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Reflection of continental ice sheets in late Quaternary sediments from the Nordic Seas

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With 4 figures and 1 table in the text

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Abstract: Late Pleistocene climatic and paleoceanographic changes in the Norwegian-Greenland Sea are reflected in eleven long sediment cores by variations in calcium carbonate content and calcareous biogenic components versus coarse terrigenous ice-rafted detritus (IRD). High contents of IRD in glacial sequences are evidence for an enhanced melting of sea ice and icebergs. In contrast, high calcium carbonate contents indicate the inflow of warm Atlantic surface waters.

The petrographic IRD composition in cores from the eastern and central Norwegian-Greenland Sea shows that the terrigenous material was predominantly derived from Scandinavia. Thus, it can be concluded that changes in the terrigenous input were caused by oscillations of the Late Pleistocene Scandinavian ice sheet. Changes in the extension of this ice sheet during the last 130 ky correlate well with our IRD data.

Zusammenfassung: An elf Sedimentkernen aus dem Europäischen Nordmeer wurden Abfolgen von Terrigen- und Karbonat-"Ereignissen" beobachtet, die weitgehend den Glazial- und Interglazialzyklen entsprechen und mit Änderungen in der Paläo-Ozeanographie und dem Paläoklima korreliert werden können. Hohe Gehalte an grobem terrigenem Material in glazialen Sedimenten des Europäischen Nordmeeres spiegeln das vermehrte Abschmelzen von Meer- und Gletschereismassen wider. Dagegen deuten hohe Karbonatanteile auf den Einstrom von warmen atlantischen Oberflächenwassermassen hin.

Die petrographische Zusammensetzung des IRD in Kernen aus dem östlichen und zentralen Europäischen Nordmeer zeigt, daß der überwiegende Anteil des terrigenen Materials von Skandinavien angeliefert wurde. Daher muß angenommen werden, daß Änderungen im Terrigeneintrag durch Oszillationen des skandinavischen Eisschildes hervorgerufen wurden. Änderungen

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in der Ausdehnung des skandinavischen Eisschildes während der letzten 130.000 Jahre lassen sich außerordentlich gut mit den hier vorgestellten IRD-Daten korrelieren.

Introduction

The growth and decay of the Quaternary ice sheets are some of the most striking features of the earth's climate. During deglaciations the Northern Hemisphere was transformed from cool to warm temperatures, and the large ice sheets in North America and especially in northern Europe disappeared. The waxing and waning of the Scandinavian ice sheet during the last interglacial/glacial cycle is documented in only few onshore locations (e. g. ANDERSEN & MANGERUD 1989, MANGERUD 1991). The Norwegian-Greenland Sea is situated adjacent to these landmasses that were strongly covered by Late Cenozoic Northern Hemisphere ice sheets. Therefore, this region is a key area where Northern Hemisphere glacial advances and retreats were documented by the input of ice-rafted detritus (IRD) into the ocean.

Today, the Norwegian-Greenland Sea is characterized by strong latitudinal gradients in the sea-surface environment, but also by strong meridional gradients due to the warm Atlantic influence in the east and the cold polar East Greenland Current in the west. The eastern part of the study area is characterized by relatively warm (6-10 °C) and saline (35.1-35.3 ‰) North Atlantic water which penetrates across the Iceland-Scotland Ridge forming the Norwegian Current (HOPKINS 1988). This surface watermass is sufficiently cooled on its way north and must have played an important role in the transport of heat and moisture between atmosphere and ocean during growth and decay of Quaternary glaciation. The modern surface-current system in the western Norwegian-Greenland Sea is characterized by the East Greenland Current which carries cold (<0 °C), less saline (30-34 ‰) polar water southward along the East Greenland shelf (Fig. 1). Between the domains of the Polar and the Atlantic waters, the so-called Arctic Surface Water (0-4 °C, 34.6-34.9 ‰) forms as a mixture of both sources and is contained in two cyclonic gyres, the Jan Mayen Current and the East Iceland Current (HOPKINS 1988).

