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Postglacial Palaeoceanography in the Skagerrak

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Abstract: Crucial periods of change in the latest glacial to early-Holocene palaeogeographic and palaeoceanographic evolution in the Skagerrak region are portrayed in four time-slice maps on a calibrated age scale at 14.0 kyr, 11.2 kyr, 10.2 kyr and 8.1 kyr. The course of palaeoenvironmental events is set in a high-resolution chronological framework using IMAGES core MD99-2286 and a grid of chirp sonar profiles. These maps visualize the complex, rapid palaeogeographic and palaeoceanographic changes during the glacial–interglacial transition, which is characterized by major changes in circulation, sediment sources, and depositional processes.

Key words: Palaeoceanography, palaeogeography, marine coastal palaeoenvironments, Holocene, Skagerrak, HOLSMEER project.

Introduction

The Skagerrak is a major sink for fine-grained sediment in the North Sea, receiving material from the entire northwest European drainage system and the North Sea coast. Modern sedimentation rates in Skagerrak's central and northeastern part are up to 1 cm/yr (van Weering, 1982a; Bøe *et al.*, 1996). These rapidly accumulating sediments contain detailed information about sediment sources and the palaeoceanographic evolution of this region. The large-scale palaeoceanographic development of the Skagerrak-Kattegat region during late Pleistocene and Holocene times has been addressed in several seismic surveys (Salge and Wong, 1988; von Haugwitz and Wong, 1993; Rise *et al.*, 1996) and sediment studies (Björklund *et al.*, 1985; Nordberg, 1991; van Weering *et al.*, 1993; Conradsen and Heier-Nielsen, 1995; Longva and Thorsnes, 1997; Jiang *et al.*, 1997; Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006). Hass (1996) noted that patterns of sedimentation in the Skagerrak are driven by a complex interplay between regional oceanography and climate, resulting in strongly variable deposition over short distances that make core-to-core correlations difficult even over a few kilometres.

Several seismo-acoustic surveys in the NE Skagerrak have portrayed postglacial sediment sequences more than 50 m thick (van Weering *et al.*, 1973; van Weering, 1982b; Bøe *et al.*, 1996; Gyllencreutz *et al.*, 2005). A 32.4 m long IMAGES core, MD99-2286 (Labeyrie *et al.*, 2003), was retrieved from such a sequence at 225 m water depth (Figure 1).

We present here four maps representing compilations of a literature review,[1] that portray the crucial periods of change in the latest glacial to early-Holocene palaeogeographic and palaeoceanographic evolution of the Skagerrak region. These maps are aimed to visualize the complex and rapid palaeogeographic and palaeoceanographic changes during a crucial period of transition from *c.* 14 kyr to *c.* 8 kyr, characterized by major changes in circulation, sediment sources and depositional processes. The course of palaeoenvironmental events are arranged in a highly resolved chronological framework using the AMS ^{14}C-dated core MD99-2286 and a set of chirp sonar profiles. The event-stratigraphic maps represent time-slices on a calibrated age scale at 14.0 kyr, 11.2 kyr, 10.2 kyr and 8.1 kyr. This study also represents a synthesis of recent work in the Skagerrak region in the time interval from 14 kyr to 2 kyr (Gyllencreutz, 2005; Gyllencreutz *et al.*, 2005; Gyllencreutz and Kissel, 2006). The development during the past 2 kyr has been recently synthesized by Hebbeln *et al.* (2006, this issue). Time-slice maps younger than 8.1 kyr have not been produced because the modern circulation system was essentially established in the Skagerrak at about 8 kyr, when the eastern North Sea coastlines by-and-large had attained their present appearance.

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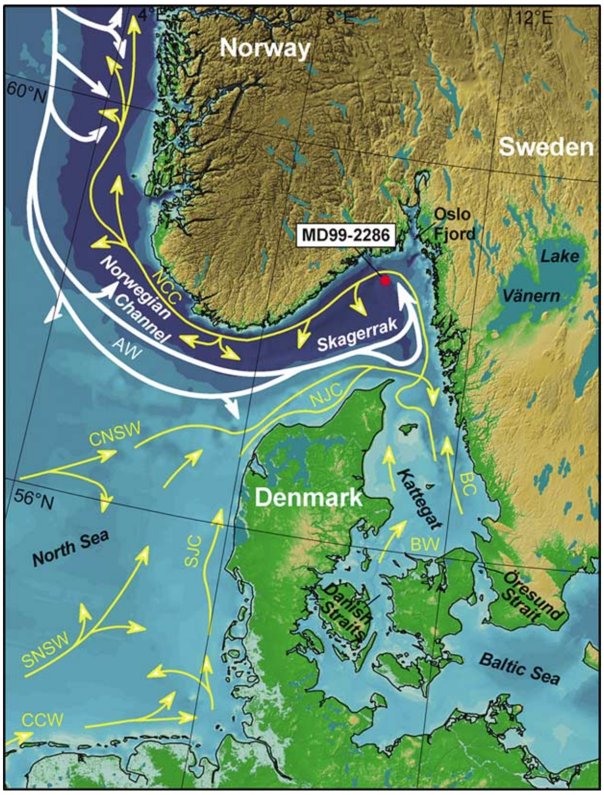

