Thickness, distribution and depositional environment of Holocene sediments in the Norwegian part of the Skagerrak

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A regional seismic reflector separating an uppermost low-reflectivity Holocene unit from an acoustically layered, Late Weichselian, glaciomarine unit below has been mapped in the Norwegian Skagerrak between Langesund and Egersund. The thickest Holocene deposits occur in the eastern part of the Skagerrak, with a generally decreasing thickness westwards. In the central part of the Norwegian Trench east of Lista, the Holocene soft clay is 7.5-15 m thick, while further west it is generally less than 7.5 m thick. On the northern slope of the trench, east of Mandal, the thickness varies between 15 m and 35 m. West of Mandal, on the northern slope, Holocene sediments occur only within local basins.

On the steepest part of the southern and southeastern slope of the Norwegian Trench, and along the northern part of the plateau south of the trench, the Holocene unit is absent. This area of erosion/non-deposition extends east-northeast for about 100 km, and terminates in a narrow trench in the easternmost part, indicating that contour-parallel currents have been responsible for the erosion. A substantial portion of the eroded sediments has been deposited to the east and northeast of the area of erosion, where up to 100 m of Holocene sediments occur. On the plateau south of the Norwegian Trench the Holocene thickness increases towards the east-southeast, to a maximum of 40-50 m near the Danish border. Large sandwaves migrating towards the southeast occur in this area, in water depths shallower than 200 m. The migration direction indicates that they are relict and that there was an important oceanographic change in the Late Weichselian/Early Holocene. Acoustic blanking of high-frequency seismic records indicates that shallow gas occurs in the Holocene sediments in the relict sandwave area and in the upper slope to the north of this.

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Introduction

Holocene sedimentation in the Skagerrak was recently addressed in a special issue of Marine Geology (Liebezeit et al. 1993). Although a number of authors described various aspects of the sediments and the sedimentary processes in the Skagerrak, it was concluded that several significant gaps exist in our present knowledge (Van Weering et al. 1993a). The main objective of the present paper is to try to close one of these gaps by presenting a map of the thickness and distribution of sediments deposited over the last 10,000-11,000 years.

Several investigations have shown that a substantial part of the sediment supply to the North Sea, and sediments reworked during storms or extreme current episodes on the shelf and along the coasts, have ended or will end their transport path in the Skagerrak. Compared with the shallower parts of the North Sea and the Norwegian Trench along the Norwegian west coast (Van Weering et al. 1973, Rise & Rokoengen 1984, Stoker et al. 1985, Long et al. 1986, Sejrup et al. 1989, Andersen et al. 1995), very high sedimentation rates have been measured in the Skagerrak (e.g. Van Weering et al. 1987, 1993b). Correlation of seismic data with ages obtained from stratigraphic cores indicates that the uppermost acoustically transparent unit in the central part of the Norwegian Trench represents sediments deposited during the last 10,000-11,000 years. The uppermost unit changes seismic character within the area, and although the character may vary due to a variable quality of the seismic records, it has been possible to provide a consistent interpretation for most of the investigated area. There are few cores that penetrate the reflector at the base of the uppermost transparent unit, but recent sediment accumulation rates indirectly support our interpretation of the Holocene sediment thickness and distribution (Bøe et al., this volume). An isopach map of the uppermost transparent seismic unit in the Norwegian Trench has previously been presented by Van Weering et al. (1973). This map was based on a very open grid of penetration echosounder data, and comparison of the interpretations is possible only within parts of the area.

Methods

During the period 1991-1994 the Geological Survey of Norway, together with several other institutions, collected more than 16,000 km of shallow seismic data (Bøe et al. 1991, 1993, Thorsnes et al. 1992, 1993, Ottesen et al. 1994) (Fig. 1), and short cores from 133 stations in the Norwegian part of the Skagerrak. Bolt single airgun and Sleevegun (20 and 40 cubic inches) were used as seismic sources, together with the high-frequency seismic source

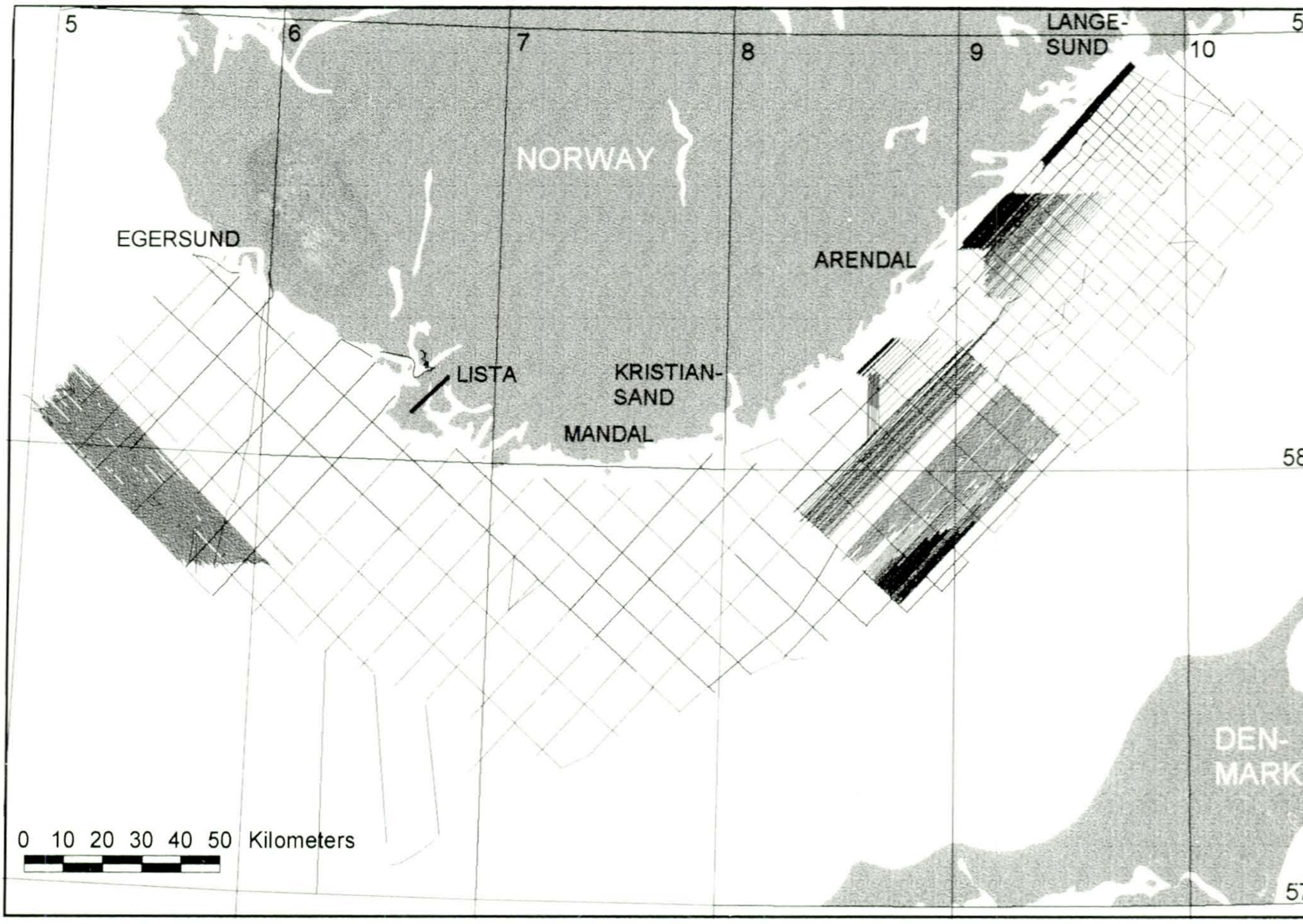

Fig. 1. NGU's shallow seismic lines in the Norwegian part of the Skagerrak used in the present study.

