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Time-slice maps of postglacial palaeoceanography in the Skagerrak

R. Gyllencreutz[1], J. Backman[2], M. Jakobsson[2], C. Kissel[3], E. Arnold[2]

[1]Department of Earth Science, University of Bergen, Norway, [2]Department of Geology and Geochemistry, Stockholm University, Sweden, [3]Laboratoire des Sciences du Climat et de l'Environnement, CEA/CNRS, Gif-sur-Yvette, France   Contact: **richard.gyllencreutz@geo.uib.no** / Phone: +47-5558-3537)

Introduction

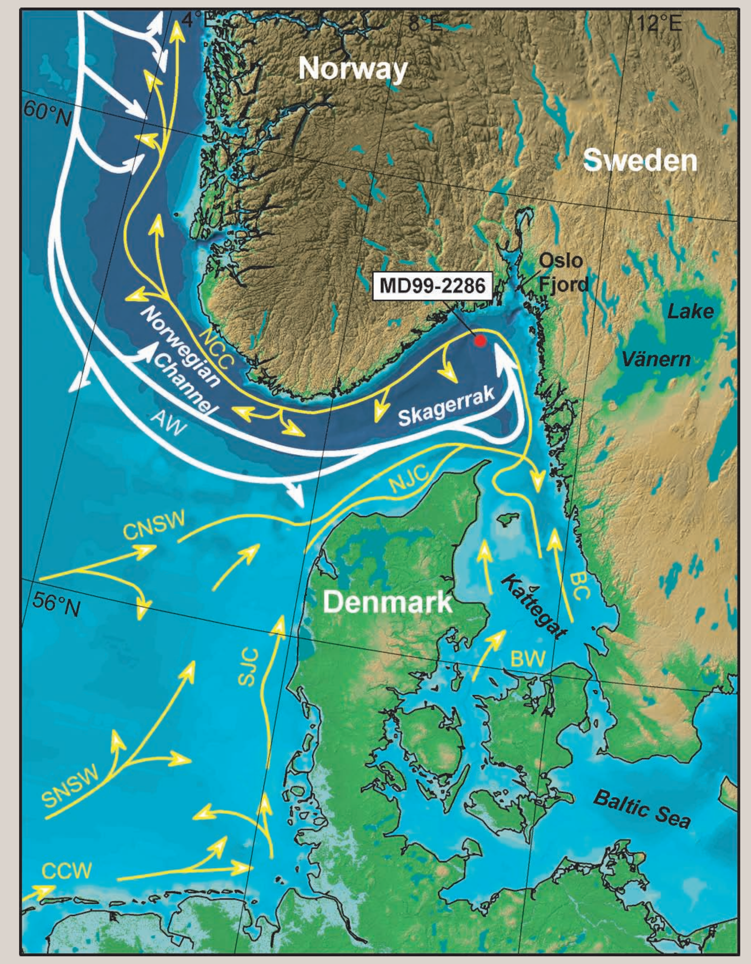
The Skagerrak is the major sink for fine-grained sediments in the North Sea region. There, almost unaltered North Atlantic water is mixed with North Sea waters, and relatively fresh Baltic Sea water, strongly affected by precipitation in northern Europe. Most of the sediments from these waters are deposited in the Skagerrak, representing an archive of past oceanographic and climatic changes in a key site for studying the interaction of the open marine and the more continental setting.

Here, we present four time-slice maps, on a calibrated age scale at 14.0 kyr, 11.2 kyr, 10.2 kyr, and 8.1 kyr, representing crucial periods of change in the latest glacial to early Holocene paleogeographic and paleoceanographic evolution in the Skagerrak region. Interpretations of that evolution are based on results from a literature review, viewed in a highly resolved chronological framework using the AMS ^{14}C dated core MD99-2286 and chirp sonar profiles from the coring site. This study represents a synthesis of recent multi-proxy studies in the Skagerrak as part of the HOLSMEER project.

