktic species *Cassigerinella chipolensis* (Cushman & Ponton) indicates correlation to the German local Hemmoorian stage of the Lower Miocene (Spiegler, 1986). The Arnum Formation was previously correlated to the Hemmoorian (Rasmussen, 1966).

Alkærsig (Fig. 3):
The Arnum Formation is well represented in the Alkærsig boring (DGU ref. No. 93.101). *Loxostomum sinuosum* (substitute marker of NSB 10) had its highest occurrence in the lower half of the boring, while *Bulimina dingdenensis* Batjes marked the top of the Arnum Formation (lithostratigraphic subdivision by Rasmussen, 1961). *Bulimina dingdenensis* is also a substitute marker of NSB 10 (King, 1989). The highest occurrence of *L. sinuosum* below the highest occurrence of *B. dingdenensis* could consequently be useful in subdividing NSB 10 in the Danish onshore area. Slightly below the top of NSB 10 the planktic *Globorotalia praescitula* Blow, index species of North Sea Planktic Zone (NSP) 11 (King, 1989), had its highest occurrence together with *C. chipolensis*. This indicates correlation to the German local Hemmoorian stage. *Asterigerina staeschei* (index species of NSB 11) dominates the fauna in the sediments of the Middle Miocene Hodde Clay (lithostratigraphic subdivision by Rasmussen, 1961). NSB 12 may be present in this boring, but according to King (1989) *Uvigerina semiornata saprophila* von Daniels & Spiegler should be present in NSB 12. In Alkærsig only *Uvigerina semiornata semiornata* d'Orbigny is present, and NSB 12 is, therefore, marked by a question mark.

Gram (Fig. 4):
The lithostratigraphical allocation of the lowermost part of the Gram boring (DGU ref. No. 141.277) is uncertain. It may belong to the Arnum Formation or the lower part of the Hodde Formation. However, a quartz gravel zone is present in the interval from 36.5-37.4 m below surface (Rasmussen, 1966). This feature has previously been described in the lowermost part of the Hodde Formation (Rasmussen, 1961, 1966). None of the characteristic species normally seen in the Arnum Formation are present in the interval below the Hodde Clay. Slightly below the top of the Hodde Clay *A. staeschei*, index species of NSB 11, has its highest occurrence. *Bolboforma reticulata* von Daniels & Spiegler and *Bolboforma badenensis* Szczechura have also their highest occurrences in this interval. In deep sea sediments these species occur in nannoplankton Zones NN 5-6 (Müller & Spiegler, 1993). This harmonizes with the fact that NSB 11 was previously correlated with NN 5 (King, 1989).
The Gram Clay is separated from the Hodde Clay by a Glauconite Clay, which is barren of foraminifera. The Gram Clay is, however, relatively rich in foraminifera. In the lower part of this formation the occurrence of *Elphidium antoninum* (d'Orbigny) indicates the presence of NSB 12b. Slightly above this event, *Bolboforma clodiusi* von Daniels & Spiegler (index species of NSP 13) has its highest occurrence. None of the index species of NSB 12c and NSP 14a are present in the boring, but the occurrence of *Uvigerina pygmaea langenfeldensis* von Daniels & Spiegler could indicate the possible presence of NSB 12c. In the range chart of King (1989, p. 439) *U. p. langenfeldensis* has a range across the boundary between NSB 12c and NSB 13a. This is the reason for the question mark and the inclined dashed line at the top of NSB 12c in Fig. 4. In the topmost sample *Bolboforma metzmacheri* (Clodius) and *Uvigerina pygmaea langeri* von Daniels & Spiegler are present. These are index species of NSP 14b and NSB 13a, respectively.

Sæd (Fig. 5):
Bolboforma metzmacheri and *U. p. langeri* were also found in the "typical" Gram Clay in the boring at Sæd (DGU ref. No. 167.445). However, a rather scattered occurrence of *U. p. langenfeldensis* in the same interval could indicated the possible presence of NSB 12c.
A clay occurs above the typical Gram Clay which "must undoubtedly be termed Gram Clay" (Rasmussen, 1966, p. 320). Previously this clay was mentioned as Sæd Clay. There are no index species present in this interval, but a substitute marker of NSB 13b, *Valvulineria mexicana grammensis* Langer, is found, and the planktic foraminifera *Neogloboquadrina acostaensis* (Blow), index species of NSP 15a, is also present. According to King (1989) the top of NSP 15a should correlate with the top of NSB 13a. This is not the case in the Sæd boring.

Correlation

Correlation of the Danish formations with the NSB/NSP zonation has changed through time (Fig. 6). The first attempt by King (1983) to correlate the Danish Upper Oligocene and Miocene formations was based on Larsen & Dinesen's (1959) and Kristoffersen's (1972) data. In 1989 King published another correlation of the Danish formations with the NSB zones. The revised version was based on additional, unpublished data and is, therefore, unfortunately lacking an explanation for the major changes: The Vejlefjord and Klintinghoved Formations are not separated and they include NSB 8c and part of NSB 9. The boundary between the Klintinghoved Formation and the Arnum Formation is rather variable but it occurs within NSB 9. The base of the Hodde Formation was moved down to within NSB 10 and the hiatus between the Gram and Hodde Formations disappeared. The boundary between these two formations coincides with the boundary between NSB 11 and 12 (Fig. 6) in King's 1989 stratigraphy.
The present review of borings previously analyzed by Kristoffersen (1972) suggests the following correlation: The Vejlefjord Formation (represented by the Brejning Clay in the boring at Høruphav) is correlated with NSB 8c on the basis of the presence of *B. antiqua*. The Klintinghoved Clay corresponds to NSB 9 because of the presence of *P. seminuda*. The gradual transition from NSB 9 to the faunas of the Arnum Formation (NSB 10) in the Høruphav boring places the upper boundary of the Klintinghoved Clay at the upper boundary of NSB 9. The presence of the substitute markers *L. sinuosum* and *B. dingdenensis* in the Arnum Formation in the Alkærsig boring indicates correlation with NSB 10. In the Borg-1 oil well the index species of NSB 10, *Uvigerina tenuipustulata* van Voorthuysen is present together with these substitute markers. The Hodde Clay contains *A. staeschei* and correlates with NSB 11. It was not possible to judge whether the Glauconite Clay at the basis of the Gram Clay can be correlated to NSB 12a because it was barren. The presence of *E. antoninum*, *U. p. langenfeldensis*, *U. p. langeri*, and *V. m. grammensis* in the Gram Clay indicates correlation with NSB 12b, 12c, 13a and 13b, respectively.

Conclusion

The comparison of the foraminifera in four Danish onshore borings with the established North Sea foraminiferal zonation by King (1983, 1989) shows that it is possible to use this zonation in the onshore region. Biozones NSB 9 - NSB 13 were all found in Danish onshore borings. In the light of this it should be possible to identify the North Sea sequences in the outcrops and borings in onshore Denmark. These results promise well for future more detailed correlations between the North Sea and the Danish land area. Analysis of land profiles should yield more information with a higher resolution than obtainable in offshore oil drillings due to closer sampling interval. This might perhaps successively result in a more detailed North Sea stratigraphy.

References

King, C., 1983: Cainozoic micropalaeontological biostratigraphy of the North Sea. Rep. Inst. Geol. Sci., 82/7, 1-40.

King, C., 1989: Cenozoic of the North Sea. In: D.G. Jenkins & J.W. Murray (Eds.): Stratigraphical Atlas of Fossil Foraminifera. Second Ed. Ellis Horwood Ltd., Chichester, 418-489.

Kristoffersen, F.N., 1972: Foraminiferzonering i det jyske Miocæn. Dansk Geologisk Forening, Årsskrift for 1971, 79-85

Larsen, G. & Dinesen, A., 1959: Vejle Fjord Formationen ved Brejning. Sedimenterne og foraminiferfaunaen (Oligocæn - Miocæn). Danm. Geol. Unders., II Række, 82, 114 pp.

Michelsen, O., Danielsen, M., Heilmann-Clausen, C., Jordt, H., Laursen, G.V. & Thomsen, E., in press: Cenozoic sequence stratigraphy in the eastern North Sea. Submitted to SEPM. 70 ms. pp.

Müller, C. & Spiegler, D., 1993: Revision of the late/middle Miocene boundary on the Voering Plateau (ODP Leg 104). Newsl. Stratigr., 28(2/3), 171-178.

Rasmussen, L.B., 1961: De Miocæne Formationer i Danmark. Danm. Geol. Unders. IV series, vol. 4(5). 45 pp.

Rasmussen, L.B., 1966: Molluscan Faunas and Biostratigraphy of the Marine Younger Miocene Formations in Denmark. part I + II. Danm. Geol. Unders., II Række, 88, 358 pp.

Spiegler, D., 1986: Gliederung des nordwestdeutschen Tertiärs (Paläogen und Neogen) aufgrund von planktonischen Foraminiferen. In: H. Tobien (Ed.): Nordwestdeutschland im Tertiär, 213-299. Gebrüder Borntraeger, Berlin-Stuttgart.

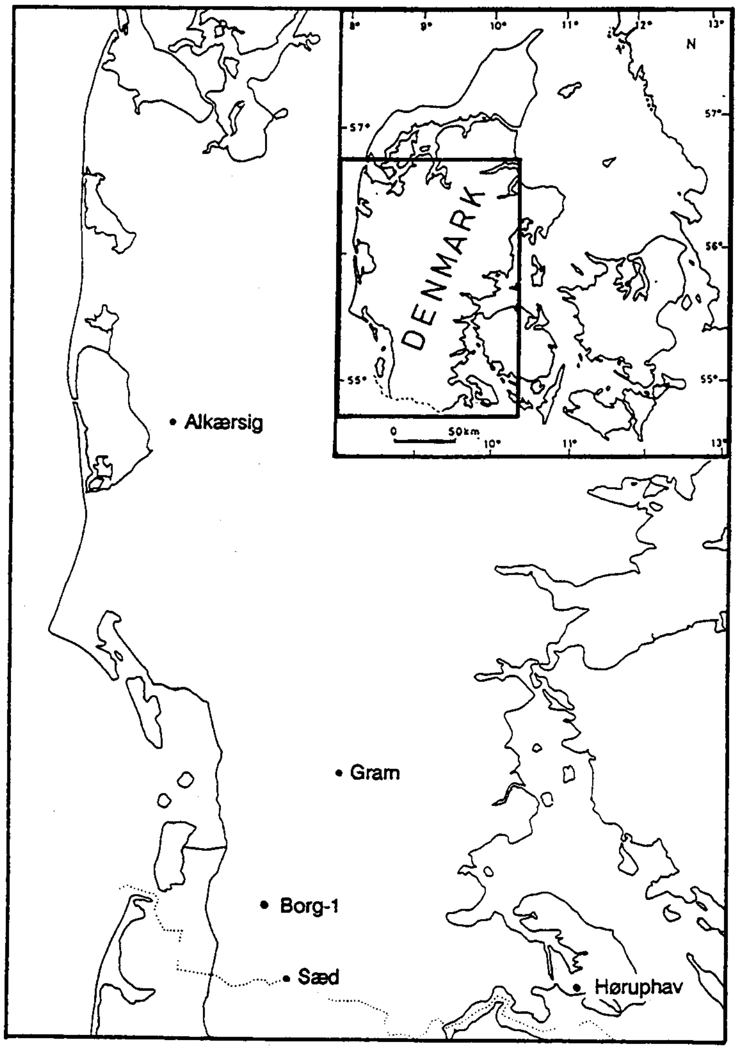


Fig. 1 The location of the borings mentioned in the text. After Rasmussen, 1966.