Figure 1 Location map and general ocean circulation (arrows) in the eastern North Sea and the Skagerrak. White arrows mark Atlantic water flowing more or less directly into the Skagerrak. The location of core MD99-2286 is marked with a red dot. Current pattern modified from Longva and Thorsnes (1997)

Oceanographic setting and premises for rapid sedimentation

The Skagerrak is part of the North Sea, a shallow semi-enclosed basin connected to the Atlantic Ocean in the north, the English Channel in the southwest and to the Kattegat and the Baltic Sea in the southeast (Figure 1). Circulation and sedimentation is largely driven by the North Atlantic Current (Svansson, 1975; Rodhe, 1987, 1998; Otto *et al.*, 1990). North Atlantic waters enter the North Sea between Scotland and Norway, and to a lesser extent through the English Channel in the south. The South Jutland Current flows north along the Danish west coast carrying mixed water masses from the English Channel and the southern North Sea. When entering the Skagerrak, the South Jutland Current is merged with the North Jutland Current, which represents a mixture of Atlantic and central North Sea waters. Fresher and colder water entering the Kattegat from the Baltic Sea adds to this circulation, before the mixed system makes an anti-clockwise turn in NE Skagerrak and subsequently exits the Skagerrak as the Norwegian Coastal Current (Figure 1). During the cyclonic turn in NE Skagerrak, water depths increase and flow velocities decrease, thus permitting fine-grained sediment to be deposited at high rates in the central and northeastern Skagerrak (van Weering, 1982a; Rodhe and Holt, 1996; Bøe *et al.*, 1996).

Most suspended sediments entering the Skagerrak are supplied by large volumes of Atlantic water with relatively low sediment concentration (Longva and Thorsnes, 1997). The South Jutland Current carries high concentrations of suspended particles along the sand-dominated western coasts of Denmark (Eisma and Kalf, 1987), but has a much smaller volume than the Atlantic waters and therefore delivers less sediment to the Skagerrak (Longva and Thorsnes, 1997). Rivers are minor sediment contributors to the Skagerrak because they discharge into silled fjords in Norway and Sweden where most of the sediment load is trapped.

Methods

Calibrated years BP versus ^{14}C years BP

All ages are given in calibrated thousand years before present (= AD 1950; kyr), according to Stuiver *et al.* (1998a, b). The chronostratigraphic control of core MD99-2286 relies on 27 AMS ^{14}C-dated samples of either mollusc shells or mixed benthic foraminifera. The radiocarbon dates were calibrated with the calibration data set MARINE98 (Stuiver *et al.*, 1998b), using the CALIB software 4.4 (Stuiver and Reimer, 1993) (for further details see Gyllencreutz *et al.*, 2005 and Gyllencreutz and Kissel, 2006). A standard reservoir correction of 400 years was used for the age model of MD99-2286 (Figure 2) and, where applicable, also for calibrated radiocarbon ages of events from the literature discussed in this paper, recognizing that reservoir ages may have been greater during the deglaciation (Bard *et al.*, 1990; Bondevik *et al.*, 1999; Sikes *et al.*, 2000).

Age calibration of previously published sediment records

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 ^{14}C ages. Details

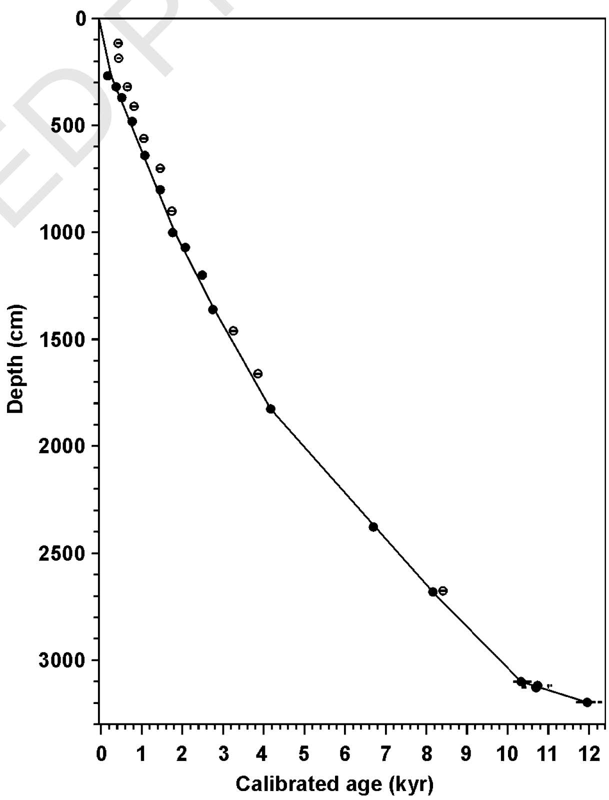

Figure 2 Age–depth model for core MD99-2286. Open circles mark age estimates excluded from the age model because of presumed reworking. 1σ calibrated age ranges are shown as horizontal error bars through the dates. Note that several error bars are smaller than the circles. Modified from Gyllencreutz *et al.* (2005)

of age models and calibration data sets for the different records are specified in Table 1. A simplified calibration approach has been used when discussing age estimates reported in the literature using indirectly derived ^{14}C-years, from sources such as cores dated by pollen stratigraphy (Nordberg, 1991), modelling results based on radiocarbon-dated sources (Lambeck, 1999) or when insufficient details of the ^{14}C dates were presented in order to enable a full calibration (Andersen *et al.*, 1995). In such cases, published ^{14}C ages for the events discussed were calibrated using an assumed uncertainty of

