Late Quaternary geological development of the Jutland Bank and the initiation of the Jutland Current, NE North Sea

JØRGEN O. LETH

Leth, J. O. 1996: Late Quaternary geological development of the Jutland Bank and the initiation of the Jutland Current, NE North Sea. *Nor. geol. unders. Bull. 430*, 25-34.

Using shallow seismic and core data, a reconstruction has been made of the Late Pleistocene-Early Holocene palaeogeography of Jutland Bank, NE North Sea. A division of Late Pleistocene and Holocene deposits into five sequences has been proposed for the study area: W5 representing the Pleistocene glacially deposits; W4 infilled channels incised into W5; W3 a composite, unspecified sequence of late-glacial glaciolacustrine/glaciomarine origin and/or deposits older than Boreal; and W1 and W2 representing the Holocene Jutland Bank Sand Unit. The seismic stratigraphy of the northwestern part of the study area reflects different stages of the Holocene transgression. A paleocoastline situated 15 km off the present Danish North Sea coast existed during the Early Holocene in connection with a protected marine environment where the Agger Clay Unit was deposited to the east. From investigations of the mollusc fauna it has been shown that simultaneous with the Agger clay deposition an open marine environment with a Boreal molluscan fauna was present in the northwestern part of the study area. An archipelago-like structure of emerging morainic islands on the Jutland Bank has been obstructive for establishing any long-shore currents. Tidally induced currents were the dominating sediment transport mechanism until flooding finally drowned the archipelago in the Mid Holocene.

Jørgen O. Leth, Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV.

Introduction

Until recently the Quaternary succession of the Danish North Sea had hardly been studied, although it forms a considerable part of the total area of the North Sea. The most recent work in the Danish sector, apart from local site surveys carried out by the petroleum industry, is by Salomonsen (1994) who studied the reflection patterns in the Quaternary succession in both the high-resolution and the petroleum industry seismic. In addition, Salomonsen & Jensen (1994) investigated Quaternary erosional surfaces based on deep high-resolution seismic data, combining the results with foraminiferal studies. Foraminiferal stratigraphic investigations of the Quaternary have previously been made by several authors (e.g. Jansen et al. 1979, Sejrup et al. 1987, Jensen & Knudsen 1988). Knudsen (1985) proposed a Late Pleistocene and Holocene foraminiferal stratigraphy for the Danish North Sea sector.

Detailed research on Late Pleistocene and Holocene sea-level changes in the Danish sector has virtually been lacking so far. Jelgersma (1979) extrapolated hypothetical Late Pleistocene and Early Holocene shorelines from the southern part of the North Sea along the Danish coastline based on a scarcity of information. Several other authors have discussed the eustatic fluctuations in the North Sea region,e.g. Tooley (1974) and Shennan (1987). Mörner (1980) concluded that the eustatic curve calculated from the Kattegat region is considered to represent the regional eustatic changes along the Northwest European coast. During the Early Weichselian regression a eustatic lowering of the sea level was most likely caused by the growth of the Laurentide ice sheet. The sea level during the Early Weichselian was at least 40 m below the present level (Jelgersma 1979). The lowest position of the Weichselian sea level at about -130 m was reached during the late Middle Weichselian at about 18,000 y. BP. However, the isostatic rebound in the northern part of Denmark was estimated by Petersen (1991) to be in order of 200 metres.

Here it must be noted that the location of the southern limit of the Weichselian glaciation in the North Sea is still controversial. The origin of the stony grounds in the North Sea region, related to end moraines, was first discussed by Pratje (1951). According to Andersen (1981), Sutherland (1984) and Sejrup et al. (1987), location of the limit of glaciation is a matter of discussion (Fig. 1). The latter authors agree that Skagerrak was covered by ice during the maximum extent of the late Middle Weichselian glacier. Andersen (1979), as well as Stabell & Thiede (1986), place the ice margin along the Little Fisher Bank Moraine, today situated at a water depth of about 50 m. Nesje & Sejrup (1988) proposed that the Scandinavian and the British Ice did not coalesce in the North Sea.

The maximum Weichselian glaciation onshore in Denmark is marked by the Main Stationary Line (C-line) in Jutland (Ussing 1907) (Fig. 2). The ice-free part in front of this line was possibly land (Stabell & Thiede 1986). A key location for studies of the Main Stationary Line in Denmark is the Bovbjerg Cliff (Fig. 1) on the west coast of Jutland (Pedersen et al. 1988). Observations on glaciodynamic structures at this location show evidence of a continuous upper kinetostratigraphic unit related to the late Middle Weichselian ice advance, demonstrating ice

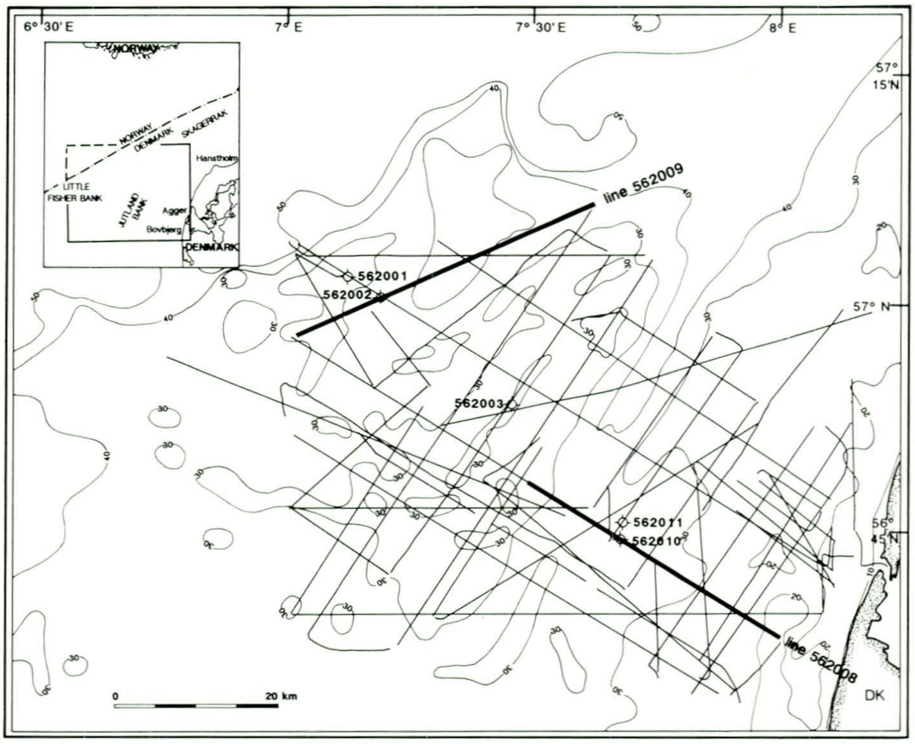


Fig. 1. Bathymetry and location map showing the seismic lines recorded during the 1991 and 1994 cruises. Water depths are in metres and depth intervals 10 m. The seismic profiles 562009 and 562008 presented in the paper are marked by thick lines. Stars mark the positions and numbers of the cores presented in the paper.

