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A seismic stratigraphic analysis of Lower Pleistocene deposits in the western Danish sector of the North Sea

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Abstract

The Lower Pleistocene is well preserved in the centre of the North Sea, in contrast to the onshore sedimentary record in Denmark. In the Central Trough area the base of the Quaternary is deeper than 1000 m, and regional subsidence appears to have been uniform throughout the Early and early Middle Pleistocene. Seismic stratigraphic analysis allows subdivision of the Lower Pleistocene depositional succession in the western Danish sector into seven subunits. The seismic reflectors bounding these subunits can be correlated with seismic third-order sequence boundaries identified and mapped in the Late Tertiary and Pleistocene succession in adjacent British and German sectors. The subunits recognized in the Danish area may equal these sequences. Structure contour maps for five of the boundaries and isopach maps for three of these subunits show the position of the depocentres in the area. The main Pleistocene depocentre coincides with the axis of the central North Sea Basin. In the Early Pleistocene (Tiglian), local depocentres were also present outside this area. The sediments represented by the seismic sequences in the Dutch, British and German sectors can be related to the depositional basin of a river system draining the northwest-European continent. In addition, climatically induced changes in depositional conditions in the area have affected the sedimentation pattern.

Introduction

The Lower Pleistocene succession in the western part of the Danish North Sea sector is divided into seismically defined mappable units. The study area is situated within the central part of the North Sea Basin, west of 4°45′ E (Fig. 1). The Cenozoic deposits in this area are less disturbed by halokinesis and faulting than in other parts of the Danish sector. They are stratigraphically the most complete succession so far known from the North Sea. This study is one of the first concerning seismic investigation of the Pleistocene in the Danish North Sea and supplements Dutch and British mapping in the adjacent area.

Geological history and previous work

Miocene, Pliocene and Early Pleistocene sedimentation in the southern North Sea Basin was characterized by large deltas building out from mainland Europe into the eastern North Sea. These deltas were fed by northwest and westward flowing rivers from present-day Germany and by former Baltic rivers draining the Baltic shield (Cameron et al. 1987, Zagwijn 1985, 1989, Cameron 1991). Early Pleistocene deposits of the Danish area are mainly of fluvial, fluvio-deltaic or shallow marine origin (Zagwijn 1989, Cameron 1991). Deltaic sedimentation ceased during the Middle Pleistocene, and the later Quaternary history was dominated by glacially controlled deposition and erosion. Climatic changes involving considerable variations in temperature were characteristic for the Pleistocene, and directly controlled changes in sea level.

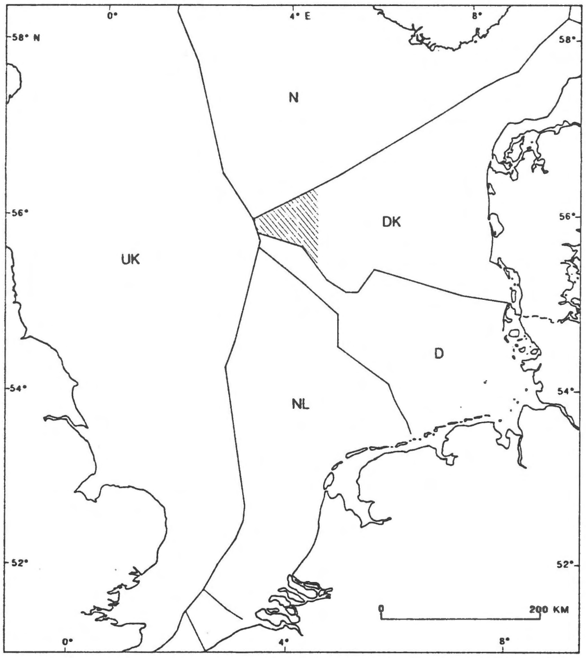

Fig. 1. Location of the study area in the Southern North Sea.

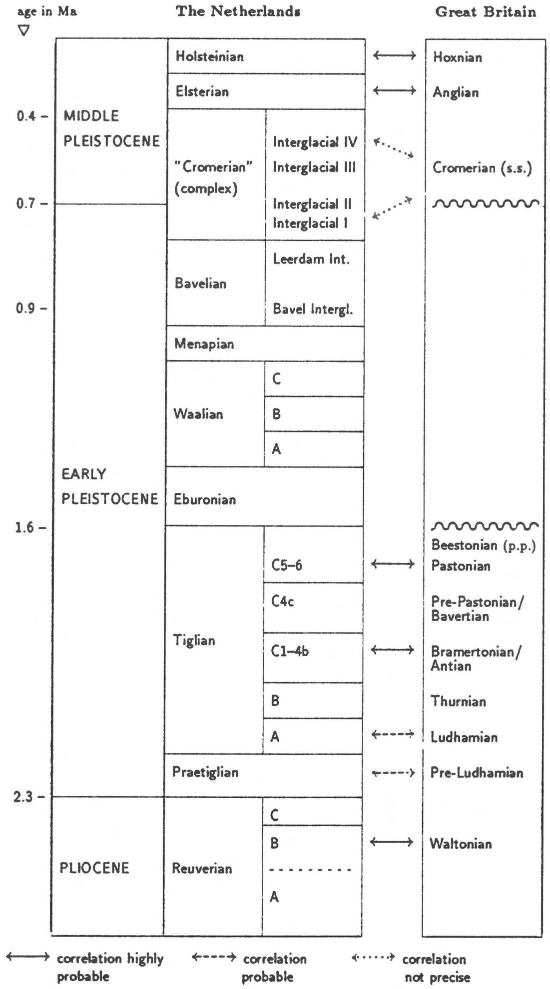

Fig. 2. Correlation of the Early and Middle Pleistocene succession of East Anglia and the Netherlands (after Gibbard et al. 1991).

During glacial stages of the Pleistocene, much of north-west Europe was above the tree-line and affected by severe permafrost (Zagwijn 1989). Erosion of the hinterland was intensive and resulted in increased sediment influx into the basin (Gibbard 1988). Intermittent cold or glacial periods are known to have occurred throughout the Pleistocene, with the first cold period, the Praetiglian, dated at approximately 2.3 million years BP (Zagwijn 1985) (Fig. 2). Each stratigraphic period of the Early Pleistocene includes a number of glacial-interglacial cycles, except the Praetiglian which is purely glacial (Zagwijn 1979, 1989).

