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Late glacial and Holocene sediment sources and transport patterns in the Skagerrak interpreted from high-resolution magnetic properties and grain size data

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Introduction

The Skagerrak is the major sink for fine-grained sediments in the North Sea region. There, almost unaltered North Atlantic water is mixed with North Sea waters, and relatively fresh Baltic Sea water, strongly affected by precipitation in northern Europe. Most of the sediments from these waters are deposited in the Skagerrak, at high relative rates.

The sediment sequences in the Skagerrak preserve records of climatic and oceanographic changes of the North Sea region including adjacent land areas, and have been the focus of many paleoceanographic studies during the last decades. Previous studies of cores from the Norwegian Channel and the Skagerrak-Kattegat area have shown marked changes in sedimentation at several times during the Holocene. However, the timing and extent of the observed shifts have been debated, due to discrepancies in the dating of these changes and the use of different time resolutions of the studied cores.

Here, we present a record of sedimentation, circulation and source area variability throughout the Holocene on a sub-centennial to sub-decadal resolution, using mineral magnetic properties and detailed grain size analysis in the 32 meter long and AMS 14C dated sediment core MD99-2286, recovered during the IMAGES-GINNA cruise on board the R/V Marion Dufresne.

Methods

Dating

The chronologic control relies on 27 AMS 14C-dated samples of shells or mixed benthic foraminifera. The dates were calibrated using the MARINE98 dataset (Stuiver et al., 1998). The chronology of core MD99-2286 was discussed in detail by Gyllencreutz et al. (2005).

Grain size

The grain size analysis of core MD99-2286 was described in detail by Gyllencreutz (2005). Sample resolution was 5 – 10 cm. The coarse fraction was measured by wet-sieving at 63 µm mesh size. The fine fraction between 63 µm and 1 µm was analyzed using a Sedigraph 5100.

Magnetic properties

The sampling for magnetic analyses was made using u-channels. Low field susceptibility (κ), anhysteretic remanent magnetization (ARM), isothermal remanent magnetization (IRM), saturated IRM (SIRM), and S-ratio were analyzed using a DC-SQUIDs cryogenic magnetometer, measured every 2 cm with a resolution of about 4 to 5 cm. Hysteresis parameters Hcr, Hc, Mrs, Ms, and paramagnetic susceptibility (χhf) were analyzed using an alternating gradient force magnetometer (AGFM 2900). Thermomagnetic analyses were performed on magnetic extracts using a horizontal Curie balance in an argon atmosphere. All magnetic analyzes were made using standard techniques at LSCE.

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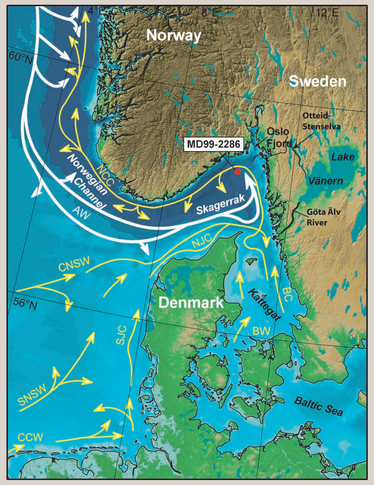
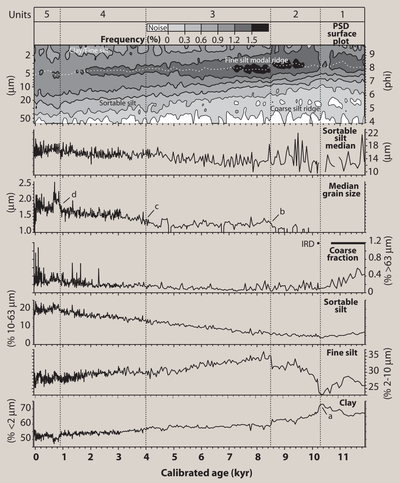
The modern circulation pattern



Location map and general ocean circulation (arrows) in the eastern North Sea and the Skagerrak. White arrows mark Atlantic water flowing more or less directly into the Skagerrak. Yellow arrows show more mixed water masses. The location of core MD99-2286 is marked with a red dot. For abbreviations of water masses, see the legend below. Current pattern modified from Longva and Thorsnes (1997).