movements from a northerly direction (Norwegian ice) with a late-stage ice movement from the east-northeast. Initially, the retreating ice front built up sandur plain deposits in front of the Main Stationary Line. At about 13,000 - 14,000 y. BP the ice front retreated to the Norwegian coast (Andersen 1979), leaving the sea level at about 70 m below the present. The Skagerrak was a fjord-like forebasin to the North Atlantic. At this time, rivers draining the present southern North Sea and the Jutland Bank/Little Fisher Bank area discharged into the Skagerrak basin leaving V-shaped infilled channels incised into the subsurface (Salge & Wong 1988). Even at 12,000 y. BP the Kattegat/Skagerrak/Northeast North Sea retained a fjord-like shape (Stabell & Thiede 1986).

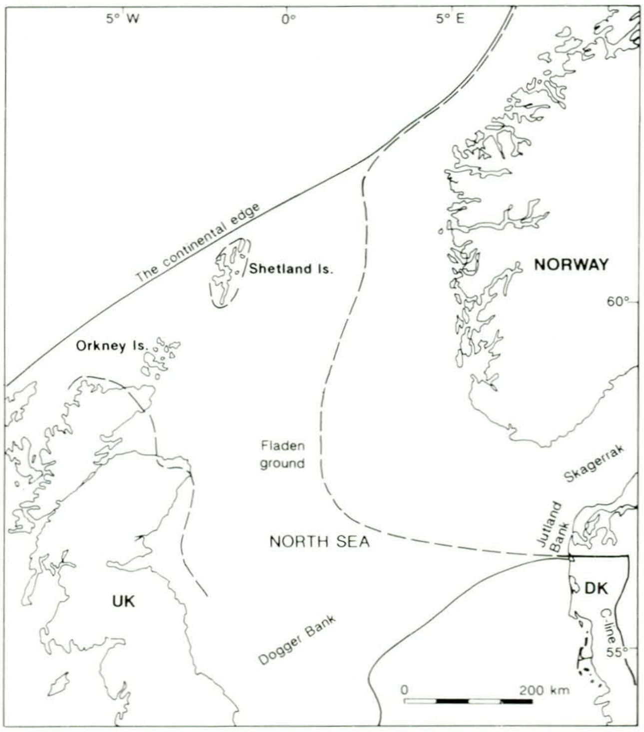


Fig. 2. The Late Weichselian / Devensian maximum ice limits. The solid lines refer to Andersen (1981), the punctured lines refer to Sutherland (1984) (Scotland) and Sejrup et al. (1987) (the North Sea). Redrawn after Nesje & Sejrup (1988). The position of the C-line indicating the Main Stationary Line in Denmark (Ussing 1907) is marked.

The Jutland Bank area, consisting of a core of glacial sediments, is of great importance in the study of the offshore continuation of the Main Stationary Line from the Bovbjerg Cliff towards the west.

After the rapid sea-level rise at the onset of the Holocene and the opening of the English Channel, a circulation pattern similar to the present came into existence (Van Weering 1975). Nordberg (1992) suggested that the opening to the English Channel at about 8,000 y. BP. led to the establishment of the North Sea current system. According to the latter author, the Jutland Current in its present form is assumed to have been established at about 4,000 y. BP. The paleoceanographic development of the NE North Sea and the Skagerrak during Late Pleistocene and Holocene will be discussed in this paper in the light of the influence from the emerging moraine deposits of the ice-marginal zone off Jutland (for location, see Figs. 1 and 2). A full account of the complete seismic stratigraphy of the Jutland Bank area, however, is outside the scope of this paper.

Methods and data processing

A regional seismic survey was carried out by the Geological Survey of Denmark during cruises made by the vessel *'M/S Gunnar Seidenfaden'* in August 1991 and May 1994 with the purpose of investigating the uppermost part of the sedimentary subsurface. The seismic setup of high-resolution shallow seismic equipment was chosen in order to map the Late Pleistocene and Holocene sediments. An EG&G Uniboom (frequency of 0.6-2.5 kHz) and an ORE 132A pinger transducer system at a frequency of 3.5 kHz were run simultaneously. Recording in 1991 was carried out on analog EPC (3200 and 9701) graphic recorders; and in 1994 digitally on an ELICS Delph2 System. To provide navigational fixes every 20 seconds the SYLEDIS system was used in 1991 and a SERCEL DGPS in 1994. The accuracy of both systems is within 10 metres. Cores of 6 m length were obtained by use of VKG-6 vibrocore equipment during the latter cruise and additionally during a cruise by the vessel *'R/V Professor Shtokman'* in 1992.

The 3-D view contour map (Fig. 5) of the glacial surface was made by use of the DGU in-house contouring program UNIKORT to improve the accuracy of interpolation of the hand-drawn contour map of the interpreted top glacial reflector. To run the UNIKORT programme the hand-drawn contour map was initially digitised. Due to the irregular distribution of datapoints the UNIKORT programme, by selecting a grid distance close to the highest density data points and a low degree of smoothing, will honour these points. Later, a relative smoothing is achieved by the programme running an iterative correction procedure through the interpolations and the corrections of the grid, still honouring the data.

The depth calculation of the glacial surface level was made by adding water depth to the thickness of the overlying sediments. For depth conversion of the late and post-glacial silty and sandy sediments, an average seismic velocity of 1700 m/sec was used.

^{14}C ages were obtained at the AMS ^{14}C Dating Laboratory at the Institute of Physics and Astronomy, University of Aarhus, Denmark. The ages published in Table 1 are presented as the conventional reservoir corrected ages in accordance with Stuiver & Polach (1977). A standard reservoir correction of 400 years has been subtracted from the ages mentioned in the text.