The Cenozoic subsidence of the Danish part of the North Sea has been illustrated in a series of structure and isopach maps constructed from oil-well data (Nielsen et al. 1986). These maps include an isopach map of the Quaternary deposits of the Central North Sea. An isopach map of the Quaternary for the entire Southern North Sea was constructed by Caston (1979), also based on commercial well data. A regional study of the Quaternary in the entire North Sea is presented by Jansen (1976).

The Quaternary succession is poorly defined in the oil-well data, and until recently the study of Quaternary stratigraphy has been of little concern. Now, however, it is attracting considerable interest. Regional seismic studies of the Quaternary evolution have now been carried out in both the British and Dutch sectors of the North Sea and presented in the sheets of the 1:250,000 series by the British Geological Survey & Rijks Geologische Dienst. The lack of shallow and deep high-resolution seismic data from the Danish part of the North Sea has so far restricted investigation of the Quaternary to mainly biostratigraphic studies based on well material. These studies cover local areas only (Buch 1972, Knudsen 1985, Knudsen & Asbjørnsdottir 1991, Konradi 1991).

A change towards a greater climatic variability started in the Late Pliocene, as is indicated by a decrease in the diversity of the foraminiferal fauna and an increase in the number of arctic species (Buch 1972). The base of the Quaternary in the North Sea is defined

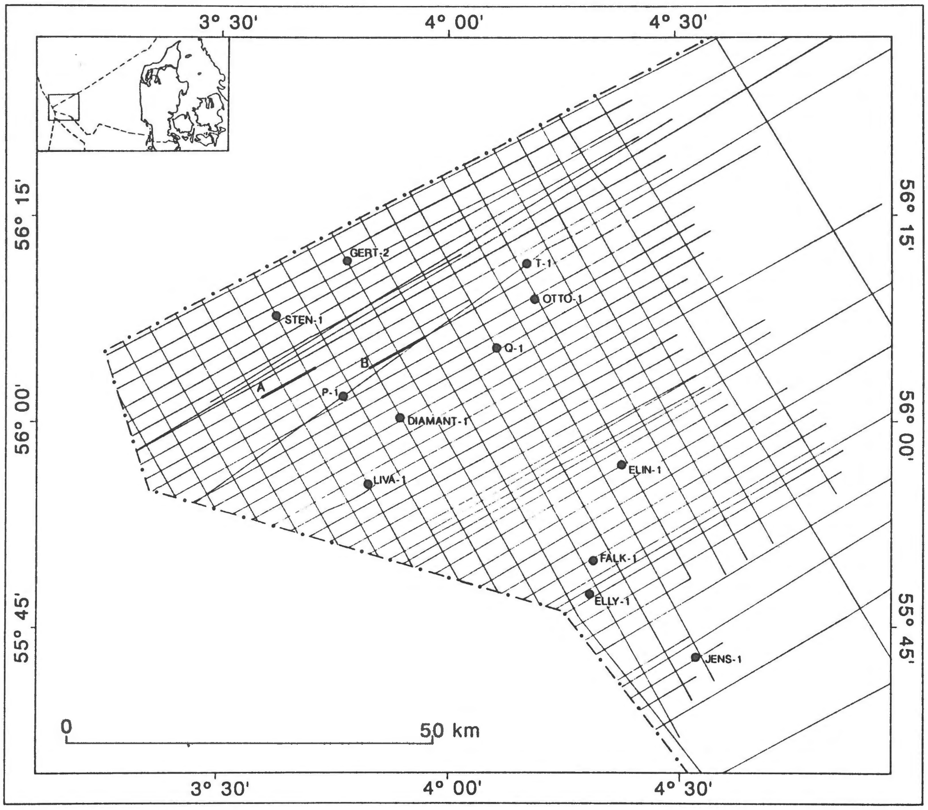

Fig. 3. Location of the seismic lines and of wells with stratigraphic data used in this study. A and B indicate positions of sections shown on Figs 4 and 6, respectively.

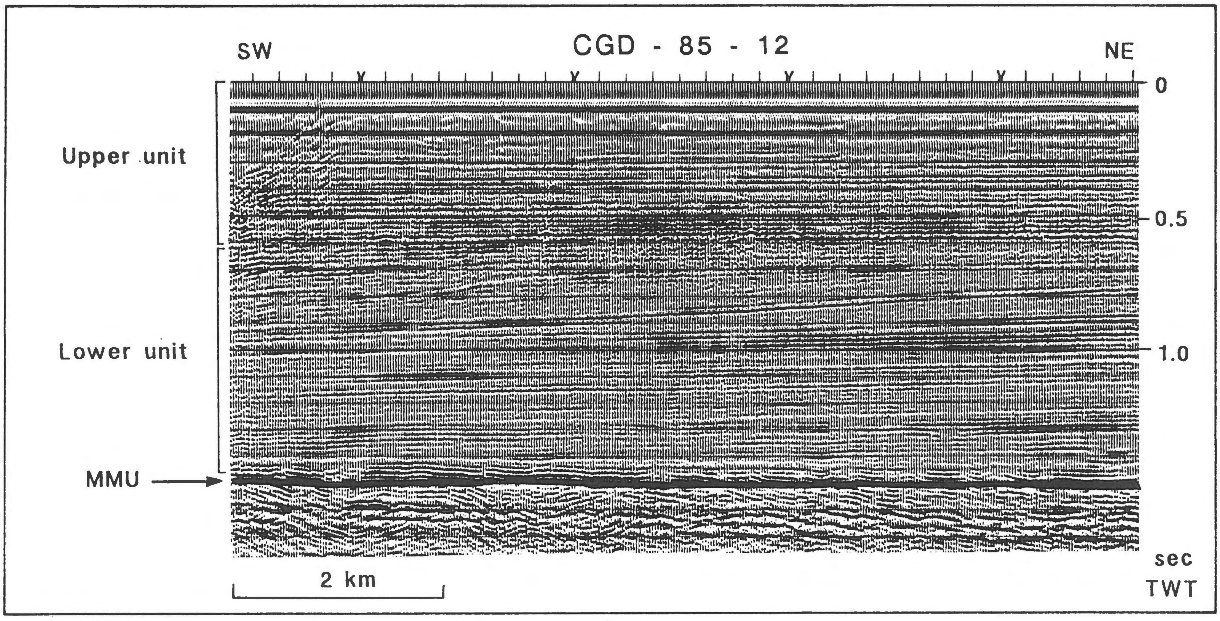

Fig. 4. Seismic section showing the two main units and the mid Miocene unconformity (MMU). Position of section shown on Fig. 3.