Table 1 Postglacial event stratigraphy for the eastern North Sea area, and calibration of ^{14}C ages of events discussed

No.	Interpreted events in order of appearence	Event reference	Age ref.	^{14}C age (ka BP)	Calibration data set	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
	End of IRD dep. in Skagerrak	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	English Channel opening	Nordberg (1991)	⇐	8	INTCAL98[5]	9.0–8.7
b	English Channel opening	Conradsen and Heier-Nielsen (1995)	j	7.6	MARINE98[1]	8.5
c	English Channel opening	Jiang *et al.* (1997)	j	7.7	MARINE98[1]	8.6
d	English Channel opening	Björklund *et al.* (1985)	⇐	8–7	INTCAL98[5]	9.0–7.7
e	English Channel opening	Lambeck (1995)	⇐	8–7	INTCAL98[5]	9.0–7.7
f	English Channel opening	Jelgersma (1979)	⇐	8.7–8.3	INTCAL98[5]	9.7–9.3
14a	Danish Straits opening	Björck (1995)	⇐	8.2	INTCAL98[5]	9.3–9.0
b	Danish Straits opening	Conradsen (1995)	⇐	8	INTCAL98[5]	9.0–8.7
c	Danish Straits opening	Jensen *et al.* (1997)	⇐	8	INTCAL98[5]	9.0–8.7
d	Danish Straits opening	Lambeck (1999)	⇐	7.5–7.8	INTCAL98[5]	8.7–8.2
e	Danish Straits opening	Bennike *et al.* (2004)	⇐	–	INTCAL98[3]	8.1*
f	Danish Straits opening	Berglund *et al.* (2005)	⇐	–	INTCAL98[3]	8.5*
15	Isolation of Dogger Bank	Lambeck (1995)	⇐	8	INTCAL98[5]	9.0–8.7
16a	S-K hydrographic shift	Conradsen (1995); Conradsen and Heier-Nielsen (1995)	j	5.5	MARINE98[1]	6.2
b	S-K hydrographic shift	Jiang *et al.* (1997)	j	5.1	MARINE98[1]	5.9
c	S-K hydrographic shift	Nordberg (1991); Nordberg and Bergsten (1988)	⇐	4	INTCAL98[5]	4.6–4.3

*Calibrated ages in the original literature; ^{14}C ages for these are not shown. 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) as presented on Björck's webpage 2006 (http://www.geol.lu.se/personal/seb/Maps%20of%20the%20Baltic.htm), (e) alternative Solberga-2 age model by Gyllencreutz (2005, table 3, figure 9), (f) Stabell and Thiede (1986), (g) Andersen *et al.* (1995), (h) Longva and Thoresen (1991), (i) Björck (1995), (j) calibrated ages from Petersen (2004) using the age model by Conradsen and Heier-Nielsen (1995). Left-facing arrows indicate that the Age reference is the same as the 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 $\pm$100 yr error in reported ^{14}C ages.

±100 years, using CALIB software (rev. 4.4) (Stuiver and Reimer, 1993) with the INTCAL98 data set (Stuiver *et al.*, 1998b). This approach does not qualify as a strict calibration in the technical sense, but was necessary in order to generate a continuous and consistently arranged event-chronology among different data sets. The purpose has been to establish a sequence of events that can be meaningfully compared with those observed in MD99-2286. The results of these calibrations (Table 1) are considered to represent a palaeoceanographic event-stratigraphy for the eastern North Sea region based on a calibrated age scale.

Chirp sonar profiling

To characterize the coring site, acoustic sub-bottom profiles were acquired from R/V *Skagerrak* with EdgeTech's X-Star chirp sonar system and the SB-512 tow-fish (for further details see Gyllencreutz *et al.*, 2005). The profile shown in Figure 3 was acquired with a 40 ms long 1.5–7.5 kHz chirp pulse. The data were processed using the software Sioseis (http://sioseis.ucsd.edu, last accessed 26 June 2006) where stored correlated chirp signal was converted to an analytical signal, envelopes were computed and an automatic gain control (AGC) over a 12.5 ms window length was applied.

Palaeoceanographic reconstructions

Rationale of reconstructions before and after 8.5 kyr

The hydrography of the eastern North Sea region prior to *c.* 8.5 kyr is poorly known, but some general characteristics are indicated from oceanographic modelling and core data. The present cyclonic circulation in Skagerrak is driven by Atlantic inflow, and thus the large-scale North Atlantic Current system (Svansson, 1975; Otto *et al.*, 1990; Rodhe, 1996, 1998). Modelling of the general circulation in the glacial NE Atlantic Ocean suggests that it was not much different from its present state, although the flow strength of the North Atlantic Current was significantly reduced (Schäfer-Neth and Paul, 2001). These results are consistent with core data from 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 estuarine circulation resulting from mixing of high-saline water from the Atlantic and out-flowing low-saline water from the Baltic, and from the North Sea wind stress field (Rodhe, 1996). The topography of the Norwegian Trench also influences today's circulation pattern (Davies and Heaps, 1980; Rodhe, 1996). Based on these general relationships, it appears tenable to assume that a general anti-clockwise circulation has prevailed in the Skagerrak since the deglaciation.