Pre-Quaternary

Major erosional truncation at the top of the pre-Quaternary depositional succession together with the presence of salt diapirs are the most important structural features of the area. Several salt domes and diapirs have been recognised in the Jutland Bank area. In a narrow NW-SE trending zone from the Agger isthmus (Fig. 1) into the North Sea, across the northern flank of the Jutland Bank, frequent earthquake activity is experienced. A fault zone is thought to have been active from the Permian to the present, and to have been the controlling factor for the distribution of the Tertiary and the Quaternary deposits. Shallow faults in these deposits are probably responses to movements of Upper Permian salt masses which in turn have possibly been activated by faulting at deeper levels (Gregersen et al. 1995).

Quaternary seismic sequences and facies

The seismic stratigraphy of the Quaternary successions presented in this paper is based on an overall interpretation of the seismic sections 562008 and 562009 (Figs. 3a and 3b), largely using the technique of seismic sequence analysis and the principles of depositional sequence stratigraphy (Vail et al. 1977). Following this approach, the framework build up of the Late Pleistocene and Holocene succession in this region is presented. On the seismic sections, the erosional truncation on the top of sequence W5 (glacial deposits) can be traced as a high-amplitude reflector. This forms the initial depositional surface for Late Pleistocene and Holocene sediments. In the northeastern part of section 562009 (Fig. 3b), this unconformity displays a horizontal to sub-horizontal morphology at a level between -53 and -55 metres over a range of more than 15 kilometres. The unconformity is cut by a series of U-shaped valleys, with sequence W4 incised into sequence W5. The internal reflector configuration of sequence W4 displays draping reflectors or a reflection-free pattern. This demonstrates an infilling of up to 20 m of sediments. Two different valley base levels (sequence W4) are registered: one at about -70 m, and another at -55 to -60 m. It is conceivable that the glacial surface unconformity extends farther north but no data are available here. Towards the southwest on section 562009 (Fig. 3b) the morphology of the unconformity becomes poorly defined. In the southwest (Fig. 3b section 562009) the shape becomes diffuse and more irregular due to a decreased seismic resolution.

The unconformity on section 562009 (Fig. 3b) is overlain by the seismic sequence W3, which has a parallel to sub-parallel reflector configuration concordant with the underlying unconformity. W3, in this context, is considered to be one sequence, but a division into several subsequences is possible, each representing late-glacial glaciolacustrine/glaciomarine deposits and/or depositional units related to the early transgressional stages in the Late Pleistocene and Early Holocene. Sequence W3 was penetrated in core 562002 in the southwestern part of section 562009, 500 metres off the line, at a depth interval between -46.80 and -48.80 m (Fig. 4a). Two metres of clay and heterolith are found without any molluscs and with a sparse foraminiferal assemblage of cold water species. Above an erosional contact and a possible hiatus, there are 4 metres of Holocene fine sand (unit W2, see