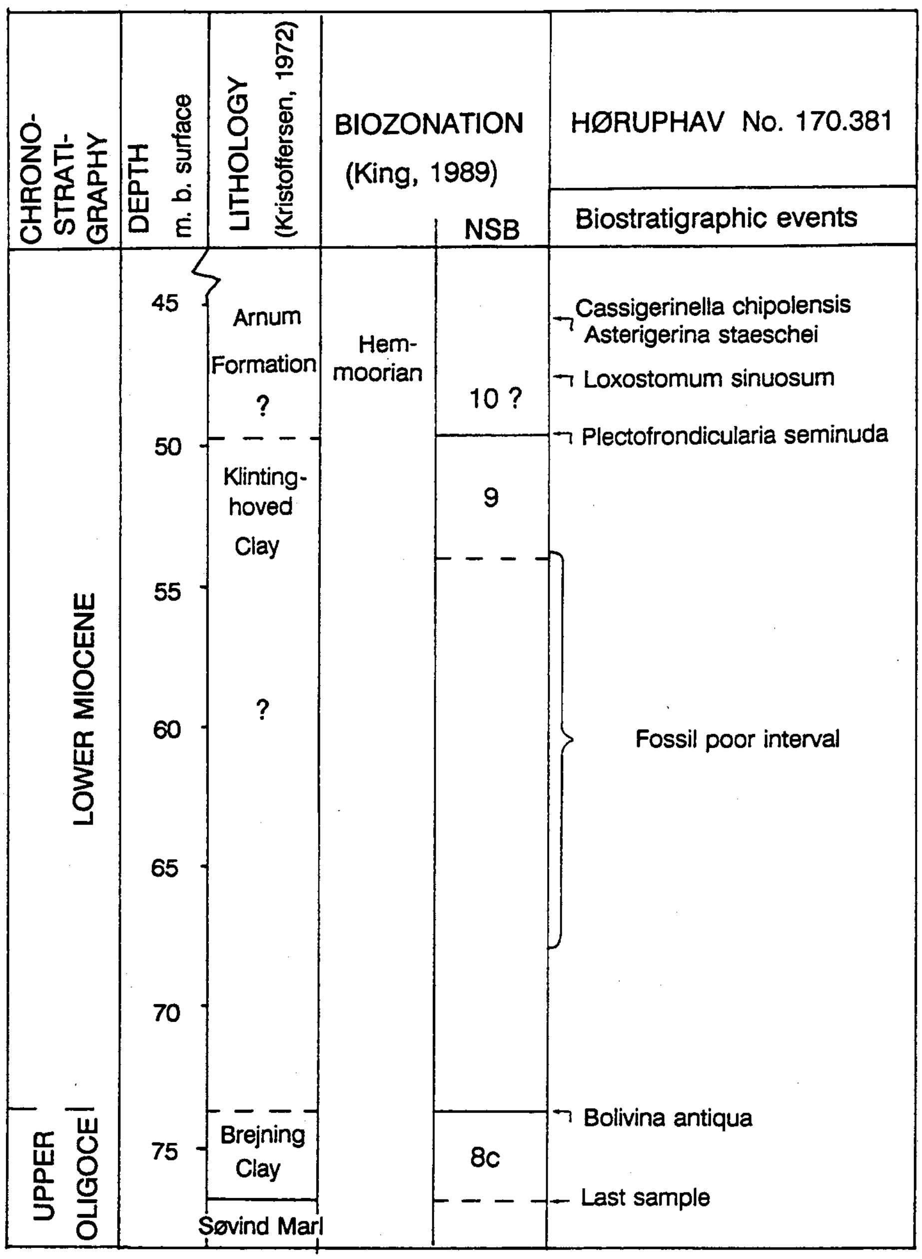


Fig. 2 Biostratigraphic events, lithological units and biozonation in the Upper Oligocene to Lower Miocene sediments of the Høruphav boring (data from Kristoffersen, 1972) (for location see Fig. 1). Arrows indicate highest occurrences.

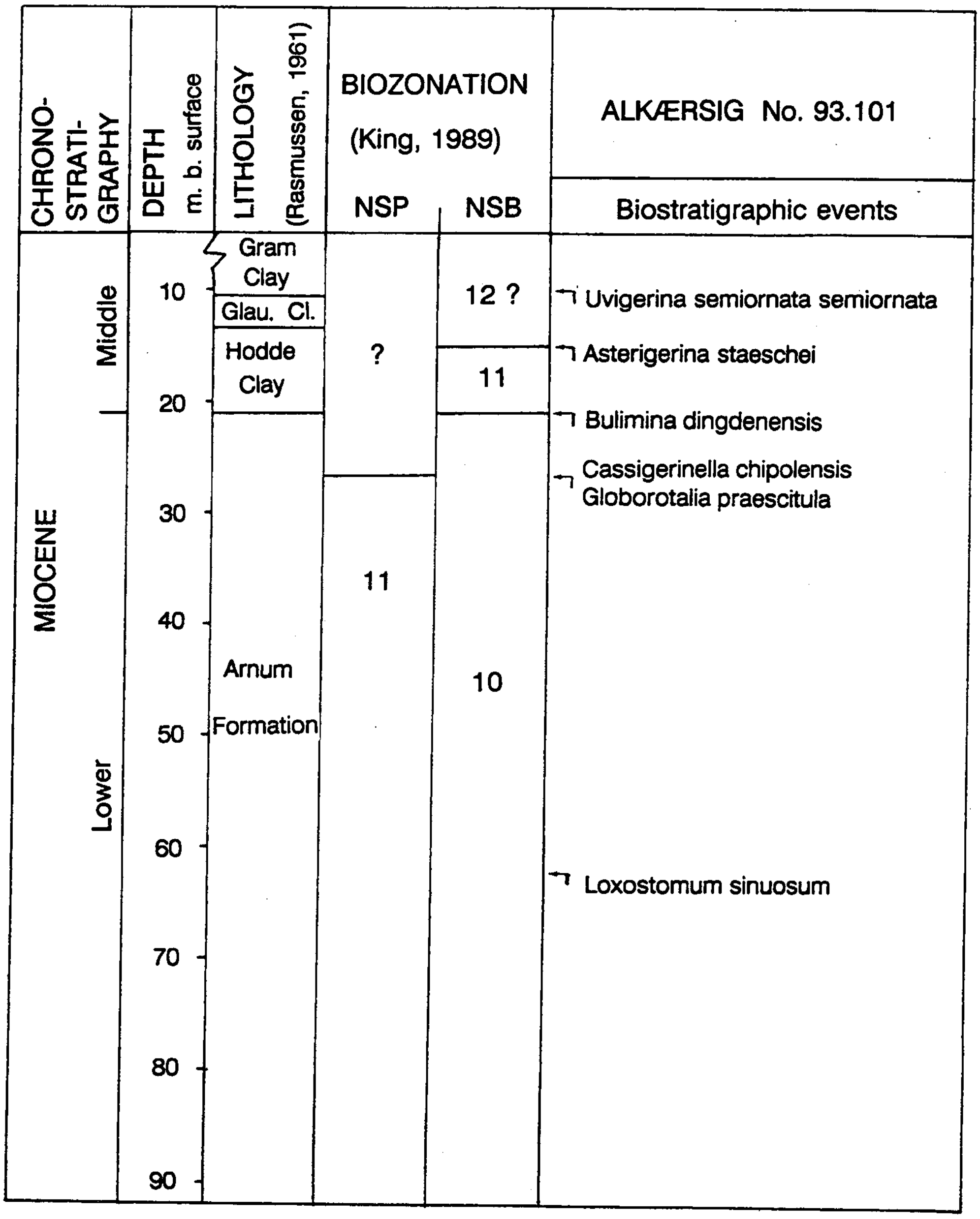


Fig. 3 Biostratigraphic events, lithological units and biozonations in the Lower to Middle Miocene sediments of the Alkærsig boring (data from Kristoffersen, 1972) (for location see Fig. 1). Arrows indicate highest occurrences.