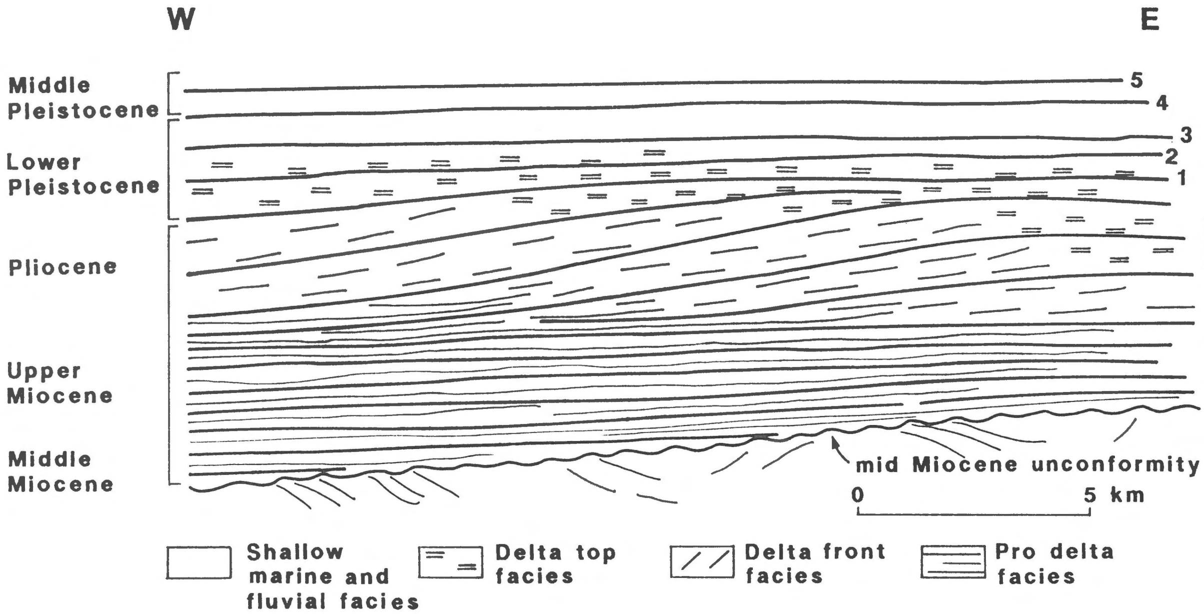

Fig. 5. Schematic section through the Upper Miocene through Middle Pleistocene deposits in the western part of the Danish North Sea area.

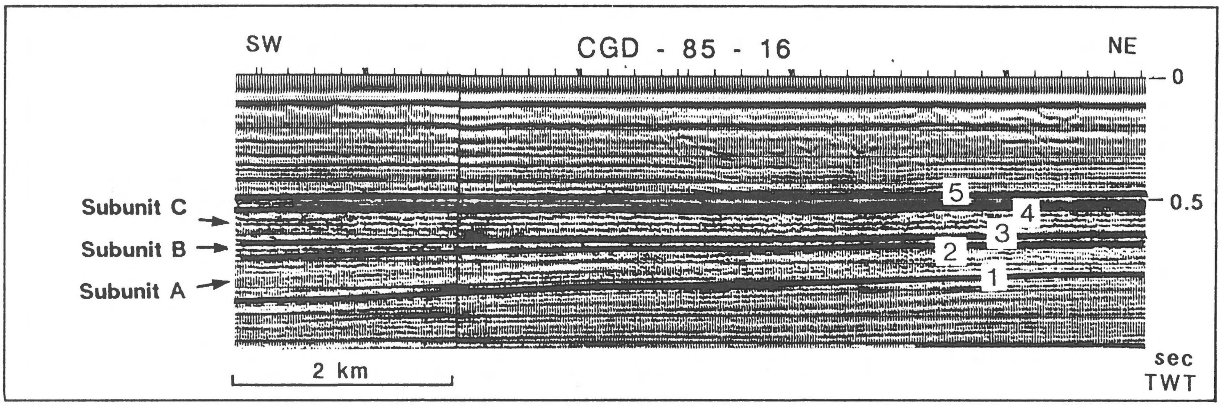

Fig. 6. Seismic section showing the mapped reflectors and subunits. Position of section shown on Fig. 3.

by evidence of a significant regional increase in climatic variations (Zagwijn & Doppert 1978). In the Netherlands, where the Tertiary to Lower Pleistocene succession is relatively complete, the Plio-Pleistocene boundary is unconformable and is placed where a decrease in herbaceous pollen indicates a change to a cold climate (Van Voorthuysen et al. 1972). The depths of the Pliocene-Pleistocene boundary derived from the wells are ambiguous. Inconsistencies between nearby wells and between different reports and logs from one and the same well indicate serious uncertainties in the determination of the depths in the Danish North Sea area.

The Plio-Pleistocene boundary is not a well defined seismostratigraphic boundary, and has not been mapped in this study.