Deep-sea sediments have been used as recorders of climatic changes associated with Late Pleistocene climatic cycles for a long time now. Many paleoceanographic and paleoclimatic studies in the world oceans have provided well-documented changes in parameters such as the $CaCO_3$ content. In the Norwegian-Greenland Sea most of these investigations focused on the southeastern Norwegian Sea and the eastern Iceland Sea. Climatically induced paleoceanographic changes are documented by changes of sediment composition (KELLOGG 1975, 1976, HENRICH et al. 1989, KASSENS 1990), by sedimentological and micropaleontological investigations (GARD 1988, BAUMANN 1990, SPIELHAGEN 1991, BAUCH 1993), as well as by isotopic studies (KELLOGG et al. 1978, VOGELSANG 1990, WEINELT 1993).

In this paper, basic sedimentological proxy data, e. g. calcium carbonate and terrigenous particle contents of well-dated sediment cores are related to glacial/interglacial changes in the surface-water regime.

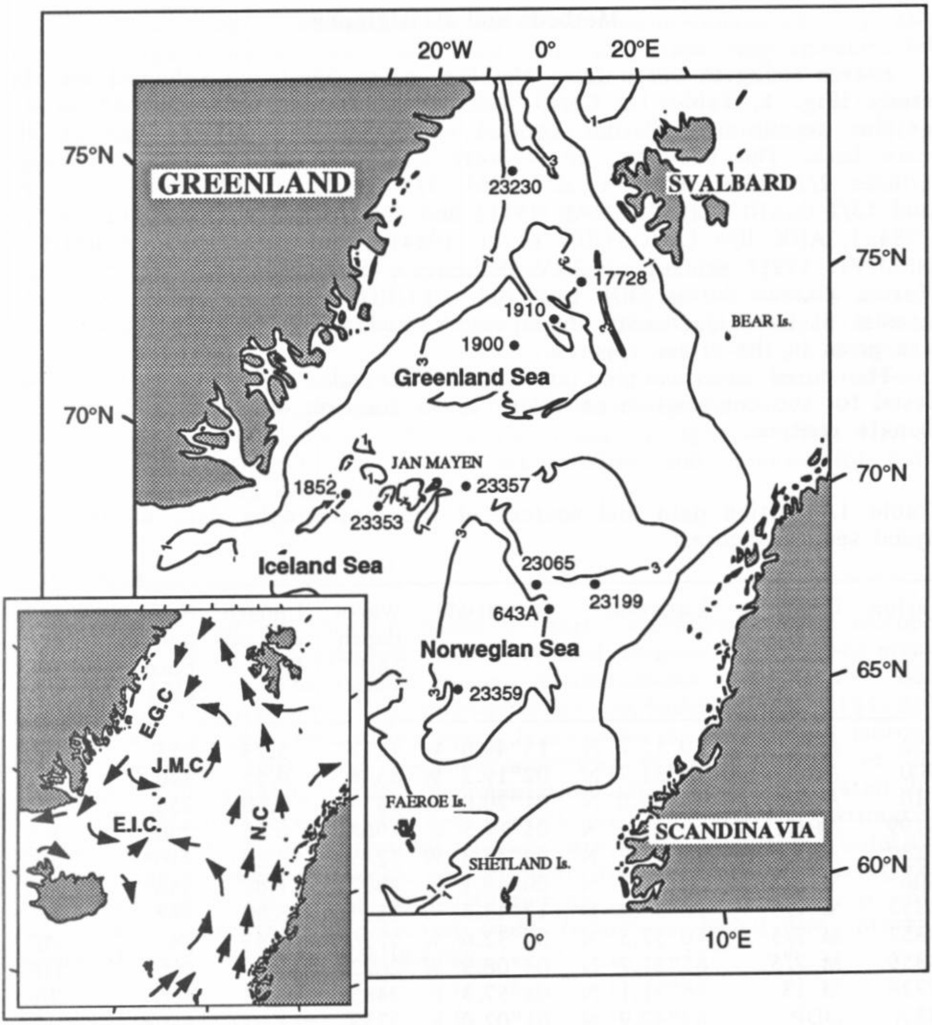

Fig. 1. Bathymetry (in km), surface-water circulation (small figure), and core locations in the Norwegian-Greenland Sea. E.G.C. - East Greenland Current, E.I.C. - East Iceland Current, J.M.C. - Jan Mayen Current, N.C. - Norwegian Current.

Down-core variations in calcium carbonate content were used as indicators for variations in biologic productivity which are strongly related to environmental conditions such as water temperatures, nutrients and degree of ice coverage. The marine records of coarse terrigenous material give evidence for several Late Quaternary pulses of increased input of ice-rafted detritus. The terrestrial record of glacier fluctuations on Scandinavia will be linked with marine sediment records from the Norwegian-Greenland Sea.