Reconstructions of palaeocurrents are 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. The hydrographic shift to the present-day current system occurs as a series of distinct changes in various sediment properties in several records from the Skagerrak, Kattegat and the Norwegian Channel (Björklund *et al.*, 1985; Nordberg and Bergsten, 1988; Nordberg, 1991; Conradsen, 1995; Conradsen and Heier-Nielsen, 1995; Jiang *et al.*, 1997; Klitgaard-Kristensen *et al.*, 2001; Gyllencreutz, 2005; Gyllencreutz and Kissel, 2006).

Time-slice 1: 14.0 kyr

The palaeoceanographic reconstruction for 14.0 kyr represents the 15.0–13.0 kyr interval (Figure 4A). Core MD99-2286 terminated in sediments having an age of $\approx 12.0 \pm 0.3$ kyr. Sedimentation in the 12.0–14.0 kyr range is hence interpreted from chirp sonar profiles (Gyllencreutz *et al.*, 2005).

The Skagerrak resembled a fjord at 14.0 kyr, bordered to the north by the ice-front and to the south by land areas. Relatively warm Atlantic waters entered the Norwegian Channel and the Skagerrak at about 15.5–15.0 kyr (event 1, Table 1) (Lehman *et al.*, 1991; Lehman and Keigwin, 1992; Veum *et al.*, 1992; Koç *et al.*, 1993; Knudsen *et al.*, 1996). Skagerrak's circulation was presumably relatively weak and cyclonic. A calving ice front was present along much of the northern and eastern flanks of the Skagerrak, with an ice shelf occupying the deep Oslo Fjord (Figure 4A). Sedimentation was dominated by rapid deposition of proximal glacial marine sediments, forming the regional seismo-acoustic unit D of Gyllencreutz *et al.* (2005). Baltic Ice Lake meltwater flowed through the Öresund Strait via Kattegat to Skagerrak (Björck, 1995). Sedimentation in NE Skagerrak changed to distal glacial marine when the ice margin had recessed far enough to permit major fjords to act as sediment traps, at about 13.4 kyr, seen as a strong regional reflector (reflector 3) in chirp sonar profiles from NE Skagerrak (Figure 3; event 2, Table 1). Break-up of the ice shelf and rapid recession of the ice margin to a more distal position resulted in sedimentation rates at the MD99-2286 site that were on average about ten times lower in the 12.0–10.3 kyr interval (≈ 0.06 cm/yr) compared with the 13.4–12.0 kyr interval (≈ 0.6 cm/yr) (Gyllencreutz *et al.*, 2005). The magnitude of this rate-decrease and its timing is consistent with other results from Skagerrak and the Norwegian Channel (Salge and Wong, 1988; Andersen *et al.*, 1995).

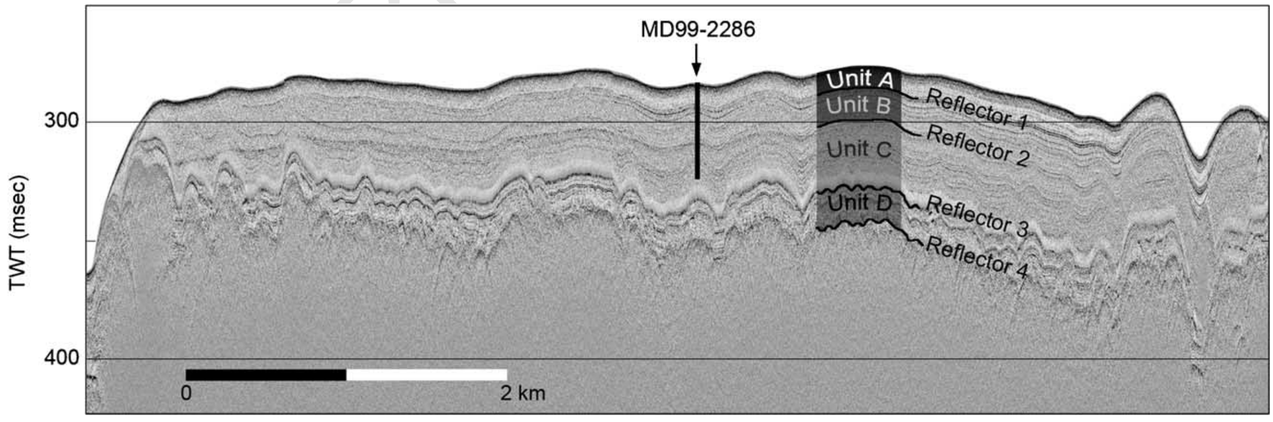

Figure 3 Chirp sonar profile from the MD99-2286 coring site. The seismic units A–D and reflectors 1–4, defined by Gyllencreutz *et al.* (1995), are indicated in the profile. The penetration depth of MD99-2286 (indicated with a black vertical line) was estimated from correlation of MST-measured GRA-density and the chirp sonar record at the coring site (Gyllencreutz *et al.*, 2005). TWT, two-way travel time

Inflow of relatively warm North Atlantic water decreased during the Younger Dryas cold period between 12.7 and 11.5 kyr, as indicated by increasing abundances of left-coiled *Neogloboquadrina pachyderma* in the Troll 8903/28-03 core from the northern Norwegian Channel (Klitgaard-Kristensen *et al.*, 2001). Increasing abundances of left-coiled *N. pachyderma* was observed also in Troll 3.1 (Lehman and Keigwin, 1992), although with a slightly older, but still overlapping, age estimate of 11.2–10.5 ^{14}C yr BP, corresponding to 13.3–12.4 kyr (event 3, Table 1).