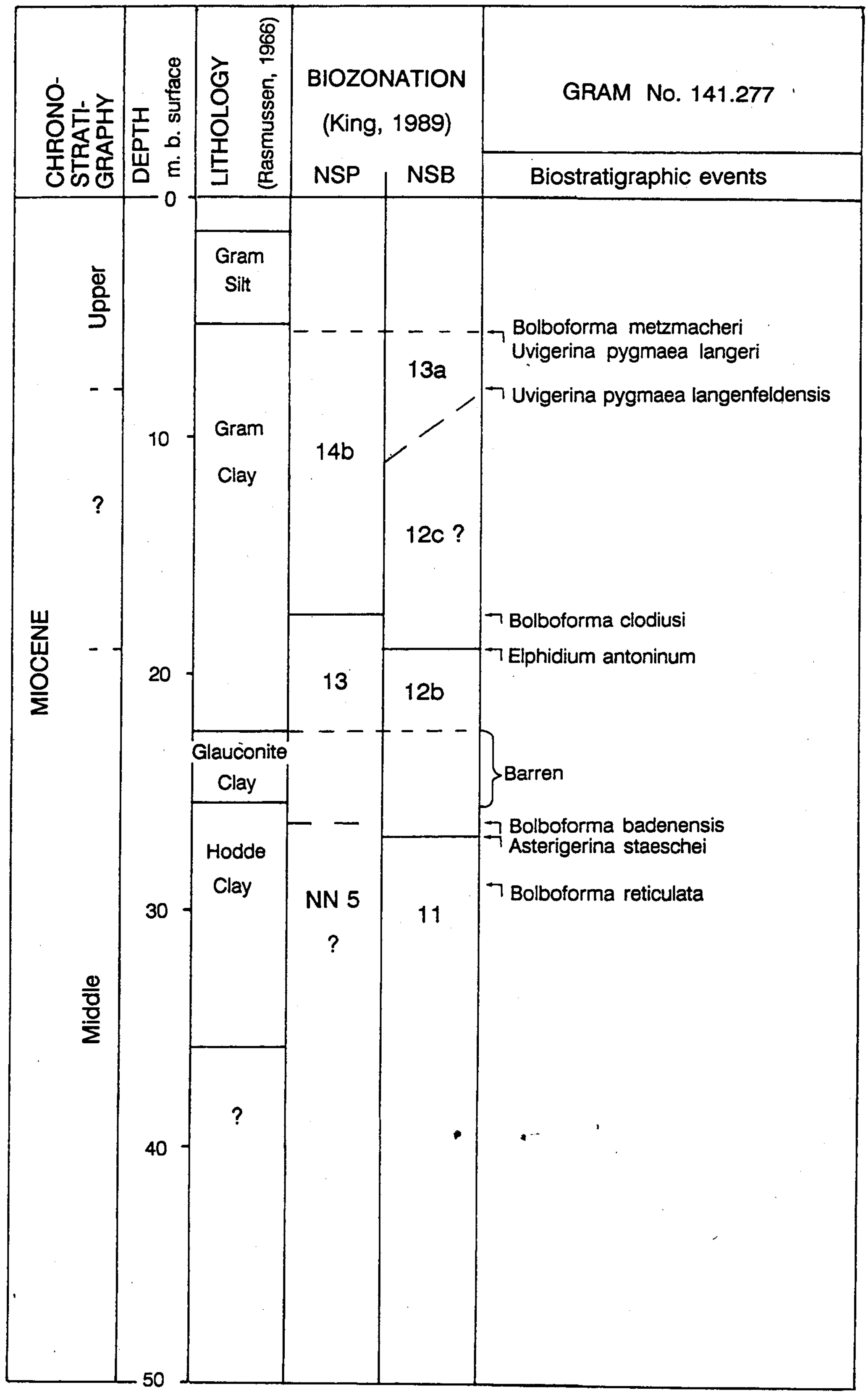


Fig. 4 Biostratigraphic events, lithological units and biozonations in the Middle to Upper Miocene sediments of the Gram boring (data from Kristoffersen, 1972) (for location see Fig. 1). Arrows indicate highest occurrences.

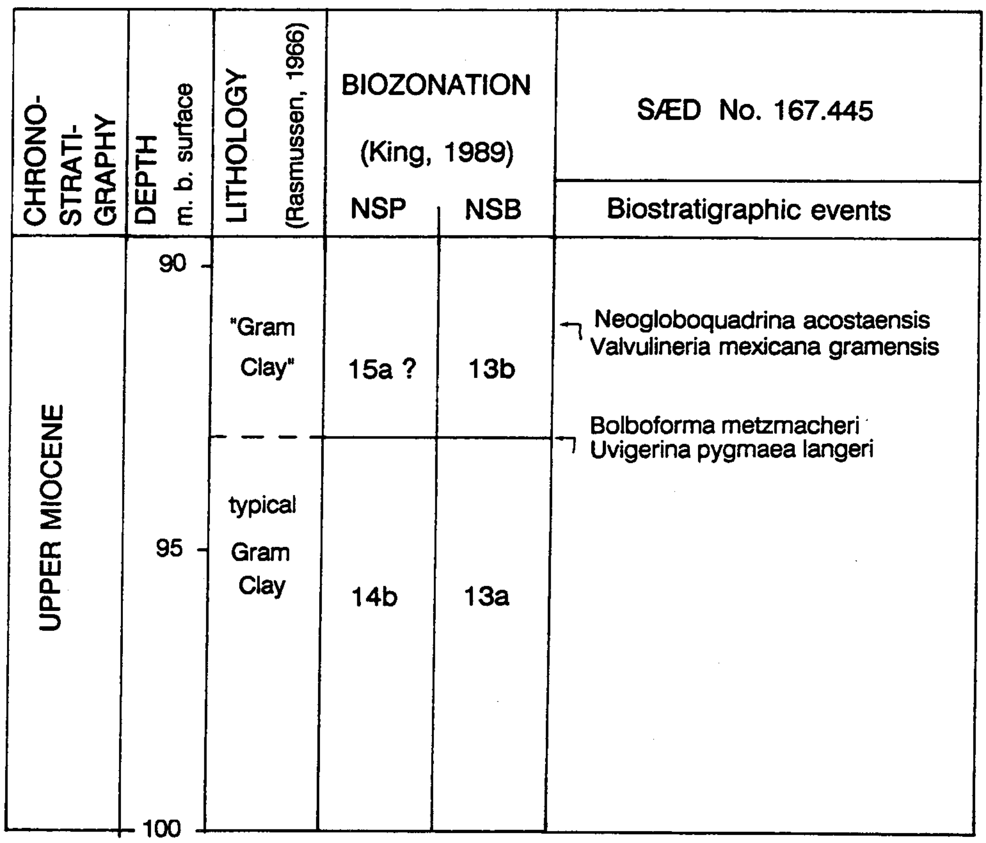


Fig. 5 Biostratigraphic events, lithological units and biozonations in the Upper Miocene sediments of the Sæd boring (data from Kristoffersen, 1972) (for location see Fig. 1). Arrows indicate highest occurrences.

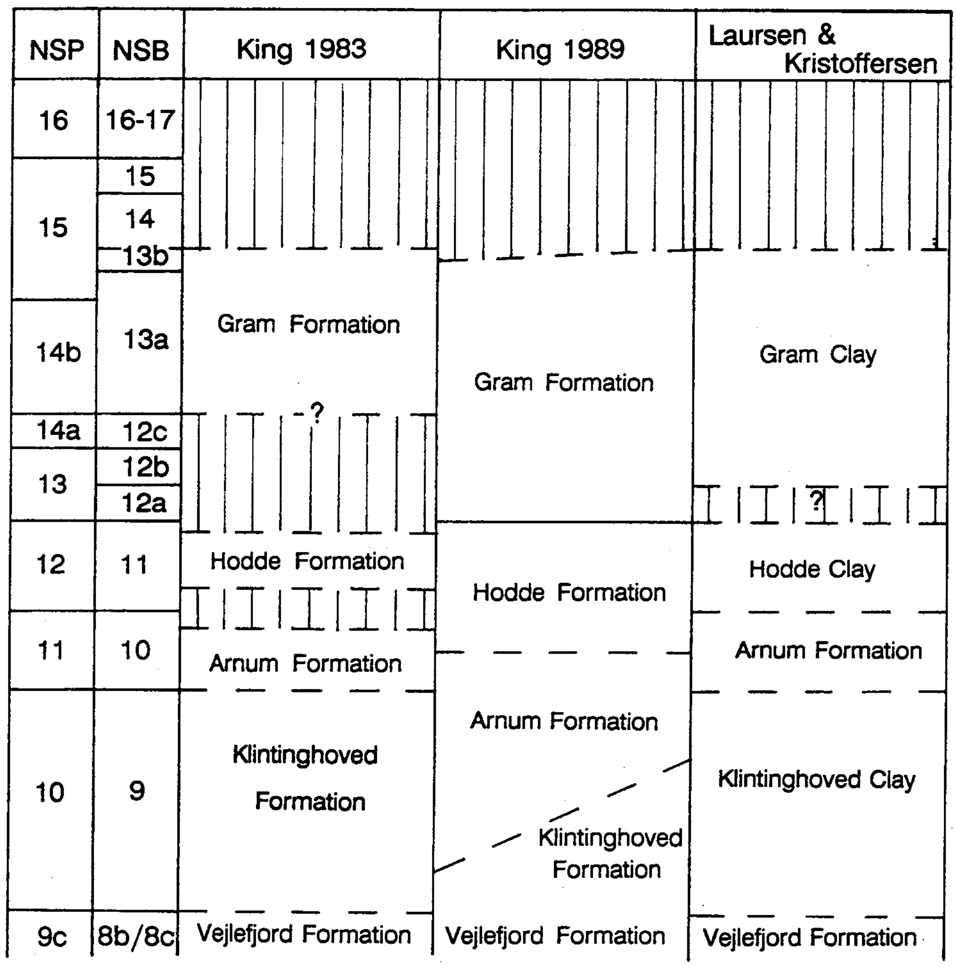


Fig. 6 Correlation between Danish onshore lithostratigraphical formations and North Sea offshore planktic (NSP) and benthic (NSB) foraminiferal zones.

A stratigraphic interpretation of the Oxfordian-Valanginian deposits in the Danish Subbasin

Ulrik Gregersen and Olaf Michelsen

Abstract

Six sequences are identified in the Upper Jurassic and lowermost Cretaceous Flyvbjerg-, Børglum- and Frederikshavn Formations of the Danish Subbasin. Sequence boundaries and maximum flooding surfaces are interpreted on the basis of log analysis, biostratigraphy and lithology of core samples. Parasequences and parasequence sets are mainly recognized in shallow marine sediments.
The gamma ray and SP logs of the sequences have an overall cyclic character, indicating the presence of upward fining deposits overlain by upward coarsening deposits. A blocky log pattern or an upward decreasing trend lowermost in the sequence represents sand-dominated sediments, and it is interpreted as lowstand deposits caused by forced regression. The overlying interval with upward fining deposits comprise transgressive deposits. The interval between maximum flooding surface and the upper sequence boundary has an upward coarsening trend, and it probably includes the highstand deposits.

Introduction

The marine siliciclastic Upper Jurassic and Lower Cretaceous deposits of the Danish Subbasin (fig. 1) are represented in several deep wells. A sequence stratigraphic study based on petrophysical logs has been carried out. The resolution of conventional seismic sections was demonstrated to be insufficient for a sequence stratigraphic analysis. The log analysis is integrated with biostratigraphic data and with sedimentary facies from core samples to establish chronostratigraphic and genetic relationships between deposits of the marginal and the central parts of the subbasin. The present paper describes the sequence stratigraphy of the Flyvbjerg, Børglum and Frederikshavn Formations in four wells (fig. 2), which represent both shallow marine and fine-grained deeper shelf environments. Sequences, parasequence sets and parasequences are identified and correlated.
Some stratigraphic analyses have previously been published, e.g. lithology and chronostratigraphy by Sorgenfrei & Buch (1964), and biostratigraphy by Davey (1982). The lithostratigraphy was described by Larsen (1966) and supplementary details are found in Michelsen (1978, 1989) and Michelsen & Nielsen (1991).