Methods and stratigraphy

Eleven sediment cores from the Norwegian Sea were selected for this study (Fig. 1, Table 1). Cores were chosen which have a good stratigraphic resolution and time control and reach a sufficient age at the core base. The sediment cores were collected during the RV Meteor cruises 2/2 (GERLACH et al. 1986), 7/5 (HIRSCHLEBER et al. 1988), and 13/2 (GERLACH & GRAF 1991) and the ARK I/3 (AUGSTEIN et al. 1984a), ARK II/4 (AUGSTEIN et al. 1984b), and ARK VII/1 (THIEDE & HEMPEL 1991) cruises of PRV Polarstern. Site 643 was drilled on the Vøring Plateau during ODP Leg 104 (ELDHOLM et al. 1987). All cores consist of Late Quaternary hemipelagic muds. Detailed core descriptions are given in the cruise reports.

The cores were sampled at <10 cm intervals. The samples were analysed for the composition of their coarse fraction and their calcium carbonate content.

Table 1. Position data and sources of the stratigraphy data of the analysed sediment cores.

Station	Cruise	Latitude	Longitude	Water depth (m)	Length of core (m)	Estimated age of core base (ka)	$\delta^{18}O$-stratigraphy
1852	ARK VII/1	70°15.7' N	15°49.8' W	1117	5.73	275	BA
1900	ARK VII/1	74°31.7' N	02°19.7' W	3546	4.55	340	BA
1910	ARK VII/1	75°37.0' N	01°20.0' E	2454	6.60	355	SCH
23199	ARK I/3	68°22.6' N	05°19.5' E	1968	6.36	250	RA
23230	ARK II/4	78°51.2' N	04°46.8' W	1235	*3.20	310*	SP
23065	M 2/2	68°29.7' N	00°49.1' E	2802	7.85	368	VO
23353	M 7/5	70°34.2' N	12°43.3' W	1394	8.90	362	JÜ
23357	M 7/5	70°57.3' N	05°32.6' W	1736	4.85	345	HE
23359	M 7/5	65°31.7' N	04°08.9' W	2822	5.99	410	HE
17728	M 13	76°31.1' N	03°57.3' E	2485	6.23	470	WE
643 A	ODP Leg 104	67°42.9' N	01°02.0' E	2753	*13.93	440*	WO

* Length/age of isotopically dated section.

BA = BAUMANN et al. (1993)
HE = HENRICH et al. (in prep.)
JÜ = JÜNGER (1991)
RA = RAMM (1989)
SCH = SCHACHT (1990)
SP = SPIELHAGEN (1991)
VO = VOGELSANG (1990)
WE = WEINELT (1993)
WO = WOLF (1991)

Methods

A LECO CS-125 infrared analyser was used for the bulk calcium carbonate measurements. Both total carbon (TC) and total organic carbon

(TOC) contents were determined by infrared measurements of CO_2 absorption. Organic carbon was calculated from CO_2 that was released by treatment with hydrochloric acid. Assuming that the inorganic carbon is exclusively bound as calcium carbonate ($CaCO_3$), the calcium carbonate content was calculated in weight percentages of the bulk sample by the equation

$$CaCO_3\ \% = (TC\ \% - TOC\ \%) * 8.33$$

where 8.33 is the stoichiometric calculation factor for $CaCO_3$.

For coarse-fraction analyses, the sediment samples were freeze-dried, weighed and washed through a 63 µm mesh. The coarse fraction was split into 63-125 µm, 125-250 µm, 250-500 µm, and >500 µm subfractions. The particle association of the 125-500 µm fractions was analysed, because its variable composition seems to be most representative to characterize pelagic sedimentation (foraminifers) and terrigenous input (IRD). A split (>500 grains) of this fraction was studied and counted for biogenic and terrigenous components.

Stratigraphy

Time control of all cores is based on high resolution oxygen isotope stratigraphy, which was adopted from published sources for all sediment cores (see Table 1). The oxygen isotope measurements were carried out on the planktic foraminifer *Neogloboquadrina pachyderma* sin. (125-250 µm fraction). Isotopic events and stage boundaries in the oxygen isotope records and their ages were assigned according to MARTINSON et al. (1987) and VOGELSANG (1990). Sedimentation rates were calculated by linear interpolation between the age control points. Thus, the estimates for the timing of paleoceanographic changes are limited by the resolution between assigned isotopic events. In particular, the duration of short-term paleoceanographic events may be calculated as too long. However, it will always be reliable that a detected event happened during the interval calculated from the given stratigraphy.