Geopulse. Due to bad weather the latter was not deployed on all lines. The Global Positioning System (GPS) was applied with differential corrections from fixed land stations. In some areas with a thin Holocene unit the interpretation was difficult, mainly where Geopulse data were lacking. The accurate positioning of the zero milliseconds two-way travel time (ms TWT) line was also difficult in some areas where Geopulse data were available, because the sea-bed pulse often hides weak reflectors in the uppermost metres. However, access to high-resolution, deep-towed boomer data enabled control and adjustment of the interpretation within some areas.

Shallow cores (59 mm core diameter and core length generally less than 50 cm) were taken at 133 locations in the middle/eastern parts of the study area. A description of these cores as well as grain-size analysis are given in reports by Bøe (1993, 1994, 1995). A paper summarising the results of the sedimentological analysis as well as presenting a compilation of all available sedimentation rates, is given by Bøe et al. (this volume).

Bathymetry and oceanography

The Norwegian Trench starts southeast of Langesund, and continues along the south and westcoast of Norway for approximately 900 km (Fig. 2). The deepest part of the Skagerrak is within the easternmost part of this trench, with maximum water depths of ca. 700 m at a distance of 50 km off the coast between Arendal and Langesund. The trench becomes gradually shallower towards a sill at 290 m water depth west of Egersund. East of the deepest trough there is a shallowing towards the outlet of the Kattegat. Towards mainland Norway the slope is generally steeper and more irregular than on the southern side, resulting in an asymmetrical shape of the trench. The sea floor is particularly irregular along the coast, where crystalline rocks crop out, and in the northeastern part of the study area.

The boundary between the Norwegian Trench and the gently northwesterly dipping plateau to the south is marked by a change in slope angle, at 250-300 m water depth. In the southwestern part of the study area there is a more gradual transition between the slope and the plateau. The slope angle decreases southwards, resulting in a large-scale convex topography along the southern slope of the trench. The lowermost part of the southern slope south of Lista is much steeper (about 10°) than the average slope angle to the east and west.

Between Langesund and the deepest parts of the Norwegian Trench the topography is characterised by several south to southwest trending trenches (Holtedahl

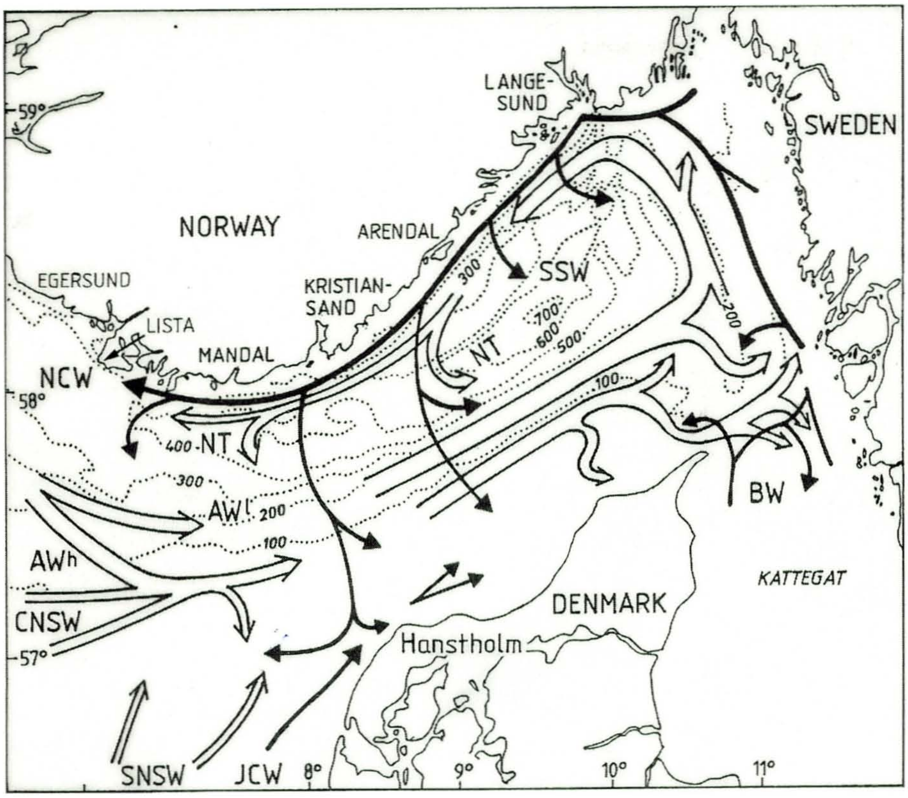

Fig. 2. General pattern of ocean currents in the Skagerrak and adjacent areas. Open and filled arrows indicate subsurface and surface water, respectively (modified from Danielsen et al. (1991)). AW: Atlantic water; CNSW: Central North Sea water; JCW: Jutland coastal water; BW: Baltic water; NCW: Norwegian coastal water; NT: Norwegian Trench.

1986). Southeast of Arendal (between 8° 30' E and 9° 30' E) there is an extensive subhorizontal area with water depths between 400 m and 450 m (here informally named the 'Arendal terrace'). On a small scale the topography of this area is irregular, with depressions and ridges a few hundred metres apart, and in the south the terrace-like feature is bounded by a steep slope down to the deepest parts of the Skagerrak. Along the northernmost part of the terrace a 15-30 m deep and up to 2 km wide, coast-parallel trench occurs. To the north of the terrace the topography of the slope is irregular.

The general and well-known cyclonic circulation of water masses in the Skagerrak is mainly regulated by in- and outflowing water from the North Sea and the locally steep topography of the Norwegian Trench (Fig. 2). Atlantic water enters the North Sea between Norway and Shetland, and follows the western side of the Norwegian Trench down to the Skagerrak. This major inflow (1 km^3/s) of high-saline water (salinity > 35‰) consists of two partly separable currents. One is the main and direct inflow along the western and southern slope of the Norwegian Trench with a deep plume located above the 150 m bottom contour, and the other is a branch of Atlantic water which has taken a more southerly route and is steered into the Skagerrak approximately along the 70 m bottom contour (Aure et al. 1990). The depths of the major inflows are thought to increase during extreme meteorological/oceanographical conditions.

