Meltwater Discharge to the Skagerrak-Kattegat from the Baltic Ice Lake during the Younger Dryas Interval

Hui Jiang
Department of Earth Sciences, Aarhus University, DK-8000 Aarhus C, Denmark

Nils-Olof Svensson
Department of Quaternary Geology, Lund University, Tornavägen 13, S-223 63 Lund, Sweden

and

Svante Björck
Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350, Copenhagen K, Denmark

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Diatom data from the Skagerrak-Kattegat show that large amounts of meltwater were discharged into the Kattegat-Skagerrak from the Baltic Ice Lake during the Younger Dryas interval. Strong meltwater discharge greatly freshened surface-water salinity in the Kattegat and areas along the Swedish west coast and possibly changed the directions of sea-surface salinity gradients from north-south to east-west or northwest-southeast. It resulted in a markedly stratified water column in salinity in the Kattegat, which complicates the environmental interpretation based on different types of microfossils. The meltwater influence on the large area of the Skagerrak during the Younger Dryas was, however, restricted along the Norwegian coast where it flowed into the Norwegian Sea. © 1998 University of Washington.

INTRODUCTION

Strong oscillations in oxygen-isotope content of Greenland ice cores are interpreted as reflecting abrupt changes in climate (Dansgaard et al., 1982, 1989). They occur too frequently and too abruptly to have been directly forced by long-term changes in incident solar radiation and are instead attributed to sudden changes in the rate of thermohaline overturn in the North Atlantic, which effectively draws heat poleward from temperate latitudes (Broecker et al., 1986). Most of this heat transport is due to the vertical overturning cell associated with North Atlantic Deep Water (NADW) formation. Broecker (1990) and Birchfield and Broecker (1990) suggest that this circulation may oscillate between “on” and “off” modes through the effect of changing ocean heat flux on the melting rate of ice sheets located near areas of convection. Meltwater discharge from the Baltic Ice Lake into the Norwegian Sea is a potential source of freshwater injection into the North Atlantic Sea (Lehman and Keigwin, 1992; Björck et al., 1996). Changes in meltwater discharge could therefore have had a significant impact on both local and regional conditions.

The Skagerrak-Kattegat is part of the epicontinental North Sea (Fig. 1) and forms a transition area between the North Sea and the Baltic Sea (Nordberg, 1991). The deglaciation history of the area provides useful information about the meltwater discharge from the Baltic Ice Lake, a likely source of large amounts of meltwater discharge. We here discuss the results of diatom analyses of four cores located in different marine settings of the Skagerrak-Kattegat. We focus on how meltwater from the Baltic Ice Lake influenced the oceanography of the Skagerrak-Kattegat. The interpretation of the diatom record draws on the study of recent diatom assemblages that document the relationships between the diatom assemblages from surface sediments and sea-surface salinity in the Skagerrak-Kattegat (Jiang, 1996). Furthermore, our interpretations of palaeoceanographic conditions and palaeoenvironments based on diatoms can be directly correlated with other diatom data from the area (Miller, 1982).

CURRENT SYSTEM AND LATE-GLACIAL GEOGRAPHY

The current system in the Skagerrak-Kattegat is marked by the inflow of saline water (30–35‰) from the North Sea and the outflow of less saline water (8–12‰) from the Baltic Sea due to the Coriolis effect (Fig. 1). The South Jutland Current (SJC) flows along the Danish west coast and is part of the cyclonic circulation of the North Sea. It forms part of the North Jutland Current (NJC) which flows into the
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MATERIAL AND METHODS

Three cores (9303, 06B-042, and Skagen 3) and a reference core (GIK 15530-4) from different marine settings in the Skagerrak–Kattegat (Fig. 1) were used in this study. Cores 9303 in the southern Kattegat and 06B-042 from the Swedish west coast are situated in the area strongly influenced by the Baltic Current. Core GIK 15530-4 lies on the southern flank of the Norwegian Channel where the Norwegian Coastal Current flows into the Norwegian Sea. Core Skagen 3, at Skagen Spit, Denmark, is located in the area where the highly saline water of the North Jutland Current flows into the Skagerrak–Kattegat. The less-saline Baltic Current affects this core site only when there is strong outflow from the Baltic (Fält, 1982). The diatom records from these four cores document changes in meltwater discharge from the Baltic Ice Lake.