Results

Calcium carbonate records

Major down-core variations in the distribution of the calcium carbonate content reflect strong changes in the general circulation pattern of surface watermasses (Fig. 2). Abrupt changes in the $CaCO_3$ content are recorded especially during all glacial/interglacial transitions. Highest $CaCO_3$ contents were generally measured in interglacial sediments from oxygen isotope stage 5 (128-71 ka), and the Holocene. Peak values are different from core to core and range from 70 wt.-% in Holocene sediments from the southernmost core 23359 to less than 10 wt.-% in the Holocene from the two westernmost cores 23230 and 1852 (Fig. 2). In most cores, $CaCO_3$ contents in stage 5 sediments are in a similar range as in the Holocene. High carbonate values (>30 wt.-%) in interglacial

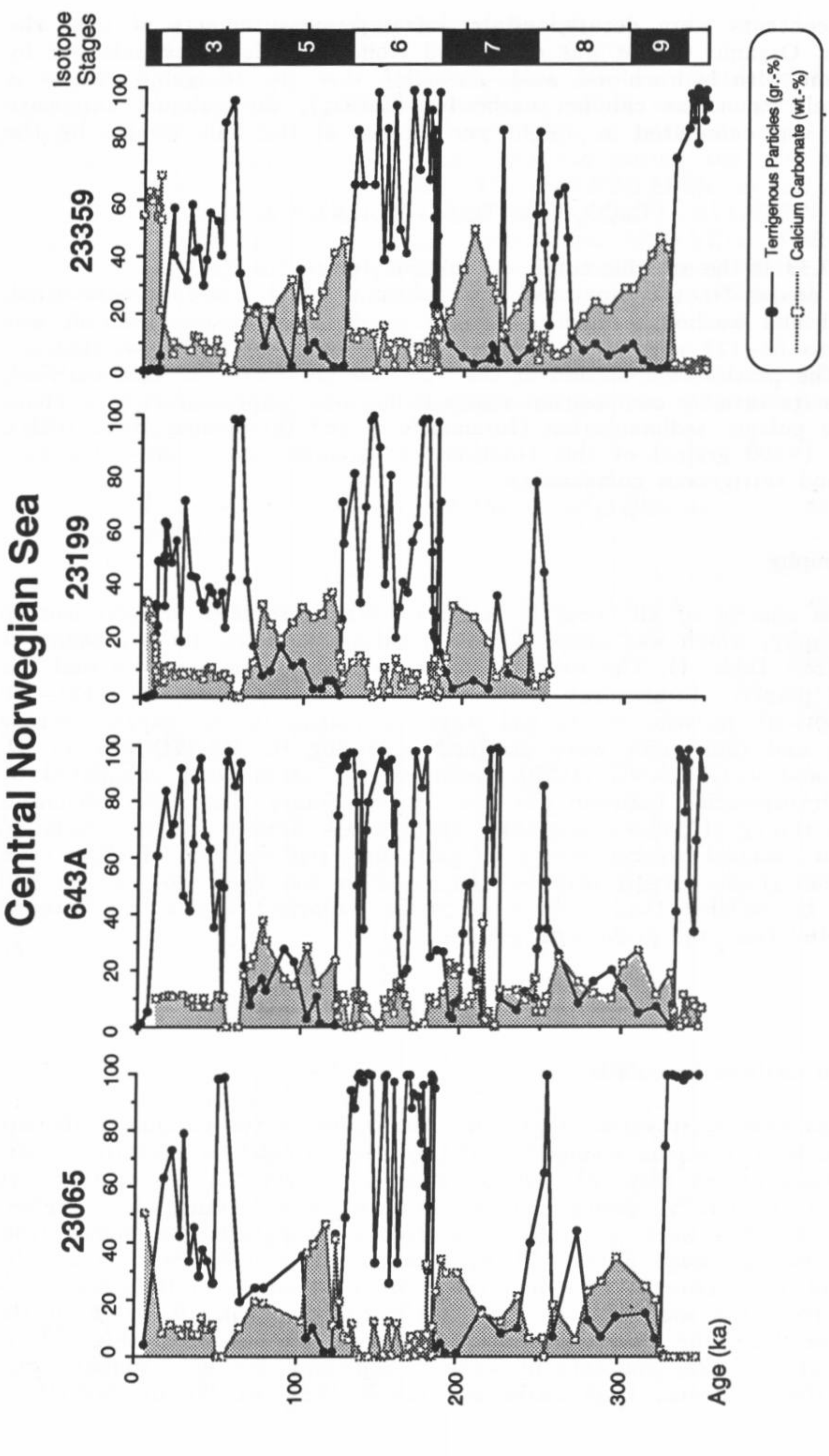

Fig. 2a. Amount of terrigenous particles (grain-%) and calcium carbonate content (weight-%) in analysed cores from the Norwegian Sea.