The different water masses from the North Sea enter the Skagerrak in an area of about 50 km width north of Hanstholm, and a mixing between all of them can occur (Fig. 2). The inflow to the Skagerrak is complex, and variable weather conditions frequently change the direction and the magnitude of several of the major ocean currents (e.g. Larson & Rodhe 1979). A general picture is that the currents from the central North Sea join the southern branch of the Atlantic Current to continue north and northeastwards. Jutland coastal water, which is a mixture of continental river water and water from the English Channel/southern North Sea, flows northwards close to the western Danish coast, parallel to the currents from the southern North Sea in deeper water further west.

Aure et al. (1990) pointed out the pulsating nature of the Jutland Current into the Skagerrak, and that large amounts of water can flow into the Skagerrak and the Kattegat over relatively short time periods. The speed and partly also the direction are highly dependent on the strength and direction of the prevailing winds. Also, the inflow of Atlantic water is known to vary from year to year, probably as a result of large-scale hydrographic changes in the North Atlantic (Sancetta et al. 1973). Water masses of Atlantic origin entering the Skagerrak outside Hanstholm seem to have a great influence on the Jutland Current. In periods with strong inflow of Atlantic water, the Jutland Current and water from the southern North Sea may be stopped, and in periods with reduced inflow of Atlantic water accumulated water in the southern North Sea can flush into the Skagerrak for 2-3 weeks (Danielsen et al. 1991). Jutland Current water is mixed with Baltic water at the outlet of the Kattegat, and contin-

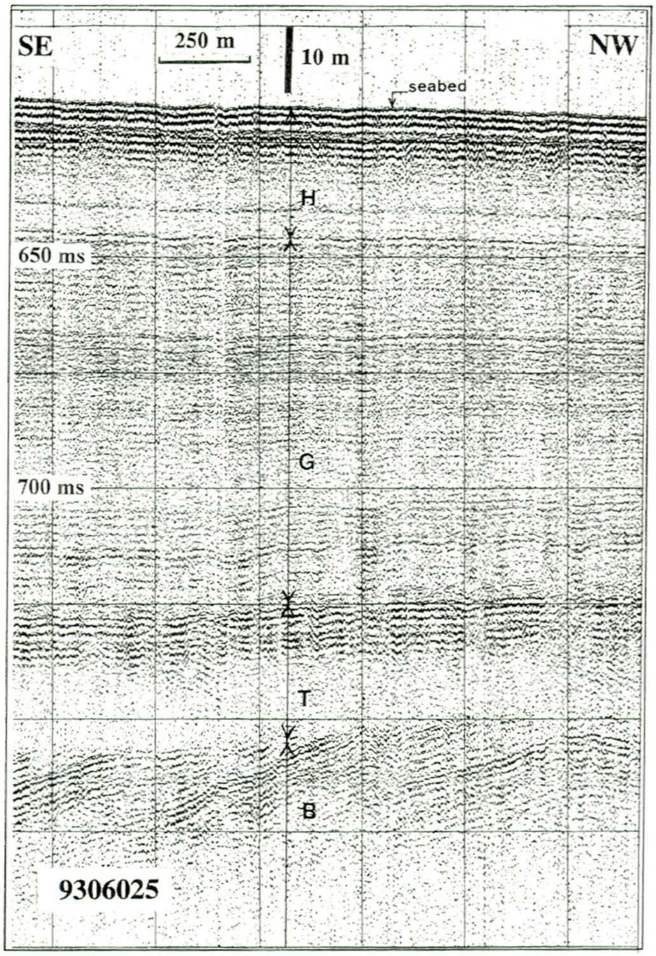

Fig. 3. Geopulse record showing the general stratigraphy of the central part of the Norwegian Trench. Southward dipping Mesozoic bedrock (B) is overlain by till (T) and a succession of acoustically layered glaciomarine sediments (G). The Holocene succession (H) on top is acoustically transparent, with only a few faint internal reflectors. The reflectors near the sea-bed are artificial, and probably caused by a delayed sea-bed return via the sea surface. Seismic section located at N57º46.1', E7º38.8'.

ues along the Swedish west coast to Norway where it turns westwards as the Norwegian Coastal Current.

Seismic stratigraphy

The seismic section shown in Fig. 3 gives a general view of the seismic stratigraphy in the central part of the Norwegian Trench. The bedrock, consisting of Mesozoic sedimentary rocks, is truncated by glacial erosion, and is overlain by one or two thin, acoustically chaotic till units (J. Sættem, pers. comm. 1996). In the southern and southwestern parts of the investigated area several till units may occur (L. Rise, unpubl. data), and make up a larger part of the Quaternary succession. In most of the Norwegian Trench (also along the west coast of southern Norway) the till is overlain by acoustically parallel-layered deposits, mainly glaciomarine sediments (Rise & Rokoengen 1984, Andersen et al. 1995, Sejrup et al. 1995).

The uppermost seismic unit is fairly easily distinguishable from the layered succession below. It is acoustically light or transparent, with only a very weak internal layering. Locally, the unit shows a more pronounced layering, particularly along the slopes of the Norwegian Trench, but a strong and continuous reflector at the base of the unit has made a confident interpretation of the boundary possible. On the northerly dipping plateau near the Danish border the seismic records become dark due to shallow gas masking geological information below the sea-bed, in particular on the Geopulse records (acoustic blanking). Large sediment waves in water depths less than 200 m indicate that fine and very fine sand constitutes a substantial part of the sediments in this area.

Thickness of Holocene sediments

Shallow seismic lines were run through the location of a multi-disiplinarily investigated core taken to the south of Mandal (the OSKAP core, Stabell et al. 1985), where the base of the uppermost seismic unit occurs at 11 ms (8.5 m). In the core, the base of the Holocene was found at 6.8 m, and Younger Dryas sediments were present in the lower part of the core at approximately 10.5 m. On a composite piston-core taken by the University of Bergen and NGU in June 1991 (PC61/62, 57° 48' N, 6° 32' E in 317 m water depth), detailed sedimentological and biostratigraphical analyses were carried out, and several radiocarbon ages were obtained (Hellesund 1994). The uppermost acoustically transparent unit was measured, on a Geopulse record, at 10-11 ms (approximately 8 m). The core data indicated, however, that the base Holocene (~ 10,000 years BP) is at 5 m depth, and that the base Younger Dryas (~11,000 years BP) level is at 7 m.

Due to friction and a tendency of plugging during the penetration of the core barrel, cores of soft sediments are often shorter than the corresponding in situ section. This may explain why the base of the transparent unit usually is interpreted as being at greater depth on the seismic records than in the corresponding cores. In previous studies the uppermost acoustically transparent layer has been regarded to be of Holocene age (Van Weering et al. 1973, Van Weering 1975, 1982a, Rise et al. 1984, Stabell et al. 1985, Andersen et al. 1995). Our data indicate that the transparent layer may also include the Younger Dryas strata, or a part of the Younger Dryas strata. A map showing the thickness of Holocene sediments is shown in Fig. 4.