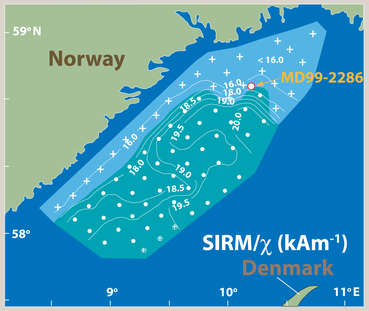
Water masses
AW = Atlantic water
NJC = North Jutland Current
SJC = South Jutland Current
NCC = Norwegian Coastal Current
CNSW = Central North Sea water
SNSW = South North Sea water
CW = Channel water
BC = Baltic Current
BW = Baltic water

Grain size data

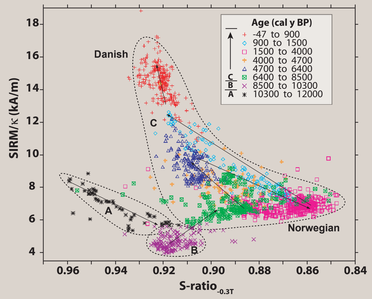


Low-pass filtered PSD surface plot and individual plots of grain size parameters in core MD99-2286. The location of defined lithological unit boundaries are marked with dotted vertical lines, and the definition points are marked a, b, c, and d with arrows. The white dotted line in the PSD surface plot marks the visually estimated grain size mode from Gyllencreutz (2005). The occurrence of IRD based on visual inspection are marked with black bars in the coarse fraction plot.

Danish or Norwegian?



The geographical distribution of the ratio of SIRM to χ (κ) from Lepland and Stevens (1996). Core MD99-2286 (circle and arrow) was recovered from a location at the border between the Danish (points) and Norwegian (crosses) mineral magnetic populations defined by Lepland and Stevens (1996).



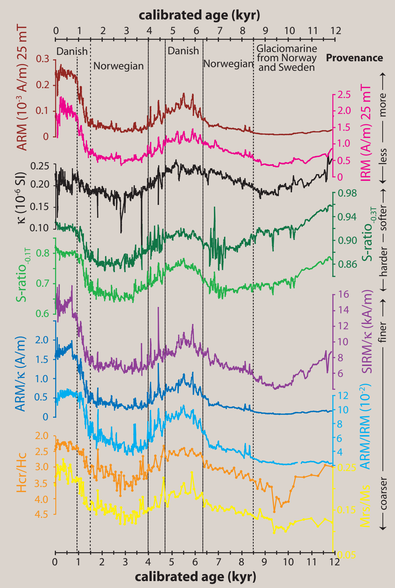
The relationship between SIRM/κ and S-ratio in core MD99-2286. The samples are plotted in age classes with different colors and symbols, with boundaries identical to the defined time intervals of characteristic grain size and magnetic properties. The three major clusters discussed in the text are marked A, B, and C, and the general development with time is indicated with arrows. *Danish* sediments have less magnetically hard minerals (lower s-ratio) and finer magnetic grain size (higher SIRM/κ) than *Norwegian* sediments, and the magnetic grain size is the most diagnostic of these parameters (Lepland and Stevens, 1996).