Geological setting

The Danish Subbasin is a part of the northwest-southeast oriented Norwegian-Danish Basin, which is considered as an epicontinental basin. It is bordered to the southwest by the Ringkøbing-Fyn High (fig. 1). To the northeast the subbasin is bordered by the Fennoscandian Border Zone, including Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform. To the west the Danish Subbasin is bordered by the middle Mesozoic Lista Nose. The Danish Subbasin experienced only minor tectonic activities since the early Mesozoic (EUGENO-S, 1988).
The Danish Subbasin developed during the Triassic, and more than 5 km of mostly continental sediments were accumulated (Bertelsen, 1980). The rate of subsidence decreased during the Late Triassic, and mainly marine sedimentation dominated the area (Michelsen, 1978; Bertelsen, 1980). A Middle Jurassic tectonically controlled local subsidence is indicated within the Sorgenfrei-Tornquist Zone (Michelsen & Nielsen, 1991). During the Late Jurassic and the Early Cretaceous the tectonic activity decreased to a minimum as a conse-

quence of the cooling of the lithosphere (Vejbæk, 1990). The Late Cretaceous to Early Tertiary tectonic inversion of this zone are described by Liboriussen et al. (1987) and EUGENO-S (1988).
Three cycles of continental/shallow marine to marine sedimentation took place during the Rhaetian-Early Jurassic, Middle-latest Jurassic, and latest Jurassic-Early Cretaceous times (Larsen, 1966). The marine influence in the Danish Subbasin increased during the Cretaceous period and culminated during the Late Cretaceous.
Parts of the second and third cycles, reflecting the Late Jurassic and earliest Cretaceous basin development, are theme of this paper. At the beginning of the Late Jurassic shallow marine sedimentation dominated in the Danish Subbasin (Flyvbjerg Formation). The succeeding deeper marine sedimentation (Børglum Formation) took place during the latest Oxfordian and the Kimmeridgian. The marine dominans continued in the western-central parts of Danish Subbasin through the remaining part of the Jurassic and through most of the Early Cretaceous (Vedsted Formation). In the northern marginal part of the subbasin, shallow marine silt and sand (Frederikshavn Formation) were deposited during the Late Kimmeridgian to Valanginian, and deeper marine conditions (Vedsted Formation) occurred in the remaining part of the Early Cretaceous (Michelsen, 1978, 1989).

Materials and methods

The interpretation of lithology and sedimentary facies is based on the petrophysical logs and cuttings and core sample descriptions from the Frederikshavn-1, Børglum-1, Haldager-1 and Hyllebjerg-1 wells. The gamma ray, SP, resistivity and sonic logs are used, and occasionally also the neutron-density logs. Cores from the Frederikshavn-1 well were studied at selected intervals to support the log interpretation, and to describe changes in sedimentary facies across some sequence stratigraphic surfaces. Interpretation of the depositional environment is supported by biostratigraphy, which also is used to establish the chronostratigraphic subdivision. Individual depositional systems are grouped into depositional sequences, bounded by unconformities and their correlative conformities in accordance with the concepts of Mitchum et al. (1977) and Van Wagoner et al. (1988; 1990).

Sequence stratigraphy

The Flyvbjerg Formation is dominated by shallow marine (and non-marine?) siltstone and claystone, and the Børglum Formation by claystone deposited in a deeper shelf situation. The Frederikshavn Formation comprises of sandy, silty and clayey deposits, reflecting repeated changes from near coastal to fully marine conditions (Larsen, 1966; Michelsen, 1978).
A sequence stratigraphic interpretation of the three formations is presented in figure 2, which includes the Frederikshavn-1, Børglum-1, Haldager-1 and Hyllebjerg-1 wells. The Frederikshavn-1 well represents a marginal situation in the basin, and Hyllebjerg-1 the central part of the basin. The two other wells are located in an intermediate position, which occasionally during the Late Jurassic-earliest Cretaceous is dominated by near coastal environments (Larsen, 1966).
The observed cyclic character of these siliciclastic sediments is the basis for recognition of candidates for sequence boundaries and maximum flooding surfaces. Parasequences and parasequence sets are identified in the individual wells, mainly on the basis of the gamma ray and SP logs.

Flyvbjerg and Børglum Formations

The Flyvbjerg Formation is probably separated from the underlying Haldager Sand Formation by a regional hiatus. The top of the Haldager Sand Formation is of Late Callovian age (or younger), and the base of the Flyvbjerg Formation is of Middle to Late Oxfordian age, being youngest in northern marginal part of the subbasin (Poulsen, 1993). The boundary between the two formations is here suggested as the lower boundary of the lowermost sequence, S-1 (fig. 2).

The log patterns of the Flyvbjerg Formation have an upward coarsening trend, reflecting a transition from claystone lowermost to silt- and sandstone uppermost. This trend is best developed in the central parts of the Danish Subbasin. The upward coarsening section probably reflects a basinward migration of the coastline, and may be interpreted as the lowermost lowstand deposits of sequence S-1.

The base of the overlying Børglum Formation is of Early Kimmeridgian age in the central part of the subbasin (Hyllebjerg-1), but seems to get younger (Late Kimmeridgian age) towards the margin of the subbasin (Poulsen, 1993). The fully marine claystones of the formation probably represent the transgressive conditions following the shallow marine prograding deposits of the Flyvbjerg Formation, and the lower boundary of the Børglum Formation is regarded as a major transgressive surface. The Børglum Formation can be divided into two parts of almost equal thickness. The lower part is characterized by upward increasing gamma ray and decreasing resistivity values, indicating an upward increasing clay content (fig. 2). Upward decreasing gamma ray values characterize the upper part of the formation, reflecting an increasing silt/clay ratio, which is probably to be a result of shallowing conditions. This interpretation is also supported by an upward increasing ratio between terrestrial and marine palynomorphs (Andersen, 1988). The lower and upper parts of the Børglum Formation are separated by a level with maximal marine conditions, that easily can be correlated between all wells (fig. 2). This level is interpreted as a maximal marine flooding surface.

The upper boundary of sequence S-1 coincides with the boundary between the Børglum and Frederikshavn Formations, which will be described below.

Frederikshavn Formation

The gamma ray and SP logs of the Frederikshavn Formation show a pronounced cyclic character, representing changes from near coastal coarse-grained deposits to fully marine clayey facies. The formation is here subdivided into five depositional sequences: The Late Jurassic S-2, S-3 and S-4 sequences and the Early Cretaceous S-5 and S-6 sequences (fig. 2).

The lower boundary of sequence S-2 coincides with the boundary between the Børglum and Frederikshavn Formations. The formation boundary is characterized by an upward decreasing gamma ray trend and an abrupt increase in sonic velocities, reflecting a change to silty and sandy deposits. A basinward shift in facies across the boundary is also seen in a core from the Frederikshavn-1 well (fig. 3). Biostratigraphic data and an abrupt decrease in the gamma ray log from the Sæby-1 well indicate the presence of a hiatus at this boundary, but the hiatus seems to disappear towards the central part of the subbasin. The sequence boundary is of Early Volgian age and is suggested to be synchronous throughout the subbasin by Poulsen (1993).

The gamma ray and SP curves of sequence S-2 reflect upward fining deposits overlain by upward coarsening deposits. The maximum flooding surface is located at the highest gamma ray values, which in the central part of the subbasin (Hyllebjerg-1) are found close to the lower sequence boundary (fig. 2). The interval between the lower boundary and the maximum flooding surface can not be interpreted clearly in the context of lowstand and transgressive deposits. However, an upward coarsening trend occurs lowermost in the Frederikshavn-1 well, indicating the presence of prograding lowstand deposits in the marginal part of the subbasin. The interval above the maximum flooding surface shows a pronounced upward shift to coarse-grained facies, which is interpreted as prograding conditions (fig. 2).

Sequence S-2 is overlain by two thin sand-dominated intervals, characterized by a blocky SP log pattern in the Børglum-1 and Haldager-1 wells (fig. 2). These two intervals are identified as sequences S-3 and S-4, and interpreted as stacked lowstand deposits situated in an intermediate position of the basin. Sequence S-3 seems to be thinning in the landward direction, and a transgressive-regressive succession following the lowstand deposits is not recognized in the present well data, but could be present northeast of the study area (in the landward direction) or it may have been removed by erosion. A Middle Volgian age is assigned to deposits at the lower boundary of sequence S-3 marginally in the subbasin (Sæby-1). Equivalent deposits is dated slightly younger in the Frederikshavn-1 well (Andersen, 1988).

The lower boundary of sequence S-4 is dated to the Early Portlandian (latest Middle Volgian) in Haldager-1 (Davey, 1982) and Middle (or Late) Volgian in the marginal Sæby-1 well. The log features of sequence S-4 changes in the landward direction from the blocky pattern to a cyclic pattern (Frederikshavn-1 in fig. 2). The sequence comprises here two parts separated by a possible maximum flooding surface. An increased content of glauconite is described from the interval comprising this surface (Larsen, 1966). The interval above the maximum flooding surface in Frederikshavn-1 comprises two upward decreasing gamma ray trends (parasequences), and is characterized by overall upward coarsening deposits (figs 2 and 4). Frequent occurrences of wood debris, decreasing content of glauconite and a higher ratio of terrestrial/aquatic palynomorphs (Andersen, 1988) in this upper part of sequence S-4 probably reflects a basinward migration of the lithofacies.

The lower sequence boundary of the overlying sequence S-5 is of latest Early Portlandian age (Davey, 1982). The deposits immidiately above the sequence boundary in the Haldager-1 well is possible of Late Portlandian age (Davey, 1982).

The gamma ray pattern of sequence S-5 shows a cyclic character with an increasing trend followed by a decreasing trend. The maximum flooding surface is located in the interval with the highest gamma ray values, which is a clay-dominated deposit. The interval below the maximum flooding surface in the Børglum-1 and Haldager-1 wells includes two sand/silt sections interbedded by a thin clayey interval. The lower sand section may be interpreted as lowstand deposits, which is not present in the more proximally located Frederikshavn-1 well, and the upper sand may represent the basal part of the transgressive deposits. The Portlandian-Ryazanian transition is found between the two sandy sections in the Haldager-1 well (Davey, 1982). Time equivalent transition is also found immidiately above the sequence boundary in the Frederikshavn-1 well (Andersen, 1988) and in the nearby Sæby-1 well.

The clay-dominated interval with the maximum flooding surface of S-5 is followed by upward coarsening deposits. The sandy/silty sections become thicker and more coarse-grained upwards; and more coarse-grained sediments occur in the Børglum-1 well than in Haldager-1. This part of the sequence is interpreted as a succession of prograding parasequence sets. The interval is terminated by a sudden decrease in gamma ray, indicating a basinward shift of lithofacies, which is interpreted as the boundary between sequence S-5 and S-6. This sequence boundary is of Valanginian age (Davey, 1982).

Sequence S-6 comprises a lower coarse-grained part and an upper fine-grained part. The log pattern of the lower part has a blocky appearance in the Frederikshavn-1, Børglum-1 and Haldager-1 wells (fig. 2). In Frederikshavn-1 the blocky interval is succeeded by increasing gamma ray values, corresponding to an upward increase in the content of clay and glauconite (Larsen, 1966). The palynoform assemblages reflect an increasing distance from coast (Andersen, 1988). The increasing gamma ray trend is separated from the upper part by a gamma ray maximum, which is interpreted as the maximum flooding surface. The upper part is thickest in landward direction (Frederikshavn-1), and it is more fine-

grained and comprises a higher content of shelf fossils than below the maximum flooding surface (Andersen, 1988). The interval above the maximum flooding surface thins in basinward direction, as it also was the case in sequence S-4 (fig. 2).
The upper boundary of sequence S-6 is located uppermost in the Frederikshavn Formation in the Børglum-1 and Haldager-1 wells and in the lower part of the overlying Vedsted Formation in the Frederikshavn-1 well. In Børglum-1 and Haldager-1, the boundary is placed at the base of a blocky log pattern, which represents coarse-grained deposits, interpreted as a basinward shift in lithofacies. If our sequence stratigraphic interpretation is correct it implies that the Frederikshavn/Vedsted Formation boundary is diachronous. The chronostratigraphic significans of our interpretation can hardly be confirmed by the available biostratigraphy, which indicates a Middle or Upper Valanginian age. Further biostratigraphic analyses are necessary to evaluate the validity of our interpretation of the transition from sequence S-6 to S-7.