Each sample represents 2-4 cm of sediment. All samples were treated with 10% HCl to remove calcareous matter, washed with distilled water, and treated with 30% H₂O₂ (1–2 h in a water bath at 60°C) to destroy organic material. Samples with a high clay content were washed repeatedly by suspending and dispersing the material in distilled water, the supernatant being decanted off only after at least 2 h. More than 300 diatom valves (excluding Chaetoceros resting spores) were counted from each sample, except in cases where the diatom preservation was poor (Jiang and Nordberg, 1996; Jiang and Klingberg, 1996; Jiang et al., 1997). Diatom percentages were calculated based on the total sum. The percentage of freshwater diatoms (including Fragilaria species) was used as an indicator of the relative importance of meltwater from the Baltic Ice Lake. The chronology was determined using AMS ¹⁴C dates of macrofossils from cores 9303, 06B-042, and Skagen 3 (Table 1). A standard marine reservoir correction of 400 yr was subtracted from the dates, although we are aware that a larger marine correction is also possible (Bard et al., 1994). Detailed discussions of the AMS ¹⁴C chronology of these cores can be found in Jiang and Nordberg (1996), Conradsen and Heier-Nielsen (1995), Knudsen et al. (1996), and Jiang and Klingberg (1996). The diatom assemblage of the Younger Dryas interval from core GIK 15530-4 (Stabell, 1985) was correlated with those from the other three cores.

DIATOM DATA AND INTERPRETATION

The remarkable characteristic of the diatom assemblages from the southern Kattegat and the Swedish west coast is the dominance of freshwater diatoms during the Younger Dryas interval (Fig. 3). The diatom assemblages between ca. 11,000 and 10,550 ¹⁴C yr B.P. in core 9303 from the southern Kattegat mainly contain Aulacoseira islandica (O. Mülller), Stephanodiscus neoatraeae Háökansson and Hickel, Achnathes minutissima Kützing, Amphora pediculus

FIG. 1. Maps of the North Sea region showing locations of the investigated area, pattern of currents, and core sites discussed in the text: Skagen 3 (Jiang et al., 1997), 06B-042 (Jiang and Klingberg, 1996), 9303 (Jiang and Nordberg, 1996), and 1 (GIK 15530-4, Stabell, 1985). NEAC, North East Atlantic Current; TBC, Tampen Bank Current; STC, South Trench Current; SJC, South Jutland Current; NJC, North Jutland Current; NCC, Norwegian Coastal Current; BC, Baltic Current. Redrawn from Jiang et al. (1997).

Skagerrak–Kattegat. The NJC is dominated by the South Trench Current (STC), which supplies the large volume of North Atlantic water flowing along the southern rim of the Norwegian Trench. The outflow of the low-salinity Baltic Current (BC), together with the NJC, makes up the Norwegian Coastal Current (NCC), which flows out of the Skagerrak along the Norwegian coast (Nordberg, 1991) (Fig. 1). The maximum surface salinity is found at the North Jutland Shelf break (Rodhe, 1992), with strong salinity gradients characterizing the Kattegat in a north–south direction (Svansson, 1975; Stigebrandt, 1983; Fält, 1982).

The Skagerrak–Kattegat has been connected with the North Atlantic through the Norwegian Channel since about 15,000 ¹⁴C yr B.P. (Knudsen et al., 1996) and formed a large fjordlike system in the earliest Holocene (Conradsen and Heier-Nielsen, 1995). During deglaciation, and up to about 10,200 ¹⁴C yr B.P., the Skagerrak was a deep fjord bordered by land areas to the south and a calving ice front along much of the northern and eastern flanks. The ice front was relatively stationary along the Norwegian coast between 11,000 and 10,200 ¹⁴C yr B.P. but retreated inland in western Sweden (Fig. 2). By about 10,200 ¹⁴C yr B.P. the ice front had begun to withdraw from southwestern Sweden (Bjö rck, 1995).
(Kützing) Grunow, *Cocconeis placentula* Ehrenberg, *Opephora martyi* Héribaud, and *Fragilaria* spp. The first two species are freshwater planktonic forms. They were abundant when the Baltic was a large lake (Risberg et al., 1996). The other species are benthonic forms and are commonly found only in freshwater and/or slightly brackish environments.