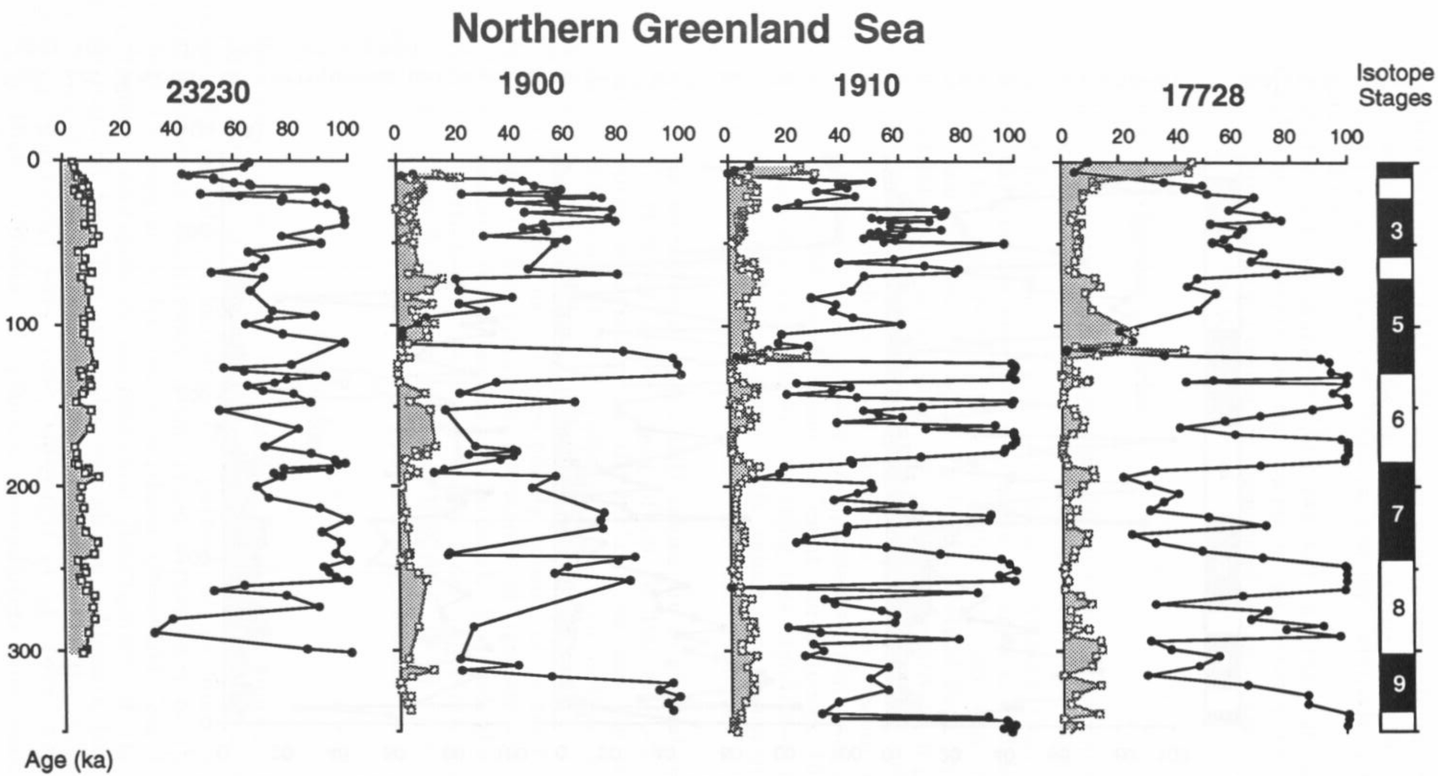

Fig. 2b. Amount of terrigenous particles (grain-%) and calcium carbonate content (weight-%) in analysed cores from the northern Greenland Sea. For legend see Fig. 2a.