Data presented by Lehman and Keigwin (1992) indicate another reduction in North Atlantic influence beginning at 9.7 ^{14}C yr BP that, according to their table 1, should be 10.2 ^{14}C yr BP. This older estimate, however, is in conflict with data from other cores (Conradsen and Heier-Nielsen, 1995; Knudsen *et al.*, 1996). Sediments deposited during the later part of the Younger Dryas are probably recovered in the bottom part of MD99-2286, but any response of decreased Atlantic inflow appears to have been obscured by local environmental conditions, especially influence of glacial meltwater, which is consistent with faunal interpretations from 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 but re-opened at *c.* 12.6 kyr (Björck, 1995). Outflow of glacial meltwater through Öresund persisted until the final drainage of the Baltic Ice Lake at *c.* 11.6 kyr (Björck, 1995; Andrén *et al.*, 2002; Björck *et al.*, 2002). The final drainage of the Baltic Ice Lake has been observed as major δ^{18}O excursions in benthic foraminifera in Skagerrak cores (Erlenkeuser, 1985; Bodén *et al.*, 1997), but this event apparently did not significantly influence sedimentation in NE Skagerrak in terms of grain size changes between about 12.0 and 11.3 kyr in MD99-2286 (Gyllencreutz, 2005). The general circulation pattern in the Skagerrak probably remained largely stable until an outlet from the Baltic, the Närke Strait, opened across south-central Sweden at about 11.3 kyr (Björck, 1995) (event 5, Table 1).

Time-slice 2: 11.2 kyr

The palaeoceanographic reconstruction for 11.2 kyr represents the 11.3–10.3 kyr interval in terms of sedimentary environment (Figure 4B). Sediments deposited between 12.0 kyr, at the bottom of MD99-2286, and 10.3 kyr, are distinguished from younger sediments in terms of grain size distribution and magnetic properties. The 12.0–10.3 kyr sediments are dominated by clay and fine silt, with little sand-sized, ice-rafted debris (IRD) (Gyllencreutz, 2005). Sediments older than 10.3 kyr show a different relationship between SIRM/κ and S-ratio in comparison with younger sediments (Gyllencreutz and Kissel, 2006). From 12.0 to 10.3 kyr sediments are characterized by high S-ratios and low SIRM/κ values, indicative of coarse-grained magnetite. The SIRM/κ to S-ratio relationship exhibits a linear trend towards lower values with younger sediments.

The Skagerrak still resembled a fjord with a general cyclonic circulation at 11.2 kyr. North Atlantic 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 the Skagerrak (Conradsen and Heier-Nielsen, 1995; Jiang *et al.*, 1997) (event 4, Table 1). The Skagerrak circulation was strongly influenced by the North Jutland Current (Figure 4B, current 1) and the coastal currents (Figure 4B, current 2) along the Swedish and Norwegian coasts (Jiang *et al.*, 1997, 1998), which is consistent with grain size and magnetic property results from MD99-2286 (Gyllencreutz and Kissel, 2006). Virtually all waters entering the Skagerrak today depart via the Norwegian Coastal Current (Longva and Thorsnes, 1997; Rodhe, 1998). Increased Atlantic advection into the Skagerrak presumably resulted in a corresponding stronger outflow along the west coast of Norway (Figure 4B, current 3). This hydrographic situation represented an important first step towards the development of the modern circulation system.

The ice-front of the eastern North Sea occupied the Oslo Fjord until the ice retreated onshore at *c.* 10.7 kyr, marked by a distinct decrease of IRD input in MD99-2286 from this retreating, calving ice-front (Gyllencreutz, 2005, figure 6) (event 8, Table 1). The 10.7 kyr estimate is roughly in agreement with the 11.3–10.8 kyr range for the position of the Aker Ice Marginal Zone in the Olso area (Andersen *et al.*, 1995) (event 9, Table 1) and the age of the marine limit, also in the Olso area, at 11.2–10.8 kyr (Hafsten, 1983) (event 10, Table 1).

Sedimentation in Skagerrak was influenced by the outflow of glacial meltwater through the Närke Strait via 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). Sedimentation changed when the Otteid-Stenselva outlet (Figure 4B, current 4) 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 southward to the Uddevalla Strait (Figure 4B, current 5) and the Göta Älv outlet (Figure 4B, current 6). This development is recorded in MD99-2286, Solberga-2 (Cato *et al.*, 1982) and the Horticultural Garden core (Bergsten, 1989, 1991, 1994), 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) (events 6 and 12, Table 1).

Time-slice 3: 10.2 kyr

The palaeoceanographic reconstruction for 10.2 kyr represents the 10.3–9.5 kyr interval in terms of sedimentary environment (Figure 4C). When the Baltic outflow through south-central Sweden diminished as a result of 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 (Figure 4C). 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), which is consistent with the stable relationship between SIRM/κ and S-ratio between 10.3 and 8.5 kyr in MD99-2286 (Gyllencreutz and Kissel, 2006) that indicates a relatively stable sediment source configuration.