A calibrated age scale

A consistent use of a calibrated age scale has been employed in order to facilitate comparison with literature data, which required recalibration of previously published 14C ages. Details about age models and calibration datasets for the different records are specified in the Event Stratigraphy Table. A simplified calibration approach was for indirectly derived 14C-ages, e.g. from cores dated by pollen stratigraphy or from modeling results, or when insufficient details for a full calibration of the 14C dates were given. In such cases, published 14C ages were calibrated using an assumed ±100 years error, using CALIB 4.4 software with the INTCAL98 dataset (Stuiver et al., 1998b). The purpose has been to establish a sequence of events that can be meaningfully compared to those observed in MD99-2286.

The present situation



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).

Acknowledgements

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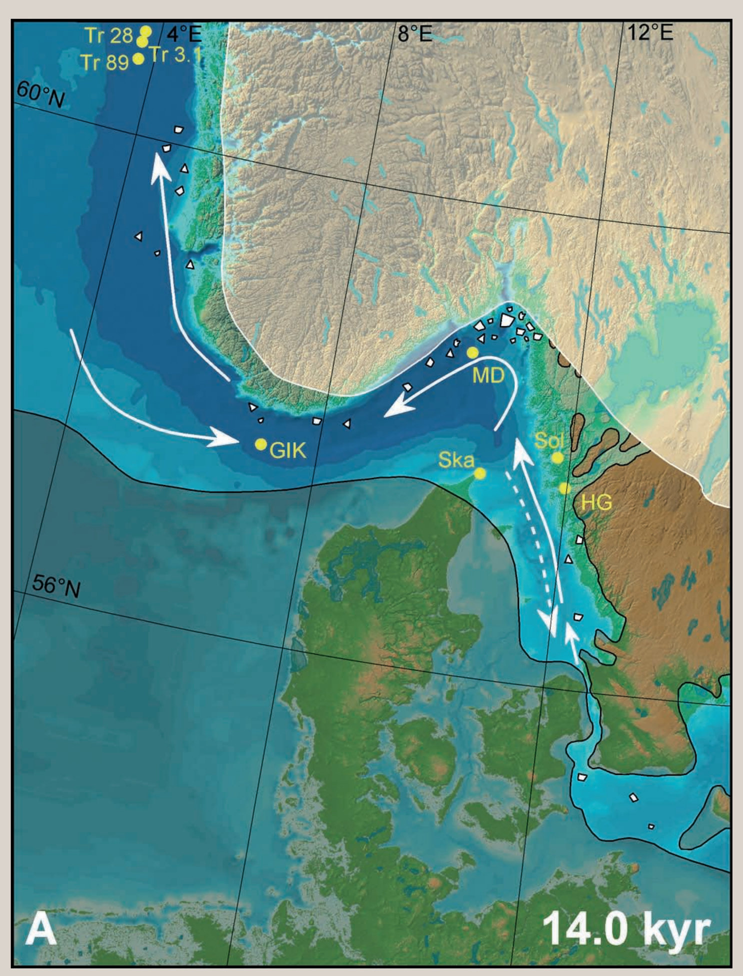
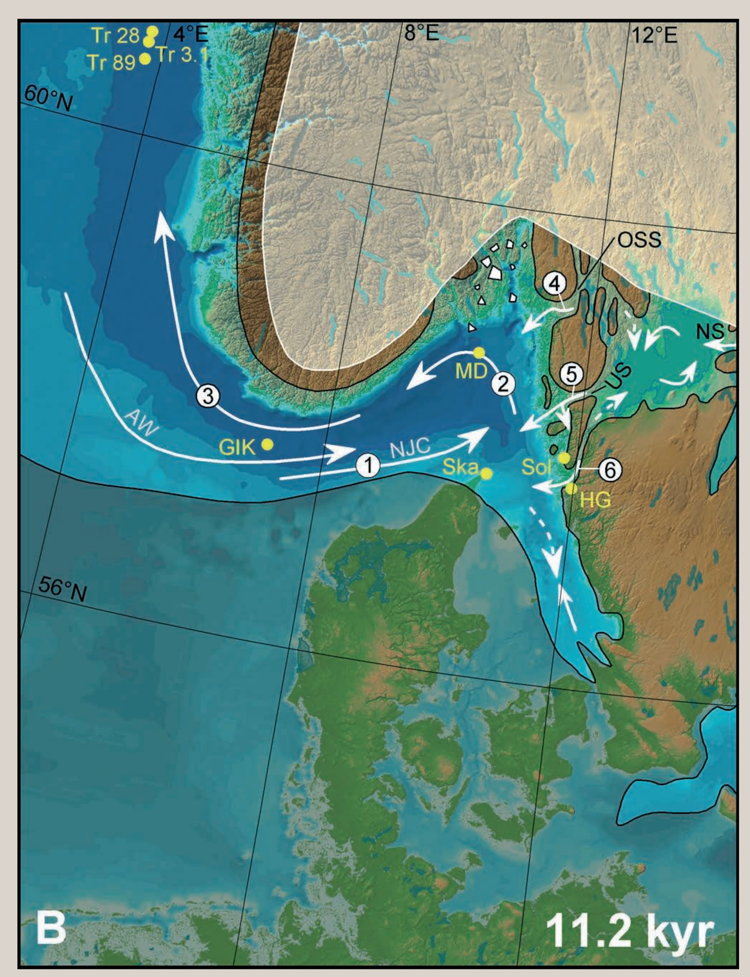
Time-slice 14 kyr (15.0-13.0 kyr interval)