Magnetic abbreviations
κ = volume low-field susceptibility
ARM = anhysteretic remanent magnetization
IRM = isothermal remanent magnetization
SIRM = saturated IRM
Hc = coercive force
Hcr = remanent coercive force
Mrs = saturation remanence
Ms = saturation magnetization

Grain size interpretation

Unit (cal. age in kyr)	Grain size observations (trends described in direction towards younger sediments)	Paleoceanographic interpretation
Unit 1 (11.9-10.3)	Mode: variable around 3 µm Median: below 1 µm Sort. silt median: highly variable, less reliable Coarse fraction: decreasing content of IRD Sort. silt: low, slightly decreasing Clay: high and rapidly increasing	Ice berg calving in the Oslofjord ceased 10.7-10.2 kyr. Deposition of clay-rich sediments from the Baltic basin via outlets on Swedish west coast. South Jutland Current absent.
Unit 2 (10.3-8.5)	Mode: around 3 µm, increasing strength Median size: varying around1 µm Sort. silt median: highly variable, less reliable Coarse fraction: low and variable Sortable silt: low, slightly increasing Clay: high but rapidly decreasing	Decreasing clay content due to closing of the Otteid-Stenselva outlet at 10.3 kyr. Postglacial normal marine sedimentation begins. South Jutland Current absent.
Unit 3 (8.5-4.0)	Mode: shifted to ca 4 µm, decreasing strength Median size: low and relatively stable Sort. silt median: gradually increasing Coarse fraction: low and stable Sortable silt: slowly increasing Clay: relatively stable	Modern circulation pattern begins at 8.5 kyr, due to opening of English Channel and Danish straits, increased Atlantic inflow and transgresion of s. North Sea. Stronger bottom current.
Unit 4 (4.0-0.9)	Mode: coarsening to 5µm, decreasing strength Median size: higher than unit 3 Sort. silt median: stable, increase at 1.4 kyr Coarse fraction: gradually increasing Sortable silt: slowly increasing Clay: slowly decreasing	Strengthening of the Jutland Current and development towards the modern type of sedimentation pattern. Sediments mostly from the Atlantic Current and the southern North Sea.
Unit 5 (0.9-0)	Mode: very weak around 5 µm Median size: highest in the record Sort. silt median: high and variable Coarse fraction: high and variable Sortable silt: high, slowly decreasing Clay: low but variable	Circulation system modified by regional climate, especially general wind directions and storm frequency. Strong and variable South Jutland Current.

Magnetic properties MD99-2286



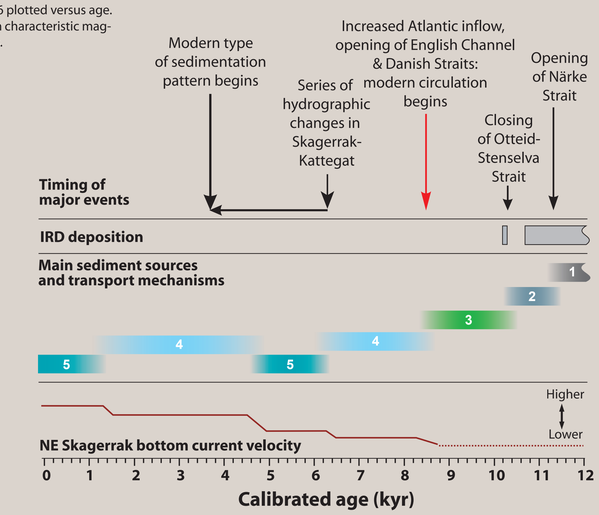
Mineral magnetic properties of core MD99-2286 plotted versus age. Boundaries between defined time intervals with characteristic magnetic properties are indicated with vertical lines.

Paleoceanographic interpretation

The spatial variation in mineral magnetic properties was previously studied in surface samples from the northern Skagerrak (Lepland and Stevens, 1996). Based on the SIRM/κ and S-ratio relationship, they defined two major source area provinces for the northern Skagerrak sediments: a "Norwegian" population (along the Norwegian coast and in the NE-Skagerrak), and a "Danish" population occupying (central Skagerrak). All of the northern Skagerrak sediments are dominated by southern North Sea and Atlantic Ocean sources, mainly transported by the N. and S. Jutland Current. In the "Danish" provenance, this domination is total, whereas the "Norwegian" sediments have 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 w. Sweden and s. Norway.