Data and methods

A number of conventional multichannel seismic surveys have been recorded in the Central Trough area of

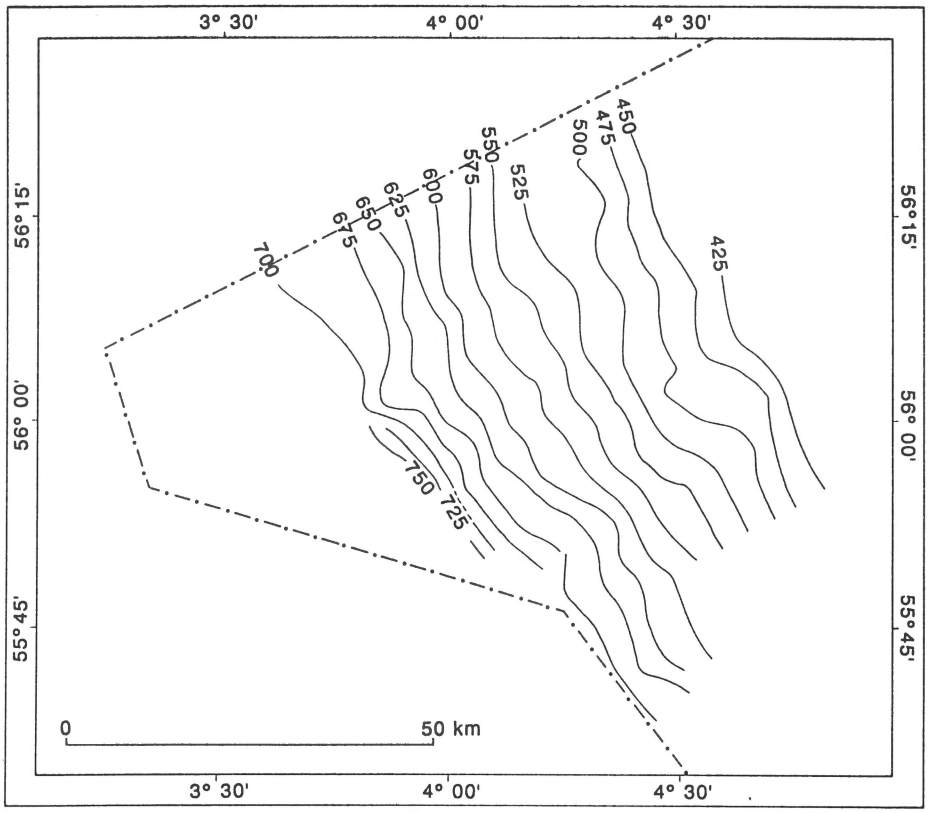

Fig. 7. Structure contour map, Reflector 1 (Near Base Pleistocene). Depths in ms TWT, contour interval 25 ms.

the Danish sector by oil-companies during the last 25 years, providing a very dense seismic coverage.

Profiles from two surveys, the CGD–85 and NP85C (both Nopec), are used in the seismic stratigraphic study. Lines from a third survey RTD–81 (Nogec) were used to trace various reflectors east of the study area. The selected seismic profiles have a sufficient resolution in the upper second TWT (Two Way reflection Time) of the section to allow detailed mapping of the Quaternary. All seismic data used in this study are airgun multichannel reflection seismic profiles recorded down to seven seconds TWT. The grid of the surveys is rectangular, with a line distance of approximately 1.25 × 2.50 km. As the geology proved to be uniform across the area, the final maps were constructed on the basis of the CGD–85 and RTD–81 surveys only (Fig. 3). Information from the NP85C survey was used to supplement these maps.

The seismic stratigraphic analysis follows the method described by Mitchum et al. (1977) and Mitchum & Vail (1977). The chronological interpretation of the data is based on Zagwijn & Doppert (1978), Zagwijn (1985), Cameron et al. (1984), Cameron et al. (1987) and Nielsen & Japsen (1991). The seismic units are dated by integrating the few available Pleistocene palaeontological and sedimentological well data (Fig. 3). However, reliable velocity data from the wells are lacking. Thus the depth conversion is based on the interval velocities obtained from the seismic data processing, multiplied with the measured depth in time (sec TWT). This method may, however, result in overestimated depths in metres. A recent study on the Lower Pleistocene of the Danish and German parts of the North Sea proposes some revisions concerning the biostratigraphic zonation based on benthic foraminifera according to King (1983, 1989) (Pedersen 1993).

Uncertainties are introduced in the age and depth determination because various criteria and sets of data have been used in the definition of the stratigraphic boundaries in the wells through time.

High-resolution seismic data are necessary to enable a more detailed study of the Pleistocene in the

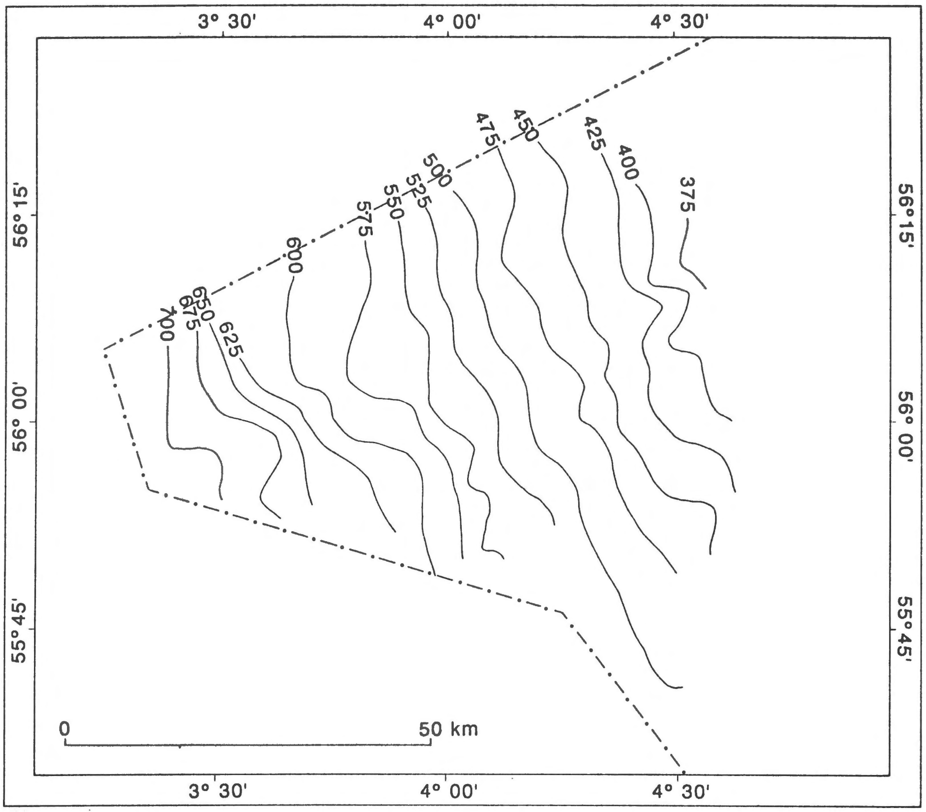

Fig. 8. Structure contour map, Reflector 2 (Top of Tiglian?). Depths in ms TWT, contour interval 25 ms.