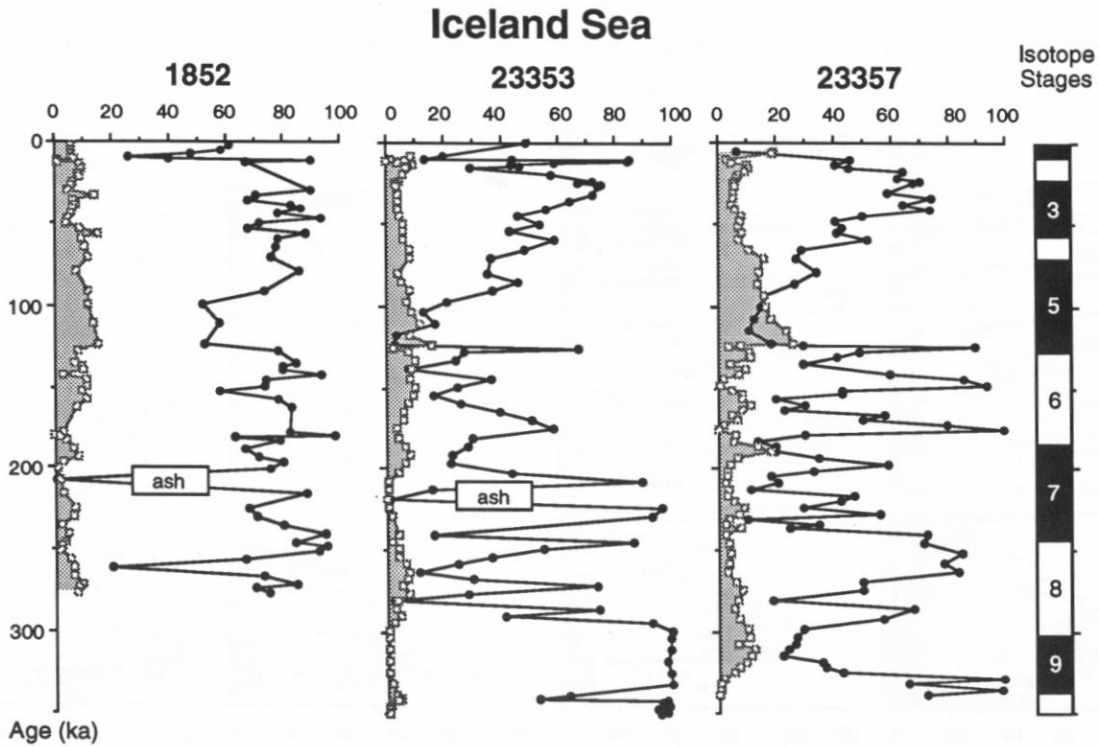

Fig. 2c. Amount of terrigenous particles (grain-%) and calcium carbonate content (weight-%) in analysed cores from the Iceland Sea. For legend see Fig. 2a.

stages 9 (339-303 ka) and 7 (245-186 ka) were observed only in sediment cores from the central Norwegian Sea. In contrast, cores from the Iceland Plateau and the Greenland Sea are characterized by relatively low carbonate contents (<20 wt.-%).

In glacial sediments from stages 8 (303-245 ka), 6 (186-128 ka), and 4-2 (71-14 ka), $CaCO_3$ contents are the lowest in all cores (<15 wt.-%). Carbonate-free sediments are present in sequences from stage 6 (186-145 ka) and earliest stage 3 (60-55 ka).

Records of coarse terrigenous particles

High amounts of coarse terrigenous particles (40-100 grain-% IRD) are present in sediments from late oxygen isotope stage 10 (>330 ka), 6 (186-128 ka), and from stages 2-3 (60-14 ka). Sediments from glacial stage 8 (303-245 ka) contain only one IRD spike at approx. 250 ka. This pattern is typical for the Norwegian Sea sediments and less distinct towards the north and the west (Figs. 2, 4). In the Iceland Sea, deposition of IRD was relatively low during stage 6, whereas relatively high IRD contents were observed in Iceland and northern Greenland Sea sediments older than about 250 ka. High-amplitude variations in the amount of IRD (0-100 grain-%) are recorded especially in sediments from the eastern Norwegian Sea, whereas the westernmost sediment cores (cores 1852 and 23230) reveal less expressed amplitudes, indicating less significant glacial/interglacial changes. In these sediments, IRD values are generally high (>50 grain-%), but extremely high contents (90-100 grain-%) are rare (Fig. 2).