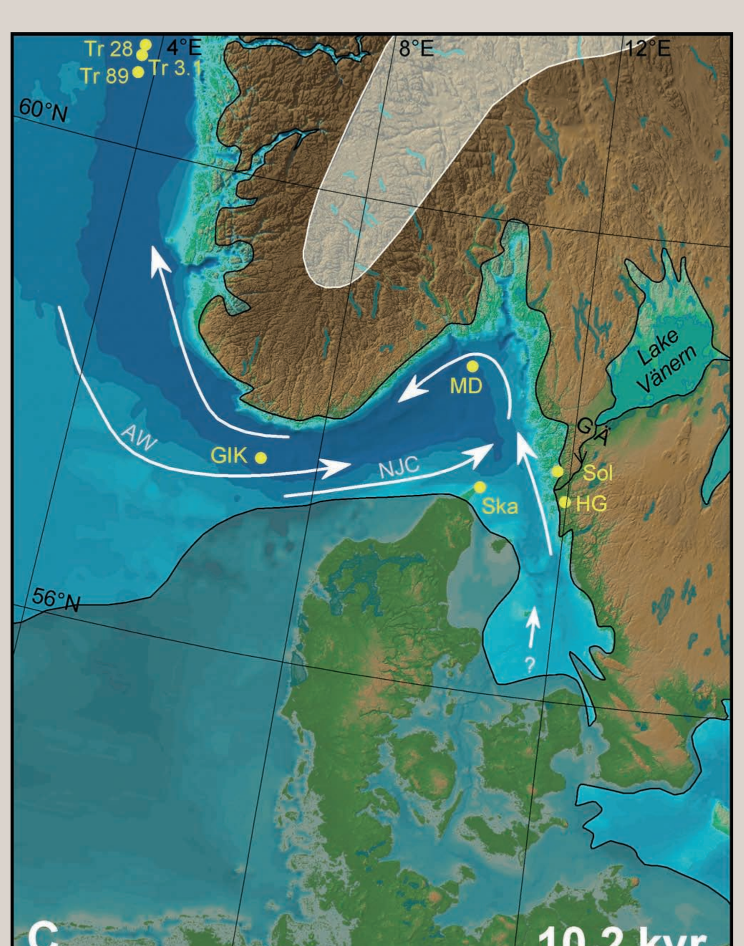
The Skagerrak resembled a fjord between the ice-front in the north and land areas in the south. Relatively warm Atlantic waters flowed through the Norwegian Channel and the Skagerrak from 15 kyr until the onset of the Younger Dryas. An ice shelf existed in the deep Oslo Fjord, and a calving ice front occupied the northern and eastern flanks of the Skagerrak. Sedimentation was dominated by rapid deposition of proximal glacial marine sediments. A strong regional seismic reflector developed around 13.5 kyr as a result of a drastic decrease in sedimentation rates due to rapid break-up of the ice shelf. Outflow of glacial melt-water through Öresund persisted until the final drainage of the Baltic Ice Lake at c. 11.6 kyr. The general circulation pattern in the Skagerrak was altered when outlet from the Baltic, the Närke Strait, opened across south-central Sweden at about 11.3 kyr.