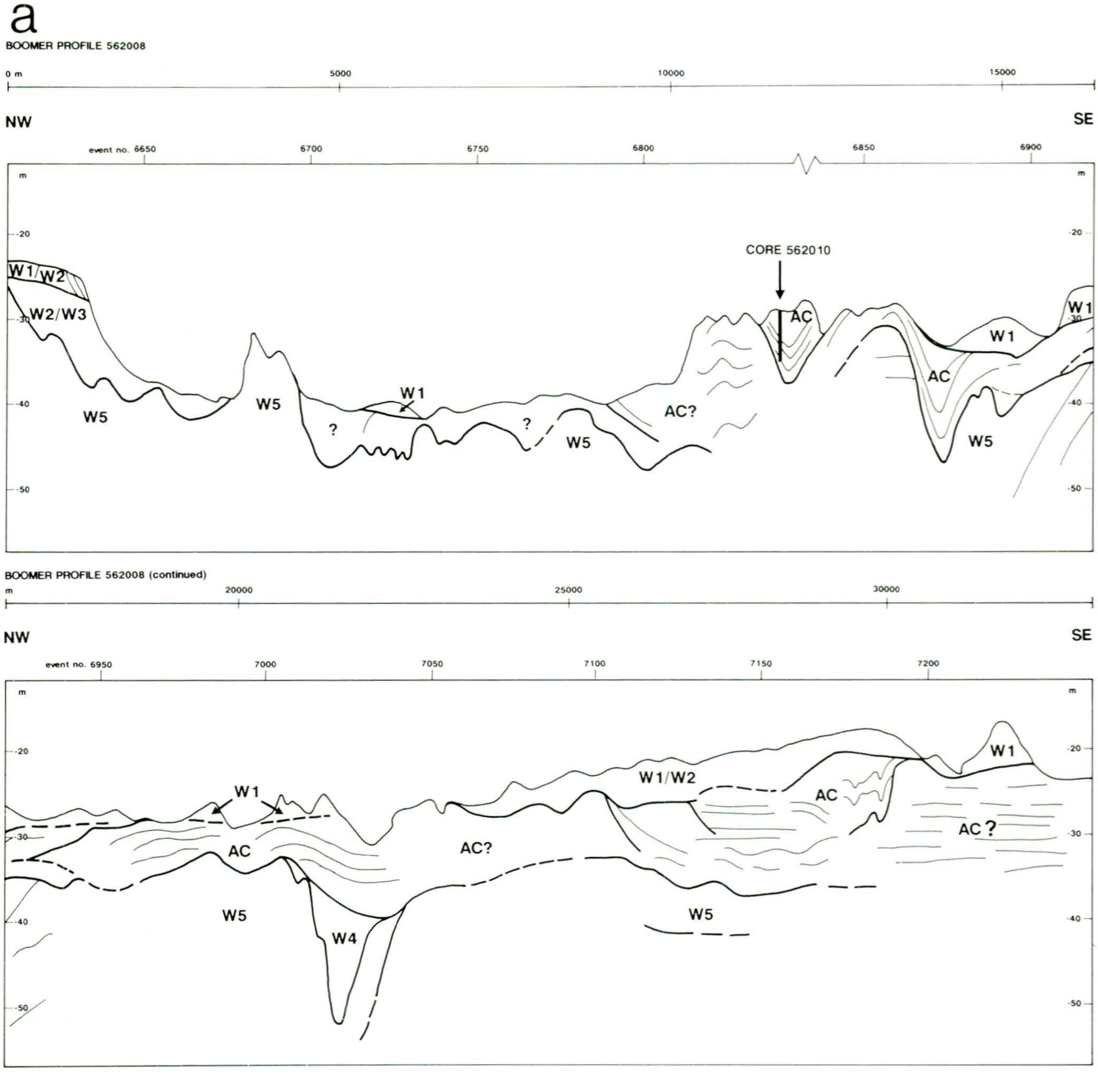


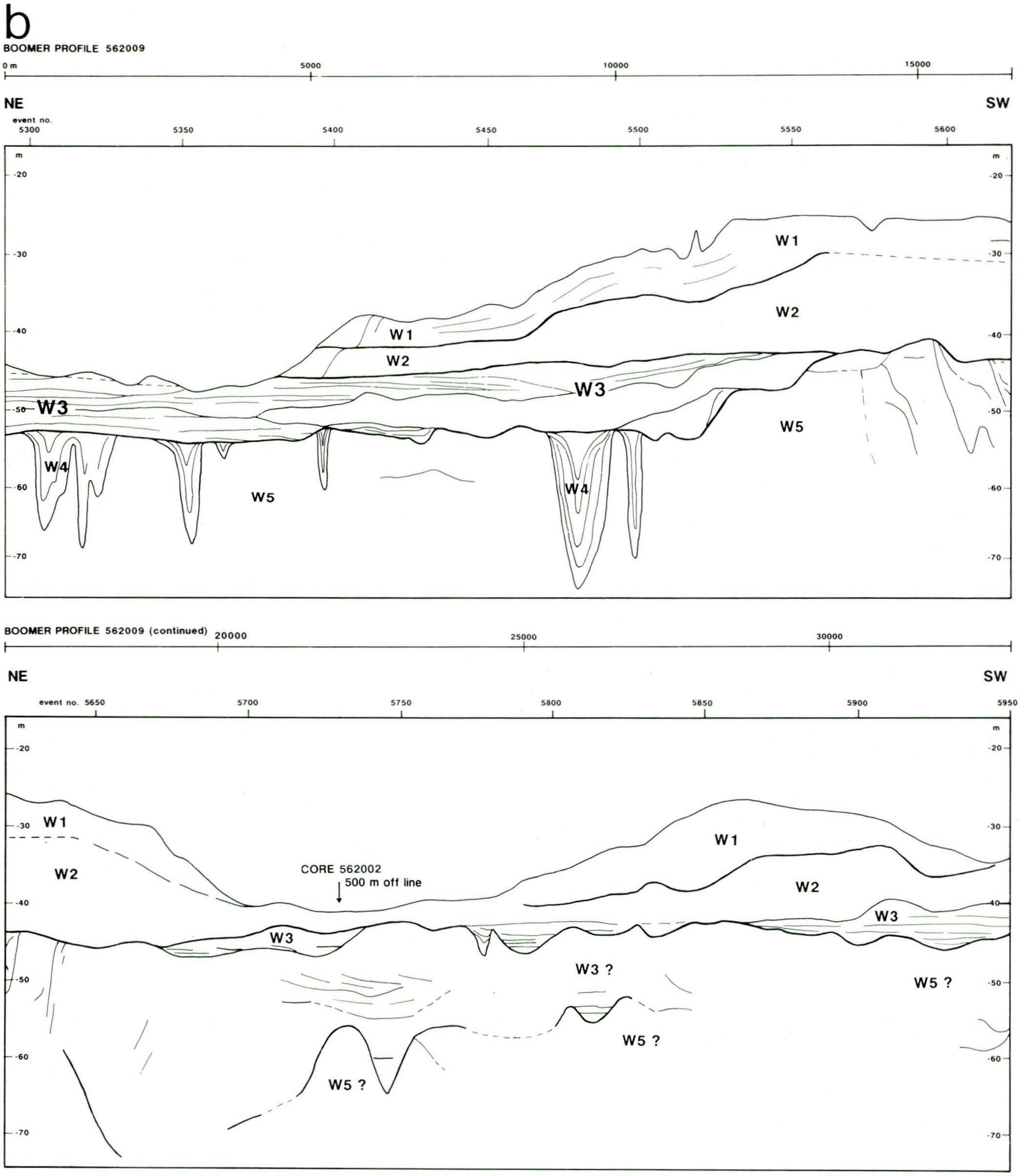
Fig. 3a and 3b. *Interpreted boomer profiles of the seismic section 562008 from SE to NW and section 562009 from NE to SW. For location see Fig. 1. The positions of the vibrocores 562002 and 562010 are indicated by arrows. W1 - W5 refer to the five seismic sequences defined in the text. AC = the Agger clay.*

below). The dating of Littorina Littorea (8,930 ± 150 y. BP) at the level of -46.00 m signifies that the composite sequence W3 is older than Boreal.

Where the Agger clay unit has not been deposited in the study area, late-glacial meltwater sediments are overlain by the Jutland Bank sand unit (informal name) indicating a continuous sand sedimentation from Preboreal until recent. However, a removal of older deposits by erosion cannot be excluded. Permanent processes of reworking the sediments of this unit have produced an extremely well sorted sediment. The distribution of sequence W1 here is mainly governed by recent dynamic forces, as seen from the sand-waves and megaripples on seismic section 562008 (Fig. 3a).

The Agger clay unit

In the eastern part of the study area a sequence characterised by a parallel concordant reflector configuration fills the topography of the glacial surface (Fig. 3a; section 562008). ^{14}C dating of the base level of this unit in core 562011 (Fig. 4b) yields an age of 9,350 ± 100 y. BP for the shallow-water species *Cardium edule*. This suggests a



transgression at the end of Preboreal with shallow-marine and more protected conditions. The well-sorted silty clay of this unit correlates with the lithology of the unit described by Petersen (1985) at the Agger isthmus. The level of 6 m. b.s.l., representing the topmost part of the unit, has been ^{14}C-dated to 3,650 ± 80 y. BP (Petersen 1985). As already suggested above, the Agger clay unit was deposited continuously during the period Late Preboreal to Subboreal.