Conclusion

The Upper Jurassic to lowermost Cretaceous Flyvbjerg, Børglum and Frederikshavn Formations are subdivided into six sequences, and the presence of parasequences and parasequence sets is indicated by log interpretation in a number of wells and by lithological analysis of core samples from the Frederikshavn-1 well. The chronostratigraphic significance of the sequences is supported by biostratigraphy in the tree wells: Frederikshavn-1, Haldager-1 and Hyllebjerg-1.
Sedimentary cycles interpreted as parasequences and parasequence sets are mainly recognized in the shallow marine sediments. More basinward the silt and sand supply is reduced, and a parasequence interpretation is difficult to perform on the basis of logs.
It has been difficult to carry out a systems tract interpretation (sensu Posamentier et al., 1988), because of the large distances (30-50 km) between the wells and of the fact that the available seismic sections were not useable. However, the cyclic log feature of the sequences is interpreted as a succession of upward fining deposits overlain by upward coarsening deposits. The blocky log pattern and the upward coarsening trend lowermost in the sequences represent sand-dominated deposits, which are regarded as lowstand deposits caused by forced regression in a epicontinental setting (Posamentier et al., 1992). The overlying interval with upward fining deposits may comprise transgressive deposits, and the gamma ray maximum is suggested to represent the maximum flooding surface. The interval between this surface and the upper sequence boundary is characterized by upward coarsening deposits, especially in sequences S-2 and S-5 and it may include highstand deposits.

References

Andersen, E., 1988: Nedre Kridt floraen i Frederikshavn nr. 1. Unpublished Thesis, Laboratory of Palynology, Aarhus University, Denmark, text volume 130 pp.

Bertelsen, F., 1980: The Upper Triassic-Lower Jurassic Vinding and Gassum Formations of the Norwegian-Danish Basin. Danm. geol. Unders., Ser. B, 3, 26 pp.

Davey, R.J., 1982: Dinocyst stratigraphy of the latest Jurassic to Early Cretaceous of the Haldager No. 1. borehole. Denmark, Danm. geol. Unders., Ser. B, 6, 57 pp.

EUGENO-S Working Group, 1988: Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO-S project). Tectonophysics, 150, 253-348.

Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988: Eustatic controls on clastic deposition I - Conceptual framework. In C.K.Wilgus, H. Posamentier, C.A. Ross & C.G.St.C. Kendall (eds.) Sea-level changes. - An integrated approach. Soc. Econ. Paleont. Mineralog., Special publication 42, 71-108.

Larsen, G., 1966: Rhaetic-Jurassic-Lower Cretaceous Sediments in the Danish Embayment. Danm. geol. Unders., II, 91, 127 pp.

Liboriussen, P., Asthon, P. & Tygesen, T., 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics, 137, 21-29.

Michelsen, O., 1978: Stratigraphy and distribution of Jurassic deposits of the Norwegian-Danish Basin. Danm. geol. Unders., Ser. B, 2, 28 pp.

Michelsen, O., 1989: Revision of the Jurassic lithostratigraphy of the Danish Subbasin. Danm. geol. Unders., Ser. A, 25, 23 pp.

Michelsen, O. & Nielsen, L.H., 1991: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark. Danm. geol. Unders., Ser. A, 29, 37 pp.

Mitchum, R.M., Vail, P.R. & Thompson III, S., 1977: Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis. In C.E. Payton (ed.) Seismic Stratigraphy- application to hydrocarbon exploration, - Am. Assoc. Petrol. Geol., Mem. 26, 53-62.

Mitchum, R.M. & Van Wagoner, J.C., 1991: High-frequency sequences and their stacking patterns: Sequence stratigraphic evidence of high-frequency eustatic cycles. Sedimentary Geology, 70, 131-160.

Posamentier, H.W., Allen, G.P., James, D.P. & Tesson, M., 1992: Forced Regressions in a Sequence Stratigraphic Framework: Concepts, Examples, and Exploration Significance. Am. Assoc. Petrol. Geol., Bull. 76, 11, 1687-1709.

Posamentier, H.W., Jervey, M.T., Vail, P.R., 1988: Eustatic controls on clastic deposition I - Conceptual framework. In C.K.Wilgus, H. Posamentier, C.A. Ross & C.G.St.C. Kendall (eds.) Sea-level changes. - An integrated approach. Soc. Econ. Paleont. Mineralog., Special publication 42, 109-124.

Poulsen, N.E., 1993: 4. Report on the Oxfordian in the Danish Subbasin based on dinoflagellate cysts. IUGS - Newsletter, June 1993, 23-30.

Sorgenfrei, T. & Buch, A., 1964: Deep Tests in Denmark 1939-1959. Danm. geol. Unders., III, 36, 146 pp.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, T.S. & Hardenbol, J., 1988: An overview of the fundamentals of Sequence Stratigraphy and Key definitions. In C.K.Wilgus, H. Posamentier, C.A. Ross & C.G.St.C. Kendall (eds.) Sea-level changes. - An integrated approach. Soc. Econ. Paleont. Mineralog., Special publication 42, 39-45.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. & Rahmanian,V.D., 1990: Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies. Am. Assoc. Petrol. Geol., Methods in Exploration Series, 7. 55 pp.

Vejbæk, O.V., 1990: The Horn Graben and its relationship to the Oslo Graben and the Danish Basin. Tectonophysics 178, 29-49.

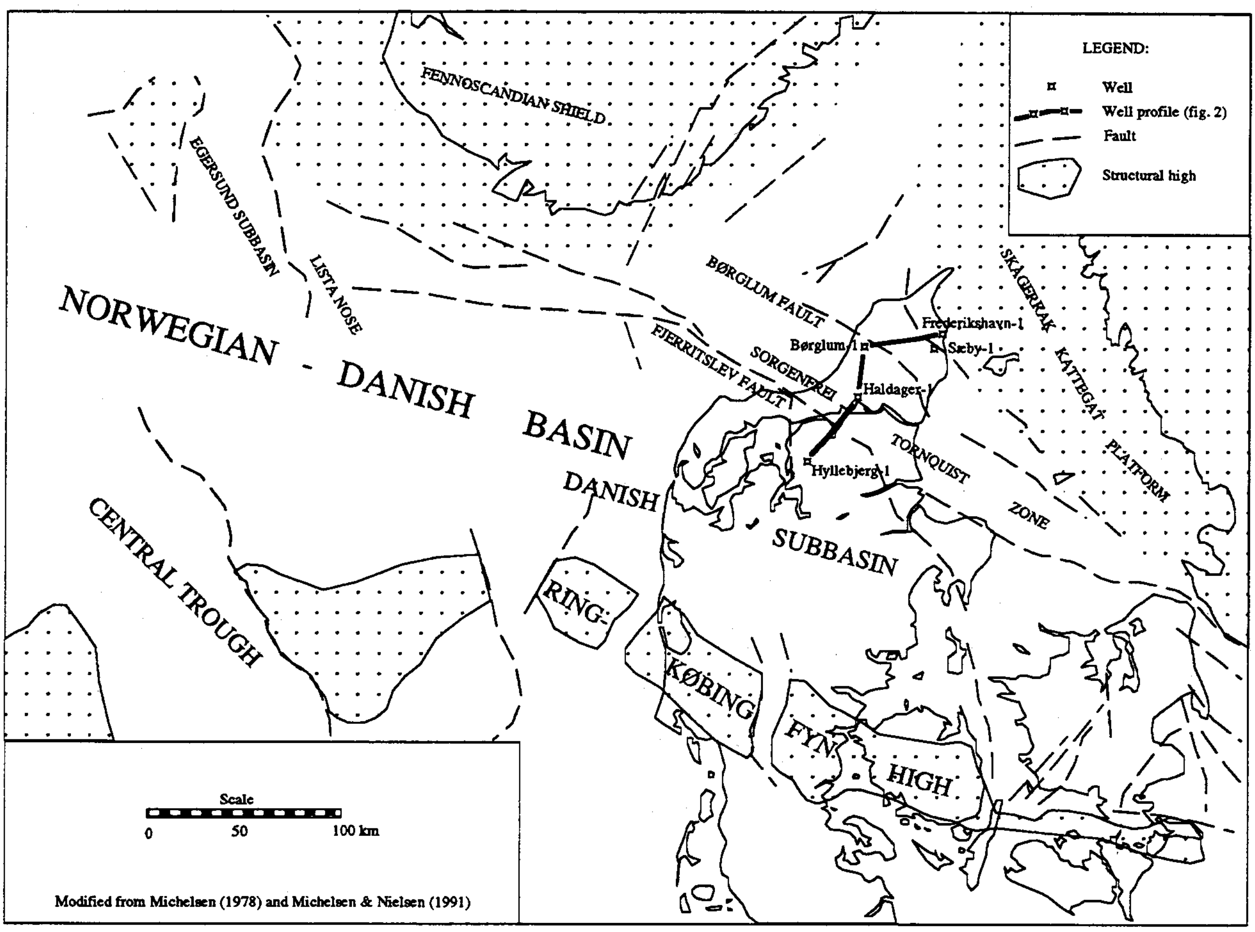


Fig. 1 Structural map of the Norwegian - Danish Basin (including the Danish Subbasin). Locations of wells mentioned in the text are indicated.