Time-slice 11.2 kyr (11.3-10.3 kyr interval)



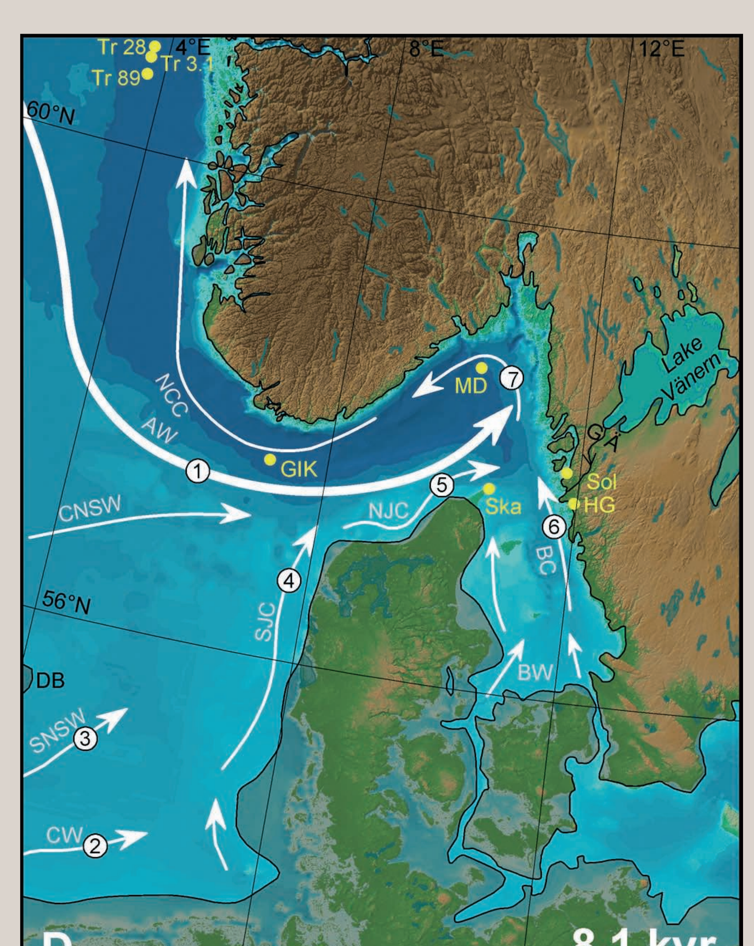
The Skagerrak still resembled a fjord. The circulation was strongly influenced by the North Jutland Current (1) and the currents along the Swedish and Norwegian coasts (2). North Atlantic water advection increased at c. 11.5 kyr, causing corresponding stronger outflow along the Norwegian coast (3). Iceberg calving and continuous deposition of IRD ended when the ice margin recessed onshore in the inner Oslo Fjord at c. 10.7 kyr. The Närke Strait opened at c. 11.3 kyr, causing deposition of clay-rich sediments from the Vänern basin, through outflow of glacial melt-water from the Baltic across south-central Sweden. The N-E gradient in isostatic uplift caused the major outflow route for these sediments to move southwards, from the Otteid-Stenselva (4) in the north, to the Uddevalla Strait (5) and finally to the Göta Älv river (6) in the south. Sedimentation in the Skagerrak began to change from distal glacial marine to normal marine sedimentation governed by the North Jutland Current at about 10.3 kyr.

Time-slice 10.2 kyr (10.3-9.5 kyr interval)



When the Baltic outflow through south-central Sweden diminished due to isostatic uplift, sedimentation in Skagerrak gradually developed further towards the modern, fully interglacial situation with marine conditions, driven by Atlantic water inflow and the North Jutland Current. The youngest IRD occurred at 10.2 kyr as a result of the sudden drainage of an ice-dammed lake in southern Norway. The circulation in the Skagerrak was strongly influenced by currents along the Norwegian coast and the Swedish west coast between about 10.9 and 9.6 kyr. Transgression of former land areas west of Denmark continued, and allowed water to flow closer to the present Danish coast, but the transgression had not yet submerged the areas south of the Dogger Bank. The north-ward flow in the Kattegat was likely significantly weaker, because the passageways through the Danish Straits were closed, inhibiting fresh water outflow from the Baltic.