The Jutland Bank sand unit

Due to the dense sandy character of the sediment, the

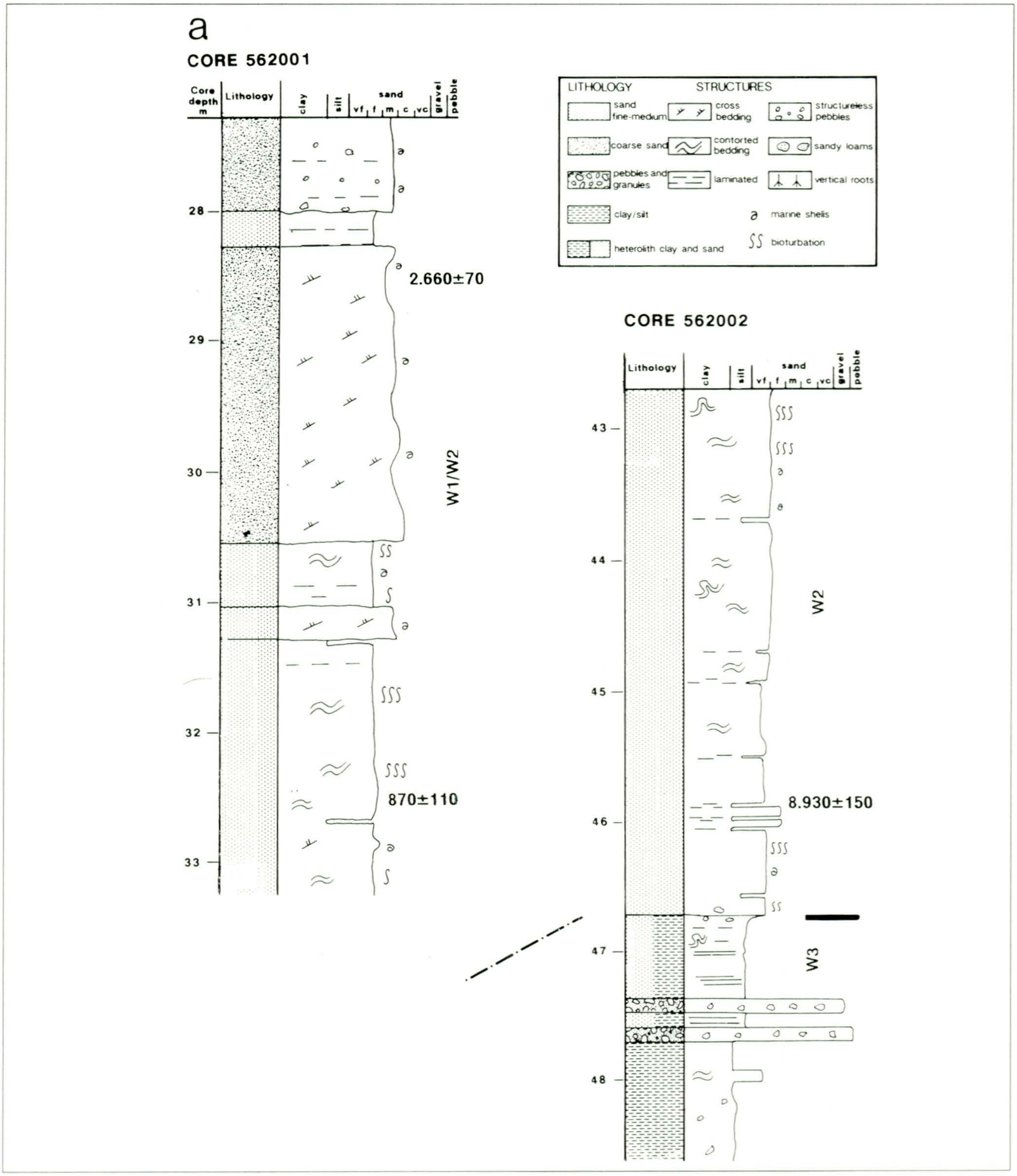
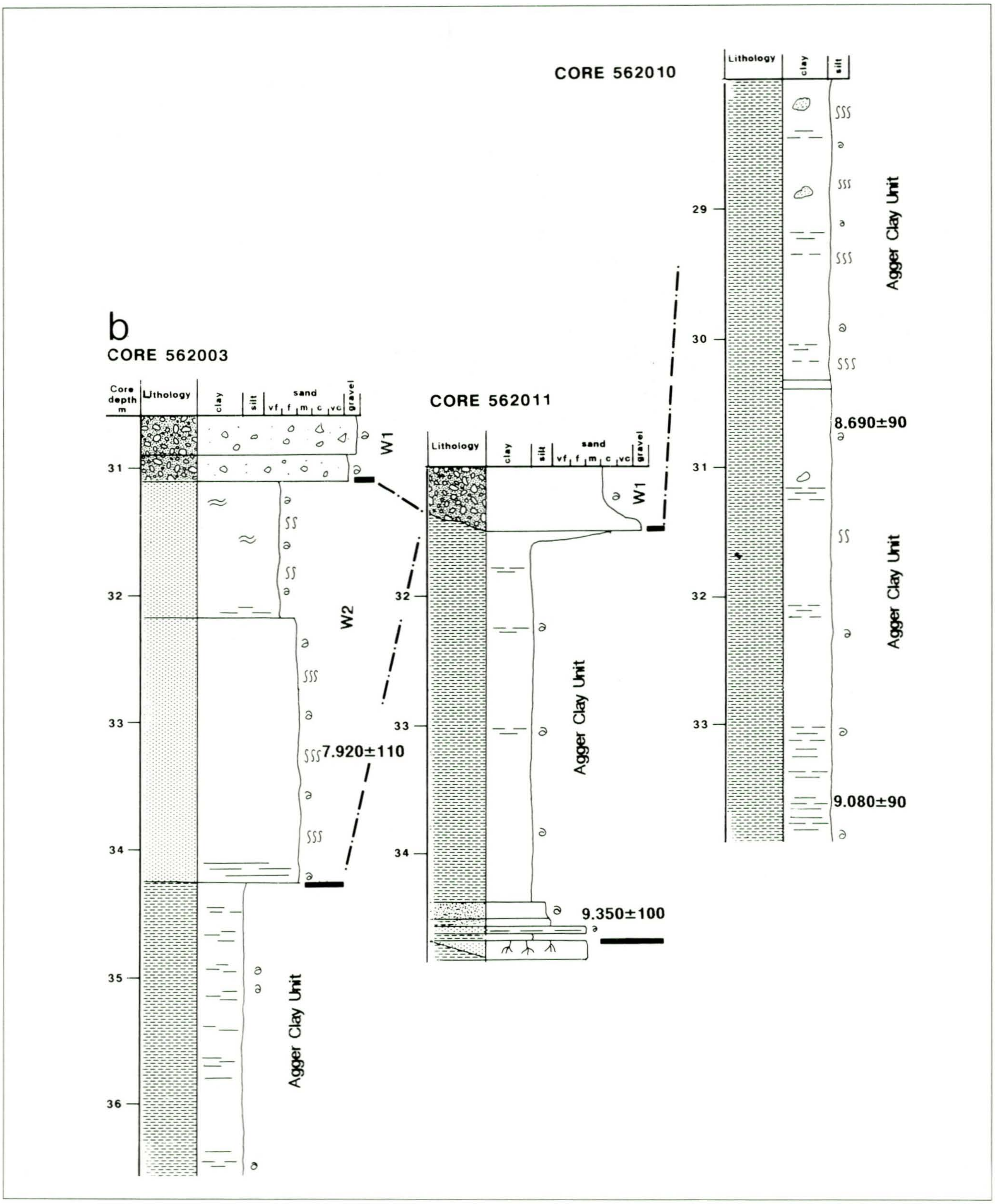