North Sea. Such data are not yet available from the Danish North Sea area.

Seismic stratigraphic analysis and mapping

The interpretation of the seismic sections allows subdivision of the sedimentary succession into seismostratigraphic units. The base of the studied section is defined by a distinct high-amplitude reflector corresponding to a truncational boundary. This reflector can be followed across the entire area and coincides with a change from a hummocky to a subparallel reflection pattern that dips gently to the west (Fig. 4). It marks a mid Miocene unconformity which represents the top of an overpressured zone (Michelsen 1982). The sediments above this boundary can be divided seismically into two main units (Fig. 4).

The lower unit is characterized by sigmoidal reflectors inclined to the west. These reflectors can be followed several tens of kilometres, and towards the base of the unit the reflectors become tangential subparallel. The unit illustrates an upward transition from prodelta to delta front and delta-top seismic facies (Fig. 5).

The upper unit has a subhorizontal parallel reflection pattern with a slight inclination to the west. Only a few high-amplitude reflectors can be traced over significant distances. Reflector truncations can locally be resolved to define sequence boundaries within the unit. The unit passes laterally westward into a unit with a sigmoidal reflection pattern. In the Dutch and British sectors, the reflectors recognized and traced are more clearly resolved by reflector truncations. Twenty-seven seismic sequence boundaries are defined and mapped (Kay 1993). The boundaries between the subunits in the Danish sector are not defined by terminations. They are developed as 'correlative conformities' to some of the seismic unconformities, which are interpreted as sequence boundaries west and southwest of the study area.

Seven boundaries are distinguished in the upper unit. Three of these can be mapped across the entire area, the other four only in part of the area. Contour maps of the five lowermost reflectors, numbered 1–

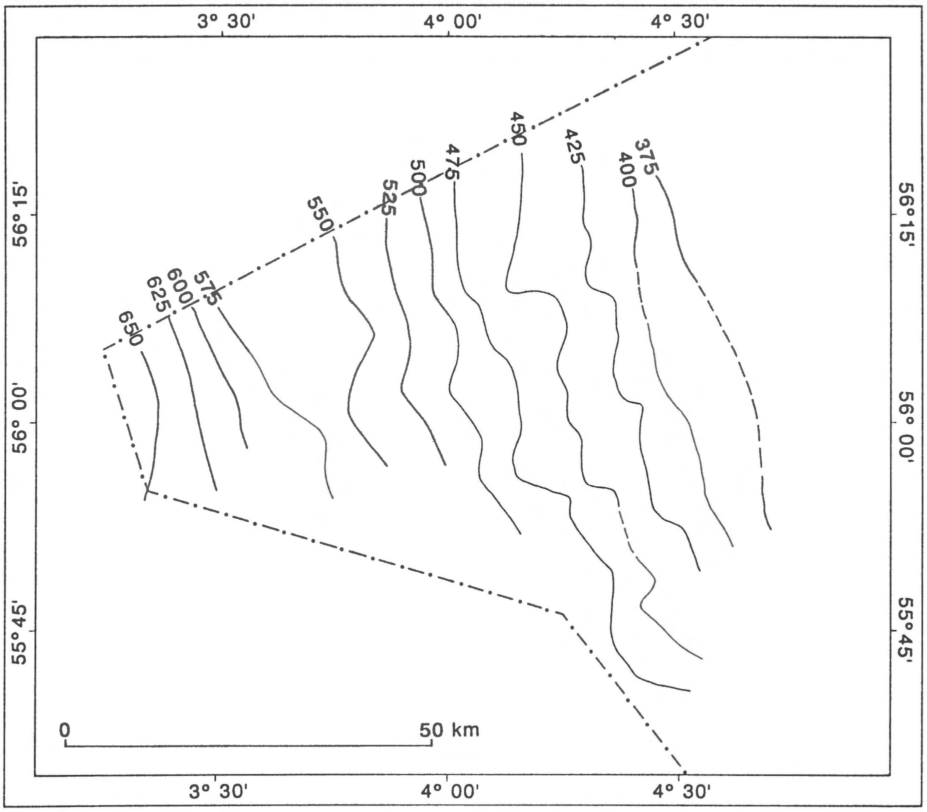

Fig. 9. Structure contour map, Reflector 3 (Eburonian or Menapian). Depths in ms TWT, contour interval 25 ms.

5 from bottom to top, are shown in Figs 7–11. The subunits between reflectors 1–4 are labelled A-C (Fig. 6), and the thickness of each of these is shown in Figs 12–14.

Reflector 1 is the lowermost of the internal boundaries. The variation of the homogeneity of the reflector is moderate and generally marks a level which can be followed rather easily in the eastern part of the area. Towards the west the reflector is dipping and due to the decrease in amplitude and continuity it can not be followed in the depth. From north to south, the amplitude changes from low-medium to high and the continuity increases.

The character of Reflector 2 varies from a low amplitude with low continuity in the west, to a generally medium amplitude with higher continuity in the east. The amplitude of the reflection also increases towards the south.

Reflector 3 also shows a variation in character from north to south. In the north it is a low to medium-amplitude reflection with low to medium continuity, which changes to medium amplitude with high continuity in the south. Generally there is a high grade of homogeneity in the whole area.

A generally low to medium amplitude and a medium continuity are characteristic of Reflector 4. The homogeneity of the reflection appears to be high throughout the area.

Reflector 5 is mapped in the northern area only. Towards the south the amplitude and continuity are too weak to be traced. The amplitude in the northern area is low to medium with a medium continuity, best expressed in the northernmost area where the reflector is most uniform.

