Holocene and Latest Glacial Paleoceanography in the North-Eastern Skagerrak

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Abstract
Detailed information on past oceanographic and climatic changes is crucial for our understanding of natural climate variability and for the assessment of future climate variations. Sediments strongly influenced by the North Atlantic Current accumulate at high rates in the northeastern Skagerrak, forming a potential high-resolution archive for information on past climatic and oceanographic processes and events. Through a high-resolution, multi-proxy study of the 32 meter long core MD99-2286 from the north-eastern Skagerrak, and interpretation of chirp sonar profiles from the coring area, this thesis provides new and detailed insights about the paleoceanographic development of the eastern North Sea region since the deglaciation.

The chronostratigraphic control of core MD99-2286 relies on 27 radiocarbon dates. Ages are presented in calibrated thousand years before present (abbreviated “kyr”). Core MD99-2286 was correlated to chirp sonar profiles using measured physical properties. This correlation demonstrates that a strong regional acoustic reflector, previously assumed to represent the Pleistocene/Holocene boundary, was formed as a result of rapid ice retreat during the latest Pleistocene. Based on the distribution of ice rafted debris in the core, ice berg calving in the Skagerrak ended at 10.7 kyr. Detailed grain-size analyses of the core were interpreted using a novel 3D-visualization technique. Between 11.3 and 10.3 kyr, clay-rich distal glacial marine sediments were deposited in the northeastern Skagerrak, derived from Baltic melt-water outflow across south-central Sweden through the Otteid-Stenselva strait. As a result of differential isostatic uplift, the route of the major outflow and the associated sediment deposition moved southwards along the Swedish west coast. After 10.3 kyr, sediment deposition in the north-eastern Skagerrak gradually adopted to a fully interglacial normal marine sedimentation dominated by Atlantic inflow and the North Jutland Current.

The establishment of the modern circulation system in the eastern North Sea is marked by abrupt coarsening of the sediments in core MD99-2286 at 8.5 kyr. This was a result of increased Atlantic inflow, opening of the English Channel and the Danish straits, and formation of the South Jutland Current. Mineral magnetic properties of the core show a distinct relationship reflecting general sediment source variability. After 8.5 kyr, sediments in the northeastern Skagerrak were derived predominantly from the Atlantic Ocean and the North Sea, with varying contributions from the South Jutland Current, the Baltic Current, and the currents along the coasts of western Sweden and southern Norway. Between 6.3 and 3.8 kyr, the eastern North Sea was further developed towards the modern situation by an increase of the South Jutland Current flow. The Skagerrak bottom currents were probably forced by strong Atlantic water inflow between 0.9 and 0.5 kyr, and after that by increased wind stress. The influence of regional climate on the eastern North Sea circulation has increased since the middle of the Holocene.

Key words: Skagerrak, Holocene, sediment, chirp sonar, grain size, mineral magnetic properties
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Papers:

Paper I
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Paper II
Gyllencreutz, R., in press. Late Glacial and Holocene paleoceanography in the Skagerrak from high-resolution grain size records. Palaeogeography, Palaeoclimatology, Palaeoecology.

Paper III
Gyllencreutz, R., Kissel., K. Late Glacial and Holocene sediment sources and transport patterns in the Skagerrak interpreted from mineral magnetic properties and grain size data. Submitted to Quaternary Science Reviews.

Paper IV

Stockholm, April 2005

Richard Gyllencreutz
To Anna and Edvin

»De rika möjligheter, som såväl vakuumlodet som det ovan beskrivna profilodet – kolylodet, som det lämpligen kan benämnas – erbjuda vid studiet av havets avlagringar, äro alltför uppenbara för att här behöva framhållas.«

Prof. Börje Kullenberg, 1944

»Med ett schysst järnrör slår man hela världen med häpnad.«

Sock-Crny, 1985
Holocene and Latest Glacial Paleooceanography in the North-Eastern Skagerrak

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Introduction

The Skagerrak is the deepest part of the otherwise relatively shallow North Sea. The circulation and subsequent sedimentation in the Skagerrak is governed by the inflow of North Atlantic Current water, with important contributions from the Jutland Current and from Baltic Sea outflow via the Kattegat (Longva and Thorsnes, 1997). The currents mix and form an anti-clockwise gyre in the eastern Skagerrak (Figure 1), causing the current speed to slow down considerably. The reduced current strength allows fine-grained sediment to accumulate at high rates in the central and north-eastern parts of the Skagerrak (Rodhe and Holt, 1996; von Weering, 1982a). As a consequence, the Skagerrak forms the major sink for fine-grained sediment in the North Sea, with inputs from the entire north-west European drainage systems and the North Sea coast. The circulation in the North Sea and the Skagerrak is linked to the North Atlantic Oscillation (NAO), because the NAO largely controls the strength and direction of winds towards Scandinavia (Marshall et al., 2001; Busuioc et al., 2001; Hurrell, 1995), and the wind has a large impact on general ocean circulation pattern in the North Sea (Svendsen et al., 1996; Rodhe, 1996; Longva and Thorsnes, 1997). In the rapidly accumulating Skagerrak sediments, much information is archived at high-resolution regarding sediment sources as well as paleoclimatic and paleooceanographic processes and events (van Weering et al., 1993). The Skagerrak is therefore an important target area for studies of the post-glacial oceanographic and climatic history of the North Sea region.

The large-scale paleooceanographic development of the Skagerrak-Kattegat region during the late Pleistocene and the Holocene has been the objective in several seismic surveys (e.g., Rise et al., 1996; von Haugwitz and Wong, 1993; Salge and Wong, 1988) and core studies (e.g. Jiang et al., 1997; Conradson and Heier-Nielsen, 1995; Nordberg, 1991; Björklund et al., 1985) during the last decades. Previous work in this region was reviewed by van Weering et al. (1993) and in an extensive study by the Geological Survey of Norway (Longva and Thorsnes, 1997). These reviews emphasized the importance of high-resolution studies of long sediment cores having accurate chronostratigraphic control in order to acquire a better understanding of past sediment sources, transport paths, and paleoclimatic variations in the Skagerrak, the North Sea and the Baltic Sea region.

Several seismo-acoustic surveys during the last decades have portrayed a thick, apparently undisturbed post-glacial sediment sequence, implying high sedimentation rates, in the north-eastern Skagerrak (van Weering et al., 1973; van Weering, 1982b; von Haugwitz and Wong, 1993; Bøe et al., 1996; Rise et al., 1996). These deposits were further investigated using high-resolution chirp sonar by Gyllencreutz et al. (in press). The promising high-resolution sedimentary archives prompted the International Marine Past Global Changes Study (IMAGES) program to select coring site MD99-2286 in this area (Figures 1 and 2). A 32 m long core was retrieved during IMAGES leg 3 with R/V Marion Dufresne in 1999 with the main objective to study the Holocene circulation changes in the Skagerrak, and the mode and amplitude of oceanographic and climatic variability.

This thesis is aimed to provide a highly resolved view of the Holocene and latest Pleistocene paleooceanography of the north-eastern Skagerrak, based on chirp sonar profiles and multi-parameter studies of the AMS 14C dated core MD99-2286. The main focus is on changes in current circulation, sediment sources and deposition processes. An important part of this work includes the consistent use of a calibrated age scale, to facilitate comparison of the present results with other records of various origins. This has required a (re-) calibration of previously reported 14C ages of discussed events. This approach does not qualify as a strict calibration in the technical sense, but is necessary for meaningful comparisons of different data-sets and to acquire a meaningful general picture of the proper sequence of events.

An age model based on 27 radiocarbon dates was established for MD99-2286 and the calibrated ages show that the core spans 12,000 calendar years, thus encompassing the entire Holocene and the latest Pleistocene. In this thesis, the age of the Pleistocene/Holocene boundary follows the informal working definition of 11,500 calendar years BP, assigned by The International Union of Geological Sciences (IUGS) and its International Commission on Stratigraphy (ICS).

The thesis includes four papers (Papers I-IV). A brief summary of these papers follows below. The remaining part of this section consists of a description of the methods used, and an expanded discussion of the results from the four papers.
Paper I: Holocene sedimentation in the Skagerrak interpreted from chirp sonar and core data

This paper is focused on the late Glacial and early Holocene development of the north-eastern Skagerrak, based on the chirp-sonar site survey and physical properties of core MD99-2286. An age model was established for core MD99-2286 using 27 AMS \(^{14}C\) dates. This age model forms the chronological framework for all results from core MD99-2286 presented in this thesis, and shows that the core spans the entire Holocene and latest Pleistocene.

The chirp sonar profiles and estimated core penetration were interpreted together with multi-beam bathymetry in a computer generated three-dimensional visualization.

The chirp sonar stratigraphy shows acoustically stratified sediments with several internal parallel reflectors overlying a rough-surfaced substratum not penetrated by the signal. The lowermost unit is interpreted as ice-proximal glacial-marine sediments rapidly deposited during the last deglaciation. The end of ice-proximal sedimentation is marked by a strong reflector, which has a regional extent and is readily distinguished in previous seismic profiles from the Skagerrak. This reflector was previously interpreted to reflect the Pleistocene/Holocene boundary at 11,500 cal y BP. Based on correlation between the chirp sonar profiles and core MD99-2286 using measured p-wave velocity and density, we propose a revised position for the Pleistocene/Holocene boundary in the seismo-acoustic stratigraphy of the investigated area. The strong regional reflector, which core MD99-2286 did not penetrate, is interpreted to have been formed during latest Pleistocene time as a consequence of rapid ice retreat and drastically lowered sedimentation rate. The base of the Holocene at 11,500 cal y BP is not represented by any seismically significant impedance contrasts in the core. The overlying units are interpreted as distal glacial-marine sediments overlain by marine Holocene sediments, deposited with an increasing sedimentation rate reflecting a strengthening of the Jutland Current in an otherwise more or less modern oceanographic environment.

Jan Backman supervised the project, and collected the chirp sonar data together with Martin Jakobsson and Arne Lif. Martin Jakobsson also developed the method for 3D visualization of seismo-acoustic data, and participated in the interpretation.