There is little IRD deposition between 10.7 kyr and 10.2 kyr. The youngest IRD in MD99-2286 is represented by a single peak occurrence at 10.2 kyr (Gyllencreutz, 2005), when icebergs were flushed out to the Skagerrak by a sudden drainage of an ice-dammed lake in southern Norway (Longva and Bakkejord, 1990; Longva and Thoresen, 1991) (event 11, Table 1).

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 (Jelgersma, 1979; Lambeck, 1995). Diatom assemblages in the Skagen 3/4 core 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 indicate sediment sources near the Swedish and Norwegian coasts (Gyllencreutz and Kissel, 2006). The northward flow in the Kattegat was likely significantly weaker, because the passageways through the Danish Straits were closed, inhibiting freshwater outflow from the Baltic (Björck, 1995; Lambeck, 1999). A drainage route for Baltic water probably existed somewhere in southern Kattegat (Björck, 1995), although the location of this route has not been confirmed (Jensen *et al.*, 1999; Lemke *et al.*, 2001). Thus, a relatively weak northward freshwater flow possibly existed in the southern Kattegat, indicated on the map as an arrow with a question mark (Figure 4C).

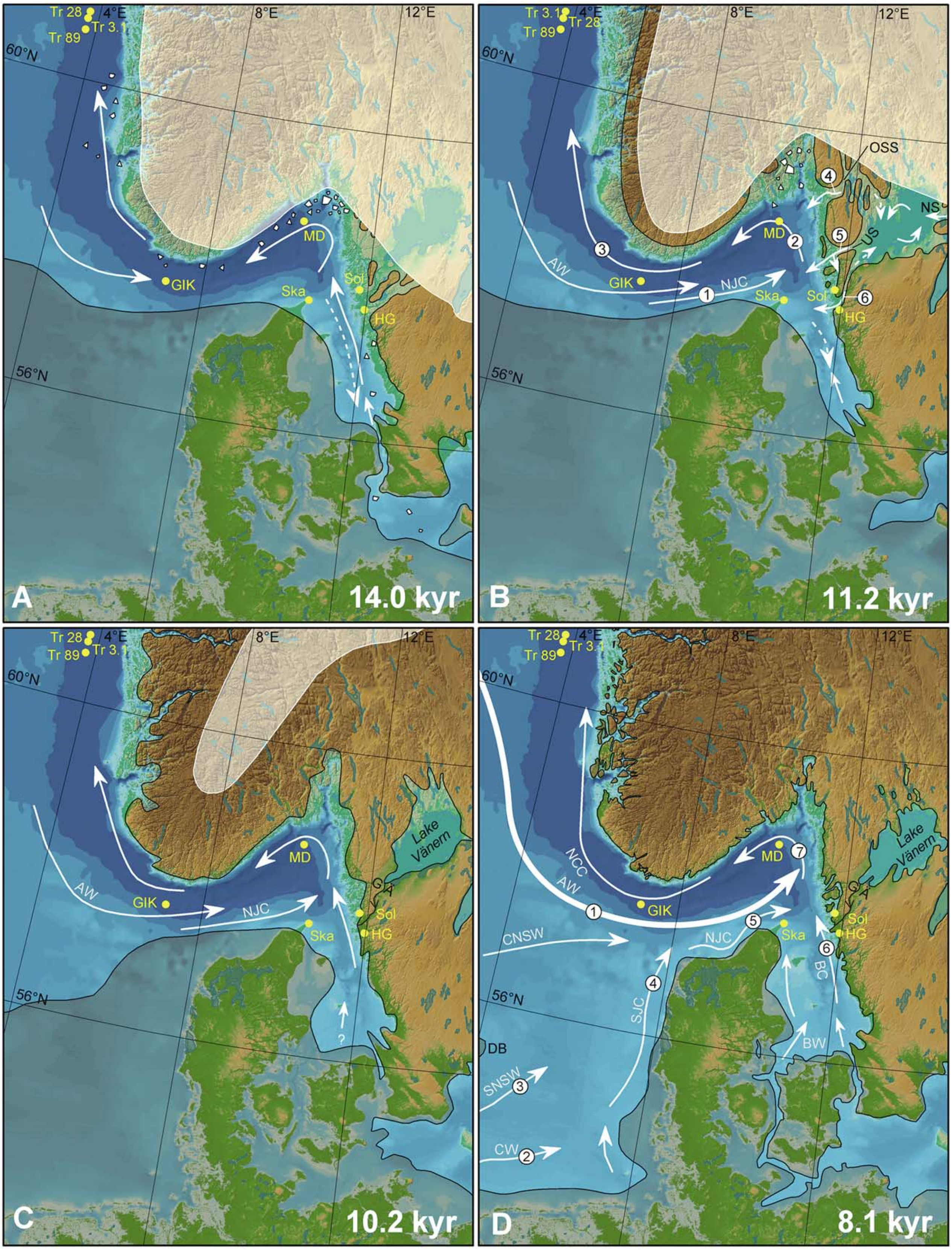

Figure 4 (*Continued*)

Time-slice 4: 8.1 kyr

The palaeoceanographic reconstruction for 8.1 kyr illustrates the establishment of the modern circulation system and serves as a representative time-slice for the general circulation pattern from about 8.5 kyr to the present (Figure 4D). The palaeogeographic environment is difficult to illustrate between 9.5 and 8.5 kyr because of the still poorly resolved changes in the southern North Sea and the Danish Straits area.