In a zone along the coast of Norway, areas of Holocene sediments alternate with areas of bedrock, glacial/glaciomarine sediments and reworked sediments. South of this zone (about 10 km off the coast east of Lista, and up to 40 km off the coast between Lista and Egersund) there is a continuous Holocene sediment cover (Fig. 4) that increases in thickness from the southwest towards the northeast. On the northern slope of the Norwegian Trench the thickest deposits occur in NE-SW trending basins, with up

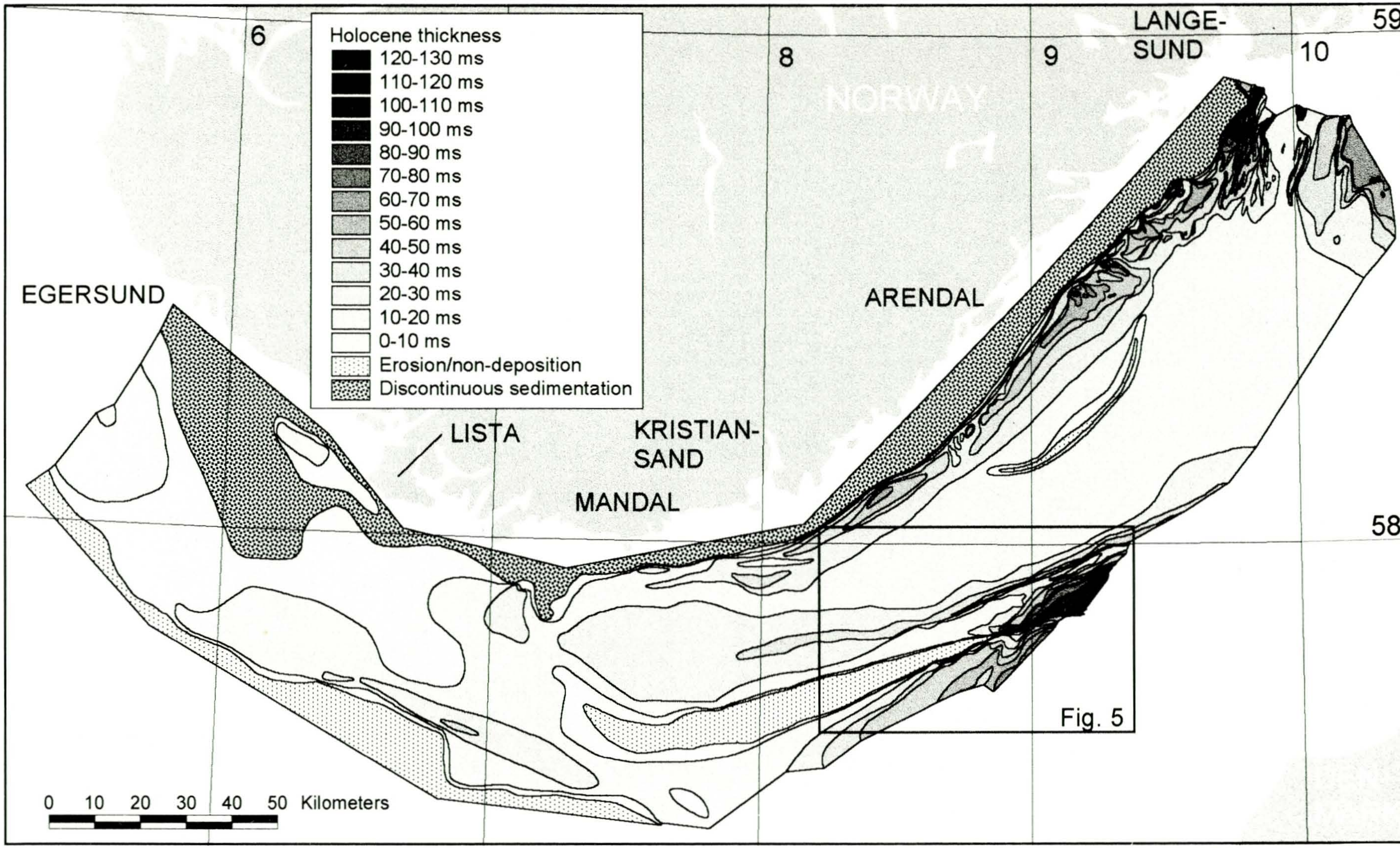

Fig. 4. Isopach map of Holocene sediments based on seismic interpretation of the grid shown in Fig. 1. The thickness is shown in milliseconds (ms) two way travel time (TWT). P-wave velocity in soft marine clays in the Norwegian Trench is 1500-1550 m/s, and milliseconds should be multiplied by 0.75 in order to obtain the thickness in metres. The more sandy deposits in the southern part of the investigated area have probably a slightly higher sound velocity (1600-1700 m/s) due to higher bulk densities (Rise & Bøe 1995), and a multiplication factor of 0.80-0.85 should be used for transformation from milliseconds to metres.