Time-slice 8.1 kyr (8.5 kyr - present)



The modern circulation pattern was established at 8.5 kyr, through a marked hydrographic shift to higher energy conditions in the Skagerrak. This shift was the combined result of four critical changes:

1) Increased Atlantic water inflow — Event 13
2) Opening of the English Channel — Event 14
3) Opening of the Danish Straits — Event 15
4) Isolation of the Dogger Bank — Event 16

This series of events enabled formation of the South Jutland Current. Since 8.5 kyr until the present, sediments in NE Skagerrak have been derived predominantly from the Atlantic Ocean (1, see numbered currents in map) and the North Sea (2-3), with varying contributions from the South Jutland Current (4 via 5) ("Danish" signature), and from the Baltic Current (6) and the currents along the coasts of southern Norway and western Sweden (7) ("Norwegian" signature).

Legend

Paleo-shorelines
Paleo-ice margins
Paleo-currents

Cores
Tr 28 = Troll 28-03
Tr 3.1 = Troll 3.1
Tr 89 = Troll 8903
GIK = GIK 15530-4
MD = MD99-2286
Ska = Skagen 3/4
Sol = Solberga-2
HG = Horticultural Garden

Locations
OSS = Otteid-Stenselva Strait
NS = Närke Strait
US = Uddevalla Strait
GÄ = Göta Älv river
DB = Dogger Bank

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

Mapping
Projection: Lambert Azim. Equal Area
Geodetic datum: WGS84
Software: GeoMedia Professional

Publication:

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Time slice background data

The modern distribution of lakes is shown in the background together with a digital elevation model (DEM) of the present day topography and bathymetry. The DEM was compiled from various elevation datasets (LMV, SRTM, GTOPO30, RDANH, IOW, ETOPO2) by Jakobsson et al. (2007).

The paleo-shorelines were compiled from Björck (1995; with his calibrated ages from http://www.geol.lu.se/personal/seb/Maps%20of%20the%20Baltic.htm), Stabell and Thiede (1986), Jensen et al. (1997), Lambeck et al. (1998), and Lambeck (1995; 1999). The ice margins were compiled from Andersen (1979), Lundqvist (1986; 1988; 1992), Sørensen (1992), Andersen et al. (1995), Kleman et al. (1997), Lundqvist and Wohlfarth (2001), and Boulton et al. (2001).

The circulation patterns in the Kattegat were modified from Klingberg (1998), and the circulation pattern in Lake Vänern was modified from Fredén (1988). A drainage route for Baltic water existed with a connection somewhere in the southern Kattegat (Björck, 1995) around 10.2 kyr, although the location of this river is unknown (Lemke et al., 2001) (outflow indicated by arrow with question mark in map C).

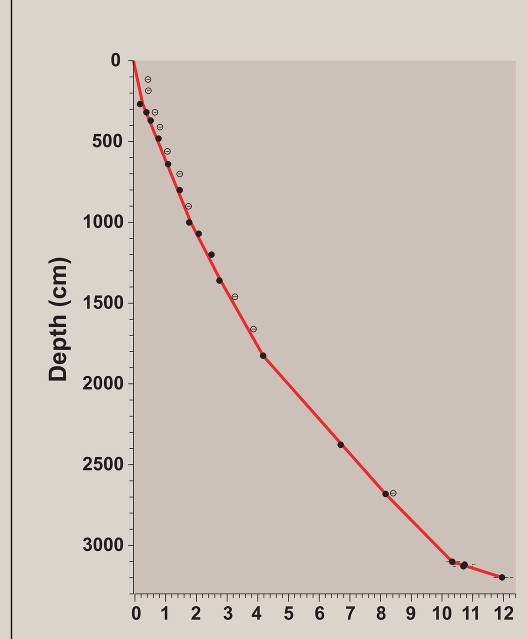
All other features are based on results from core MD99-2286 (Gyllencreutz et al. 2005; Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006) and a literature review synthesized by Gyllencreutz et al. (2006).