Abbreviations used in the thesis

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>AMS</td>
<td>accelerator mass spectrometry</td>
</tr>
<tr>
<td>ARM</td>
<td>anhysteretic remanent magnetization</td>
</tr>
<tr>
<td>BIL</td>
<td>Baltic Ice Lake</td>
</tr>
<tr>
<td>BP</td>
<td>before present (present = 1950)</td>
</tr>
<tr>
<td>cal. yr BP</td>
<td>calibrated years before present</td>
</tr>
<tr>
<td>GRA</td>
<td>gamma-ray attenuation</td>
</tr>
<tr>
<td>Hc</td>
<td>coercive force</td>
</tr>
<tr>
<td>Hcr</td>
<td>remanent coercive force</td>
</tr>
<tr>
<td>IMZ</td>
<td>ice marginal zone</td>
</tr>
<tr>
<td>IRD</td>
<td>ice rafted debris</td>
</tr>
<tr>
<td>IRM</td>
<td>isothermal remanent magnetization</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>volume low-field susceptibility</td>
</tr>
<tr>
<td>kyr</td>
<td>calibrated thousand years before present</td>
</tr>
<tr>
<td>MAR</td>
<td>mass accumulation rate</td>
</tr>
<tr>
<td>Mrs</td>
<td>saturation remanence</td>
</tr>
<tr>
<td>Ms</td>
<td>saturation magnetization</td>
</tr>
<tr>
<td>MSCL</td>
<td>multi-sensor core logger</td>
</tr>
<tr>
<td>PSD</td>
<td>particle size distribution</td>
</tr>
<tr>
<td>SIRM</td>
<td>saturated IRM</td>
</tr>
<tr>
<td>TWT</td>
<td>two-way travel time</td>
</tr>
</tbody>
</table>

Paper II: Late Glacial and Holocene paleoceanography in the Skagerrak from high-resolution grain size records
(Richard Gyllencreutz, in press, Palaeogeography, Palaeoclimatology, Palaeoecology)

Paper II is focused on paleoceanographic and sedimentary changes in the north-eastern Skagerrak during the late Glacial and the Holocene, based on high-resolution
grain size analyses of core MD99-2286. The grain size variations were studied using conventional wet-sieving and sedigraph analysis. The sedigraph data was visualized in its entirety in the form of a three-dimensional particle size distribution (PSD) surface plot, where the grain size frequency variations are shown against the calibrated age scale established in Paper I. The interpretation was based on the PSD surface plot along with individual plots of median grain size, sortable silt (10-63 μm) median, and the contents of sortable silt, fine silt (2-10 μm), clay (<2 μm), and coarse fraction (>63 μm). The coarse fraction was studied using reflectance microscope for determination and size measurement of ice rafted debris (IRD).

The distinct ending of IRD in core MD99-2286, which was retrieved from a location down current from the final calving ice margin in the region, indicates that iceberg calving in the Skagerrak ended between 10.7 and 10.2 kyr. The final occurrence of IRD at 10.2 kyr in core MD99-2286 was possibly caused by a catastrophic flooding of a dammed ice lake in southern Norway, flushing out icebergs into the Skagerrak from grounded glacier ice.

A distinct increase in clay content starting at ca 11.3 kyr and abruptly ending at ca 10.3 kyr is attributed to outflow from the Baltic basin through the Otteid-Stenselva strait in south-eastern Norway. The age of the end of the increase in clay content matches the closing of the Otteid-Stenselva passage. The increased clay content between 11.3 and 10.3 kyr is correlated to similar clay-rich units in cores further south along the coast; supporting a previously proposed hypothesis that differential glacio-isostatic uplift caused a southward migration of the main depositional area for the Baltic outflow sediments.

A distinct coarsening of the sediments in core MD99-2286 indicates a hydrographic shift at 8.5 kyr, which is correlated to a previously reported shift in the Skagerrak, Kattegat and the Norwegian Channel. This shift reflects the establishment of the modern circulation system in the eastern North Sea, as a consequence of the opening of the English Channel and the Danish straits and increased Atlantic water inflow, and the subsequent development of the South Jutland Current.

A series of changes from ca 6.3 to ca 3.8 kyr in core MD99-2286 reflects strengthening of the Jutland Current towards the present day sedimentation system in the Skagerrak-Kattegat. These changes are correlated to previously reported hydrographic shifts at 5.5 14C years BP in the Skagerrak and at 4.0 14C years BP in the Kattegat. It is suggested that these shifts were separate features of a transitional period related to strengthening of the current system. The resulting changes are differently manifested in different parts of the Skagerrak-Kattegat, due to the complex circulation system.

The latest 800 years are characterized by poorly sorted sediments with a relatively high and variable proportion of coarse material, reflecting a circulation system significantly modified by regional climatic conditions, especially the general wind directions and storm frequency over the southern North Sea.

![Figure 2. Chirp sonar profile from the MD99-2286 coring location, showing the general stratigraphy of the survey area in north-eastern Skagerrak. The strong regional reflector 3 is indicated with an arrow, and the estimated penetration of core MD99-2286 (Paper I) is shown with a white rectangle. Depth labels in meters are based on 1500 m/s sound velocity.](image)

**Paper III: Late Glacial and Holocene sediment sources and transport patterns in the Skagerrak interpreted from mineral magnetic properties and grain size data**

(Richard Gyllencreutz and Catherine Kissel, submitted to Quaternary Science Reviews)

This paper is focused on Late Glacial and Holocene changes in circulation, sedimentation and provenance in north-eastern Skagerrak, based on high resolution mineral magnetic analyses of core MD99-2286 interpreted together with the grain size data presented in Paper II.

The magnetic signal in core MD99-2286 is dominated by pseudo-single domain to multi-domain magnetite. Two main magnetic assemblages can be distinguished, similar to the “Norwegian” and “Danish” populations observed by Lepland and Stevens (1996) in the northern Skagerrak surface sediments. The “Norwegian” assemblage is composed of coarse grained magnetite mixed with variable amounts of one or more high coercivity minerals, whereas the “Danish” assemblage consists of high amounts of fine grained magnetite. The different compositions of these two magnetic assemblages are attributed to differences in sediment source areas and transport pathways. The “Danish” provenance is totally dominated by sediments from the southern North Sea and the Atlantic Ocean, mainly transported by the North and South Jutland Current. Most of the “Norwegian” sediments are also derived from the southern North Sea and the Atlantic.
Ocean, but with important contributions from the Baltic Sea and reworked coastal sediments in Sweden and Norway, mainly transported by the Baltic Current and currents along the coasts of western Sweden and southern Norway.

Between 12 and 11.3 kyr, a calving ice front occupied the Oslo fjord, and sedimentation was strongly influenced by melt-water carrying re-deposited glacial sediments from southern Norway and western Sweden. Between 11.3 and 10.3 kyr, sedimentation was dominated by re-deposited glacial sediments transported by melt-water outflow across south-central Sweden. After the Otteid-Stenselva outlet was closed at 10.3 kyr, glacial marine sedimentation changed to normal marine sedimentation. At 8.5 kyr, a hydrographic shift, marking the onset of modern circulation in the Skagerrak-Kattegat, occurred as a result of increased Atlantic inflow, transgression of former land areas, and opening of the English Channel and the Danish Straits. After 8.5 kyr, sedimentation was governed by input from the Atlantic Ocean and the North Sea, with varying contributions from the South Jutland Current, Baltic Current, and currents along the coasts of western Sweden and southern Norway. From 0.9 kyr until present, the sedimentation was totally dominated by southern North Sea and Atlantic Ocean sources.

Catherine Kissel performed the magnetic measurements, and wrote the magnetic methods chapter and parts of the discussion.

Paper IV: Late Holocene coastal hydrographic and climate changes in the eastern North Sea

This paper presents results from the EU-project Late Holocene Shallow Marine Environments of Europe (HOLSMEER). The paper is focused on paleoenvironmental variability in the eastern North Sea during approximately the past 2000 years, based on multi-parameter studies of cores from the north-eastern and southern Skagerrak (MD99-2286 and GeoB 6003-2), the Norwegian margin (HM115-16) and the German Bight (GeoB 4801-1). The studied parameters include faunal assemblages and stable isotopes of benthic foraminifera, sea surface salinity from diatom transfer functions, grain size, major element chemistry from X-ray fluorescence (XRF), and sea surface salinity and temperature from dinoflagellate transfer functions.

Virtually all data-sets show a marked environmental shift between AD 700 and AD 1100. The most pronounced changes, including a remarkable increase in bottom current strength, occurred around AD 900. This shift is attributed to an observed enhancement of Atlantic water advection to the North Sea, causing major circulation and productivity changes to both surface and bottom waters. An interpreted decrease in productivity between about AD 1100-1700 is suggested to result from a lowering of the sea surface salinity and increased stratification of the eastern North Sea waters. This could be explained by a documented warming of the eastern North Atlantic, leading to enhanced evaporation and subsequent precipitation over north-western Europe, with a consequent increase in river run-off to the investigated area.

The Atlantic water advection decreased at AD 1500, whereas the high bottom current strength persisted through the following climate period with colder North Atlantic waters and increased storminess, to the present. This indicates that the bottom currents were forced by a different mechanism, likely enhanced wind stress, after AD 1500. The bottom current strength remains high during a change through climate periods of opposite temperature forcing, indicating that the marine environmental conditions in the eastern North Sea are largely controlled by the strength of the forcing.

A substantial part of the results are based on records of grain size, stable isotope variations in benthic foraminifera, and foraminifer- and diatom assemblages from core MD99-2286, obtained by Richard Gyllencreutz in collaboration with Karen Luise Knudsen and Peter Kristensen at the University of Aarhus, Denmark. Richard Gyllencreutz also made significant contributions to the manuscript.
Oceanographic and sedimentary setting

The Skagerrak is bordered by the coasts of Norway, Sweden and Denmark, and consists of a glacially-eroded sedimentary basin that forms the inner end of the Norwegian Trench (Flodén, 1973; Sejrup et al., 1995; 2000) (Figure 1). Water depths in the Skagerrak basin exceed 700 m (Figure 1), making it the deepest part of the North Sea, where the average water depth is 94 m (Svansson, 1975). The North Sea is a semi-enclosed basin, with connections to the Atlantic Ocean in the north and via the English Channel in the south-west, and a connection to the Kattegat and to the Baltic Sea in the south-east.

The slope of the Skagerrak basin is generally steeper and more irregular close to the Norwegian coast than on the southern slope, resulting in an asymmetrical shape and profile of the trench. The seafloor is particularly irregular in the north-eastern part of the Skagerrak, where the topography is characterized by several trenches (Flodén, 1973; Holtedahl, 1986). North-east of this fractured area, the sea-bottom topography is more regular, as sediment has accumulated with sufficient thickness to smooth the underlying bedrock topography (Flodén, 1973; van Weering, 1982b; Rise et al., 1996). The MD99-2286 coring site is located in this relatively flat and smooth area.

The following summary of the present large-scale circulation in the Skagerrak is based on Svansson (1975), Rodhe (1987; 1998) and Otto et al. (1990).

The circulation and subsequent sedimentation in the Skagerrak is largely governed by the North Atlantic Current. North Atlantic waters enter the North Sea between Scotland and Norway, and to a minor extent through the English Channel in the south. The most important feature of the Skagerrak circulation is the Jutland Current, which consists of two branches. The South Jutland Current flows north-ward along the Danish west coast and is formed of mixed water masses from the English Channel and the southern North Sea (Figure 1). The South Jutland Current continues to the north-east and enters the Skagerrak, where it is further mixed with the North Jutland Current, formed of Atlantic Water and Central North Sea water. Passing the Kattegat, the North Jutland Current is subsequently mixed with relatively fresh and cold water from the Baltic Sea, before it makes a cyclonic turn in the north-eastern Skagerrak. The water mass continues west-ward and exits the Skagerrak in the south-west as the Norwegian Coastal Current (Figure 1). In the course of the cyclonic turn in the Skagerrak, the water depth increases and the current speed is greatly reduced, causing fine-grained sediment to be deposited in the central and north-eastern parts of the Skagerrak (Rodhe and Holt, 1996) at a high rate, up to 1 cm/year (van Weering, 1982a; Bøe et al., 1996).