**Table 1.** AMS 14C Dates in Cores 9303, Skagen 3, and 06B-042

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>14C dates from core 9303 (yr B.P.)</th>
<th>Depth (cm)</th>
<th>14C dates from Skagen 3 (yr B.P.)</th>
<th>Depth (cm)</th>
<th>14C dates from core 06B-042 (yr B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>117–119</td>
<td>10,550 ± 85</td>
<td>114.8</td>
<td>10,050 ± 100</td>
<td>250</td>
<td>10,260 ± 110</td>
</tr>
<tr>
<td>146–148</td>
<td>10,535 ± 95</td>
<td>115.1</td>
<td>10,300 ± 85</td>
<td>376</td>
<td>10,095 ± 105</td>
</tr>
<tr>
<td>325</td>
<td>10,730 ± 90</td>
<td>115.1</td>
<td>10,420 ± 130</td>
<td>406</td>
<td>10,600 ± 115</td>
</tr>
<tr>
<td>373</td>
<td>10,525 ± 85</td>
<td>115.2</td>
<td>10,400 ± 110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>490–493</td>
<td>10,860 ± 90</td>
<td>115.3</td>
<td>10,450 ± 110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>547–548</td>
<td>10,848 ± 90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>650–653</td>
<td>10,925 ± 75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note.* For detailed discussions on 14C dates, see Jiang and Nordberg (1996), Conradsen and Heier-Nielsen (1995), Knudsen et al. (1996), and Jiang and Klingberg (1996). A standard reservoir correction of 400 yr has been subtracted from the 14C dates.
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In contrast to the southern Kattegat and the Swedish west coast, marine species dominate the diatom assemblages in the Skagen 3 core (Jiang et al., 1997). Freshwater diatoms comprise less than 10% of the assemblage (Fig. 3). This fact, combined with relatively low sediment accumulation rates, suggests that the meltwater influence from the Baltic Ice Lake was small along the northern coast of Denmark during the Younger Dryas. Stabell (1985) shows that the Younger Dryas diatom assemblage from core GIK 15530-4 at the southern flank of the Norwegian Channel is characterized mainly by marine polar planktonic species; few freshwater diatoms were found. She suggests that the freshwater was probably forced north and westward along the Norwegian coast and would therefore not have affected the conditions at the core site.

Another marked characteristic of the Younger Dryas assemblage in cores 9303 and 06B-042 is relatively high numbers of marine planktonic diatoms in an assemblage dominated by freshwater species. The numbers of brackish diatoms are the lowest or slightly higher than marine diatoms with almost no changes during this period in the above two cores. If there had been a uniform water column with low salinity, the diatom assemblage in such an environment would have mainly been composed of freshwater species with some brackish diatoms, and few marine planktonic diatoms would have been found. With increasing salinity, the numbers of brackish diatoms would have become higher. Marine planktonic diatoms would not increase until the salinity became high enough, e.g., close to that in a normal saline environment. The cooccurrence of freshwater and marine planktonic diatoms with only a few transitional brackish diatoms suggests the existence of two water masses with different characteristics. This is supported by foraminiferal data, which show that benthonic foraminiferal fauna during this period were dominated by marine–brackish species in the southern Kattegat (Bergsten and Nordberg, 1992) and marine species along the Swedish west coast (Bergsten, 1994).

INFLUENCE OF MELTWATER FROM THE BALTIC ICE LAKE

Our data demonstrate that meltwater discharged from the Baltic Ice Lake during the Younger Dryas strongly influenced the southern Kattegat and the areas where the Baltic Current and currents along the Swedish west coast flow today, and may even have affected the Norwegian coast in the Skagerrak. However, meltwater discharge had little impact on large areas of the Skagerrak where the North Jutland Current now flows and on the southern flank of the Norwegian Channel.
The influence of meltwater discharged from the Baltic Ice Lake on the Kattegat during the Younger Dryas is obvious. First, meltwater discharge greatly freshened the Kattegat and areas along the Swedish west coast, and possibly the Norwegian coast, and sea-surface salinity in these areas was much lower than that of today. It resulted in a diatom assemblage dominated by freshwater species, which is totally different from those in surface sediments having marine or marine–brackish species as main components of the assemblages (Jiang, 1996; Jiang and Nordberg, 1996).