Interpretation

The lateral transition from delta-top to delta-front seismic facies is marked by the development of prograding clinoforms between divergent sequence boundaries. The height of the clinoforms reflects the minimum water depth. In the central part of the North Sea the Late Miocene-Pliocene water depth is thus estimated

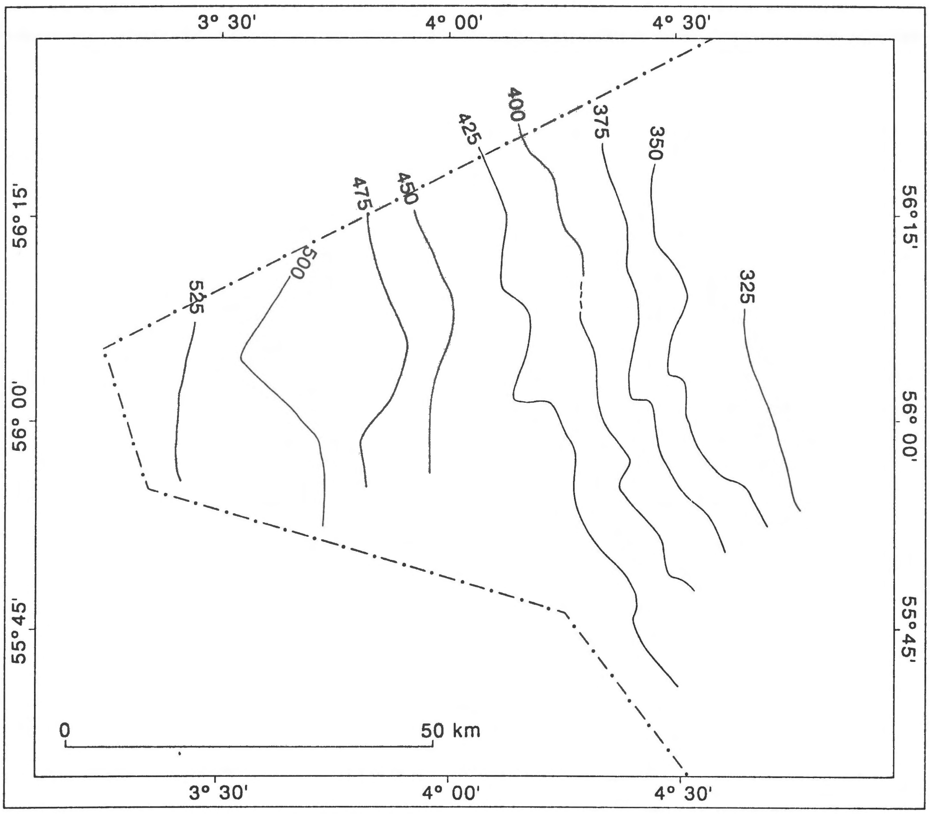

Fig. 10. Structure contour map, Reflector 4 (Near Top Lower Pleistocene). Depths in ms TWT, contour interval 25 ms.

to be in the order of 200–250 m. The inclinations of the clinoforms are approximately 5° to the west.

The maps

The structure contours of Reflector 1 are indicated in Fig. 7. This reflector corresponds closely with the interpreted Plio-Pleistocene boundary in a few wells such as Otto–1, Elly–1 and Elin–1. The reflector dips WSW between 425 and 750 ms TWT, continuing westward to greater depths in the westernmost part of the study area and beyond. Its inclination is very uniform; its depth contours are subparallel and follow the main trend of the Central Trough.

Reflector 2 corresponds to the top of a biostratigraphic subzone characterized by a high content of the foraminifera genera *Stainforthia* and *Bulimina*. These indicate a warm period, possibly of Tiglian age (Pedersen 1993). The reflector forms a WSW-dipping planar surface which is mapped across the entire area (Fig. 8). Its contours are less uniformly spaced than those of Reflector 1, but they are still more or less parallel to the trend of the Central Trough. The depth varies between 375 and 700 ms TWT.

The contours of Reflector 3 show a more N-S-wards orientation than Reflectors 1 and 2 (Fig. 9). The reflector forms a planar surface that is more gently inclined than Reflectors 1 and 2, and deepens westward from 375 to 650 ms TWT. Biostratigraphic data from boreholes suggest that Reflector 3 marks a glacio-eustatic lowering of the sea-level, caused by development of arctic conditions of possibly Eburonian or Menapian age. The occurrence of *Elphidiella gorbunovi* in the Central North Sea indicates this (Pedersen 1993).

The uppermost two reflectors show a slight, but regular dip towards the west. Reflector 4, interpreted to be close to top Lower Pleistocene, deepens westward from 325 to 525 ms TWT, with a NNW strike (Fig. 10). Reflector 5 has a slightly more northerly strike, and deepens westwards from 300 ms to 475 ms TWT (Fig. 11). It is mapped in the northern part of the area only. No chronostratigraphic interpretation has been made, but on the composite log from the well Sten–1 the upper boundary of the Lower Pleistocene is placed at