Most of the suspended sediment entering the Skagerrak is supplied by the large amounts of inflowing Atlantic water with low sediment concentration (Longva and Thorsnes, 1997). The South Jutland Current carries a high concentration of suspended particles as a result of extensive erosion along the sand-dominated western and north-western coasts of Denmark (Eisma and Kalf, 1987), but is a low-volume water body and therefore delivers less sediments to the Skagerrak that the Atlantic water (Longva and Thorsnes, 1997). The major rivers of Sweden and Norway are only minor contributors to the Skagerrak sedimentation, because the rivers discharge into silled fjords where most of the sediment load is trapped before the water flows into the Skagerrak.

Methods

Reviews of paleoceanographic research of the Skagerrak (Longva and Thorsnes, 1997; van Weering et al., 1993) show patterns of sedimentation are driven by a complex interplay between regional oceanography and climate. Sedimentation patterns vary strongly in different parts of the Skagerrak-Kattegat, and core-to-core correlation is often difficult even over distances less than five kilometers (Hass, 1996). In order to understand the details of the paleoceanographic and paleoclimatic development of this region, it is necessary to use a wide variety of paleoenvironmental proxy parameters at a high temporal resolution (decadal or better). Long, highly resolved and undisturbed sediment records combined with accurate age control are crucial for correlation of observed changes. This requires, in addition to a large amount of high-quality dates, coring at a site with a high sedimentation rate, and dense sampling of the core material. This study follows this approach and has employed the following major analytical tools:

1. High-resolution chirp sonar profiling
2. CALYPSO coring of a 32 m long piston core
3. Macroscopic core description
4. AMS ¹⁴C dating
5. Multi-Sensor Core Logging (GRA-density, P-wave velocity, magnetic susceptibility)
6. Grain size distributions from sieving and Sedigraph analysis
7. Calcium carbonate concentration (wt %)
8. Mineral magnetic properties (κ, ARM, IRM, SIRM, Hc, Hc, Mrs, Ms).
9. Stable carbon isotope variations (δ¹³C) measured on benthic foraminifera

1. Chirp sonar profiling

Chirp sonar profiling was used to investigate the post-glacial sediments in the north-eastern Skagerrak to determine a suitable coring location providing a highly resolved Holocene and latest Pleistocene (post-glacial) stratigraphy. The chirp sonar profiles were obtained along the same track lines as those of Rise et al. (1996), although their seismic acquisition system offered deeper penetration but lower resolution. This approach enabled a correlation of the major acoustic reflectors of the chirp profiles with those of Rise et al. (1996), and provided stratigraphic information over a large region around the coring site.
The high-resolution chirp sonar data was acquired from R/V Skagerrak using an EdgeTech X-Star chirp sonar system and the SB-512 tow-fish. The reflected acoustic signal was digitally recorded after real time processing through a correlation filter (Schock et al., 1989). Surveying was performed with a 1.5-7.5 kHz chirp pulse with 40 ms duration. This set-up yielded a sediment penetration of between 40 and 90 ms in water depths ranging between 100 and 300 m, resulting in a vertical resolution of ca 12 cm. About 217 km of chirp profiles were collected. The positioning system consisted of a differential GPS. Soundings from the ship’s hull-mounted Skipper GDS 101 echo sounding system were used to adjust variations in the chirp sonar tow-fish depth.

2. Coring

A 32.4 m long CALYPSO core, MD99-2286, was retrieved in 1999 from 225 water depth by R/V Marion Dufresne at 58°43.77’N, 10°12.31’E (Figure 1), using a 40 m long core barrel. The coring site was selected from a high-sedimentation area as interpreted from the seismo-acoustic chirp profiles. The CALYPSO corer is a giant variety of the conventional piston corer, capable of retrieving up to ~65 m long cores. In addition, a 2.4 m long gravity core, Sk000209-2, was retrieved in year 2000 from 226 m water depth by R/V Skagerrak at 58°43.84’N, 10°11.78’E (622 m from core MD99-2286) in order to ensure full recovery of the surface sediments.

3. Core description

The sediment in core MD99-2286 was visually described onboard R/V Marion Dufresne after core-splitting, with respect to macroscopic sedimentology, color (using the Munsell soil color chart), and macrofossils.

4. Dating

The chronostratigraphic control of core MD99-2286 relies on twenty-seven AMS 14C dates, performed by the Institute of Particle Physics, ETH, Zürich, Switzerland. The dated samples consist of either mollusc shells of known species or mixed benthic foraminifera. The radiocarbon dates were standardized to a δ13C value of -25 ‰, and were calibrated using the CALIB (rev 4.4) software (Stuiver and Reimer, 1993). The samples were assumed to consist of 100 % marine carbon, and the calibration data set MARINE98 (Stuiver et al., 1998b) was used. In order to facilitate comparison with other studies, a standard reservoir correction of 400 years was used for all samples, although it is recognized that the reservoir age may have been greater during part or all of the deglaciation (Bard et al., 1990; Bondevik et al., 1999). The results of the calibrated AMS 14C dates are presented using the probability method (Telford et al., 2004) (Figure 3).

The MD99-2286 core top was indirectly dated as recent (~0.050 kyr), by correlation to the 230Th-dated (Sennset, 2002) gravity core Sk000209-2.

5. Physical properties (MSCL)

Gamma Ray Attenuation (GRA) density and low-field magnetic susceptibility were measured with 2-cm resolution by whole-core logging using a GeoTek Multi Sensor Core Logger (MSCL) onboard R/V Marion Dufresne. High-resolution point measurements of p-wave velocity were performed on split core halves at the Department of Geology and Geochemistry, Stockholm University, also using a GeoTek MSCL, equipped with acoustic rolling contact transducers for better coupling. Prior to measurements, the core was stored in the core-logging laboratory until the sediment attained a stable room temperature. P-wave measurements were carried out on three discrete samples in constant-volume containers from the top, middle and bottom of the core, on a GeoTek MSCL at the University of Rhode Island.

The MSCL data were also used for core-chirp profile correlation. The physical property data together with the age model provided a tentative age control on the chirp profiles, which facilitated the stratigraphic interpretation.

6. Grain size analysis

Grain size variability was studied because grain size is a fundamental sediment property, and has been showed to provide sensitive records of spatial (Lepland and Stevens, 1996; Stevens et al., 1996) as well as temporal (Hass, 1996; Bergsten, 1994) oceanographic differences in the Skagerrak.

Sampling resolution for the grain size analysis was 5 cm in the core depth intervals 0-1500 cm and 3100-3200 cm, and 10 cm in the interval 1500-3100 cm. De-ionized water saturated with pure calcium carbonate (Pro Analysi) was used as dispersing liquid throughout the grain size analysis. Between 2.5 and 3 grams of freeze-dried sediment per sample were re-suspended on a shaker-table overnight, and was then wet-sieved using the 63 μm mesh size. The coarse fraction was oven dried in 70°C overnight and weighed after cooling to room temperature. The fine fraction samples were analyzed using a Sedigraph 5100 supplied with a Micromeritics MasterTech 051 automatic sample-handling device. The sedigraph was set to measure grain sizes between 63 μm and 1 μm using the ‘standard’ analysis type, sample material set to ‘glass’ with a density of 2.615 g/cm3 and analysis liquid set to ‘water’. Sedigraph-samples were analyzed in batches of ten, and the sample order was randomized within each batch. Prior to the sedigraph analysis, the centrifuged samples were re-suspended using an ultra sonic bath and a tube vortex, and were agitated using an ultra sonic probe for 30 seconds. All coarse fraction samples from 3060 cm core depth and downward were visually studied for composition and grain size using a reflectance microscope, with an ocular-scale calibrated to a precision of 0.1 mm at the magnification used.
5. Grain size visualization

The sedigraph grain size data is visualized in its entirety in the form of three-dimensional particle size distribution (PSD) surface plots (Beierle et al., 2002), because the grain size measurements were characterized by a complex poly-modal nature. This permitted a better portrayal of the grain size variability. Grain size measurements were automatically recorded by the sedigraph software expressed as cumulative-mass percent of equivalent spherical diameter in 250 size intervals set to range from 63 to 1 μm. The sedigraph data was corrected for the coarse fraction removed through sieving, by multiplying all cumulative values with the weight percentage of the < 63 μm fraction for each sample. For computing reasons, a smoothed dataset with 72 size intervals was used for the 3D PSD visualization. The data used for the PSD surface plot was gridded using the Nearest Neighbor algorithm, with 5-cm resolution in order to avoid data loss from under-sampling, and the output grid model was smoothed using a 9x9 term 2D Gaussian filter. The resulting grid was visualized using a contouring software package as a three-dimensional contour map with grain size versus age in the x-y plane and percentages of each size class on the z-axis.

8. Carbonate content

Carbonate content was used to facilitate the grain size interpretation, because carbonate is a major constituent of the core MD99-2286 sediments, and carbonate was not removed prior to the grain size analysis. The carbonate content was also used for correlation between cores MD99-2286 and Sk000209-2 (Figure 4). Carbonate content in core MD99-2286 was measured on a UIC Coulometrics coulometer. The sampling interval was 10 cm from 15 to 32.4 m, 5 cm from 0 to 15 m, and 2 cm from 1 to 2.5 m. Analyses were performed on 60 mg of milled, freeze-dried bulk sediment samples. The carbonate data were calibrated using a regression based on measurements of pure CaCO₃ (Pro Analysi) on 88 samples, with a standard deviation of 0.76 % CaCO₃.

9. Mineral magnetic properties

Mineral magnetic properties were used to distinguish different sediment source areas, based on the spatial results from previous mineral magnetic studies of the Skagerrak surface sediments (Lepland and Stevens, 1996). For mineral magnetic analyses, core MD99-2286 was sampled with u-channels (Tauxe et al., 1983, Weeks et al., 1993) along the entire core. The volume low field susceptibility (κ) was measured with a small diameter Bartington coil with 4-5 cm resolution. The anhysteretic remanent magnetization (ARM) and the isothermal remanent magnetization (IRM) was measured using a high resolution DC-SQUID cryogenic magnetometer in the mu-metal shielded room at Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Gif-sûr-Yvette, France. Measurements were made every 2 cm with a resolution of about 5 cm. ARM was imparted along the axis of the u-channel by applying a 100 mT alternating field and a 50 μT bias field. During acquisition, the u-channels were translated through the coils at a speed of about 1 cm/s. After acquisition, the ARM was stepwise demagnetized using 9 successive steps at 10, 15, 20, 25, 30, 40, 50, 60 and 80 mT. Saturated IRM (SIRM) was then acquired in 6 steps (0.05, 0.1, 0.2, 0.3, 0.5 and 1 T) using a 1.6 m long pulsed solenoid. Backfield magnetization to 0.1 and 0.3 T were applied after saturation in order to calculate the S-ratios (S₉₀.₅₇ = abs(IRM₉₀.₅₇/IRM₁T) and S₉₀.₅₈ = abs(IRM₉₀.₅₈/IRM₁T)). SIRM was stepwise demagnetized using the same steps as for ARM. During the demagnetization of ARM and IRM, the u-channel was moving at a speed of about 4 cm/s through the demagnetization coils. All the data were acquired using software developed at LSCE.
For the analysis of the hysteresis parameters, small sediment samples of a few mg were taken every 20 cm along the core. The measurements of the saturated magnetization (Ms), the saturated remanent magnetization (M_r), the coercitive force (Hc), the remanent coercitive force (Hcr) and the paramagnetic susceptibility (χhf) were performed using an alternating gradient force magnetometer (AGFM 2900). Thermomagnetic analyses were performed on magnetic extracts using a horizontal Curie balance in an argon atmosphere to minimize oxidation.