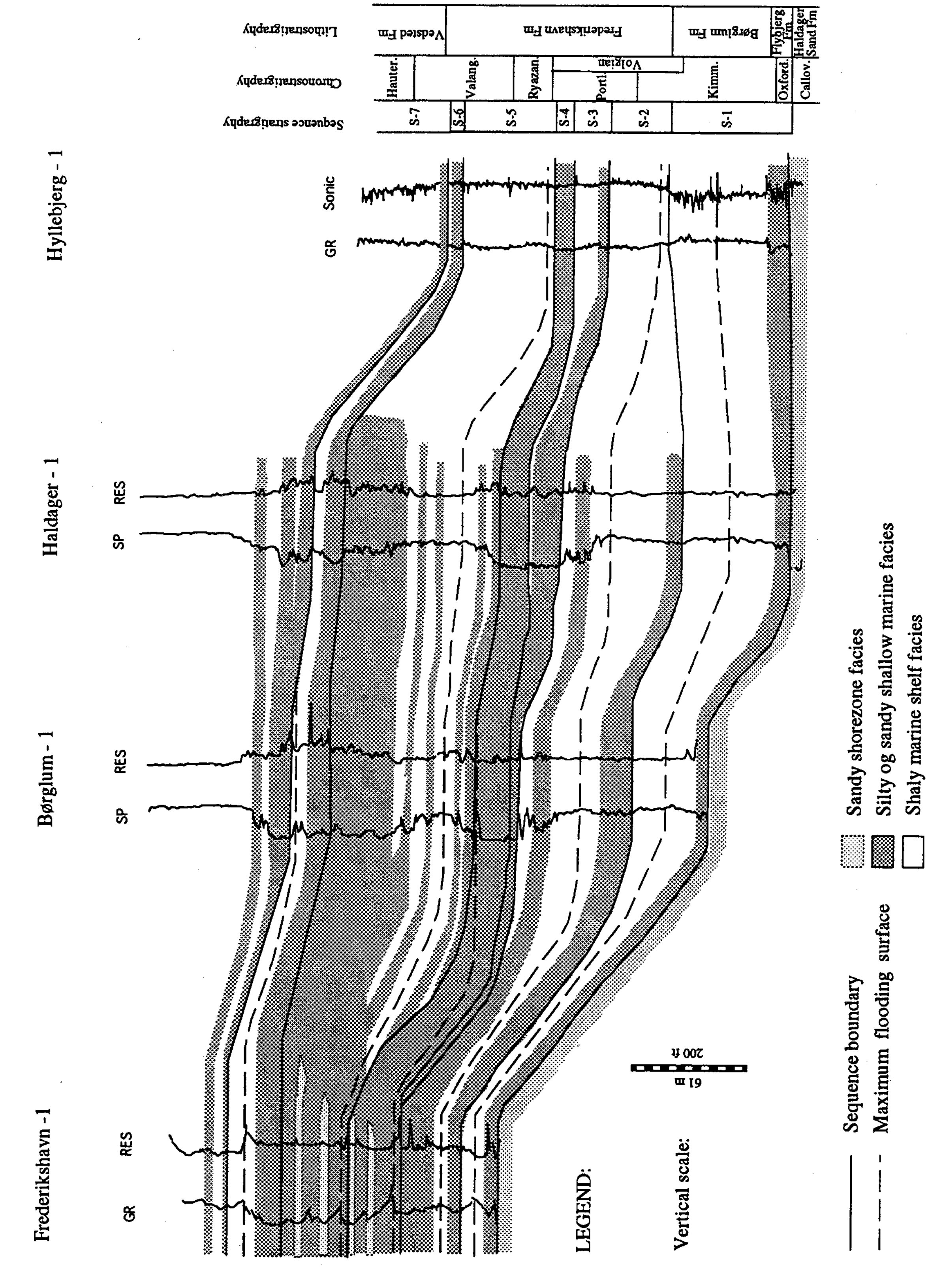
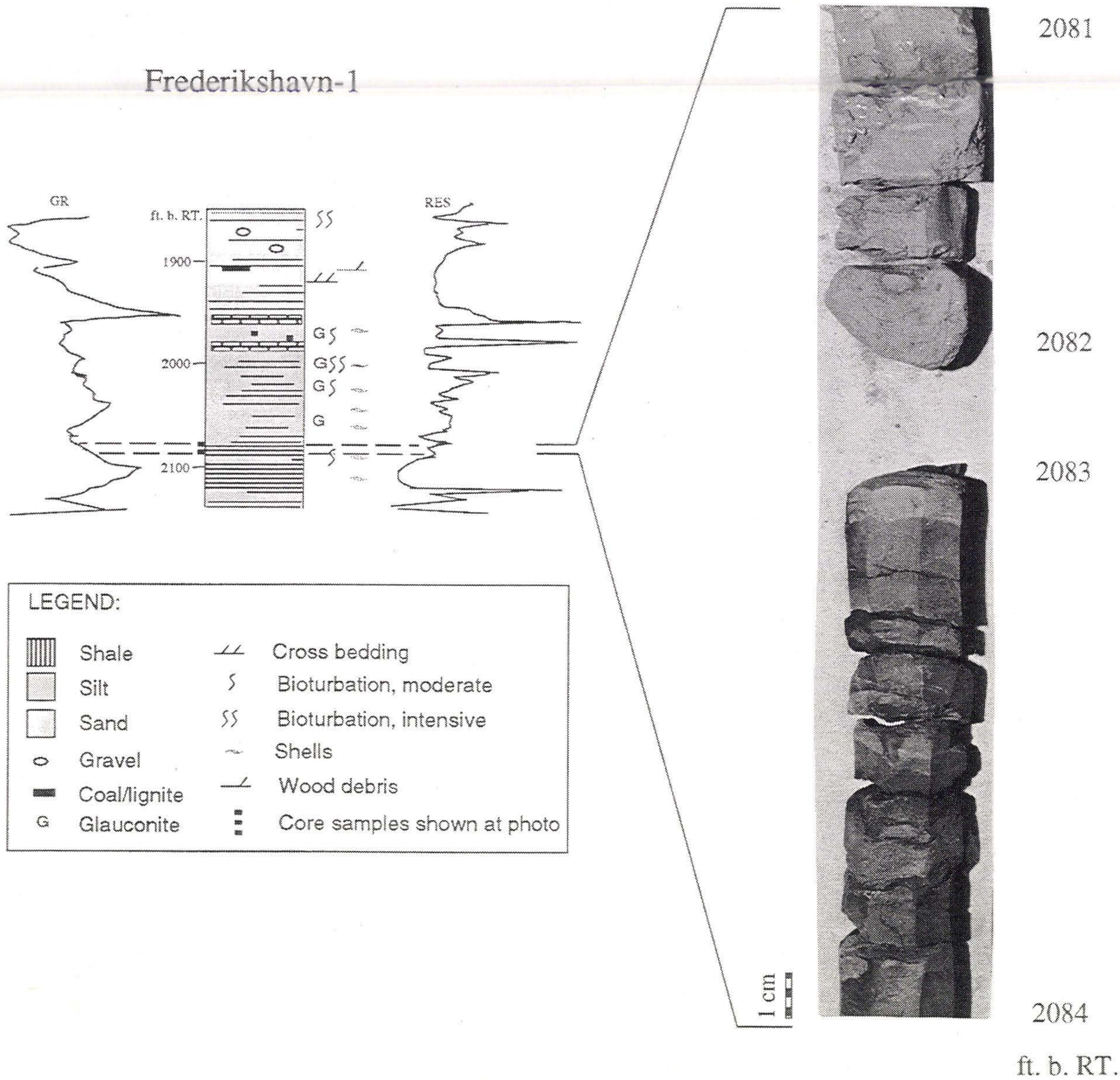


Fig. 2 Sequence interpretation of the Flyvbjerg-, Børglum- and Frederikshavn Formations in four wells from the marginal and central parts of the DanishSubbasin. See fig. 1 for well locations.



Core description:

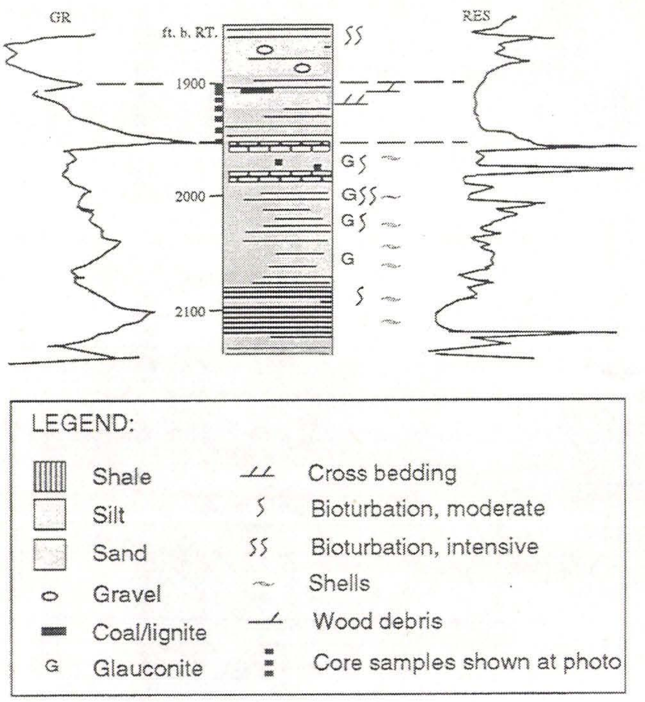
2081-2082 ft. b. RT:
Light grey to light green silt interbedded with thin shales.
More greenish glauconitic sediments and more bivalve debris, than the core samples below.

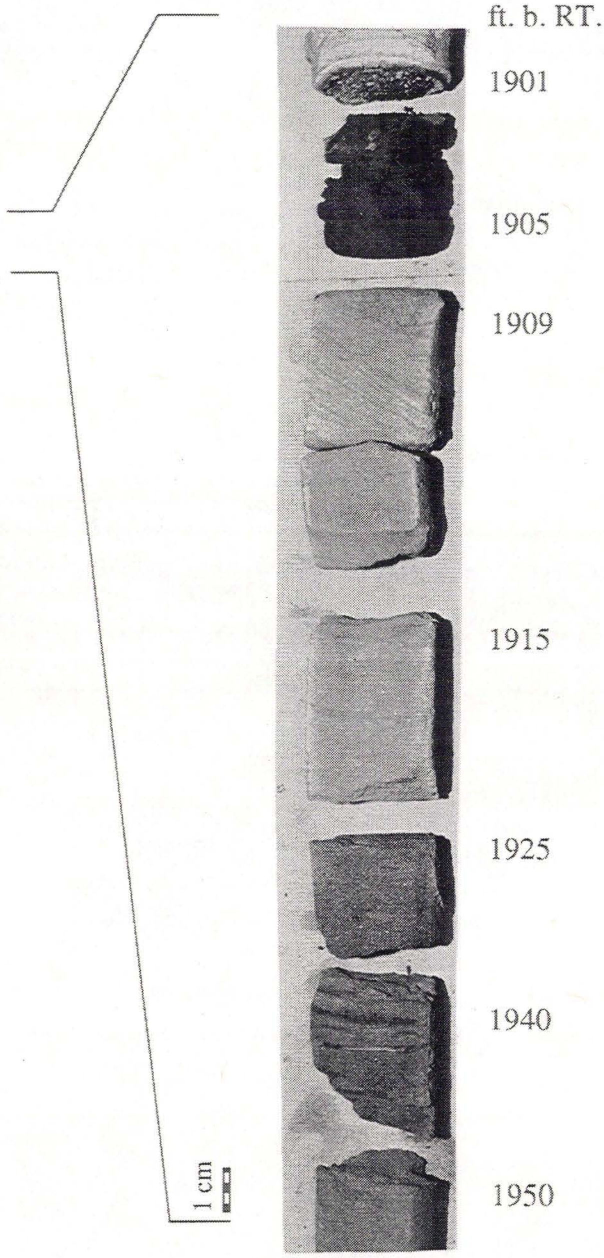
2083-2084 ft. b. RT:
Dark grey shale and claystone, interbedded by thin light grey clayey fine silt layers (thickness: 0,5-1 cm). The claystone is consolidated and contains some light deform areas, inpartikular just above the clayey fine silt layers and some small thin bivalve shells.