Second, the steepest surface salinity gradient in the Skagerrak–Kattegat today is in the Kattegat where the surface water salinity decreases north to south from ca. 30 to ca. 15‰ (Fält, 1982). Diatom assemblages in the surface sediments respond to this salinity gradient by an increase in numbers of brackish and freshwater diatoms and a decrease of marine planktonic diatoms from north to south (Jiang, 1996). Comparison of the Younger Dryas diatom assemblages from cores 9303, 06B-042, and Skagen 3 shows that the largest salinity gradient during most of the Younger Dryas interval was in an east–west or northwest–southeast direction across the boundary of the Skagerrak and the Kattegat. This interpretation is consistent with modern observations. Kuippers et al. (1992) suggested that the modern hydrographic conditions can be greatly modified by strong outflow of springtime meltwater from the Swedish west coast, and, therefore, can differ remarkably from the general current pattern. Figure 4 shows a regional sea-surface salinity gradient of nearly east–west direction because of the strong springtime meltwater flow. Since the meltwater discharge from the Baltic Ice Lake during the Younger Dryas was more or less constant and much stronger than springtime meltwater today, the east–west sea-surface salinity gradient during the Younger Dryas should have been steady and more pronounced than during springtime today.

Third, the strong meltwater discharge gave rise to a markedly stratified water column in salinity in the Kattegat. Co-occurrence of freshwater and marine planktonic diatoms with only a few brackish diatoms and cooccurrence of the diatom assemblages dominated by freshwater species and benthonic foraminiferal fauna with marine species as main elements, suggest that two water masses existed having different characteristics. A pronounced stratified water column is a likely interpretation for diatom assemblages like these.

A large difference in water density would give rise to a pronounced stratified water column. Sinking of highly dense water and the rise of low-density water would drive the currents and mix the layers. On the other hand, the lowering of surface water density, such as by a decrease in salinity and an increase in water temperature, would intensify the stratification. Cold marine water flowed into the Kattegat from the north during the Younger Dryas at the same time as large amounts of meltwater were discharged from the Baltic Ice Lake; this greatly freshened the surface water and resulted in a large density difference. Due to this circulation pattern, the stratified water column in the Kattegat was formed as does today, but the stratification must have been much more pronounced because the water discharged into the Kattegat from the Baltic Ice Lake was fresh and the water flowing into the Skagerrak–Kattegat was cold. When a climatic amelioration occurred ca. 10,600–10,500 14C yr B.P., with associated increased meltwater discharge and relatively higher surface-water temperature, the stratification was further intensified because a cold marine bottom environment still existed (Jiang and Klingberg, 1996). This pronounced stratification in salinity was limited to areas where meltwater flowed through. Stratification in the water column complicates the environmental interpretations based on the different methods used. The climatic warming based on diatom data was recorded about 500 14C yr earlier than that based on the benthonic foraminiferal data, as shown in Skagen 3 (Knudsen et al., 1996; Jiang et al., 1997). A combination of various methods with different ecological habitats would be needed in such an area.

Significant forcing by meltwater from the Baltic Ice Lake
over the larger area and on the regional climate during most of the Younger Dryas is questionable. It seems unlikely that meltwater from the Baltic Ice Lake was sufficient to damp ocean circulation during the Younger Dryas, for it had little impact on the northern coast of Denmark and was restricted along the Norwegian coast where meltwater flowed into the Norwegian Sea (Stabell, 1985). Reconstruction of the oxygen isotopic composition ($\delta^{18}O$) of planktonic foraminifera from the North Atlantic during the Younger Dryas event indicates that there is no evidence of major continental meltwater injection during the Younger Dryas (Duplessy et al., 1996). The westernmost cores do not exhibit lower $\delta^{18}O$ values that would reflect strong meltwater flux from the St. Lawrence, whereas the easternmost cores in the Norwegian Sea do not reflect any significant injection of meltwater from either the Baltic Ice Lake or the Barents ice shelf.

Meltwater from the Baltic Ice Lake had a strong impact on the southern Kattegat during the late Allerød (Jiang and Nordberg, 1996). It seems also to have influenced the northern coast of Denmark, because the samples from just below the Younger Dryas sediments in the Skagen 3 core contain mainly freshwater species, although diatom concentrations are low (H. Jiang, unpublished data). This may be explained by a sudden drainage of the Baltic Ice Lake (Björck and Digerfeldt, 1984) when the Scandinavian Ice Sheet receded from the water-divide at Mt. Billingen in south-central Sweden, 200 km northeast of the Skagen 3 core. Such a short meltwater peak would have produced a much stronger meltwater signal than would continuous meltwater flux during the Younger Dryas. Meltwater could have been discharged into the Norwegian Sea, and may even have been strong enough to reach the North Atlantic. It could have played a part in suppressing the oceanic circulation and may have contributed to an interval of extreme oceanic cooling, such as the Younger Dryas cold event (Björck et al., 1996).

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