### Stable carbon isotopes

Stable carbon isotopes (δ^{13}C) were analyzed in order to study variations in bottom waters induced by time-dependent changes in productivity. Analysis of δ^{13}C was performed with 2-cm resolution, equivalent to a 2-year temporal resolution above 268 cm core depth and a 4-year resolution below this depth. The analysis was performed on 80-130 μg (ca 3 – 8 tests) of monospecific samples of the benthic foraminifer species Melonis bareelanus, picked by Peter Kristensen at Aarhus University, Denmark. Tests filled with pyrite were not used. The foraminifer tests were crushed, and organic material was removed by hydrogen peroxide (3%) for 30 minutes in room temperature. Samples were then cleaned in methanol in an ultra-sounding bath for 30 seconds, after which the methanol with dissolved and suspended contaminants was siphoned off using a cellulose filter cylinder. After cleaning, samples were oven dried in 50 °C overnight. Stable isotope analysis was performed using a Finnegan MAT 252 mass spectrometer equipped with a Kiel-device for automatic sample handling. The results are reported using the conventional δ notation versus the Pee Dee Belemnite (PDB) standard. The reproducibility for the system is ± 0.06 ‰ for δ^{13}C.

Results and discussion

### Core MD99-2286 radiocarbon age model

The chronostratigraphic control of core MD99-2286 is based on 27 AMS ¹⁴C dates. Of these, 13 dates were obtained from molluscs. Virtually all mollusc shells or shell fragments found in the core were dated, provided that they were large enough (generally >10 μg), that they belonged to species known to burrow not deeper than ca 10 cm into the substratum, and that they showed no obvious signs of reworking such as abrasion marks. The other 14 dates were obtained from mixed assemblages

<table>
<thead>
<tr>
<th>Lab. reference No.</th>
<th>Depth (cm)</th>
<th>¹⁴C age ±1σ (BP)</th>
<th>Max. (1σ)</th>
<th>Median probability</th>
<th>Min. (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA5324</td>
<td>19.75</td>
<td>1930 ±60</td>
<td>1537</td>
<td>1474</td>
<td>1402</td>
</tr>
<tr>
<td>AA5380</td>
<td>170</td>
<td>7500 ±90</td>
<td>8033</td>
<td>7947</td>
<td>7842</td>
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<tr>
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<td>12396</td>
<td>12268</td>
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<tr>
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<td>13104</td>
<td>12909</td>
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<tr>
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<td>12170 ±170</td>
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<tr>
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<tr>
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<td>15792</td>
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<tr>
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<td>2263</td>
<td>15125 ±120</td>
<td>17795</td>
<td>17516</td>
<td>17222</td>
</tr>
</tbody>
</table>

Table 1. Calibrated ages for core Troll 3.1, from radiocarbon ages reported by Lehman et al. (1991) and Lehman and Keigwin (1992). 440 years were added to the ¹⁴C ages, to remove the reservoir correction made by Lehman et al. (1991) and Lehman and Keigwin (1992).

**Age convention: calibrated years BP versus ¹⁴C years BP**

All ages are given in calibrated thousand years before present (= AD 1950), abbreviated ‘kyr’, unless otherwise noted. The calibrated age scale is not entirely equivalent to the calendar age scale, because the radiocarbon dating method is probabilistic, but also because no accurate ocean reservoir correction model has been established for the deglaciation and the transition to the Holocene (Lowe and Walker, 2000). The calibrated age scale is, however, standardized by the use of well established calibration data-sets (Stuiver et al., 1998a; 1998b), and is therefore useful for correlation between various records. In order to enable comparison with other studies of marine sediments from the region, a standard reservoir correction of 400 years was used for the age model of core MD99-2286, and where applicable, also for calibrated radiocarbon ages of discussed events from the literature. It is however recognized that the reservoir age may have been greater during the deglaciation (Bard et al., 1990; Bondevik et al., 1999; Sikes et al., 2000). Thus, to facilitate comparison of the present results with other records of various origins, all discussed age estimates are based on a calibrated age scale. This has implications on both the age model of core MD99-2286, and of age calibrations for other discussed records, as described below.
of benthic foraminifera. Mono-specific foraminifer samples was not used for the dating, because the low foraminifer abundance would require the collection of foraminifer tests from larger sections of the core at each dated level, resulting in lower precision of the dates.

Some of the dates in core MD99-2286 are problematic as they appear to be of older or of identical age as the closest underlying sample. The problematic samples appear to be about 150-250 years older than the linear age model. This is most pronounced in the top ten meters of the core, where age reversals are shown by almost every other sample. This consistent pattern cannot be explained by the order of analysis, because the samples were measured in random order (see laboratory codes in Table 1, Paper I). Too old ages could be explained by contamination with older carbon or, more likely, by reworking. Too young ages could be explained by contamination with modern carbon or by deep burrowing of the dated species. Because of the higher radioactivity in modern carbon, smaller amounts of young carbon, in comparison to old carbon, can cause large radiocarbon dating errors (Olsson, 1974). Therefore, contamination errors causing apparently too young ages are more likely than those causing apparently too old ages. Contamination errors are generally only likely in the foraminifer samples, as these are not etched during pre-treatment as shell samples are. Errors from deep burrowing is less likely because all dated species are known not to burrow more than ca 10 cm into the substratum (Anders Warén, Museum of Swedish Natural History, pers. comm., 2002). Thus, based on the assumption that all samples yielding older or identical ages as the closest underlying samples are reworked, these (ten) samples were excluded from the construction of the age model (dates in parentheses in Table 1, Paper I).

The calibrated radiocarbon ages are presented using the probability method (Telford et al., 2004), giving the median of the probability distribution for each calibrated date as single age estimators. The reason for this is that the probability method is more robust than the commonly used intercept method, where a small shift in radiocarbon age can produce a large shift in the intercept (Telford et al., 2004). An age model based on radiocarbon dates can be constructed in several ways, for example by polynomial fits, fuzzy regression (Boreux et al., 1997), or smoothing by hand. The most appropriate method cannot unambiguously be determined from the radiocarbon dates, and the uncertainties between the dated levels are difficult to estimate (Bennett, 1994). For core MD99-2286, the age model was chosen to be composed of linear segments, fitted through the 1 σ error limits of 17 dates and using the above described criteria. The exact error limits along a radiocarbon age model are difficult to assess, due to the inherent uncertainties in the radiocarbon measurement and calibration methods, and in the age model construction. Using the 1 σ sigma errors of the calibrated ages of the age model as a crude measure, the age uncertainties of core MD99-2286 are ca ±50-100 years for parts of the core younger than ca 10.3 kyr, and ca ±200-300 years for the older parts (see 1 σ ranges of Table 1, Paper I).

Age relationships in other, literature records

The handling of ages used in previous studies requires different approaches, depending on the type of record and dating method used:

1. The age model for core Sk000209-2 is based on seven 210Pb dates and two AMS 14C dates (Senneset, 2002). The 210Pb measurements produced consistent results and show that the core top is of modern (zero) age (Senneset, 2002). Correlation between cores MD99-2286 and Sk000209-2 was done using carbonate content data (Figure 4). To enable statistical evaluation of the correlation, the carbonate record of core MD99-2286 was resampled to the same sampling intervals of core Sk000209-2 using linear interpolation. Optimal correlation (R=0.67, significant at a confidence level of 99.9 %) was obtained using different depth scales for the two cores, so that 235.5 cm in core Sk000209-2 corresponds to 365 cm in core MD99-2286 (Figure 4). This depth discrepancy is probably a result of the different coring techniques used (CALYPSO giant piston corer for MD99-2286 and gravity corer for Sk000209-2). Regardless of the cause, the relative depth relationship between the cores is well constrained, and the strong correlation between the two carbonate records suggests that the MD99-2286 core top is of modern (zero) age. The 14C dates in the two cores, however, are not in agreement (Figure 4). In core MD99-2286, ten dates were excluded from the age model because of suspected reworking (Paper I), and three of the excluded dates are from depths within the core-correlation interval (Figure 4). Therefore, the two 14C dates in core Sk000209-2 should be regarded with caution.

2. For the Horticultural garden core (Bergsten, 1989; 1991; 1994) an age model was constructed based on calibrated radiocarbon dates of shell macrofossils (Bergsten, 1994). The calibration was performed based on the 1993 calibration dataset (Stuiver and Braziunas, 1993), which differs slightly from the MARINE98 calibration dataset (Stuiver et al., 1998b) used for core MD99-2286. The age difference for the discussed interval is small and therefore considered negligible, and the Bergsten (1994) age model is therefore used in discussing events in the Horticultural garden core (Paper II).

3. New age models have been constructed for previous cores, where published age models were based on non-calibrated radiocarbon dates of marine carbonate material. This approach regards the age models for the cores a) Solberga-2 (Bodén et al,
a) For the Solberga-2 core, an age model based on repository corrected but not calibrated radiocarbon ages was presented by Bodén et al. (1997). The published radiocarbon dates (Bodén et al., 1997) were added 440 years to obtain standard (not corrected) $^{14}$C ages, and calibrated using the same method as for core MD99-2286, i.e. using the CALIB (rev. 4.4) software (Stuiver and Reimer, 1993) with the MARINE98 calibration data set (Stuiver et al., 1998b), assuming 100% marine carbon, and presenting the calibrated radiocarbon ages using the probability method (Telford et al., 2004). An alternative age model based on the calibrated ages for the Solberga-2 core was suggested (Paper II), in order to be consistent with the paleomagnetic, sedimentological and faunal interpretations of the Solberga-2 core (Abrahamsen, 1982).

b) For the Troll 3.1 core, an age model based on reservoir corrected but not calibrated radiocarbon ages was presented by Lehman et al. (1991) and discussed by Lehman and Keigwin (1992). Their published radiocarbon dates were calibrated as in a) above. A calibrated age model for core Troll 3.1 is suggested herein (Table 1), using the Lehman and Keigwin’s (1992) depths for control points. This age model includes the date at 170 cm core depth (7060±90 $^{14}$C years BP, Lehman et al., 1991), which was missing in Table 1 by Lehman and Keigwin (1992), but apparently was used, according to their interpolated ages.

c) For the chronostatigraphic control of the Skagen 3/4 core, 69 radiocarbon dates from both shells and foraminifera were presented by Heier-Nielsen et al. (1995). A large number of the foraminifera dates were 1-5 kyr older than ages inferred from dated mollusc shells at the corresponding levels. Heier-Nielsen et al. (1995) suggested that the foraminifer samples resulted in too old radiocarbon ages due to reworking, and proposed that the shell dates represent the true age of the sediment. An age model based on the reservoir corrected but not calibrated radiocarbon dates from the shell material was presented by Conradsen and Heier-Nielsen (1995). Based on the identical data-set, a differently constructed age model with a larger number of control points was presented by Jiang et al. (1997), used also by Jiang et al. (1998), but the differences between these age models are negligible. The Skagen 3/4 shell macrofossil dates were calibrated by Jan Heinemeier (in Petersen, 2004), using the CALIB program (Stuiver and Reimer, 1993) and the calibration data-set MARINE98 (Stuiver et al., 1998b). In order to enable comparison of results from the Skagen 3/4 core on a calibrated age scale with core MD99-2286, a new age model for core Skagen 3/4 was constructed using the calibrated ages from Petersen (2004), accepting that the shell dates represent the sediment age (Heier-Nielsen et al., 1995) and using the same samples for age control points as Conradsen and Heier-Nielsen (1995) (Paper II).