The development towards the modern type of circulation in the North Sea and the Skagerrak includes four critical changes: increased Atlantic inflow; opening of the Danish Straits and Öresund; opening of the English Channel; and isolation of the Dogger Bank.

Increased Atlantic inflow

Atlantic inflow was strengthened at *c*. 9.0 kyr, as indicated by foraminiferal assemblages in the Troll 8903/28-03 composite record from the Norwegian Channel (Klitgaard-Kristensen *et al.*, 2001) and 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 in hydrography to events recorded in the Skagen 3/4 core at 8.6–8.5 kyr (Table 1, event 13b–c) (Conradsen and Heier-Nielsen, 1995; Jiang *et al.*, 1997). This increase in Atlantic influence has been observed also in the western Skagerrak at *c*. 9.0–7.7 kyr (Table 2, event 13d) (Björklund *et al.*, 1985).

Opening of the Danish Straits and Öresund

Three straits presently link the marine Kattegat-Skagerrak region with the brackish Baltic Sea, of which the Great Belt (Figure 1) is the deepest, accounting for more than 75% of the water exchange (Bennike *et al.*, 2004). The opening of the Danish Straits and Öresund (Figure 1) 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 marine conditions were established around 9–8 kyr (Björck, 1995; Lambeck, 1999; Andrén *et al.*, 2000; Bennike *et al.*, 2004; Berglund *et al.*, 2005). Jensen *et al.* (1997) suggest that the marine ingression through the Great Belt occurred at about 9.0–8.7 (recalibrated) kyr (Table 1, event 14c), and through the Öresund slightly later. The oldest reported marine shells from the Great Belt are 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.

Opening of the English Channel

The English Channel opened between about 9.0 kyr and 7.7 kyr (Table 1, event 13e) (Lambeck, 1995). This event is independently observed also as pronounced changes in diatom and foraminiferal assemblages within the Skagerrak, dated to 9.0–8.7 kyr (Table 1, event 13a) by Nordberg (1991), to 8.5 kyr (Table 1, event 13b) by Conradsen and Heier-Nielsen (1995) and to 8.6 kyr (Table 1, event 13c) by Jiang *et al.* (1997). The proposed opening at about 9.7–9.3 kyr from studies of submerged peat deposits in the southern North Sea (Jelgersma, 1979) is inconsistent with the above data sets.

Isolation of the Dogger Bank

The Dogger Bank was isolated as an emerged platform soon after about 9.0–8.7 kyr (Table 1, event 15) (Lambeck, 1995), thus permitting Atlantic water from the SW North Sea to flow close to the Danish west coast for the first time since deglaciation and hence forming the South Jutland Current. This event is observed as a drastic coarsening of sediments in core Skagen 3/4 at *c*. 8.5 kyr and in the acceleration of the development of the Skagen Spit in northernmost Jutland (Conradsen and Heier-Nielsen, 1995).

The opening of the English Channel and the isolation of the Dogger Bank both contributed to increase the supply of coarse material to the Skagerrak, as these events permitted formation of the South Jutland Current (Figure 4D). The overall strengthening of Atlantic inflow and the opening of the Danish Straits were crucial for the mixing of fresh and saline water masses, and the establishment of a strong cyclonic circulation in the eastern Skagerrak, resulting in increased transport of suspended sediments.

Although these 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 MD99-2286 (Gyllecreutz, 2005), consistent with similar changes at 8.6–8.5 kyr in Skagen 3/4 (Conradsen-Heier-Nielsen, 1995; Jiang *et al.*, 1997). The magnetic properties in core MD99-2286 show a more gradual response to the hydrographic change around 8.5 kyr, but sediments younger than 8.5 kyr are characterized by different SIRM/κ and S-ratio relationships than older sediments (Gyllencreutz and Kissel, 2006).

Palaeoceanographic development between 8.1 kyr and 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. A series of grain size changes in MD99-2286 from *c*. 6.3 kyr to *c*. 3.8 kyr are considered to reflect strengthening of the South Jutland Current and further development towards the present sedimentation system in the Skagerrak-Kattegat. These changes are correlated to hydrographic changes at 6.2–5.9 kyr (Table 1, event 16a–b) in the Skagerrak (Conradsen and Heier-Nielsen, 1995; Jiang *et al.*, 1997), and 4.5 kyr (Table 1, event 16c) in the Kattegat (Nordberg and Bergsten, 1988; Nordberg, 1991), changes that have been considered to represent a single event

Figure 4 (A) Time-slice at 14.0 kyr. (B) Time-slice at 11.2 kyr. (C) Time-slice at 10.2 kyr. (D) Time-slice at 8.1 kyr. The modern distribution of lakes is shown in the background together with a digital terrain model of the present-day topography and bathymetry. Palaeo-shorelines are indicated with black contour lines around brown shaded areas. Palaeo-ice margins are indicated with white contour lines around light grey shaded areas. Palaeo-currents are indicated with white arrows. The palaeo-shorelines were compiled from Björck (1995; with calibrated ages from Björck's webpage 2006 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). 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 occurring at 5.5 ^{14}C yr BP, or 6.2 kyr (Conradsen, 1995; 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 the observed changes represent one or two events.