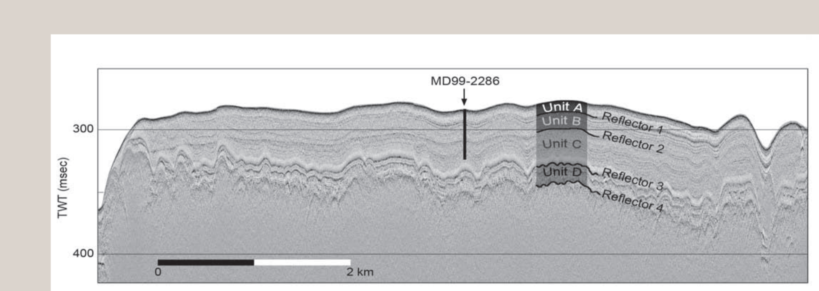
Event stratigraphy and age calibration

No.	Interpreted events in order of appearence	Event reference	Age ref.	^{14}C age (ka BP)	Calibration dataset	Cal. Age (kyr)
1	Warm Atlantic inflow begins	Lehman et al. (1991); Lehman and Keigwin(1992); Veum et al. (1992); Koç et al. (1993); Knudsen et al. (1996)	a	13.5-13.0	MARINE98 [1]	15.5-15.0
2	Sedimentation rates decrease; forms strong seismic reflector	Salge and Wong(1988); Andersen et al.(1995); Gyllencreutz et al. (2005)	b	-	MARINE98 [1]	13.4*
3	Decrease in Atlantic inflow	Lehman and Keigwin(1992); Klitgaard-Kristensen et al. (2001)	c	-	Ash layers, GRIP [2]	12.7-11.5*
4	Increase in Atlantic inflow	Lehman and Keigwin(1992); Koç et al. (1993); Sejrup et al. (1995); Conradsen and Heier-Nielsen, (1995); Jiang et al. (1997); Klitgaard-Kristensen et al. (2001);	c	-	Ash layers, GRIP [2]	11.5*
5	Närke Strait opening	Björck (1995)	d	10.2-10.1	INTCAL98 [3]	11.4-11.3
6	Baltic outflow begins through					
	- Otteid-Stenselva strait	Gyllencreutz (2005); Björck (1995)	b	-	MARINE98 [1]	11.3*
	- Uddevalla strait	Cato et al. (1982); Bergsten (1994); Björck (1995)	e	-	MARINE98 [1]	11.1-10.7*
	- Göta Älv	Bergsten (1994)	⇐	-	INTCAL93 [4]	10.2*
7	Transgression of s. North Sea	Stabell and Thiede(1986); Lambeck(1995)	f	10	INTCAL98 [5]	11.6-11.3
8	End of IRD dep. in Skagerrak	van Weering (1982a)	⇐	10	INTCAL98 [5]	11.6-11.3
	-"-	Gyllencreutz (2005)	⇐	-	MARINE98 [1]	10.7*
9	Aker IMZ, Oslo area	Andersen et al (1995); Gjessing (1980); Gjessing and Spjeldnaes(1979); Sørensen(1979)	g	9.8-9.6	INTCAL98 [5]	11.3-10.8
10	Marine limit, Oslo area	Hafsten (1983)	⇐	9.7	INTCAL98 [5]	11.2-10.8
11	Glomma drainage event	Longva and Bakkejord (1990); Longva and Thoresen(1991)	h	9.1	INTCAL98 [5]	10.4-10.2
12	Otteid-Stenselva strait closing	Björck (1995); Lambeck(1999)	i	9.1	INTCAL98 [5]	10.4-10.2
13a	Increase in Atlantic inflow	Klitgaard-Kristensen et al. (2001)	c	-	Ash layers, GRIP [2]	9.0*
b	-"-	Koç Karpuz and Jansen(1992); Lehman and Keigwin (1992); Koç et al. (1993	j	7.7-7.6	MARINE98 [1]	8.6-8.5
c	-"-	Björklund et al. (1985)	⇐	8-7	INTCAL98 [5]	9.0-7.7
14a	English Channel opening	Nordberg (1991)	⇐	8	INTCAL98 [5]	9.0-8.7
b	-"-	Conradsen and Heier-Nielsen (1995)	j	7.6	MARINE98 [1]	8.5
c	-"-	Jiang et al. (1997)	j	7.7	MARINE98 [1]	8.6
d	-"-	Björklund et al. (1985)	⇐	8-7	INTCAL98 [5]	9.0-7.7
e	-"-	Lambeck (1995)	⇐	8-7	INTCAL98 [5]	9.0-7.7
f	-"-	Jelgersma (1979)	⇐	8.7-8.3	INTCAL98 [5]	9.7-9.3
g	-"-	Behre (2007)	⇐	-	INTCAL98 [5]	9.1-8.7*
15a	Danish straits opening	Björck (1995)	⇐	8.2	INTCAL98 [5]	9.3-9.0
b	-"-	Conradsen (1995)	⇐	8	INTCAL98 [5]	9.0-8.7
c	-"-	Jensen et al. (1997)	⇐	8	INTCAL98 [5]	9.0-8.7
d	-"-	Lambeck (1999)	⇐	7.5-7.8	INTCAL98 [5]	8.7-8.2
e	-"-	Bennike et al. (2004)	⇐	-	INTCAL98 [3]	8.1*
f	-"-	Berglund et al. (2005)	⇐	-	INTCAL98 [3]	8.5*
16a	Isolation of Dogger Bank	Lambeck (1995)	⇐	8	INTCAL98 [5]	9.0-8.7
b	-"-	Behre (2007)	⇐	-	INTCAL98 [5]	>9.1*
17a	S-K hydrographic shift	Conradsen (1995); Conradsen and Heier-Nielsen (1995)	j	5.5	MARINE98 [1]	6.2
b	-"-	Jiang et al. (1997)	j	5.1	MARINE98 [1]	5.9
c	-"-	Nordberg (1991); Nordberg and Bergsten(1988)	⇐	4	INTCAL98 [5]	4.6-4.3