4. A different, simplified, approach was used for discussed events from the literature in which ages were reported in $^{14}$C-years, but the dating results were obtained indirectly. Such records include for example cores dated by pollen stratigraphy (e.g. Nordberg, 1991), or modeling results based on radiocarbon dated sources (e.g. Lambeck, 1999), or reviews where insufficient details of the radiocarbon results were presented in order to enable a full calibration (e.g. Andersen, 1995a). For this type of information sources, published $^{14}$C ages for the discussed events were calibrated with an assumed uncertainty of ±100 years, using the calibration data-set INTCAL98 (Stuiver et al., 1998a). This approach does not qualify as a strict calibration in the technical sense, but is used in order to get a meaningful general picture of the proper sequence of events. The results of these calibrations have been summarized in Table 2, which can be viewed as a first-order paleoceanographic event stratigraphy for the eastern North Sea region based on a calibrated age scale.

**Discussion and paleoceanographic reconstructions**

In the following discussion, the results from the chirp sonar profiling (Paper I), interpretations of the sedimentary record of core MD99-2286 (Papers II-IV), and results from the literature are combined to reconstruct primarily the Holocene paleoceanographic environment of the north-eastern Skagerrak since the deglaciation. The resulting conclusions are presented in the form of a series of map reconstructions of the paleo-sedimentary environment of the Skagerrak, Kattegat and the eastern North Sea area for time intervals of special interest since 14 kyr (Figures 5-8). Because of the rapidly changing positions of the ice margin and the coastlines during this long time period, the maps characterize time slices of the most important changes for which sufficient information is available, and hence does not represent a continuous development. The reconstructions are based on a calibrated age scale.

The geographic contexts for the maps are based on previous paleogeographic reconstructions by Stabell and

The reconstructed paleo-current pattern is relatively well constrained for the period after about 8.5 kyr, when the modern circulation pattern in the eastern North Sea and the Skagerrak was established (Paper II). The hydrographic shift to the present-day current system can be observed as distinct changes in various sediment properties in several records from the Skagerrak, Kattegat and Norwegian Channel (Björklund et al., 1985; Nordberg and Bergsten, 1988; Nordberg, 1991; Conradsen and Heier-Nielsen, 1995; Conradsen, 1995; Jiang et al., 1997; Klitgaard-Kristensen et al., 2001).

The exact hydrographic circulation pattern of the eastern North Sea region prior to the shift at ca 8.5 kyr is not known, but some general characteristics of the circulation are indicated from oceanographic modeling results and previous core data. As the present-day cyclonic circulation in the Skagerrak is governed by Atlantic water inflow, it is closely connected to the large scale North Atlantic Current system (Rodhe, 1996, 1998; Otto et al. 1990; Svansson, 1975). Large scale modeling of the Glacial Atlantic have shown that the general circulation pattern in the north-eastern Atlantic during the last Glacial was not very different from the present-day state, although the flow strength of the North Atlantic Current was significantly reduced (Schäfer-Neth and Paul, 2001). These modeling results are consistent with interpretations from cores in the southern Norwegian Sea (Lehman et al., 1991; Koç et al., 1993). The basic cyclonic circulation in the Skagerrak is principally controlled by a combination of the estuarine circulation resulting from the mixing of high-saline water from the Atlantic and out-flowing low-saline water from the Baltic, and wind stress over the entire North Sea (Rodhe, 1996). The shape of the Norwegian Trench affects both of these factors, and is thus a crucial topographic feature for the present-day circulation pattern (Davies and Heaps, 1980; Rodhe, 1996). Based on these general relationships, it seems reasonable to assume that a generally cyclonic circulation has prevailed in the Skagerrak since the deglaciation.

### Table 2: Calibration of $^{14}$C dates of discussed events in the eastern North Sea area.

<table>
<thead>
<tr>
<th>Interpreted event</th>
<th>$^{14}$C age (ka BP)</th>
<th>Cal. Age (kyr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Transgression of s. North Sea</td>
<td>10</td>
<td>11.6-11.3</td>
<td>Stabell and Thiede, 1986; Lambeck, 1995</td>
</tr>
<tr>
<td>2 End of IRD dep. in Skagerrak</td>
<td>10</td>
<td>11.6-11.3</td>
<td>van Weering, 1982</td>
</tr>
<tr>
<td>3 Aker IMZ, Oslo area</td>
<td>9.8-9.6</td>
<td>11.3-10.8</td>
<td>Andersen et al., 1995; Gjessing, 1980; Gjessing and Spjeldnaes, 1979; Sørensen, 1979</td>
</tr>
<tr>
<td>4 Marine limit, Oslo area</td>
<td>9.7</td>
<td>11.2-10.8</td>
<td>Hafsten, 1983</td>
</tr>
<tr>
<td>5 Glomma drainage event</td>
<td>9.1</td>
<td>10.4-10.2</td>
<td>Longva and Bakkejord, 1990; Longva and Thoresen, 1991</td>
</tr>
<tr>
<td>6 Otteid-Stenselva strait closing</td>
<td>9.1</td>
<td>10.4-10.2</td>
<td>Lambeck, 1999; Björck, 1995</td>
</tr>
<tr>
<td>7a English Channel opening</td>
<td>8</td>
<td>9.0-8.7</td>
<td>Nordberg, 1991</td>
</tr>
<tr>
<td>b</td>
<td>7.6</td>
<td>8.5</td>
<td>Conradsen and Heier-Nielsen, 1995</td>
</tr>
<tr>
<td>c</td>
<td>7.7</td>
<td>8.6</td>
<td>Jiang et al., 1997</td>
</tr>
<tr>
<td>d</td>
<td>8-7</td>
<td>9.0-7.7</td>
<td>Björklund et al., 1985</td>
</tr>
<tr>
<td>e</td>
<td>8-7</td>
<td>9.0-7.7</td>
<td>Lambeck, 1995</td>
</tr>
<tr>
<td>f</td>
<td>8.7-8.3</td>
<td>9.7-9.3</td>
<td>Jelgersma, 1979</td>
</tr>
<tr>
<td>8a Danish straits opening</td>
<td>8.2</td>
<td>9.3-9.0</td>
<td>Björck, 1995</td>
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<tr>
<td>b</td>
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<td>9.0-8.7</td>
<td>Conradsen, 1995</td>
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<tr>
<td>c</td>
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<td>Jensen et al., 1997</td>
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<tr>
<td>d</td>
<td>7.5-7.8</td>
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</tr>
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<td>9 Isolation of Dogger Bank</td>
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<td>9.0-8.7</td>
<td>Lambeck, 1995</td>
</tr>
<tr>
<td>10a S-K Hydrographic shift</td>
<td>5.5</td>
<td>6.2</td>
<td>Conradsen, 1995; Conradsen and Heier-Nielsen, 1995</td>
</tr>
<tr>
<td>b</td>
<td>5.1</td>
<td>5.9</td>
<td>Jiang et al., 1997</td>
</tr>
<tr>
<td>c</td>
<td>4</td>
<td>4.6-4.3</td>
<td>Nordberg, 1991; Nordberg and Bergsten, 1988</td>
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</table>

Table 2. Calibration of $^{14}$C dates of discussed events in the eastern North Sea area. Unless otherwise indicated, quoted $^{14}$C ages were calibrated using the CALIB software (rev. 4.4) (Stuiver and Reimer, 1993) and the INTCAL98 calibration dataset (Stuiver et al., 1998a) with an assumed error of ±100 years. IRD=Ice Rafted Debris. IMZ= Ice Marginal Zone. S-K= Skagerrak-Kattegat. *inferred from the age model by Conradsen and Heier-Nielsen (1995) and the calibrated ages from Petersen (2004), ages given in calibrated years BP in the reference.
Descriptions of the maps

**Map 1: 14.0 kyr**

The paleoceanographic reconstruction for 14.0 kyr is a representative time-slice for the general current pattern during the 15.0-13.0 kyr interval (Figure 5). Because this time interval is not recovered in core MD99-2286, interpretations of the sedimentation pattern are mainly based on the seismo-acoustic stratigraphy.

The Skagerrak resembled a fjord, bordered to the north by the ice-front and to the south by land areas. A general northward flow of warm Atlantic water reached the Norwegian Channel and the Skagerrak at about 15.5-15.0 kyr (13,500-13,000 $^{14}$C years BP) (Lehman et al., 1991; Lehman and Keigwin, 1992; Veum et al., 1992; Köc et al., 1993; Knudsen et al., 1996). The circulation in the Skagerrak was relatively weak and probably anticyclonic. A calving ice front was present along much of the northern and eastern flanks of the Skagerrak, probably with an ice shelf occupying the deep Oslo Fjord (Figure 5). The sedimentation was dominated by rapid deposition of proximal glacial marine sediments, forming the regional seismo-acoustic unit D (Paper I: Gyllencreutz et al., 2005). Glacial melt-water from the Baltic Ice Lake flowed through the Öresund Strait via the Kattegat to the Skagerrak (Björck, 1995). The sedimentation in the north-eastern Skagerrak was drastically changed to distal glacial marine when the ice margin retreated far enough to permit major fjords to act as sediment traps at about 13.4 kyr (Paper I). The rapid retreat of the ice margin to a more distal position probably caused formation of reflector 3 in the chirp profiles, mainly as a result of a drastic reduction in sedimentation rates (Paper I). Despite this reduction, the average sedimentation rates in the interval from about 13.4 to 12.0 kyr (from reflector 3 to the base of core MD99-2286) must have been significantly higher than the rate measured in the bottom of the core (ca 0.06 cm/yr), to account for the ca 8 m of sediment deposited during this time (Paper I).

Such high sedimentation rates could be caused by current reworking of near-coastal sediments that were exposed by the rapid relative lowering of the sea level.