Fig. 4a and 4b. Core logs showing lithology and sedimentological structures in the vibrocores: 562001, 562002, 562003, 562010 and 562011. A correlation between lithofacies and seismic sequenses is presented. Seismic sequence boundaries are marked by thick solid lines. ^{14}C ages (years BP) are indicated by the corrected ages.

sequences W1 and W2 have a very low degree of seismic penetration. The configuration of the internal reflectors on section 562009 (Fig. 3b) locally displays an oblique to shingled reflection pattern. The two sequences have been separated by a regional unconformity and by a lithological change reflected in the samples (W1 - medium to coarse sand; W2 - fine sand). Together they form the Jutland Bank sand unit of Holocene age and the sub-recent/recent sandy-gravelly deposits. Several cores have penetrated this unit. The best evidence is encountered in



cores 562001 and 562003 (Fig. 4a and b). Two ages of molluscs from core 562001 reflect the reworked character of the Jutland Bank sand unit. The *Dosinia lincta* (870 ± 110 y. BP) found unbroken in situ at level -32.50 m, is overlain by a fragment of *Tracia papyracea* (2,660 ± 70 y. BP) at level -28.50 m. Dating of the gracile species *Tellina fabula* at level -33.25 m in core 562003 suggests an increasing bedload transport and accumulation of sandy sediments starting shortly after 7,920 y. BP. The deepest level of the Jutland Bank sand unit (W2) has been recorded in core 562002. ^{14}C dating of the species *Littorina littorea* at the level -46.80 m has given an age of 8,930 ± 150 y. BP.

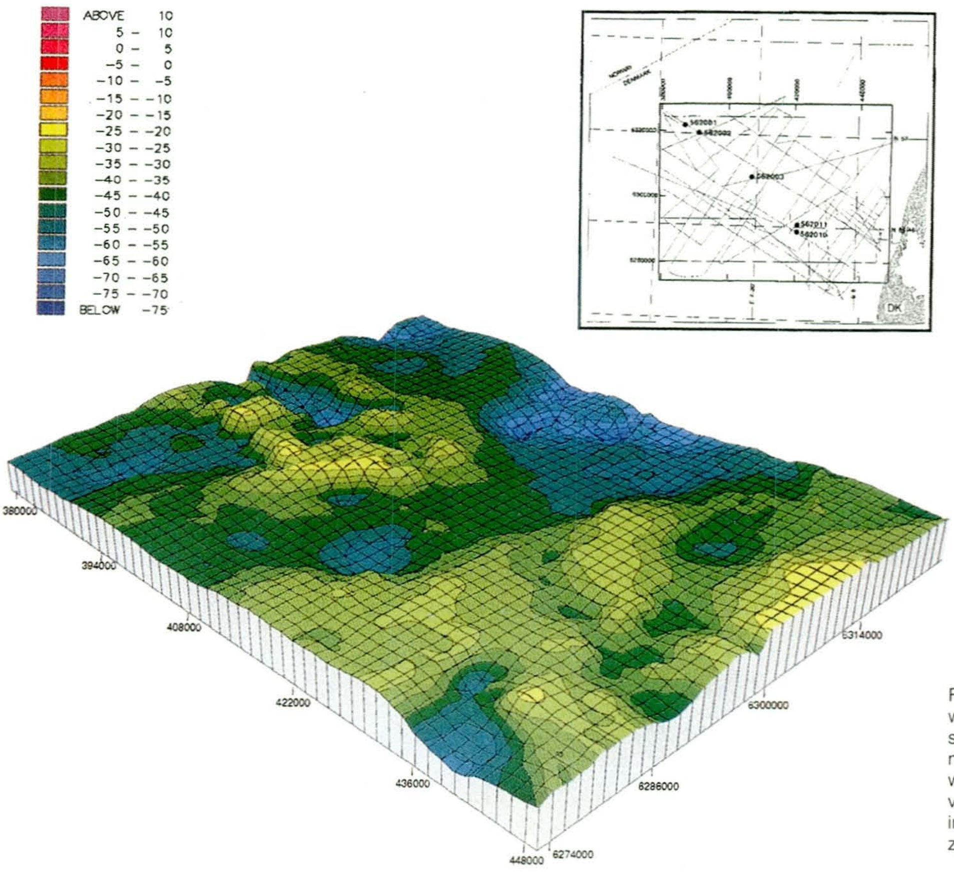


Fig. 5. 3-D view glacial contour map showing the modified topography of the glacial surface in the Jutland Bank area (see inset map). View from the southeast to the northwest across the study area. Contour interval, 5 metres. The numbers on the sides indicate UTM eastings and northings (UTM zone 32).

Results and discussion

The Pleistocene glacial surface

From an interpretation of the boomer records an erosional truncation on top of the glacial deposits (Fig. 3, units W4 and W5) has been recognised and mapped throughout the entire study area (Fig. 5). It is not possible to re-establish the original glacial topography, but by stripping off Late Pleistocene and Holocene deposits the modified topography left by the melting of the Weichselian ice-cap appears. This surface reflects the palaeogeography at the end of the glacial low-stand period. Due to the rising sea-level during the Late Pleistocene and Holocene, an erosion and reworking of the glacial sediments took place. Despite the varying distance between the seismic lines and data points, the 3-D-View contour map (Fig. 5) yields an overview of the main morphological elements at the end of the glacial period. A morphological analysis of individual parts of the study area and its interpretation in the light of the Late Pleistocene /Holocene transgression are given below.