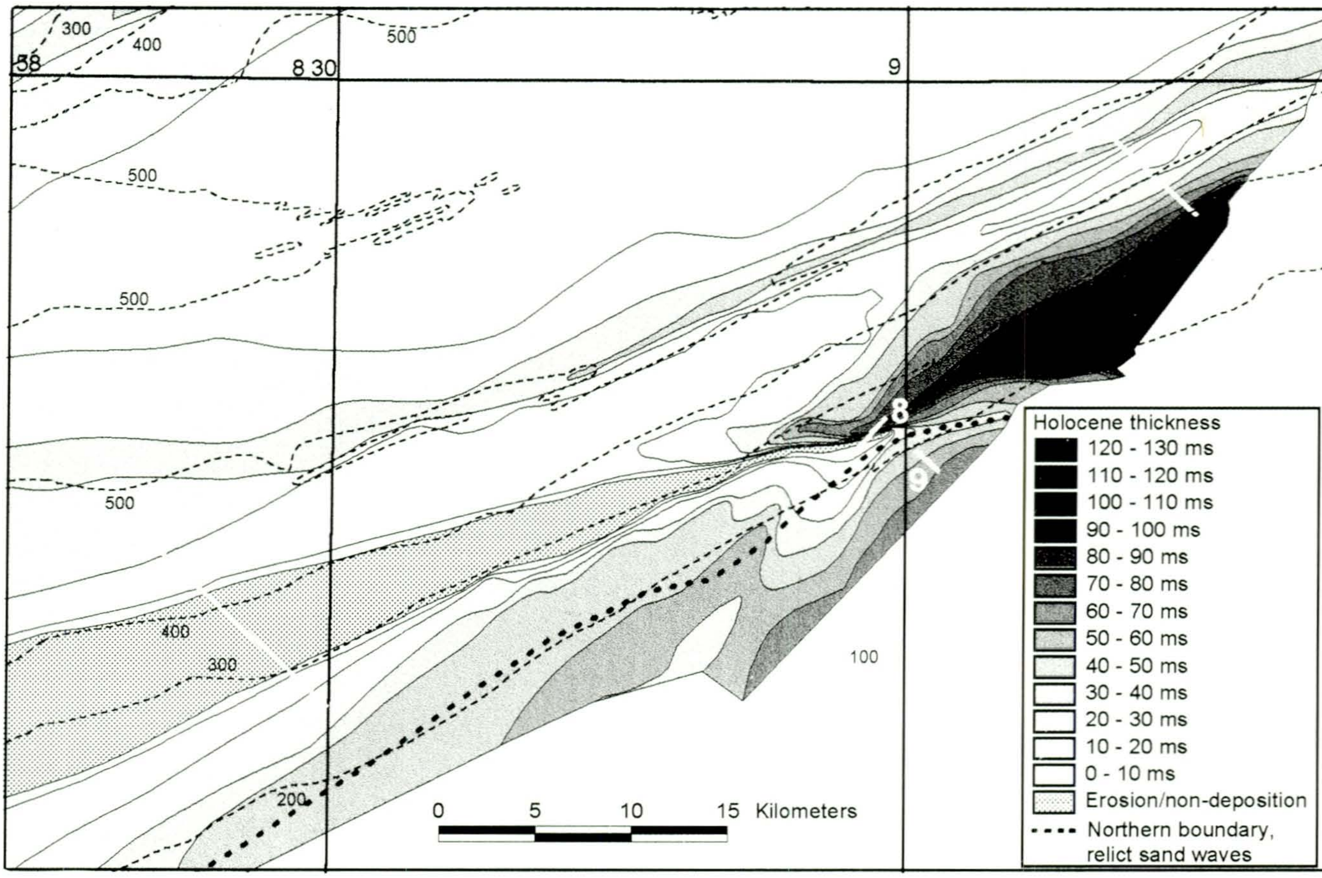

Fig. 5. Isopach map of Holocene sediments showing the eastern part of the area of erosion/non-deposition on the southern slope of the Norwegian Trench and the northern part of the plateau along the Danish borderline. The locations of Figs. 6, 7, 8 and 9 and the northern boundary of the relict sandwave area, are shown. See Fig. 4 for location of map area.

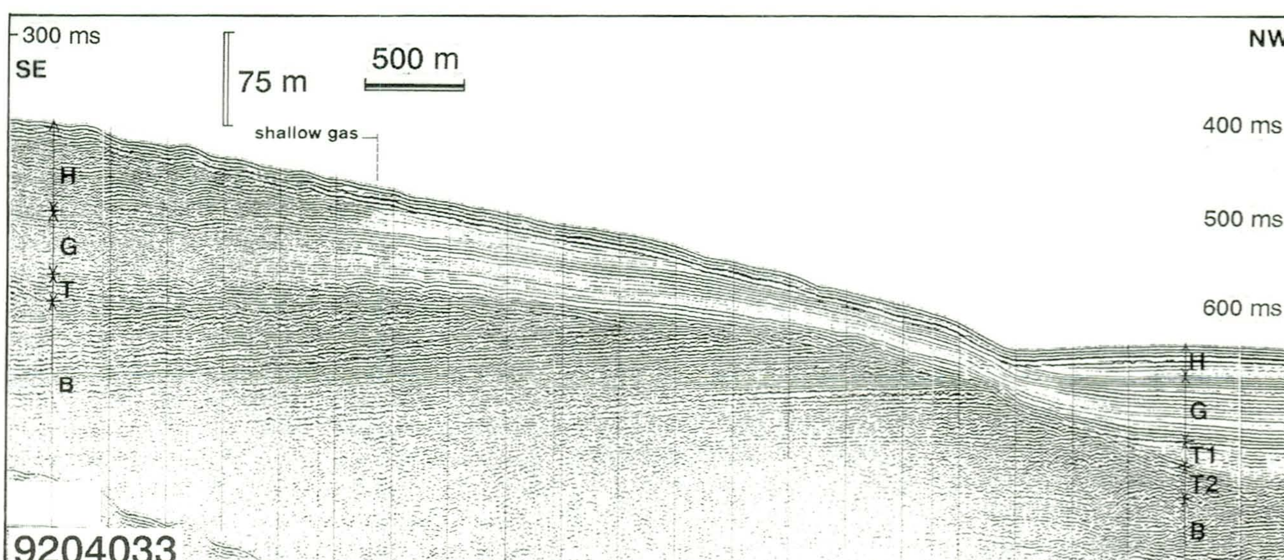

Fig. 6. Sleevegun record from the southeastern slope illustrating increasing Holocene thickness up the slope. Note the abrupt shift in acoustic reflectivity in the sediments due to shallow gas. B: Mesozoic bedrock; T: till; G: glaciomarine clay; H: Holocene clay. For location, see Fig. 5.

to 50-60 ms thickness, on the inner part of the Arendal terrace (see also Holtedahl 1964,1989, 1993, Haugwitz & Wong 1993) (Fig. 4). On the steep slope south of the terrace, the Holocene unit is very thin and locally absent. To the northeast of the Arendal terrace, there is a large variation in Holocene sediment thickness, probably due to a