The inflow of North Atlantic water decreased during the Younger Dryas cold period between 12.7 and 11.5 kyr, based on a pronounced increase in abundance of the planktonic foraminifer *N. pachyderma* (sinistral) in the compiled Troll 8903/28-03 record from the northern Norwegian Channel (Klitgaard-Kristensen et al., 2001). The same relationship was found in the neighboring core Troll 3.1 by Lehman and Keigwin (1992), although with an older age estimate of 11.2-10.5 $^{14}$C years BP (corresponding to 13.3-12.4 kyr, Table 1). Lehman and Keigwin (1992, p. 759) further suggests another reduction in the North Atlantic circulation beginning at 9.7 $^{14}$C years BP, interpreted from an increase in *N. pachyderma* (sinistral) at 385 cm core depth. This core depth, however, is dated to 10.2 $^{14}$C years BP according to their age model (Table 1, Lehman and Keigwin, 1992, p. 758), and at 9.7 $^{14}$C years BP (351 cm core depth) the *N. pachyderma* (sinistral) abundance is decreasing. This implies that correlations of Lehman and Keigwin’s (1992) circulation decrease at 9.7 $^{14}$C years BP with data from other cores (e.g. Conradsen and Heier-Nielsen, 1995; Knudsen et al., 1996) may not be fully accurate. Based on the calibrated ages in Table 1, the 385 cm level in core Troll 3.1 (10.2 $^{14}$C years BP) corresponds to 12.0 kyr. The core Troll 3.1 chronology is based solely on 9 AMS $^{14}$C dates, whereas the chronology for the compiled Troll 8903/28-03 record is based on 22 AMS $^{14}$C dates as well as the occurrence of the Vedde and Saksnuravatn Ashes and correlation to the GRIP ice core δ$^{18}$O record (Haflidason et al., 1995; Klitgaard-Kristensen et al., 2001), and both records span the same approximate time interval. Therefore, the chronology of Troll 8903/28-03 is here regarded as the more accurate of the two.

Sediments deposited during the later part of Younger Dryas is probably recovered in the bottom of core MD99-2286, but any response of a decreased Atlantic inflow (Lehman and Keigwin, 1992; Klitgaard-Kristensen et al., 2001) has likely been obscured by local environmental influences, especially by glacial melt-water. This assumption is in accordance with the faunal interpretations of the Skagen 3/4 record (Knudsen et al., 1996).

The Öresund Strait, connecting the Kattegat with the Baltic, was closed at about 13.0 kyr, and opened again ca 400 years later (Björck, 1995). Outflow of glacial melt-water through Öresund then persisted until the final drainage of the Baltic Ice Lake at ca 11.6 kyr (Björck, 1995; Andrén et al., 2002; Björck et al., 2002). The final drainage of the Baltic Ice Lake has been detected as distinct δ$^{18}$O spikes in benthic foraminifera in Skagerrak cores (Erlenkeuser, 1985; Bodén, 1997), but apparently did not have a significant impact on the sedimentation in the north-eastern Skagerrak, as no distinct grain size changes are recorded between 11.9 and 11.3 kyr in core MD99-2286 (Paper II). The general circulation pattern in the Skagerrak probably remained largely unaltered until an outlet opened across south-central Sweden about 11.3 kyr (the Närke Strait, Björck, 1995).

**Map 2: 11.2 kyr**

The paleoceanographic reconstruction for 11.2 kyr is a representative time-slice for the general current pattern during the 11.3-10.3 kyr interval (Figure 6). In core MD99-2286, the sediments deposited in the time interval from ca 12 kyr at the bottom of the core to ca 10.3 kyr are distinct from the younger sediments in grain size distribution and magnetic properties. These sediments are dominated by clay and fine silt, with markedly low amounts of coarse material, except for a distinct ice rafted debris (IRD) component in the sand fraction (Paper II). Magnetically, the sediments older than 10.3 kyr show a clearly different relationship between SIRM/$k$ and S-ratio than in younger sediments (cluster A, Figure 9) (Paper III). From 12 to 10.3 kyr, the sediments are magnetically characterized by high S-ratios and low SIRM/$k$ values, indicative of coarse grained magnetite, and the SIRM/$k$ to S-ratio relationship
Figure 5. Map 1: 14.0 kyr. The paleo-shoreline east of 9°E is modified from Figure 3 of Björck (1995), with the calibrated age (pers. comm. Svante Björck, 2005) available at the website http://www.geol.lu.se/personal/seb/Maps%20of%20the%Baltic.htm [27 Jan 2005]. The paleo-shoreline west of 9°E is modified from map 4 of Stabell and Thiede (1986). The ice margin east of 9°E is modified from Lundqvist and Wohlfarth (2001). The ice margin west of 9°E is more uncertain, and is tentatively drawn from Boulton et al. (2001, fig. 11-12) and Andersen (1979) and Andersen et al. (1995a). The paleo-current pattern in the Kattegat is modified from Klingberg (1998). Core abbreviations: MD = MD99-2286, Ska = Skagen 3/4, Sol = Solberga-2, HG = Horticultural Garden, GIK = GIK 15530-4.
describes a linear trend towards lower values with younger sediments (Figure 9) (Paper III).

The Skagerrak still resembled a fjord with a general anti-cyclonic circulation. The North Atlantic water advection increased at about 11.5 kyr, as indicated by core data from the Norwegian margin (Lehman and Keigwin, 1992; Koç et al., 1993; Sejrup et al., 1995; Klitgaard-Kristensen et al., 2001) and from the Skagerrak (Conradsen and Heier-Nielsen, 1995; Jiang et al., 1997). The Skagerrak circulation experienced a strong influence of the North Jutland Current (current 1 in Fig. 6) and the coastal currents along the Swedish and Norwegian coasts (current 2 in Fig. 6) (Jiang et al., 1997; Jiang et al., 1998), which is consistent with the grain size and magnetic property results from core MD99-2286 (Paper III). Considering the modern situation, where virtually all of the waters passing through the Skagerrak exits as the Norwegian Coastal Current (Longva and Thorsnes, 1997; Rodhe, 1998), the general strengthening of the circulation probably resulted in a stronger outflow along the west coast of Norway (current 3 in Fig. 6). These hydrographic changes appear to represent an important first step towards the development of the modern circulation system.

The last calving ice front of the eastern North Sea occupied the Oslo Fjord until the ice retreated on-shore at ca 10.7 kyr, as indicated by the IRD signal in core MD99-2286 and by considering the location of the ice margin in relation to the sea level (Paper II). The sedimentation in the Skagerrak was highly influenced by outflow of glacial melt-water through the Närke Strait via the outlets on the Swedish west coast. When the Närke Strait opened at about 11.3 kyr, the main path of Baltic outflow was through the Otteid-Stenselva outlet (Björck, 1995).

The Skagerrak sedimentation was changed when the Otteid-Stenselva outlet (current 4 in Fig. 6) was closed at about 10.3 kyr as a result of differential isostatic uplift (Björck, 1995; Lambeck, 1999). As a consequence of the uplift gradient, the main path of Baltic outflow migrated south-westward to the Uddevalla Strait (current 5 in Fig. 6) and the Göta Älv outlet (current 6 in Fig. 6). This development is recorded in the cores MD99-2286, Solbergøya-2, and Horticultural Garden as a distinct increase in clay content beginning progressively later in cores further south, supporting the course of events proposed by Bergsten (1994) and Björck (1995) (Paper II).

The distinct SIRM/κ to S-ratio relationship in core MD99-2286 between 12 and 10.3 kyr (Figure 9) is probably controlled by sediment sources dominated by glacial sediments in south western Sweden and southern Norway. The melt-water outflow from Lake Vänern through the Otteid-Stenselva strait had a major influence on the sedimentation in north-eastern Skagerrak, as indicated by the MD99-2286 grain size record (Paper II). Therefore, the SIRM/κ to S-ratio relationship between 11.3 and 10.3 kyr probably reflects influence of glacial sediments from the Vänern basin. The linear trend in the SIRM/κ to S-ratio relationship ending at 10.3 kyr (cluster A, Figure 9) is probably related to how the Otteid-Stenselva and its threshold towards Lake Vänern responded to the north-easterly uplift gradient described by Björck (1995) and Lambeck (1999).

The paleoceanographic reconstruction for 10.2 kyr is a representative time-slice for the general current pattern from 10.3 kyr to about 9.5 kyr (Figure 7).

When the Baltic outflow through south-central Sweden diminished due to the uplift, the Skagerrak sedimentation started to gradually adapt to a full-interglacial marine sedimentation governed by Atlantic water inflow and the North Jutland Current (Figure 7). The Skagerrak sediments were predominantly derived from westerly sources, as indicated by results from the Skagen 3/4 core (Conradsen and Heier-Nielsen, 1995; Jiang et al., 1997). This interpretation is consistent with the markedly stable relationship between SIRM/κ and S-ratio between 10.3 and 8.5 kyr in core MD99-2286 (cluster B, Figure 9) (Paper III), indicating a relatively simple and stable configuration of sediment sources during this period.

The youngest indication of IRD in core MD99-2286 at 10.2 kyr, is suggested to represent deposition from flood-transported ice bergs (Paper II) in connection with the sudden drainage of an ice-dammed lake in southern Norway (not indicated on the map), described by Longva and Bakkejord (1990) and Longva and Thoresen (1991). The continued transgression of former land areas west of Denmark allowed water to flow closer to the present Danish coast, but had not yet submerged the areas south of the Dogger Bank (Lambeck, 1995; Jelgersma, 1979). In the south-western part of the Skagerrak, seismic profiles show large relict sand waves formed during the early Holocene (Rise et al., 1996). These sand waves cannot be explained by the present current system, and appears to have formed by a cyclonic gyre in the south-eastern Skagerrak (not shown on the map) (Rise et al. 1996).

Diatom assemblages in core Skagen 3/4 indicate a strong influence of the currents along the Norwegian coast and the Swedish west coast between about 10.9 and 9.6 kyr (Jiang et al., 1997). This is consistent with the MD99-2286 mineral magnetic data, which shows a pronounced “Norwegian” signal during this period, indicative of sediment sources near the Swedish and Norwegian coasts (Paper III). The north-ward flow in the Kattegat was likely significantly weaker, because the passageways through the Danish straights were closed, inhibiting fresh water outflow from the Baltic (Björck, 1995; Lambeck, 1999). A drainage route for Baltic water existed with a connection somewhere in the southern Kattegat (Björck, 1995), although the location of such a river has not been confirmed (Jensen et al., 1999; Lemke et al. 2001). Thus, a relatively weak north-ward fresh water flow possibly existed in the southern Kattegat, indicated on the map as an arrow with a question mark (Figure 7).