Table 1. Radiocarbon ages of molluscs from the vibrocores of Jutland Bank. The reservoir correction is 400 years.

core#	Sample ID	Sample Level (m)	Sample type (Molluscs)	^{14}C age (BP)	Reservoir corrected ^{14}C Age (BP.)
562001	AAR-1817	-28.50	Tracia papyracea	3060±70	2660±70
562002	AAR-1818	-46.00	Littorina littorea	9330±150	7930±150
562003	AAR-1819	-33.25	Tellina fabula	8320±110	7920±110
562010	AAR-1820	-33.60	Cardium edule	9480±90	9080±90
562010	AAR-1821	-30.60	Nucula nitida	9090±90	8690±90
562011	AAR-1822	-34.50	Cardium edule	9750±100	9350±100
562001	AAR-1823	-32.50	Dosinia lincta	1270±110	870±110

The eastern part

At an average distance of 15 km off the present Danish North Sea coastline the topographic map (Fig. 5) displays a NE-SW trending depression parallel to sub-parallel to the coastline. Depths of less than 30 metres southeast of this line together with incised fjord-like structures indicate a palaeo-coastline separating an open marine environment from a protected shallow-marine environment with fjord-like depressions. The seismic sections from this area display the dominating Agger clay unit (Fig. 3a; section 562008). Vibrocores into this sequence (Fig. 4b; cores 562010 and 562011) penetrated a facies of well-sorted, marine silty mud interbedded with some fine-grained sand layers. The Agger clay unit is widespead in the eastern part of the Jutland Bank as well as in the westernmost part of the present Limfjord (e.g. Penney 1992, Petersen 1994). The thickness and areal extent of the unit are variable, governed by the underlying glacial topography (Fig. 5). Cores in the westernmost part of the study area (Fig. 4a and b; Cores 562002 and 562003), nearly 70 km off the present North Sea coast, yield evidence of residuals of the Agger clay unit overlain by Holocene sand. The available seismic records do not make any connection possible between the eastern Agger clay depositional basin and the unit in these cores. At the time of deposition a connection between the depositional basins might have existed.

A study of the molluscan fauna of the Agger clay unit (Petersen 1994), datings of molluscs (Table 1) and sedimentological studies all show that the unit was continuously accumulating in a marine basin, still protected by the emerging glacial landscape. This situation persisted in the time interval Preboreal to Subboreal, when the area was finally flooded by the ongoing transgression. Erosive events have subsequently removed parts of the unit during the rapid Holocene sea-level rise and the opening of the English Channel. This was followed by the initiation of southern North Sea water flowing through the Jutland Bank area (see below).

The central and western part

West of the palaeo-coastline described above there is a 12 km wide, NE-SW striking, strait-like structure with depth contours at levels between -30 and -50 m (Fig. 5). It separates the eastern shallow-water area from an irregular achipelago-like glacial topography with depth contours less than -18 metres to the west, coinciding with the presumed Weichselian ice margin. The hydrographic system of the Jutland Bank area changed dramatically, when the Holocene transgression flooded the highest part of this outcropping glacial landscape.

The present small tidal amplitude of this area of less than 1 m (Kristensen 1991) is caused by an interference of the tidal waves of the two governing amphidromic systems in the adjacent part of the North Sea. Tidal forces of higher tidal amplitudes than the present dominated the sediment transport pattern until the final submergence of the Jutland Bank area. The obstructive effect on longshore currents from the glacial islands is assumed to have favoured a tidally dominated current system, different from the present Jutland Current system. The present current pattern is strongly influenced by meteorological conditions (Kristensen 1991).

Comparing the glacial contour map (Fig. 5) and the bathymetric map of the study area in Fig. 1, a striking coincidence between the strait-like structure in the subglacial surface (see Fig. 3a for seismic section 562008; Top of unit W5) is below -40 metres and a depression is seen in the sea bed, indicating a low rate of deposition and/or even erosion during the time span from Late Pleistocene until recent (i.e. post unit W5).

Infilled erosional features incised into the glacial deposits are seen in the central part of the Jutland Bank unit (Fig. 3b; unit W4). Unfortunately, the data do not allow further interpretation of the deposition history of these features.

By 9.000 y. BP the sea-level in the North Sea Basin had risen to about 50 m below the present (Jelgersma 1979). As with the Jutland Bank, the Dogger Bank was still emergent at this time, with a narrow strait between it and the British Isles (Davis & Balson 1991). Strong tidal currents moved through this strait until the sea-level rose to its present position resulting in a substantial reduction of tidal current strength. Large areas in the central and southern North Sea were flooded during the Holocene sea-level rise. Consequently, the newly established current system (Backhaus & Reimer 1981) caused increasing bed-load transport along the European coastline to the main depocenter of the western and central part of the Skagerrak (Salge & Wong 1988). The change of deposition from unit W3 to unit W2 in core 562002 (Fig. 4a) in the present investigation yields evidence of such an increase in bed load transport at about 9,000 y. BP. However, a considerable amount of the sediment supply into the Skagerrak at this time must still have originated from coastal erosion processes of the emerged glacial deposits on the Jutland Bank and also possibly on the Little Fisher Bank.

The development of the Skagen Spit has recently been analysed by Conradsen (1995). A sudden change from fine to coarser sediments, and the appearance of the foraminifer *Eoeponidella laesoensis* indicate a sudden change in the hydrography with an increasing flow energy at 5,500 y. BP. This probably reflects the final flooding of the emerged Jutland Bank followed by a strengthening of the Jutland Current and increasing inflow of North Sea water into the Kattegat.

The northern part

In the northern part of the Jutland Bank, channels incised into the glacial surface are seen striking N-S with a base level between 70-90 m (Fig. 5). As suggested by Salge & Wong (1988) the sea-level in the Skagerrak region in the Late Pleistocene (13,000 - 14,000 y. BP) was at about 70 metres below the present. The channels are apparently older, related to the period when Jutland Bank was draining towards the north into the Skagerrak.

Conclusions

From a seismic analysis of the topography of the erosional truncation representing the top of the glacial deposits, a model has been proposed for the development of the Jutland Bank area during postglacial time. The Quaternary seismic stratigraphy of the northwestern part of the area was studied and 5 seismic sequences were defined: W5 is glacial deposits, W4 is incised valley fill, W3 is a postglacial composite sequence older than Boreal, and W1 and W2 represent the Jutland Bank sand unit. A palaeo-coastline 15 km west of and parallel to the present Danish North Sea coastline has been found to have existed in connection with a protected marine environment. In this environment silty clay and silt (the Agger clay unit) were deposited continuously in the time span Preboreal to Subboreal. This occurred diachronously with respect to the deposition of sandy sediments (the Jutland Bank Sand Unit), which included a Boreal molluscan fauna indicative of an open marine environment to the west. An archipelago-like pattern of emerging islands of glacial deposits had an obstructive effect to the establishment of longshore currents. These conditions persisted until the flooding of the highest parts of the residual glacial landscape at levels of about -18 metres below the present sea-level. An strait-like N-S striking opening across the Jutland Bank formed the main gateway for watermasses to pass. Prevailing tidal currents of higher tidal amplitudes than the present (< 1 m at Jutland Bank) must have governed the sediment transport at Jutland Bank/Little Fisher Bank in the early parts of the Holocene. The establishment of the Jutland Current in its present form was synchronous with the final drowing of the Jutland Bank archipelago. The change observed in the Skagen Spit sedimentary record at 5,500 y. BP possibly reflects the latter hydrographical change.