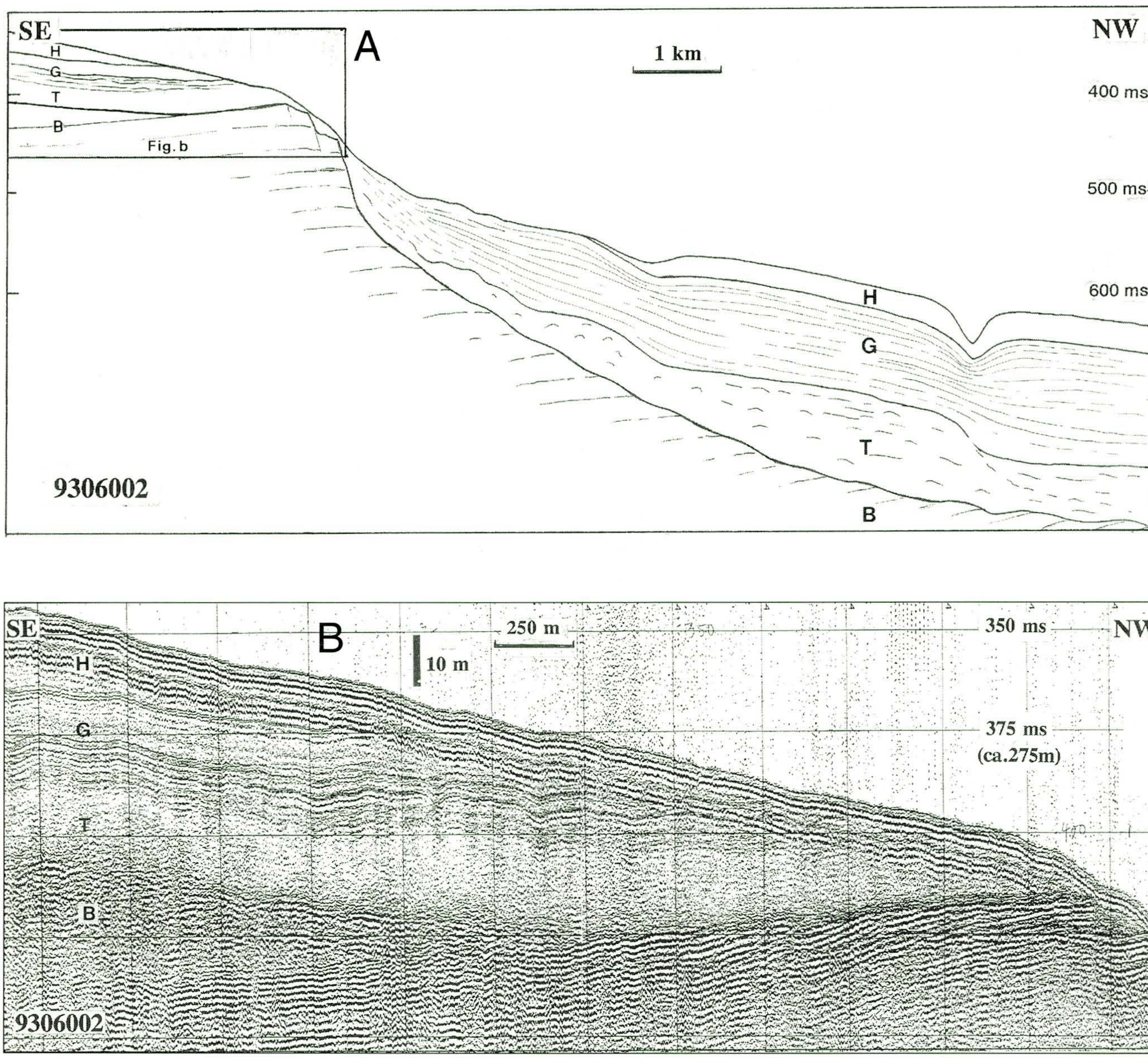

Fig. 7. (a) Interpreted Geopulse profile showing pinchout of the Holocene unit and transition to non-deposition on the southern slope of the Norwegian Trench, and erosional cutting of the base Holocene reflector (and older reflectors) at the gently northwestward sloping plateau. The areal extent of the area of erosion/non-deposition is shown in Fig. 4. (b) Profile from the plateau. See Fig. 5 for location and Fig. 6 for explanation of abbreviations.

complex topography (Fig. 4). In Langesundsrenna southwest of Langesund, several trenches are partly filled with sediments, separated by bedrock ridges with sparse overburden (see also Holtedahl 1986, 1989). The thickness of Holocene sediments may be up to 100 ms on the western slopes of the trenches, whereas no sediments have been deposited on the eastern slopes (Fig. 4).

The thickness of the Holocene succession in the Norwegian Trench east of Lista is 10-20 ms (Fig. 4). In the southeastern part of the area with a sub-horizontal sea bottom, near the transition to the slope, there is an accumulation zone with more than 30 ms sediment thickness. In the southern part of the trench south of Lista the largest thickness of the Holocene succession is approximately 30 ms. West of Lista the thickness of Holocene sediments is generally less than 10 ms, and the seismic unit pinches out in the northern part of the trench.

On the southern slope southeast of Kristiansand there is an area of erosion/non-deposition, which terminates in the east in a 500-1000 m wide and 20-30 m deep trench. The greatest thickness of the Holocene succession (120-130 ms, ca. 100 m) is found to the east and north of this trench (Figs. 4 and 5). Southeast of the area of erosion/non-deposition, on the northwest sloping plateau, the thickness of the uppermost unit reaches a maximum of 60-70 ms near the Danish border (Fig. 5). In this area the resolution of the map is slightly reduced due to acoustical blanking caused by shallow gas in the sediments (Fig. 6). Along the northern margin of the area of erosion/non-deposition, the Holocene unit onlaps and pinches out, while at the northwesterly sloping plateau just south of the steepest slope (Fig. 7) the base Holocene reflector and some older reflectors are truncated.

On the southern slope southwest of Lista, south of where the Holocene clay pinches out, side scan sonar records indicate that hard clays crop out mainly at ridges and that lower areas inbetween are infilled with 1-2 m of sandy and silty fine-grained sediments, probably of Holocene age (Lien 1995). In shallower water further to the south, extensive erosional areas have been identified, as well as active sand waves (Lien 1995).

Discussion

Several studies have shown that a substantial portion of the fine-grained material supplied to the North Sea is deposited in the Norwegian Trench (Eisma 1981, Eisma & Kalf 1987, Van Weering et al. 1987, 1993a, b). Comparison with the thickness of Holocene sediments in the Norwegian Trench along western Norway (Van Weering et al. 1973, Rise & Rokoengen 1984, Andersen et al. 1995) shows that the Skagerrak has been the main catchment area for fine-grained sediments in the North Sea throughout the Holocene. Our seismic interpretation shows that the major depocenters are on the southeastern slope, in the eastern part of the Skagerrak and partly in local depressions on the northeastern slope. Although the palaeoceanography and the relative importance of sediment sources in the North Sea have changed during the Holocene (Nordberg & Bergsten 1988), recent sediment accumulation rates (Van Weering et al. 1987, 1993b, Bøe et al., this volume) seem to broadly correspond with the Holocene thickness.

In the central, deep parts of the Norwegian Trench sediment accumulation rates of 10-20 cm/100 years correspond with our interpretation of 10-20 m of Holocene sediments, indicating that the sedimentation rate in that area has been more or less constant throughout the Holocene. On the plateau along the Danish borderline, present sedimentation rates of around 20 cm/100 years indicate that much of the up to 50 m thick succession was deposited in the Late Weichselian/Early Holocene. Locally on the southeastern slope and in the easternmost parts of the trench, sedimentation rates of 50-100 cm/100 years (Bøe et al., this volume) correspond well with Holocene sediment thicknesses of 50-100 m.

The displacement of shorelines in southeastern Norway and western Sweden, caused by rapid isostatic uplift in the Early Holocene, probably exposed a substantial amount of material to erosion and transport into the Skagerrak. Most of the thick, fine-grained succession in the Langesundsrenna is thought to have been deposited during the Early Holocene (see also Holtedahl 1986). A high deposition rate at that time may also explain the thick Holocene deposits found in basins along the southeastern coast of Norway (Fig. 4).