The paleoceanographic reconstruction for 8.1 kyr illustrates the establishment of the modern circulation system, and serves as a representative time-slice for the general current pattern from about 8.5 kyr to the present (Figure 8). The
Figure 6. Map 2: 11.2 kyr. The paleo-shoreline east of 9°E is modified from Figure 7 of Björck (1995) with the calibrated age (pers. comm. Svante Björck, 2005) available at the website http://www.geol.lu.se/personal/seb/Maps%20of%20the%20Baltic.htm [27 Jan 2005], except for the paleo-shoreline of Norway, which was modified after Figure 12 of Jensen et al. (1997). The paleo-shoreline west of 9°E is modified from map 6 of Stabell and Thiede (1986), except for the paleo-shoreline of Norway, which was erroneous due to a misprint (pers. comm. Bjørg Stabell, 2005). The paleo-shoreline of Norway is therefore tentatively drawn from the shore displacement data compiled by Stabell and Thiede (1986), and from the glacio-hydro-isostatic modeled map for 10,000 14C years BP by Lambeck et al. (1998, Fig. 10c). The ice margin is based on the Ski ice marginal zone (Andersen et al., 1995a), and its correlations to the east (Lundqvist, 1988, 1992) and to the west (Sørensen, 1992; Boulton et al., 2001). The age of the Ski ice marginal zone was calibrated to 11.4-10.8 kyr (Paper I) from 14C ages of Andersen et al. (1995a). The circulation pattern in the Kattegat was modified from Klingberg (1998), and the circulation pattern in Lake Vänern was modified from Fredén (1988). The legend is shown in Figure 5.
paleogeographic environment is difficult to illustrate between 9.5 and 8.5 kyr, because of the complex changes in the southern North Sea and the Danish Straits area. Paleoceanographic changes during the period after 8.5 kyr are described below, with indications on the map by numbering of the currents.

Four factors can be specified as particularly important for the development towards the modern type of circulation in the North Sea: 1) a general strengthening of the current system by increased North Atlantic water advection, 2) the opening of the Danish straits permitting water flow between the Baltic Sea and the North Sea via the Kattegat-Skagerrak, 3) the opening of the English Channel enabling Atlantic water inflow from the south, and 4) transgression of former land areas in the southern North Sea, crucial for the north-ward water flow along the west coast of Denmark and formation of the South Jutland Current.

1) A strengthening of the Atlantic water inflow occurred at ca 9.0 kyr, interpreted from foraminiferal assemblages in the Troll 8903/28-03 composite record from the Norwegian Channel (Klitgaard-Kristensen et al., 2001). This is supported by results from other North Atlantic cores (Koç Karpuz and Jansen, 1992; Lehman and Keigwin, 1992; Koç et al., 1993). Klitgaard-Kristensen et al. (2001) correlated this change to the hydrographic shift recorded in the Skagen 3/4 core at 8.6 – 8.5 kyr (Table 2, event 7b-c) (Jiang et al. 1997; Conradsen and Heier-Nielsen, 1995). The increase in Atlantic water influence was recorded in core GIK 15530-4 from the western Skagerrak at ca 9.0 – 7.7 kyr (Table 2, event 7d) (Björklund et al., 1985).

2) At the present, three straits connect the Kattegat-Skagerrak with the Baltic Sea, of which the Great Belt is the deepest, accounting for more than 75 % of the water exchange between these seas (Bennike et al., 2004). The opening of the Danish Straits and Öresund was complex, and several periods of transient flow through these straits occurred over an extended time period (starting at 10.1 kyr, Andrén et al., 2000), before full marine conditions in these straits were established between 9 and 8 kyr (Björck, 1995; Lambeck, 1995; Andrén et al., 2000; Bennike et al., 2004; Berglund et al., 2005). Jensen et al. (1997) conclude that the marine ingression through the Great Belt occurred at about 9.0-8.7 kyr (recalibrated, Table 2 event 8c), and through the Öresund slightly later. The oldest reported marine shells from the Great Belt were dated to 8.1 kyr, but brackish water conditions prevailed for some centuries before that (Bennike et al., 2004). Based on these results, it seems reasonable to assume that the Öresund and the Great Belt were open at 8.1 kyr.

3) The English Channel opened between about 9.0 and 7.7 kyr (Table 2, event 7e), according to isostatic rebound modeling results by Lambeck (1995). The opening was dated to about 9.7 – 9.3 kyr (Table 2, event 7f) by Jelgersma (1979) based on studies of submerged peat deposits from the southern North Sea. This event is reflected in pronounced changes in the diatom and foraminifer assemblages of the Skagerrak, dated to 9.0-8.7 kyr (Table 2, event 7a) by Nordberg (1991), to 8.5 kyr (Table 2, event 7b) by Conradsen and Heier-Nielsen (1995), and to 8.6 kyr (Table 2, event 7c) by Jiang et al. (1997). From these consistent results, the younger age estimate for the opening suggested by Lambeck (1995) appears more reasonable than the older estimate suggested by Jelgersma (1979).

4) The Dogger Bank was isolated as an emerged platform soon after about 9.0-8.7 kyr (Table 1, event 9) (Lambeck, 1995). This permitted Atlantic water from the south-western North Sea to flow close to the Danish west coast for the first time since deglaciation, forming the South Jutland Current. The formation of the South Jutland Current is reflected in drastic sediment coarsening in core Skagen 3/4 at ca 8.5 kyr, and in acceleration of the development of the Skagen Spit at northern-most Jutland (Conradsen and Heier-Nielsen, 1995).

In the establishment of the modern circulation system and sedimentary environment, these four principal factors affected both the sediment supply and the strength and direction of the currents, as well as habitats and migration routes for flora and fauna. The opening of the English Channel and the isolation of the Dogger Bank were the most important factors for increased supply of coarse material to the Skagerrak, as these changes permitted formation of the South Jutland Current (Figure 8). The overall strengthening of the circulation from increased Atlantic inflow and the opening of the Danish Straits were crucial for the mixing of fresh and saline water masses and establishment of the strong cyclonic circulation in the eastern Skagerrak, and for increased transport of suspended sediments.

Although these major changes to the eastern North Sea hydrography probably were gradual and not simultaneous, a distinct grain size coarsening is recorded at 8.5 kyr in core MD99-2286, consistent with the changes at 8.6-8.5 in core Skagen 3/4 (Conradsen-Heier-Nielsen, 1995; Jiang et al., 1997). The abrupt transition in core MD99-2286 at 8.5 kyr is attributed to the combined effect of the environmental changes 1-4 above, although formation of the South Jutland Current probably had a major influence.

The magnetic properties in core MD99-2286 show a more gradual response to the hydrographic change around 8.5 kyr (Figure 4, Paper III), but a distinctly different SIRM/x and S-ratio relationship is evident in sediments younger than 8.5 kyr (cluster C, Figure 9) (Paper III).
Figure 7. Map 3: 10.2 kyr. The paleo-shoreline east of 9°E, except the Oslo Fjord area, is modified from Figure 15 of Björck (1995) with the calibrated age (pers. comm. Svante Björck, 2005) available at the website http://www.geol.lu.se/personal/seb/Maps%20of%20the%20Baltic.htm [27 Jan 2005]. The Oslo Fjord paleo-shoreline is modified from Figure 5 of Stabell and Thiede (1986), and the paleo-shoreline west of 9°E is modified from map 6 of Stabell and Thiede (1986). The ice margin is modified from Lundqvist (1986) and Kleman (1997), but should be regarded as tentative because of the rapid ice retreat during this time. A drainage route for Baltic water existed with a connection somewhere in the southern Kattegat (Björck, 1995), although the location of this river is unknown (Lenke et al., 2001). The legend is shown in Figure 5.
Paleoceanographic development 8.1-2.0 kyr

By about 8 kyr, the eastern North Sea coastlines had attained most of their present appearance, and all major features of the current system had been established. For this reason, the subsequent paleoceanographic development is described but not illustrated by map reconstructions.

After about 8.5 kyr, the MD99-2286 grain size record is characterized by a general trend of coarsening, poorer sorting and increasing variability. This trend is mainly attributed to increasing strength and influence of the variable South Jutland Current, and an increasing dependence of the regional climate. A series of grain size changes from ca 6.3 to ca 3.8 kyr is interpreted as a result of strengthening of the South Jutland Current and a further development towards the present-day sedimentation system in the Skagerrak-Kattegat (Paper II). These changes are correlated to previously reported hydrographic shifts at 6.2-5.9 kyr (Table 2, event 10a-b) in the Skagerrak (Jiang et al., 1997; Conradsen and Heier-Nielsen, 1995), and 4.5 kyr (Table 2, event 10c) in the Kattegat (Nordberg, 1991, Nordberg and Bergsten, 1988). These shifts were argued to be identical, and the older age (6.2 kyr or 5.5 ^14C years BP) for this shift was suggested to be correct by Conradsen (1995) and Conradsen and Heier-Nielsen (1995).

In the records presented by Nordberg and Bergsten (1988), Nordberg (1991), and Conradsen (1995), however, the chronology is too uncertain, and the resolution is too low, to resolve whether or not two distinct shifts occurred. Based on the grain size changes between about 6.3 and 3.8 kyr in core MD99-2286, and by considering the different sedimentary settings of the core locations where this hydrographic change has been observed (NE Skagerrak, N Jutland, Kattegat), it is suggested that these shifts were not synchronous, but separate features of a long transitional period related to strengthening of the current system. Owing to the complex circulation system, the resulting changes are differently manifested in different parts of the Skagerrak-Kattegat (Paper II).

In the MD99-2286 mineral magnetic parameters, two main assemblages can be identified. The first assemblage is characterized by low bulk κ, SIRM and ARM values, low SIRM/κ and S-ratio values, and is thus constituted of coarse grained magnetite mixed with variable amounts of high coercivity minerals. The second assemblage is characterized by high values of κ, SIRM and ARM and of the magnetic grain size proxies ARM/κ, SIRM/κ, ARM/SIRM, Mrs/Ms, and by high S-ratio values, and is interpreted to consist of mostly fine grained magnetite. These assemblages are similar to the magnetic assemblages in 74 surface samples from the northern Skagerrak, described by Lepland and Stevens (1996).

The two magnetic assemblages are distinguished by their geographical distributions, where the first assemblage was ascribed to a “Norwegian” sediment source and the second one to a “Danish” supply (Lepland and Stevens, 1996). Core MD99-2286 was recovered from a location at the border between these two populations. At present, the “Norwegian” population is distributed along the Norwegian coast and in the northeastern Skagerrak, while the “Danish” population occupies the central part of the Skagerrak. The “Danish” sediment population is totally dominated by sediments from the southern North Sea and the Atlantic Ocean, mainly transported by the North and South Jutland Current (currents 1-5, Figure 8). Most of the “Norwegian” sediments are also derived from the southern North Sea and the Atlantic Ocean, but with important contributions from the Baltic Sea and reworked coastal sediments in Sweden and Norway, mainly transported by the Baltic Current (current 6, Figure 8) and currents along the coasts of western Sweden and southern Norway (currents 7-8, Figure 8).