Interpretation of depositional environment:

The lower clayey part seems to be bioturbated. The relative dark clayey facies with small thinshelled bivalves indicates a marine shelf environment. The increasing silt content and increasing bed thicness reflects a relative abrupt change to shallow marine conditions.
Notice the horisontal boundary between the dark shelf sediments and the lighter silt just below 2083 ft. It is considered to be the first regional basinward faciesshift, indicating a more close position of the coast.

Fig. 3 Description of lithology and interpretation of depositional environment in core samples from 1901-1950 ft. b. RT. in the Frederikshavn-1 well.





Core description:

1901 ft. b. RT:
Light greyish green fine-grained glauconite sand interbedded with thin claystone.

1905 ft. b. RT:
Dark grey brown coal/lignite and shale with silt and wood debris.

1909 ft. b. RT:
Light grey green fine- and medium-grained sandstone interbedded by thin grey shale.
The sandstones (1909-1915 ft) is mostly thicker than in the interval below and crossbedded (20-45°).

1915 ft. b. RT:
Light green micacous coarse-grained siltstone interbeded by shale.
Core pieces with siltstone is thinner than above and contains in part planar bedded sandstone.

1925 &1940 ft. b. RT:
Grey to red brown silty shale og siltstone.
Where it is reddish it seems more consolidated and sometimes it is ionstone.
The grey green fine grained siltstone resamples the core sample at 1915 ft, but is more fine-grained.

1950 ft. b. RT:
Olive greenish glauconite silt- and fine-grained sand.

Interpretation of depositional environment:

The high content of greenish glauconite in the lower and upper part of the succession indicates with the silty sediments shallow marine conditions.
From bottom to the top the content of glauconite decreases, and the grain size and the thickness of the fine- and medium-grained sandstone increases and crossbedding can be seen.
This indicates upward increasing (wave-) energy level, that could be due to a relative lowering of sealevel or increased sediment supply.
This progradation is terminated by lagunal shale.
The succession probably reflects a prograding beach- or barrier-island environment, drowned and succeed by shallow marine glauconitic silt- and fine-grained sandstone.

Fig. 4 Description of lithology and interpretation of depositional environment in core samples from 2081-2084 ft. b. RT. in the Frederikshavn-1 well.

Jurassic palynostratigraphy of Bornholm, Baltic Sea, Denmark

Eva Bundgaard Koppelhus

Material and methods

Samples of the Rønne Formation have been collected from exposures at Munkerup, Sose Bugt and Galgeløkke and two boreholes, Galgeløkke-1 and -2, at Galgeløkke south of Rønne (Fig. 1). The Hasle Formation was sampled at the type section south of Hasle harbour, at Korsodde and from the Levka-1 and Hasle-1 boreholes. The Bagå Formation, that consists of the previously defined Levka, Sorthat and Bagå beds (Gry, 1969; Gravesen et al. 1982), was sampled from two sections within the Hasle Klinkerfabrik clay pit, from the coastal section at Korsodde, and from four cored boreholes the Levka-1, 106, 107 and 109 at the Hasle Klinkerfabrik clay pit (Nielsen & Koppelhus 1989, 1991; Koppelhus & Nielsen 1994). The samples were processed for their palynological content using the standard techniques developed at the Geological Survey of Denmark (Poulsen et al., 1990). They were examined by transmitted light microscopy. All of the slides are stored in the collections of the Department of Stratigraphy at the Geological Survey of Denmark.

Biozones

The palynomorph assemblages from the Rønne Formation are refered to two miospore zones, the *Pinuspollenites-Trachysporites* Zone and the *Cerebropollenites macroverrucosus* Zone (Fig.2) (Koppelhus 1991). These miospore zones were established in a palynological study of the Rhaetian and lower Jurassic sequence penetrated by the Rødby no. 1 well (Lund, 1977). Most of the samples from the Hasle Formation were barren. However, close to the boundaries to the underlying Rønne and overlying Bagå Formations, the Hasle Formation yielded palynomorph assemblages, which can be refered to the *Chasmatosporites* Zone and the *Mendicodinium reticulatum* Zone (proposed in Koppelhus & Nielsen 1994). Six biozones are recognized in the Bagå Formation; three are based on miospores and three on dinoflagellate cysts. The three miospore zones are the *Chasmatosporites* Zone, the *Spheripollenites-Leptolepidites* Zone of Dybkjær (1991) and the *Callialasporites-Perinopollenites* Zone also of Dybkjær (1991) but emended in Koppelhus & Nielsen (1994). The dinoflagellate cyst zones are the *Mendicodinium reticulatum* Zone, and the *Luehndea spinosa* and *Nannoceratopsis gracilis* Zones of Woollam & Riding (1983), emended by Riding & Thomas (1992).

Discussion

The palynological analysis of the lower part of the Bagå Formation showed that beside the previously recognized megaspores (Gry 1969; Koppelhus & Batten 1992) the palynomorph assemblages not only contained miospores, but also dinoflagellate cysts, which added new information to the interpretation of the environment and stratigraphy.
Mendicodinium reticulatum was found in the uppermost part of the Hasle Formation and the lowermost part of the Bagå Formation. This species is known from the Late Pliensbachian (*Margaritatus* zone) in northern Germany (Morgenroth, 1970). It shows an acme in the Bagå Formation, before any other dinoflagellate cysts appears. Further up section in the Bagå Formation several species from the genus *Nannoceratopsis* (*N. senex, N. gracilis, N. triceras)* become common. *Nannoceratopsis gracilis* has its first appearance in the Late Pliensbachian (*Margaritatus* zone) in UK (Woollam & Riding 1983; Wall, 1965). A thin interval in the middle part of the formation contain *Luehndea spinosa* and *Mancodinium semitabulatum.* These two species are also known from Late Pliensbacian in northwest Europe (Morgenroth 1970; Prauss 1989; Poulsen 1992; Riding & Thomas 1992). *L. spinosa* range from the *Margaritatus* to *Tenuicostatus* zone, however the range of *M. semitabulatum* is from the

Margaritatus zone to the upper part of early Bajocian. The recovered assemblages therefore indicate that Late Pliensbachian and Toarcian deposits are present onshore Bornholm.

Conclusions

The depositional environment changed repeatedly between non-marine and brackish-marine during the deposition of the Jurassic section. Thus the first and last appearances of various miospores and dinoflagellate cyst species are influenced by these changes. Therefore, to obtain the best stratigraphic resolution both the miospore and dinoflagellate cyst lowest appearences and acmes are used in the age determinations.
The combined palynological data show that the *Pinuspollenites-Trachysporites* Zone and the *Cerebropollenites macroverrucosus* Zone can be identified in the Rønne Formation and the *Chasmatosporites, Spheripollenites-Leptolepidites* and *Callialasporites-Perinopollenites* miospore Zones and the *Mendicodinium reticulatum, Luehndea spinosa* and *Nannoceratopsis gracilis* dinoflagellate cyst Zones can be identified in the Bagå Formation.
The biozones thus indicate that the Hettangian to Middle Jurassic time intervals are represented on Bornholm. It is not clear, however, how much of the Aalenian, Bajocian and Bathonian stages that are represented. This conclusion differs from that of Gry (1969) who referred both the exposures at Korsodde and the Levka, Sorthat and Bagå beds exclusively to the Middle Jurassic. Our data show that the lower part of the Korsodde section and the examined part of the Levka and Sorthat beds are of Late Pliensbachian-Toarcian age. The palynostratigraphy further confirms that the Levka and Sorthat beds are time equivalent units. The Bagå beds belong to the Middle Jurassic and do not appear to contain Toarcian deposits, contrary to the interpretation of Hoelstad (1985). The upper part of the Korsodde section is also dated as Middle Jurassic.

References

Dybkjær, K., 1991: Palynological zonation and palynofacies investigation of the Fjerritslev Formation (Lower Jurassic -basal Middle Jurassic) in the Danish Subbasin. Danmarks Geologiske Undersøgelse Serie A 30. 150 pp.

Fenton, J. & Riding, J., 1987: *Kekryphalospora distincta* gen. et sp. nov., a trilete spore from the Lower and Middle Jurassic of North-West Europe. Pollen et Spores 19, 427-434.

Gravesen, P., Rolle, F. & Surlyk, F., 1982: Lithostratigraphy and sedimentary evolution of the Triassic, Jurasssic and Lower Cretaceous of Bornholm, Denmark. Danmarks Geologiske Undersøgelse Serie B 7. 51 pp.

Gry, H., 1969: Megaspores from the Jurassic of the Island of Bornholm, Denmark. Meddelelser fra Dansk Geologisk Forening 19, 69-89.

Hoelstad, T., 1985: Palynology of the uppermost Lower to Middle Jurassic strata on Bornholm, Denmark. Bulletin of the Geological Society of Denmark 34, 111-132.

Koppelhus, E.B., 1991: Palynology of the Lower Jurassic Rønne Formation on Bornholm, eastern Denmark. Bulletin of the Geological Society of Denmark 39, 91-110.

Koppelhus, E.B. & Batten D.J., 1992: Megaspore assemblages from the Jurassic and lowermost Cretaceous of Bornholm, Denmark. Danmarks Geologiske Undersøgelse Serie A 32. 81 pp.

Koppelhus, E.B. & Nielsen, L.H., 1993: Palynologisk zonation af Nedre og Mellem Jura på Bornholm. Maringeologisk møde, Århus Universitet, Nordsøens og Skagerraks geologi. Abstract vol., 21.

Koppelhus, E.B. & Nielsen, L.H., MS.: Palynostratigraphy and palaeoenvironments of the Lower to Middle Jurassic Bagå Formation of Bornholm, Denmark. Palynology, 18, 139-194.

Lund, J.J., 1977: Rhaetic to lower Liassic palynology of the onshore south-eastern North Sea Basin. Danmarks Geologiske Undersøgelse II Række 109, 1-129.

Morgenroth, P., 1970: Dinoflagellate cysts from the Lias Delta of Lühnde/Germany. Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, 136, 345-349.

Nielsen, L.H. & Koppelhus, E.B., 1989: Results of the project: Biostratigraphy and organic geochemistry of the Mesozoic on Bornholm. Final report 1.7.1989. Report no. 49. Geological Survey of Denmark, 44 pp.

Nielsen, L.H. & Koppelhus, E.B., 1991: Reworked Carboniferous palynomorphs from Lower Jurassic deposits on Bornholm and their palaeogeographic implications. Bulletin of the Geological Society of Denmark 38, 253-266.

Poulsen, N.E., 1992: Jurassic dinoflagellate cyst biostratigraphy of the Danish Subbasin in relation to sequences in England and Poland; a preliminary review. Rev. Palaeobot. Palynol. 75, 33-52.