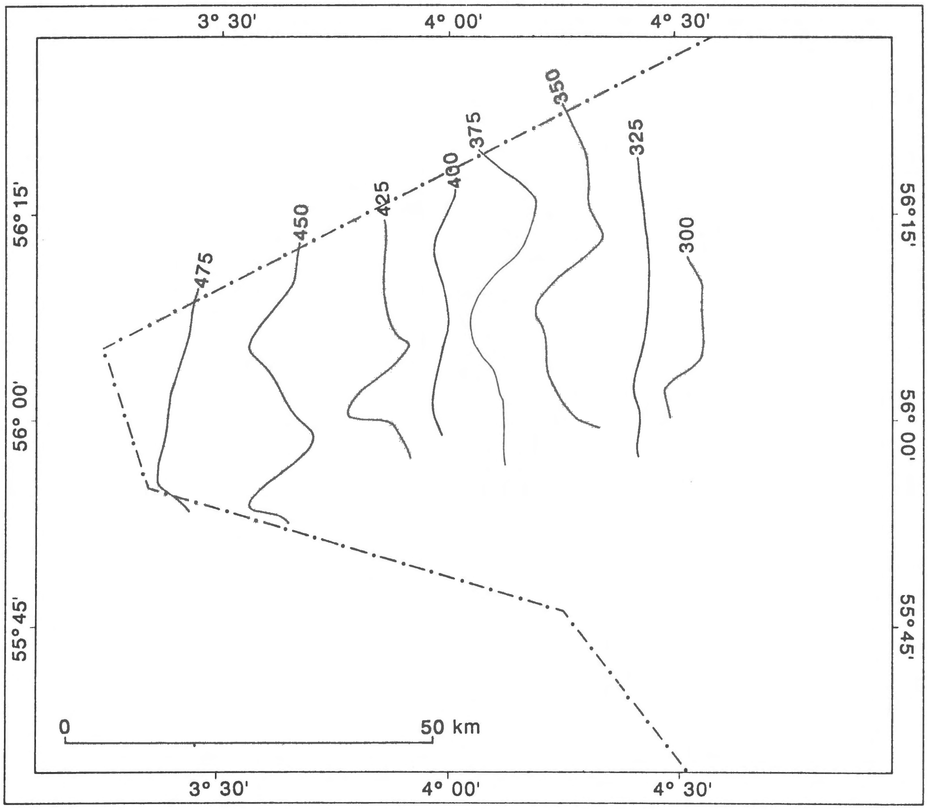

Fig. 11. Structure contour map, Reflector 5 (Top Lower Pleistocene?). Depths in ms TWT, contour interval 25 ms.

1332′ (405 m) below mean sea level. This corresponds to a depth of approximately 450 ms TWT, which is close to that of Reflector 5, the uppermost continuous reflector in the area.

The isopachs of the lowest subunit, A, show more or less the same overall trend as its boundary reflectors (Fig. 12). The subunit is thickest towards the west, and the thickness increases rapidly following the increasing dip of the lower boundary and the divergence of the bounding surfaces. Sediments of this subunit were deposited during the Praetiglian and Tiglian, at the beginning of the Early Pleistocene.

Subunit B is also thickest in the west. In general a rather irregular contour pattern is evident illustrating variations of the thickness of this subunit in the area mapped. The area of maximum accumulation seems to have shifted to the east compared to the underlying subunit (Fig. 13). A local depocentre developed near 3°40′E/55°55′ N. This eastward shift of the depocentre may have occurred due to the higher sea level of the warm Tiglian and possibly also Waalian periods. During these periods the ice sheets of north west Europe were melting, causing a eustatic rise of sea level. An associated transgression may have induced an eastward backstepping of the deltaic deposits of the Baltic and North German rivers, affecting the depositional environment. The subunit is of Tiglian to Eburonian possibly Waalian-Menapian age.

Figure 14 shows the thickness of Subunit C of possible Eburonian-Menapian and partly early 'Cromerian complex' age (Bavelian, sensu Zagwijn 1985). This subunit reaches its maximum thickness in the western part of the Danish sector, like the underlying subunits. The depocentre was probably situated in the centre of the North Sea Basin. Towards the east a more irregular pattern can be observed which may indicate a change of depositional or perhaps tectonic conditions. At this time the Baltic river system had ceased to flow through the area and fluvio-deltaic deposition had changed to shallow marine conditions (Gibbard 1988, Gibbard et al. 1991). The variations in thickness in this eastern part of the mapped area may be attributed to the influence of new fluvial systems draining the Scandinavian area.

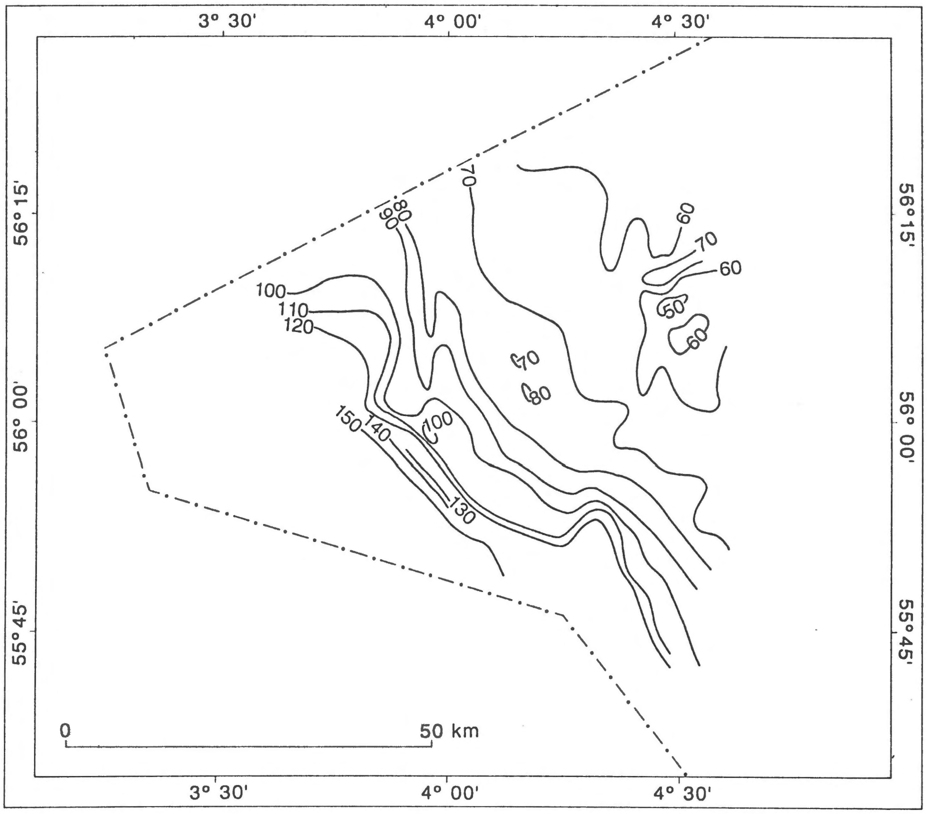

Fig. 12. Isopach map, Subunit A (Praetiglian and Tiglian?). Thickness in ms TWT, contour interval 10 ms.

Discussion and conclusion

The seismic units identified in this study are interpreted as representing Early to early Middle Pleistocene deposits.

Seismic and well data indicate that a change of depositional environment occurred near the beginning of the Pleistocene in the Danish sector of the North Sea Basin. This change took place during a transition from a stable climatic period to a period of greater climatic variations characterized by repeated advances and melting of ice caps in northwest Europe.