During the deglaciation (ca. 15,000-10,000 years B.P.) the Skagerrak was a deep fjord-like basin (Stabell & Thiede 1985, 1986, Thiede 1987), with land areas to the south and a calving ice front along much of the northern and eastern flanks. At that time the large rivers in central Europe and Britain carried suspended material northwards to the Norwegian Trench area. The establishment of the temperate Atlantic Current along the rim of the western and southern slopes of the Skagerrak had an important impact on the sedimentological conditions in the Skagerrak from about 10,000 years B.P. Extensive winnowing of the sediments in the very shallow northern North Sea at that time (Rokoengen et al. 1982, Rise et al. 1984, Rise & Rokoengen 1984, Carlsen et al. 1986) may also have made fine-grained sediments available for transport to the Skagerrak in the latest Weichselian/earliest Holocene. The Baltic Ice Lake, which was emptied into the Skagerrak from around 10,200 years B.P., probably also influenced the palaeocurrents and the deposition of fine-grained sediments.

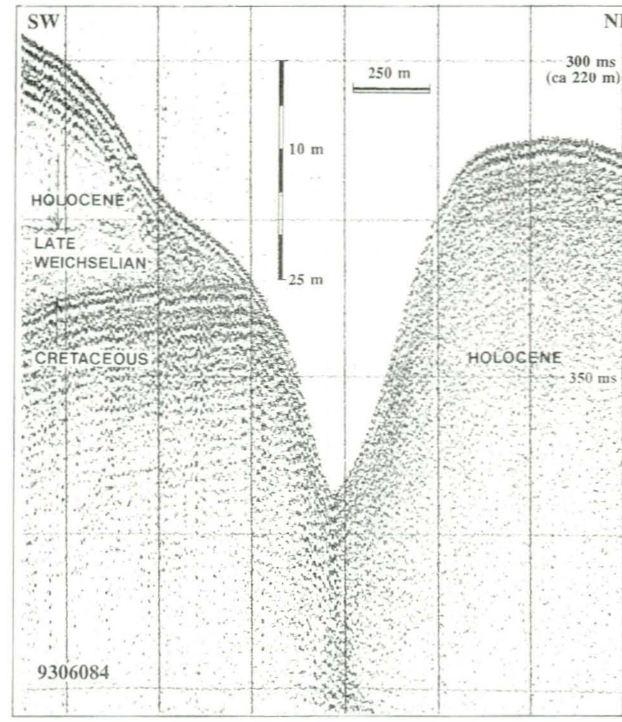

Fig. 8. Narrow trench in the eastern termination of the area of erosion/non-deposition on the southern slope of the Norwegian Trench. Note erosion of the base Holocene reflector, and outcropping Cretaceous bedrock in the southern slope of the trench. The Holocene succession is up to 50 m thick northeast of the channel. See Fig. 5 for location.

The land area south of the Skagerrak was transgressed in the period 10,000- 8,000 years B.P., and the English Channel opened at about 7,800 years B.P., probably initiating a circulation pattern similar to the present (Stabell & Thiede 1986). The flooding of the southern North Sea with coastal erosion and reworking must have had an important impact on the transport of sand and fines towards the Skagerrak. Large sandwaves at present-day water depths shallower than 200 m are seen in the sout-

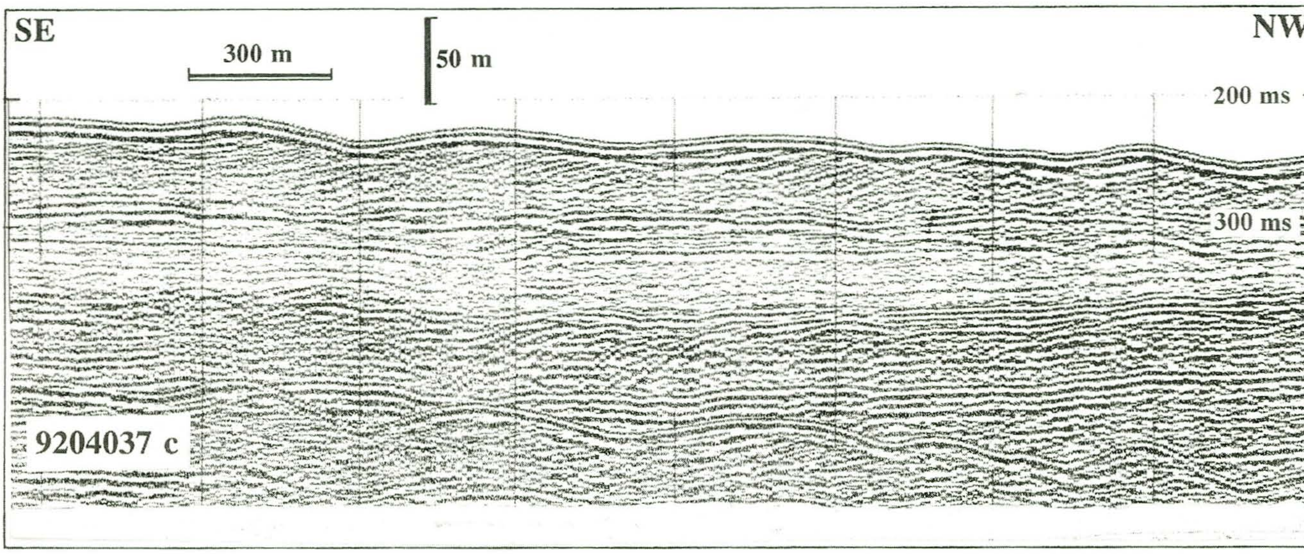

Fig. 9. Relict sandwaves on the plateau along the Danish borderline. Internal reflectors indicate sediment transport towards the southeast, which is different from the presently dominating sediment transport towards the northeast. Note the slightly rounded sandwave crests, indicating modification of the sea-bed after the sandwaves were active. Fig. 5 shows the northern boundary of the relict sandwave area. See Fig. 5 for location.

heastern part of the investigated area, near the Danish border line (Figs. 5 and 9). These have migrated towards the southeast, and cannot be explained by the present hydrographic regime with dominating sediment transport towards the east/northeast. Most of the 20-50 m thick sand succession was probably deposited in the Early Holocene in shallower water than occurs at the present. The seismic data indicate that modifications of the sea floor have occurred since the sandwaves were active, e.g. the sandwave crests are commonly symmetrically rounded, giving them a sinuous appearance. Salge & Wong (1987, 1988), however, suggested that Holocene sediments are absent and that Pleistocene deposits constitute the sea floor in a zone from about 70 m water depth north of Denmark to the shelf edge (about 200 m). They interpreted the deposits in this area to represent a prodelta slump facies. Our interpretation of a thick Holocene succession in this area is, however, supported by the seismic interpretation of Haugwitz & Wong (1993).

So far we have only a limited understanding of the observed sandwaves, though a northerly sediment source area in deeper water is unlikely. An explanation could be that sediments transported from the west were diverted towards the southeast due to strong currents formed by a cyclonic gyre in the southeastern Skagerrak. The drainage of the huge Baltic Ice Lake and/or the Ancylus Lake (8,500 years B.P.) could theoretically be such events, but it seems unlikely that the duration of these floods were long enough to form such a thick sand unit.