Poulsen, N.E. Gudmundson, L., Hansen, J.M. & Husfelt, Y., 1990: Palynological preparation techniques, a new macerationtank-method and other modifications. Danmarks Geologiske Undersøgelse Serie C 10. 22 pp.

Prauss, M., 1989: Dinozysten-Stratigraphie und Palynofazies im Oberen Lias und Dogger von NW-Deutschland. Palaeontographica B 214, 1-124.

Riding, J.B. & Thomas, J.E., 1988: Dinoflagellate cyst stratigraphy of the Kimmeridge clay (Upper Jurassic) from the Dorset coast, Southern England. Palynology, 12, 65-88.

Riding, J.B. & Thomas, J.E., 1992: Dinoflagellate cysts of the Jurassic system. *In*: Powell, A.J. (ed.), A stratigraphic index of dinoflagellate cysts. British Micropalaeontological Society Series, Chapman & Hall, London, xii + 290 pp.

Wall, D., 1965: Microplankton, pollen and spores from the Lower Jurassic in Britain. Micropaleontology 11, 151-190.

Woollam, R. and Riding, J.B., 1983: Dinoflagellate cyst zonation of the English Jurassic. Institute of Geological Sciences Report, 83 (2), 42 pp.

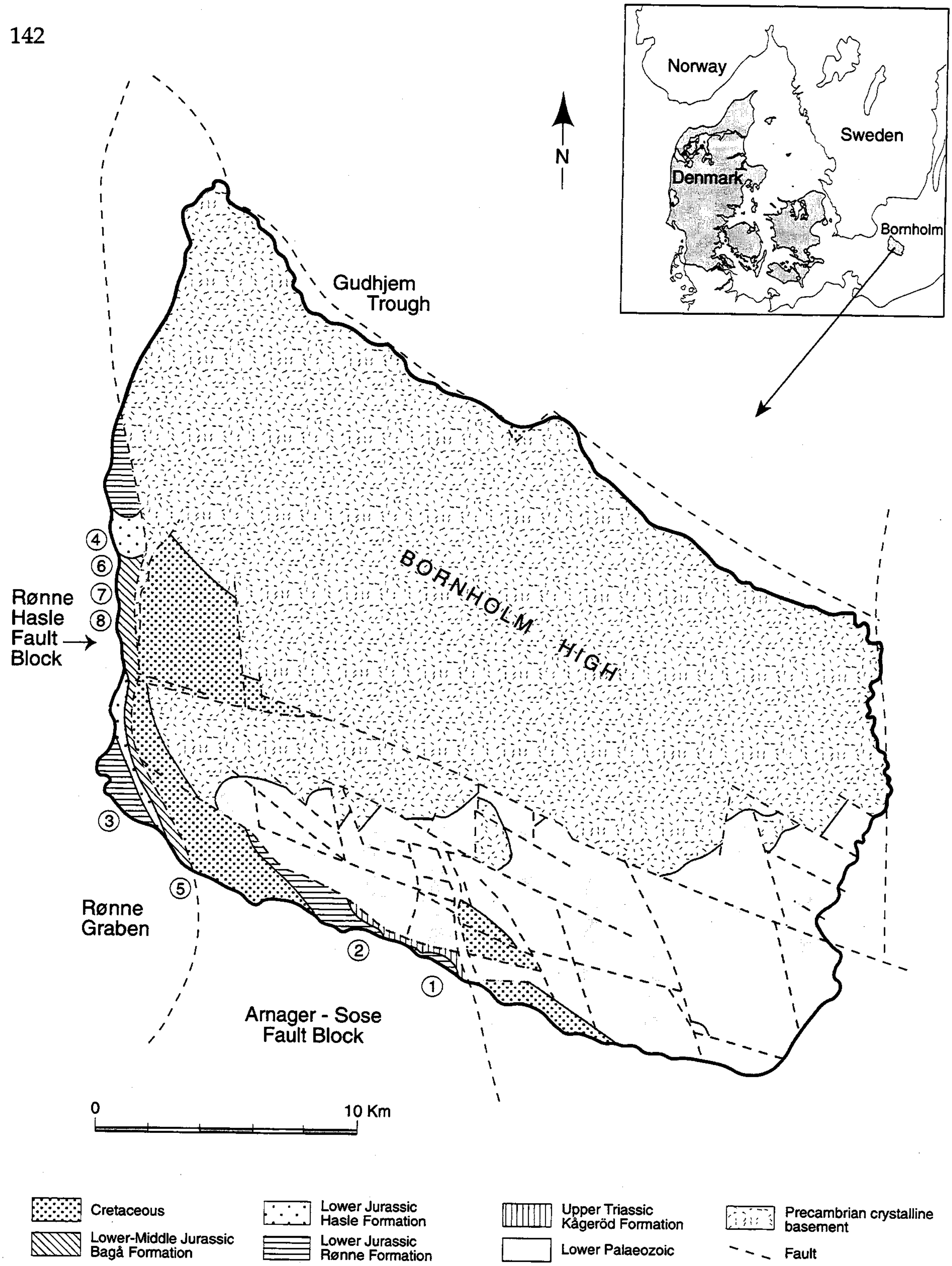


Fig. 1 Geological map of Bornholm with outcrop localities and boreholes indicated. Loc. 1: Type section of the Munkerup Member. Loc. 2: Type section of the Sose Bugt Member. Loc. 3: Type section of the Galgeløkke Member, and well-site of the Galgeløkke-1 & -2 borehole Loc. 4: Type section of the Hasle Formation Loc. 5: The Korsodde section. Loc. 6. The Hasle-1 borehole. Loc. 7: The Levka-1 borehole. Loc. 8: Hasle Klinkerfabrik clay pit, with boreholes 106, 107 and 109. Modified fra Gravesen et al. (1982). Inset map shows Denmark and Bornholm.

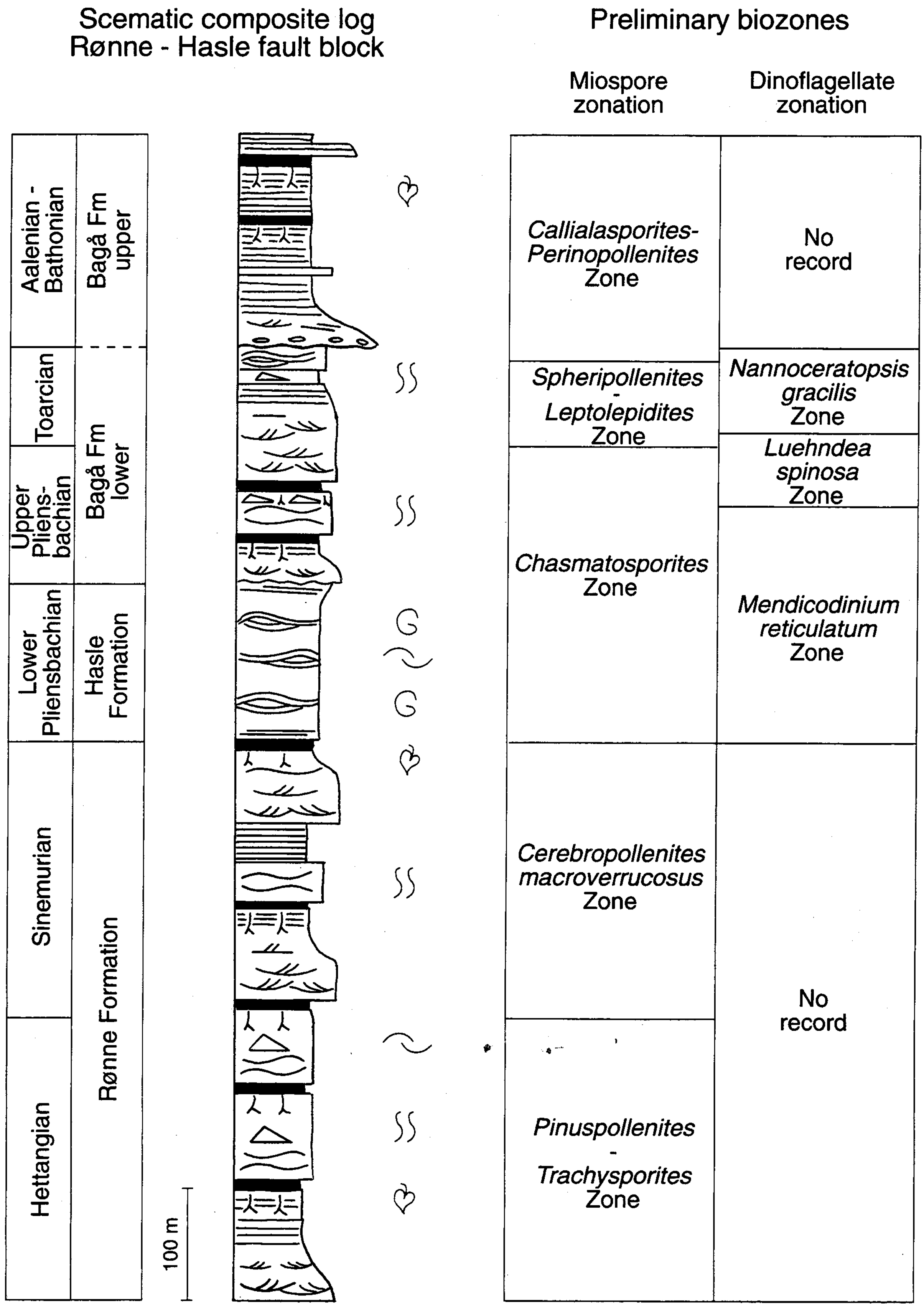


Fig. 2 Schematic composite log representing the Jurassic deposits in the Rønne-Hasle Fault Block, Bornholm.

STAGE	BORNHOLM	MIOSPORE ZONATION	DINOFLAGELLATE ZONATION
Bathonian	? ?	*Callialasporites-Perinopollenites* Zone	No record
Bajocian	Bagå Fm		
Aalenian			
Toarcian		*Spheripollenites-Leptolepidites* Zone	*Nannoceratopsis gracilis* Zone
Pliensbachian	Hasle Fm	*Chasmatosporites* Zone	*Luehndea spinosa* Zone; *Mendicodinium reticulatum* Zone
Sinemurian	Rønne Fm: Galgeløkke Mb; Sose Bugt Mb	*Cerebropollenites macroverrucosus* Zone	No record
Hettangian	Rønne Fm: Sose Bugt Mb; Munkerup Member	*Pinuspollenites & Trachysporites* Zone	

Fig. 3 Preliminary palynozonation on Bornholm.

The 2nd Marine Geology Symposium was held at Aarhus University, 7 - 8 October 1993. The work presented at the symposium resulted in 10 articles included in this volume, covering a large range of geological topics, embracing biostratigraphy, sequence stratigraphy, sedimentology and structural geology.

ISBN 87-89813-14-6
ISSN 0900-6362