Acknowledgements

Financial support for this study was given by the Geological Survey of Denmark and the Danish Research Academy. Kaj Strand Petersen is thanked for his investigation of the molluscs from the cores and for inspiring discussions. I greatly acknowledge the AMS-Laboratory, The University of Aarhus, for carrying out the ^{14}C datings, to Bruno A. Schwede for handling the UNIKORT program, and to Antoon Kuijpers for critically reading the manuscript.

References

Andersen, B. 1979: The deglaciation of Norway 15.000-10.000 BP. *Boreas 8*, 79-87.

Backhaus, J. & Reimer, U. 1981: Seasonal circulation pattern in the North Sea. *In* Sündermann J. & Lenz W. (eds.): *North Sea Dynamics*. Springer, Heidelberg, 63-85.

Conradsen, K. 1995: Holocene palaeoceanography and palaeoenvironment of the Skagerrak-Kattegat, Scandinavia. *Palaeoceanography* (in press).

Davis, R. A. & Balson, P. S. 1991: Stratigraphy of a North Sea tidal sand ridge. *Jour. Sed. Petr. 62*, 116-121.

Gregersen, S., Leth, J. O., Lind, G. & Lykke-Andersen, H. 1995: Earthquake activity and its relation to geologically recent motion in Denmark. *Tectonophysics* (in press).

Jensen, K. A. & Knudsen, K. L. 1988: Quaternary foraminiferal stratigraphy in boring 81/29 from the central North Sea. *Boreas 17*, 273-287.

Jansen, J. H. F., van Weering T. C. E. & Eisma, D. 1979: Late Quaternary sedimentation in the North Sea. In Oele E., Schüttenhelm R.T.E. & Wiggers A.J. (eds.): *The Quaternary History of the North Sea*, 175-187. *Acta Univ. Ups. Symp. Univ. Ups. Annum Quingentesimum Celebrantis: 2*, Uppsala.

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

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

Kristensen, K. B. 1991: Den jyske kyststrøm. *Havforskning fra Miljøstyrelsen 6*, 58 pp.

Mörner, N.-A. 1980: The northwest European 'Sea-level Laboratory' and regional Holocene eustasy. *Palaeogeogr., Palaeoclim., Palaeoeco. 29*, 281-300.

Nesje, A. & Sejrup, H. P. 1988: Late Weichselian/Devensian ice sheets in the North Sea and adjecent land areas. *Boreas 17*, 371-384.

Nordberg, K. 1992: Oceanography in the Kattegatt and Skagerrak over the past 8000 years. *Palaeoceanography 6*, 461-484.

Pedersen, S. A. S., Petersen, K. & Rasmussen, L. A. 1988: Observations on glaciodynamic structures at the Main Stationary Line in western Jutland, Denmark. *In* Croot, D.G. (ed.): *Glaciotectonics: Form and Processes*. Balkema, Rotterdam, 177-183.

Penney, D. N. 1992: Sejlruter fra Limfjorden: forbindelser til Nordsøen i Holocænet belyst ved mikrofossilanalyser. *Limfjordsprojektet, Rapport no. 5; Kommunikation ved Limfjorden fra fortid til nutid*, 31-44.

Petersen, K. S. 1985: Late Weichselian and Holocene marine transgressions in Northern Jutland, Denmark. *Eiszeitalter und Gegenwart 35*, 71-78.

Petersen, K.S. 1991: Holocene coastal and faunal development of the Skagen Odde, Northern Jutland. *Quater. Internat. 9*, 53-60.

Petersen, K. S. 1994: Limfjordstangerne. Holocæn marin udvikling. *DGU Service Report no. 85*, 30 pp.

Pratje, O. 1951: Die Deutung der Steingrunde in der Nordsee als Endmoränen. *Deutsche Hydrogr. Zeitschrift 4*, 106-114.

Salge, U. & Wong, H. K. 1988: Seismic stratigraphy and Quaternary sedimentation in the Skagerrak (northeastern North Sea). *Mar. Geol. 81*, 159-174.

Salomonsen, I. 1994: A seismic analysis of Lower Pleistocene deposits in the western Danish sector of the North Sea. *Geol. Mijnbouw 72*, 349-361.

Salomonsen, I. & Jensen, K. A. 1994: Quaternary erosional surfaces in the Danish North Sea. *Boreas 23*, 244-253.

Sejrup, H. P., Aarseth, I., Ellingsen, K. L., Løvlie, R., Reither, E., Bent, A., Brigham-Grette, J., Jansen, E., Larsen, E. & Stoker, M. S. 1987: Quaternary stratigraphy of the Fladen area, central North Sea: A multidisciplinary study. *Jour. Quat. Sci. 2*, 35-58.

Shennan, I. 1987: Holocene sea-level changes in the North Sea. In Tooley J. & Shennan I (eds.): *Sea-level Changes*, 109-151. Blackwell Scientific Publications, Oxford, 109-151.

Stabell, B. & Thiede, J. 1986: Palaeobathymetry and palaeogeography of southern Scandinavia in the late Quaternary. *Meyniana 38*, 43-59.

Stuiver, M. & Polach, H. A. 1977: Discussion: Reporting of ^{14}C data. *Radiocarbon 19*, 355-363.

Sutherland, D. G. 1984: The Quaternary deposits and landforms of Scotland and the neighbouring shelves: A review. *Quat. Sci. Rev. 3*, 157-254.

Tooley, M. 1974: Sea-level changes during the last 9000 years in north-west England. *Geogr. J. 140*, 18-42.

Ussing, N. V. 1907: Om Floddale og Randmoræner i Jylland. *Overs. K. Vidensk. Selsk. Forh. No. 4*, 161-213.

Vail, P. R., Mitchum, R. M. Jr., Todd, R. G., Widmeier, J. M., Thomson, S., III, Sangree, J. B.J. N. & Hatlelid, W. G. 1977: Seismic stratigraphy and global changes of the sea-level. In Clayton, C. E. (ed.): *Seismic stratigraphy - Application to Hydrocarbon Exploration. Am. Assoc. Pet. Geol. Mem. 26*, 49-212.

Van Weering, T.C.E. 1975: Late Quaternary history of the Skagerrak: an interpretation of acoustic profiles. *Geol. Mijnbouw 54*, 130-145.

Manuscript received April 1995; revised version accepted February 1996.