Core MD99-2286 was retrieved from a location at the border between these sediment provinces, and shows two main magnetic assemblages, similar to the "Norwegian" and "Danish" populations, with different compositions attributed to differences in sediment source areas and transport pathways.

Based on the mineral magnetic properties and grain size variability in core MD99-2286 and previous paleoceanographic studies from the Skagerrak-Kattegat, the following conclusions can be drawn about the history of circulation, sedimentation and provenance in northeastern Skagerrak since Late Glacial times.



Development of Skagerrak sedimentation
Schematic illustration of Important circulation, sedimentation and provenance changes in the Skagerrak during the Late Glacial and the Holocene. The interpreted bottom current velocity is based on the sortable silt median, and the dashed line indicate an interval where this proxy is less reliable due to low amounts of sortable silt.

1 **12 - 11.3 cal. kyr:** Sedimentation in NE-Skagerrak strongly influenced by meltwater discharge with re-deposited glacial sediments from s. Norway and w. Sweden. A calving ice front was still present in the Oslo Fjord. The sediment transport pattern changed when a passageway for meltwater across south-central Sweden opened at ca 11.3 cal. kyr.

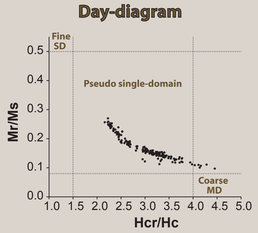
2 **11.3 - 10.3 cal. kyr:** Sedimentation dominated by re-deposited glacial sediments from the Baltic Sea and the Vänern Basin, transported by meltwater outflow across south-central Sweden. The sediment transport pattern changed when the Otteid-Stenselva outlet closed at ca 10.3 cal. kyr.

3 **10.3 - 8.5 cal. kyr:** Sedimentation changed from clay-rich distal glacial marine to normal marine sedimentation, governed by the North Jutland Current, with sediments predominantly from the eastern North Sea.

At c. 8.5 cal. kyr: Hydrographic shift towards modern type of circulation in the Skagerrak-Kattegat occurred as a result of increased Atlantic inflow, transgression of former land areas west of Denmark, and the opening of the English Channel and the Danish Straits.

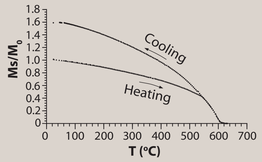
4 5 **8.5 cal. kyr – Present:** Sediment input chiefly from the southern North Sea and the Atlantic Ocean, transported by the North and South Jutland Current; 4 is distinguished from 5 through sediment input from the Baltic Sea and reworked coastal sediments in Sweden and Norway transported by the Baltic Current and currents along the coasts of western Sweden and southern Norway.

Day-diagram



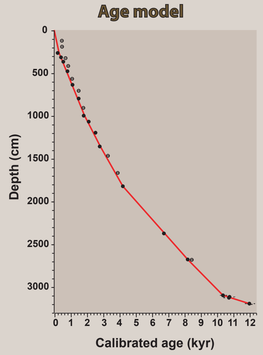
Hysteresis parameters for core MD99-2286.
SD = single domain
MD = multi domain

Thermomagnetic



Thermomagnetic curves obtained from magnetic extracts, showing the normalized evolution of the saturated magnetization versus temperature.

Age model



Age-depth model for core MD99-2286, based on 27 AMS 14C-dated samples of shells or mixed benthic foraminifera. The dates were calibrated using the MARINE98 dataset (Stuiver et al., 1998). Open circles mark age estimates excluded from the age model because of presumed reworking. 1 σ calibrated age ranges are shown as horizontal error bars through the dates. Note that several error bars are smaller than the circles. Modified from Gyllencreutz et al. (2005).

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