Delta-front sedimentation stopped in the Praetiglian before the deposition of Subunit A, and the depositional environments of the younger sediments appear to be fluvial and fluvio-deltaic to shallow marine. Delta-top facies deposits of 150–250 m thickness are seen, comprising sediments of possibly four or five seismic sequences. The facies boundaries are diachronous, being youngest in the southern part of the area and older towards the north and northeast.

Sea level changes associated with successive climatic cycles in the Early Pleistocene are represented by unconformable third-order sequence boundaries in seismic profiles from the British sector (Kay 1993). Some of these boundaries can be correlated with the conformable seismic boundaries recognized in the Danish sector and the subunits may correspond to third-order sequences. As the resolution of the conventional seismic profiles does not allow a detailed interpretation, it is probable that more sequences are present than the subunits mapped.

The constructed maps indicate a rather regular sediment supply to a uniformly subsiding basin during the Early Pleistocene. The depth of Reflector 1 increases basinwards from approximately 400 to 750 m. In the area adjacent to the British sector, the reflector probably occurs as deep as about 1000 m. The thickness of the Lower Pleistocene is estimated to be at least 80 m in the east and more than 500 m in the west of the study area. The basal Praetiglian to Tiglian subunit A is approximately 200 m.

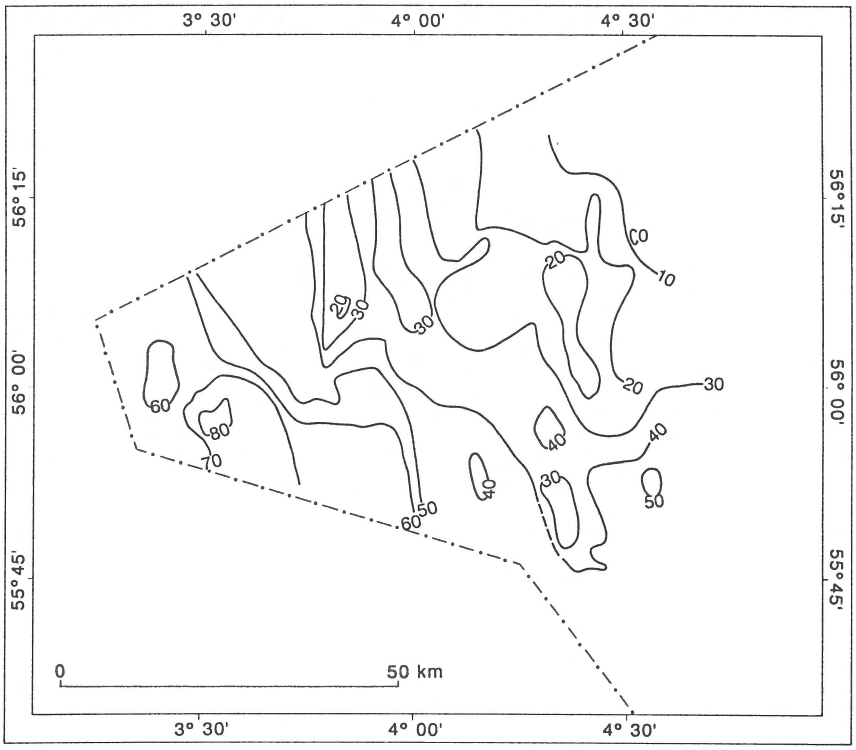

Fig. 13. Isopach map, Subunit B (Tiglian (?) to Eburonian or Menapian). Thickness in ms TWT, contour interval 10 ms.

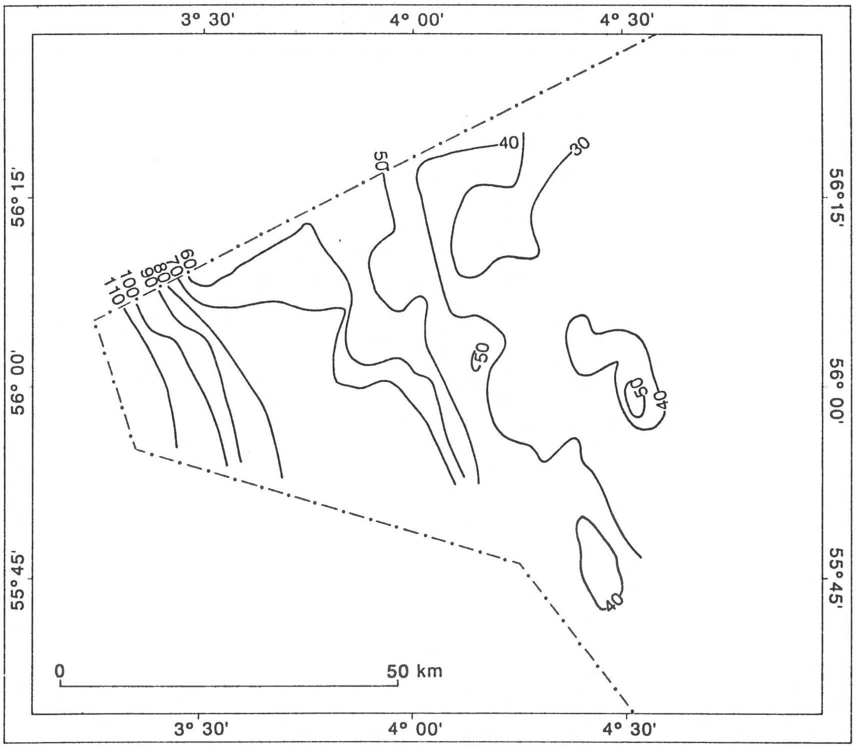

Fig. 14. Isopach map, Subunit C (Eburonian to Menapian and partly Lower Cromerian). Thickness in ms TWT, contour interval 10 ms.

As the Baltic rivers progressed towards the west and northwest of the North Sea Basin, the sediment supply apparently decreased in the Danish area. The main accumulation took place in the centre of the North Sea Basin; during the Tiglian a local depocentre developed in the Danish sector. This probably occurred as a response to climatically induced changes of the depositional environment. High sea-level occurred in the Tiglian interglacial, when the area of main deposition changed to a more easterly position.

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