The most conspicuous features of the Holocene thickness map are the extensive area of erosion/non-deposition on the southern slope and the trench ('moat') in the eastern termination of this area (Figs. 5 and 8). It is probable that these features have originated due to contour-parallel currents directed towards the northeast, along the southern slope of the Norwegian Trench, and that the thick Holocene deposits to the north and east of the narrow trench can be interpreted as contourites. A contourite-like sedimentation pattern in this area has also been indicated by Jørgensen et al. (1981), Hass (1993) and Bøe et al. (this volume) on the basis of sedimentary structures.

Erosion of the base Holocene reflector, to the south of the area of erosion/non-deposition, shows that at some time during the Holocene contour-parallel currents increased in importance and caused reworking and transport of sea-bed sediments, including Early Holocene sediments. Also the present sea-floor morphology of the southeastern slope of the trench indicates that the sedimentological conditions locally became more variable during deposition of the upper part of the Holocene succession, e.g. elongated erosional depressions and sediment gravity slides (Bøe et al., in prep., Rise et al., in prep.). The underlying glaciomarine, stratified sediments and also the Early Holocene sediments show a higher degree of lateral continuity, or conform sedimentation through time (sheet drape sedimentation).

Erosion/non-deposition along the upper part of the southern slope has also been suggested in previous studies, e.g. Van Weering (1982b, 1987), Quale & Van Weering (1985) and Delhez & Martin (1992). Also Lien (1995) has shown that inflow of Atlantic water may be of sufficient strength to resuspend fines and transport sand-sized particles eastwards on the southwestern slope (Fig. 4). This process was corroborated by Eisma & Kalf (1987), who noticed high contents of suspended matter near the bottom along the southern slope, probably caused by resuspension of bottom sediments.

Erosion of the Holocene succession has also been observed on the western slope of the Norwegian Trench west of Bergen. High-resolution deep-towed boomer data show that the acoustically transparent Holocene unit, and also glaciomarine sediments, have been subject to extensive erosion, particularly in contour-parallel elongated depressions (Hovland 1983, 1984). This author estimated that a 5-10 m thick layer of sediments had been eroded in some areas during the Late Holocene, and suggested that a combined effect of bottom currents and gas escape had caused the erosion.

In the southern Kattegat, Nordberg & Bergsten (1988) have presented evidence for a pronounced hydrographic change at about 4000 years B.P. The hydrographic shift was attributed to changes in the inflow-outflow regime between the North Sea and the Skagerrak-Kattegat-Baltic, and tentatively to changes in the large-scale circulation patterns of the North Atlantic.

The present configuration of the Jutland Current and the Southern North Sea Current was probably established about 4000 years ago (Van Weering et al.1993a,b). Although these currents are small in volume compared to the Atlantic Current, it is generally considered that the bulk of the Holocene sediments in the Skagerrak are derived from the southwest (Svansson 1975, Eisma 1981, Van Weering 1981, 1982a, Kuijpers et al. 1993a, b, Zøllmer & Irion 1993, Van Weering et al. 1993b). Van Weering et al. (1987) suggested that most of the inferred sea-floor erosion takes place in the southern half of the North Sea during extensive storm periods in the winter. Our data show increased sea-floor erosion during the later part of the Holocene, and suggest that erosion still occurs on the southern slope of the Norwegian Trench and on the plateau further to the south.

The depocenter of Holocene fine-grained sediments east of the area of erosion/non-deposition (Figs. 4 and 5) requires that a large portion of these sediments are transported from the west; however, most of the fines have probably been carried by the Jutland and the Southern North Sea Currents during extreme hydrographic events. There are probably both westerly and southwesterly sources for the thick succession of fine-grained sediments of Holocene age on the southeastern slope. This was also indicated by Zöllmer & Irion (1993) who interpreted smectite-rich sediments from the southern and southeastern North Sea to be carried by the Jutland Current into the Skagerrak, where a northward decreasing proportion of smectite suggests an increasing influence of the Central and Northern North Sea Currents (more illite and chlorite-rich sediments).

The Holocene depocenter in the easternmost Skagerrak is in the area where Atlantic water and water from the North Sea join the Baltic Current and then turn to the north to form the Norwegian Coastal Current. In this area a large cyclonic circulation pattern with slow currents is present, which may explain the high rates of deposition.

Suspended matter from the Norwegian rivers is mainly trapped in the fjords (Pederstad et al. 1993), and only minor amounts of suspended matter are thought to reach the Skagerrak via the Baltic Current. Measurements of the bottom nepheloid layer (Van Weering et al. 1993b), suggested local current induced erosion of the eastern Skagerrak margin, but the presented data give no idea of the importance of such a process. Sediments presently deposited along the northern slope are therefore to a large extent thought to be derived from the southwest, and to have been deposited after a long transport in suspension.

Summary and concluding remarks

The thickness and distribution of Holocene sediments in the Norwegian part of the Skagerrak has been mapped based on a dense, regular grid of shallow seismic lines. A well expressed basal Holocene reflector separates the uppermost low-reflectivity Holocene unit from the acoustically layered unit below, consisting of Late Weichselian glaciomarine sediments. The isopach map (Figs. 4 and 5) shows that the thickest Holocene deposits occur on the south-eastern slope of the Norwegian Trench, in an area where also the present sedimentation rates are high, and on the eastern slopes of the Norwegian Trench. In the deepest trench there is a general decrease in thickness towards the west. The Holocene succession is 7.5-15 m thick in the central Norwegian Trench east of Lista, and generally less than 7.5 m thick further west. Recent sedimentation rates in the deepest part of the Norwegian Trench are generally 10-20 cm/100 years (Bøe et al. this volume), indicating that sedimentation has been stable and continuous throughout the Holocene. On the northern slope, east of Mandal, the thickness of Holocene sediments varies between 15 m and 35 m, while to the west of Mandal Holocene sediments occur only in local basins.

Erosion of the Holocene succession is evident on the steepest part of the southern and south-eastern slope of the Norwegian Trench, and along the northern part of the northwest sloping plateau (Figs. 4, 7a and b). The area of erosion/non-deposition, which can be traced along a NE-SW trend for about 100 km, indicates strong currents within this part of the Norwegian Trench. Sediments eroded from this area, and suspended sediments brought in from the west and the southwest, have to a large extent been deposited by contour-parallel currents to the northeast of a narrow trench in the easternmost part of the eroded area (Figs. 5 and 8). This is the most extensive Holocene depocenter in the Norwegian part of the Skagerrak, with up to 100 m of Holocene sediments.

On the plateau in the south the thickness of Holocene sediments increases to a maximum of 40-50 m near the Danish border. Large relict sandwaves (Fig. 9) occur in water depths shallower than 200 m. The sandwaves were probably formed in shallower water than the present during the latest Weichselian/Early Holocene. Acoustic blanking of high-frequency seismic records indicates that shallow gas occurs in the Holocene sediments in the relict sandwave area and in the upper slope to the north of this.

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