After the establishment of the modern type of circulation at about 8.5 kyr, the magnetic parameters in core MD99-2286 show that the contribution from “Danish” and “Norwegian” sediments sources have varied over time. The “Danish” and “Norwegian” populations are clearly distinguished in a SIRM/κ versus S-ratio plot (Lepland and Stevens, 1996). In the SIRM/κ versus S-ratio plot for core MD99-2286 (Figure 9), the sample points are color-coded by age and thereby reveal the temporal variations in principal sediment source areas. The MD99-2286 mineral magnetic record indicates a strong influence of the Baltic Current and the currents along the Swedish and Norwegian coasts (“Norwegian” type, currents 6-8, Figure 8) during 8.5-6.4 kyr and 4.0-1.2 kyr (Figure 9). The period between 6.2 and 4.7 kyr is characterized by weaker Baltic outflow and enhanced transport by the Jutland Current (“Danish” type, Figure 9 and currents 4-5, Figure 8). This development is in agreement with the changes in current pattern suggested by Jiang et al. (1998), based on a sea-surface salinity reconstruction from diatoms in the Skagen 3/4 core. The record from ca 0.9 kyr until the present is characterized by a strongly “Danish” mineral magnetic signal (Figure 9), indicating sediment transport dominated by Atlantic water and the Jutland Current (currents 1, 4, and 5, Figure 8) (Paper III).

Paleoceanographic development during the last 2.0 kyr

The paleoceanographic development during the last 2000 years was addressed in a multi-proxy study of four sediments cores, retrieved from the north-eastern Skagerrak (MD99-2286), the southern Skagerrak (GeoB 6003-2), the Norwegian margin (HM115-16) and the German Bight (GeoB 4801-1) (Paper IV). Ages in this chapter are given in calibrated years BC/AD, where 0 (zero) equals 1950 years BP (1.95 kyr).

The bottom current strength in the northeastern Skagerrak, indicated by the sortable silt median in core MD99-2286, increased to the present-day level at ad 650 (1.3 kyr) (Paper II). A major environmental shift occurring between AD 700 and AD 1100, with the most pronounced changes around AD 900, is apparent in several data sets from the investigated cores (Paper IV). This shift is manifested as a strong increase in Atlantic Water advection, recorded as lighter δ18O values in
Figure 8. Map 4: 8.1 kyr. The paleo-shoreline east of 9°E is modified from Figure 16 (early Litorina Sea) of Lambeck (1999), except for the Oresund and the Great Belt, which were probably open at 8.1 kyr (Björck, 1995; Conradsen, 1995; Jensen et al., 1997; Lambeck, 1999; Andrén et al., 2000; Bennike et al., 2004; Berglund et al., 2005). The paleo-shoreline west of 9°E is modified from Figure 3h of Lambeck (1995). The legend is shown in Figure 5.
benthic foraminifers at the Norwegian margin site, and a significant increase in the bottom current strength in the Skagerrak, indicated by a marked coarsening of the sediments in the Skagerrak cores (Paper IV). In core MD99-2286, this change is seen as a distinct increase in the grain size median at AD 1050 (0.9 kyr) (Paper II). The interpreted increase in Atlantic inflow is in agreement with the strong “Danish” magnetic signal during the last 900 years (Figure 9) (Paper III). The increased bottom current strength was likely a result of a general strengthening of the circulation caused by the increased Atlantic water inflow.

The environmental shift between AD 700 and AD 1100 is also reflected in a marked decrease in productivity, as indicated by decreased abundance of foraminifera and diatoms in the Skagerrak cores, and heavier δ¹³C values in both benthic and planktonic foraminifera in the southern Skagerrak core (Paper IV). The δ¹³C values from core MD99-2286 show relatively little variability. Because both planktonic and benthic species were influenced, the hydrographic change between AD 700 and AD 1100 apparently affected both the surface layer and the bottom waters. The decrease in productivity could be a result of increased fresh water outflow from the Baltic causing increased stratification of the eastern North Sea waters, which would hamper the delivery of nutrients from deeper waters to the photic zone. This could be explained by warmer temperatures of the eastern North Atlantic, documented in several cores from the Norwegian margin between ca AD 1200 and AD 1400-1450 (Koç and Jansen, 2002; Risebrobakken et al., 2003; Andersson et al., 2003), and from fjords in western Norway from ca AD 1300-1350 to AD 1550-1600 (Mikalsen, 2001; Klitgaard-Kristensen et al., 2004). The ocean warming likely caused enhanced evaporation and subsequently enhanced precipitation over north-western Europe, with a consequent increase in river runoff to the investigated area (Paper IV). This interpretation is supported by the observed salinity minimum between AD 1400 and 1500 in the German Bight δ¹⁸O record, which has been correlated with changes in the Elbe river discharge (Scheurle and Hebbeln, 2003).
The Atlantic water advection decreased at AD 1500, whereas the high bottom current strength persisted through the following climate period with colder North Atlantic waters and increased storminess, to the present. This indicates that the strength of the bottom currents was forced by a different mechanism, likely enhanced wind stress, after AD 1500. This is supported by data from Björck and Clemmensen (2004), where eolian sand influx in raised bogs in south-western Sweden indicate increased winter storminess from ca AD 1450 to AD 1900, preceded by about 700 years of weaker wind activity. The bottom current strength thus remains high during a change through climate periods of opposite temperature forcing, indicating that the marine environmental conditions in the eastern North Sea are largely controlled by the strength of the forcing.

Conclusions

The main conclusions reached in this thesis are:

- The strong regional seismic reflector separating the top-most acoustically relatively transparent unit from the underlying stratified unit, previously assumed to represent the Pleistocene/Holocene boundary, is proposed to be of latest Pleistocene age. The change to Holocene conditions in north-eastern Skagerrak appears to have been a gradual process of increasingly normal marine deposition, gradually substituting distal glacial marine sedimentation. The strong regional reflector was probably formed around 13.5 kyr (kyr = calibrated thousand years BP), by a drastic lowering of the sedimentation rate due to rapid ice recession to a position where nearby fjords were exposed as sediment traps.

- After deglaciation, the sedimentation in the Skagerrak was dominated by glacial marine sediments until ca 10.3 kyr. Iceberg calving in the Skagerrak ended at about 10.7 kyr.

- The outflow of glacial melt-water from the Baltic across south-central Sweden, beginning at about 11.3 kyr, caused deposition of clay-rich distal glacial marine sediments from the Vänern basin in the Skagerrak. The main depositional area for sediments from this outflow migrated southwards along the Swedish west coast as a result of a north-easterly gradient in the isostatic uplift. The differential uplift changed the major outflow route from the Otteid-Stenselva to the Uddevalla Strait and finally to the Göta Älv river.

- At about 10.3 kyr, the sedimentation gradually began to change from distal glacial marine to normal marine sedimentation, governed by the North Jutland Current, with sediments derived predominantly from the eastern North Sea.

- The modern circulation pattern was established at 8.5 kyr, with a marked hydrographic shift to higher energy conditions in the Skagerrak. This shift was caused by the combined results of an increased Atlantic water inflow, opening of the English Channel and the Danish straits, and transgression of the southern North Sea enabling formation of the South Jutland Current.

- After 8.5 kyr, sediments in the north-eastern Skagerrak were derived predominantly from the Atlantic Ocean and the North Sea, with varying contributions from the South Jutland Current, the Baltic Current, and the currents along the coasts of western Sweden and southern Norway.

- Between about 6.3 and 3.8 kyr, the strength of the South Jutland Current increased, marking a further development towards the present day sedimentation system in the Skagerrak-Kattegat. The freshwater outflow from the Baltic Sea was lower between about 6.2 and 4.7 kyr, and the north-eastern Skagerrak sedimentation was less influenced by the currents along the Swedish and Norwegian coasts.

- Between about 4.0 and 1.5 kyr, the north-eastern Skagerrak sedimentation was subject to a relatively strong influence of the Baltic Current and the currents along the Swedish and Norwegian coasts, and the bottom current strength was relatively stable. Modern bottom current strengths in the north-eastern Skagerrak have prevailed since an increase at about 1.3 kyr.

- The bottom current strength in the Skagerrak was probably forced by increased inflow of Atlantic water between 0.85 and 0.45 kyr, and by enhanced wind stress after 0.45 kyr. The sedimentation in the north-eastern Skagerrak has been totally dominated by southern North Sea and Atlantic Ocean sources since ca 0.9 kyr.

- The eastern North Sea circulation has experienced increased regional climate dependence since the middle of the Holocene.

- The three-dimensional particle size distribution surface plot is an efficient way to display grain size data, and is useful for interpretation purposes as it shows the entire grain size distribution as it is measured, revealing all details of the data.

- Many studies of Skagerrak’s Holocene paleoenvironmental evolution have employed the 14C-dating method and have reported results in 14C years, corrected 14C years or calibrated 14C years. In order to facilitate meaningful comparisons of these records, a common chronological framework based on a calibrated 14C age scale was established for all discussed records in the thesis, with a standard reservoir correction of 400 years.
Potential for future work

To increase our understanding of the late Pleistocene and Holocene paleoceanography of the Skagerrak-Kattegat sea region, the following suggestions highlight fields where important contributions can be made.

1. Studies of the clay mineralogy, by X-ray diffraction (XRD) analyses of the sediments from core MD99-2286 and other cores, could give important information on the sediment provenance and hence paleo-current patterns. The interpretation of such records would be greatly facilitated by the relatively extensive and existing knowledge about present-day spatial distribution of clay minerals in the Skagerrak-Kattegat (e.g. Bengtsson and Stevens, 1998; Pederstad et al., 1993; Zöllmer and Irion, 1993; Wirth and Wiesner, 1988).

2. Obtaining accurate correlation of well dated cores, penetrating into the glacial sediments, with seismo-acoustic profiles could greatly improve the paleoceanographic knowledge of the sediments in the Skagerrak basin. Such work would require detailed p-wave velocity logging of the core material and the construction of synthetic seismograms, which then could be correlated to the seismic profiles. Extensive seismo-acoustic profiling has been performed in the Skagerrak during the last decades (van Weering et al., 1973; van Weering, 1975; van Weering, 1982b; Fält, 1982; Stabell et al., 1985; Holtdahl, 1986; Salge and Wong, 1988; von Haugwitz and Wong, 1993; Andersen et al., 1995b; Rise et al., 1996; Gyllencreutz et al., in press), but core-seismic correlations is to the author’s best knowledge limited to the studies by Stabell et al. (1985) and Gyllencreutz et al. (in press).

3. The timing of the opening of the English Channel is poorly constrained. This event could probably be more accurately dated through glacio-hydro-isostatic modeling with higher spatial and temporal resolution than was used by Lambeck (1999). This, in turn, requires quality control and calibration of radiocarbon dates for local sea-level data.

4. Further studies of faunal assemblages and stable isotope variations ($\delta^{18}$O, $\delta^{13}$C) in benthic foraminifera in core MD99-2286 are in progress by Richard Gyllencreutz and scientists at the University of Aarhus, Denmark. Results from these analyses may provide further details about Holocene hydrographic changes in the Skagerrak.

5. Retrieving and studying cores penetrating through the Holocene from the area with high accumulation rates (>60 cm/y, Bøe et al., 1996) in the south-central Skagerrak, could improve the correlation of events and further increase our understanding of paleoceanographic changes in the Skagerrak-Kattegat since the deglaciation.

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