Judging from the grain size changes observed between about 6.3 kyr and 3.8 kyr in MD99-2286 (Gyllencreutz, 2005), and the different sedimentary settings of the various locations of the observed hydrographic changes (NE Skagerrak, N Jutland, Kattegat), it appears tenable to suggest that these changes were not synchronous. A long transitional period characterized by a progressive strengthening of the current system resulted in changes that are manifested differently in different parts of the Skagerrak-Kattegat region.

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 composed 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 (Gyllencreutz and Kissel, 2006). These assemblages are similar to two magnetic assemblages recognized in surface samples from northern Skagerrak (Lepland and Stevens, 1996). They distinguished two geographically controlled magnetic mineral assemblages. One was ascribed to a ‘Norwegian’ and the other to a ‘Danish’ sediment source.

Core MD99-2286 was retrieved from a location at the border between these two mineral assemblages. At present, the ‘Norwegian’ assemblage is distributed along the Norwegian coast and in the NE Skagerrak, while the ‘Danish’ assemblage occupies the central part of the Skagerrak (Lepland and Stevens, 1996). Moreover, the ‘Danish’ assemblage is dominated by sediments from the southern North Sea and the Atlantic Ocean, chiefly transported by the North and South Jutland Currents (Figure 4D, currents 1–5). Most of the ‘Norwegian’ assemblage is 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 (Figure 4D, current 6), and currents along the coasts of western Sweden and southern Norway (Figure 4D, currents 7–8).

Following the establishment of the modern type of circulation at about 8.5 kyr, the magnetic parameters in MD99-2286 show variable contributions from the ‘Danish’ and ‘Norwegian’ sources. The period between 6.2 and 4.7 kyr is characterized by weaker Baltic outflow and enhanced transport by the Jutland Current, giving rise to a ‘Danish’ mineral magnetic assemblage, a development that agrees with circulation changes proposed by Jiang *et al.* (1998) based on a sea surface salinity reconstruction using diatoms in the Skagen 3/4 core. The record from *c.* 0.9 kyr until the present is characterized by a strong ‘Danish’ signal, indicating sediment transport dominated by Atlantic water and the Jutland Current (Figure 4D, currents 1, 4–5).

Conclusions

Four time-slice maps are presented 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 palaeogeographic and palaeoceanographic 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. The postglacial development of the Skagerrak region can thus be summarized as follows.

A strong regional seismic reflector separates a top-most acoustically relatively transparent unit from an underlying stratified unit. This reflector developed around 13.5 kyr as a result of a drastic decrease in sedimentation rates. The change to Holocene sedimentary conditions in NE Skagerrak occurred gradually, where glacial marine sediments were substituted by increasing proportions of normal marine sediments. Iceberg calving and continuous deposition of IRD ended at about 10.7 kyr, indicating the time when the ice margin recessed onshore. The youngest IRD occurred at 10.2 kyr as a single event, with the sudden drainage of an ice-dammed lake in southern Norway. Glacial marine sediments dominated deposition in the Skagerrak until *c.* 10.3 kyr.

Outflow of glacial meltwater from the Baltic across south-central Sweden at about 11.3 kyr caused clay-rich distal glacial marine sediments from the Vänern basin to be deposited in the Skagerrak. The northeasterly gradient in isostatic uplift caused the major outflow route for these sediments to progressively migrate southwards along the Swedish west coast, from the Otteid-Stenselva in the north to the Uddevalla Strait and finally to the Göta Älv river in the south.

Sedimentation in the Skagerrak began to gradually change from distal glacial marine to normal marine sedimentation governed by the North Jutland Current at about 10.3 kyr.

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 increased Atlantic water inflow, opening of the English Channel and the Danish Straits, and transgression of the southern North Sea. 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 and the North Sea, with varying contributions from the South Jutland Current, the Baltic Current, and the currents along the coasts of southern Norway and western Sweden.

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Note

1. van Weering *et al.* (1973); Andersen (1979); van Weering (1982a, b); Björklund *et al.* (1985); Stabell and Thiede (1986); Lundqvist (1986, 1988, 1992); Fredén (1988); Salge and Wong (1988); Nordberg (1991); Koç Karpuz and Jansen (1992); Lehman and Keigwin (1992); Sørensen (1992); von Haugwitz

and Wong (1993); Koç *et al.* (1993); Andersen et al. (1995); Björck (1995); Conradsen and Heier-Nielsen (1995); Lambeck (1995, 1999); Sejrup *et al.* (1995); Bøe *et al.* (1996); Knudsen *et al.,* (1996); Rise *et al.* (1996); Jiang *et al.* (1997, 1998); Longva and Thorsnes (1997); Jensen *et al.* (1997); Kleman *et al.* (1997); Rodhe (1998); Klingberg (1998); Andrén *et al.* (2000, 2002); Boulton *et al.* (2001); Klitgaard-Kristensen *et al.* (2001); Lundqvist and Wohlfarth (2001); Bennike *et al.* (2004); Berglund *et al.* (2005).

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