Post-glacial event stratigraphy for the eastern North Sea area, and calibration of ^{14}C ages of discussed events. *represent calibrated ages in the original literature. All other ^{14}C ages have been recalibrated from age models or single age estimates from a) Lehman and Keigwin (1992), b) Gyllencreutz et al. (2005), c) Klitgaard-Kristensen et al. (2001), d) Björck (1995) and http://www.geol.lu.se/personal/seb/Maps%20of%20the%20Baltic.htm, e) alternative Solberga-2 age model by Gyllencreutz (2005), f) Stabell and Thiede (1986), g) Andersen et al. (1995), h) Longva and Thoresen (1991), i) Björck (1995), j) Petersen (2004) and Conradsen and Heier-Nielsen (1995). ⇐ Age reference = Event reference. IRD = Ice Rafted Debris. IMZ = Ice Marginal Zone. S–K= Skagerrak–Kattegat.

[1]Stuiver et al. (1998a). [2]Vedde and Saksunarvatn ash layers in core Troll 8903/28-03 and correlation with the GRIP ice core (Klitgaard-Kristensen et al. 2001). [3]Stuiver et al. (1998b). [4]Stuiver and Braziunas (1993). [5]Simplified calibration using the CALIB software (rev. 4.4) (Stuiver and Reimer, 1993) and INTCAL98 (Stuiver et al., 1998b), assuming a ±100 years error in reported ^{14}C ages. Modified from Gyllencreutz et al. (2006).





Chirp sonar profile from the MD99-2286 coring site

The seismic units A-D and reflectors 1-4, defined by Gyllencreutz et al. (1995), are indicated in the profile. The penetration depth of MD99-2286 (indicated with a black vertical line) was estimated from correlation of MST-measured GRA-density and the chirp sonar record at the coring site (Gyllencreutz et al., 2005). TWT = Two-way travel time.

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).