In sediments from interglacial stages IRD values are in general relatively low (<50 grain-%). However, single peaks of up to 100 grain-% can be identified in some cores, especially from the Iceland Sea and the northern Greenland Sea, in sediments which correspond to oxygen isotope stages 9 (339-303 ka) and 7 (245-186 ka).

In all cores, the terrigenous particles mainly consist of monocrystalline grains (quartz, feldspar), polycrystalline fragments of igneous rocks, and fragments of sedimentary rocks (shales, sandstones). Most of the mono- and polycrystalline particles in sediment cores from the Norwegian Sea probably originate from Scandinavia (see also BISCHOF 1990). The amount of detrital carbonate rock fragments is generally neglectable.

Discussion

The down-core variations in the calcium carbonate content reflect strong climate-induced changes in the inflow of warm Atlantic surface watermasses and in paleoproductivity. The pattern of calcium carbonate minima and maxima is synchronous in the cores within each of the three distinct areas (Norwegian - Iceland - northern Greenland Sea; Fig. 3), indicating regional contrasts in environmental development of the whole Norwegian-Greenland Sea. The variability of calcium carbonate has proved to be useful to differentiate the surface watermasses in the Norwegian-Greenland Sea (KELLOGG 1975, 1976, HENRICH et al. 1989, BAUMANN et al. 1993). High contents of planktic foraminifers and coccolitho-

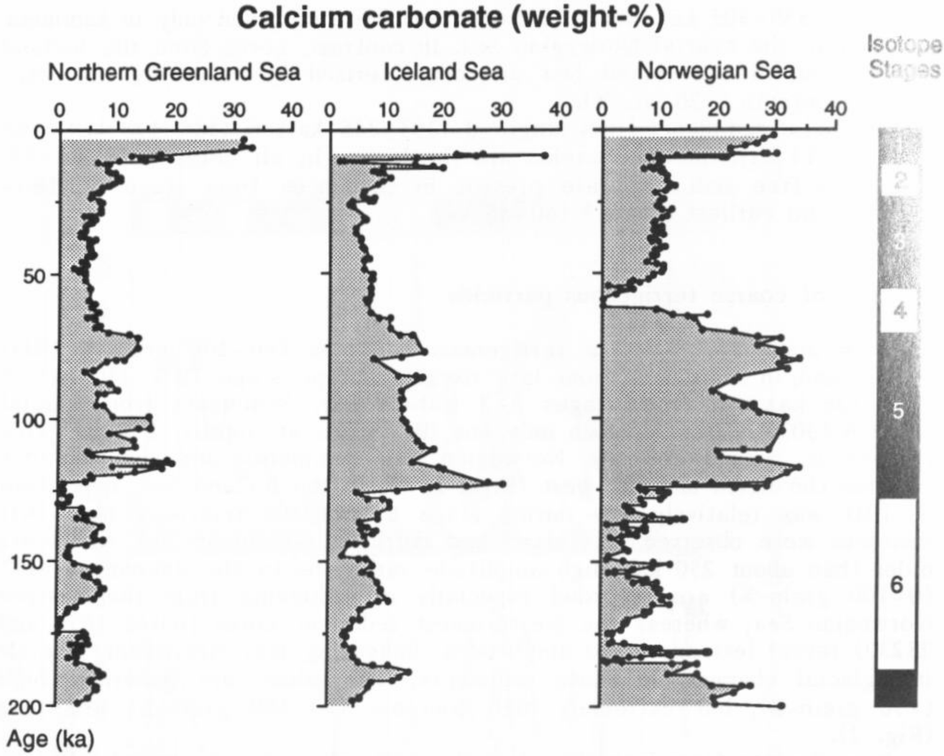

Fig. 3. Stacked and 3-point average smoothed records of calcium carbonate content (weight-%) in cores from the northern Greenland (23230, 1900, 1910, 17728), Norwegian (23065, 643 A, 23199, 23359), and Iceland Sea (1852, 23353, 23357).

phorids are found in plankton samples from the Atlantic water masses, especially from the Norwegian Current, indicating high calcium carbonate shell production (SAMTLEBEN & SCHRÖDER 1992). In contrast, low production of $CaCO_3$ and relatively high calcium carbonate dissolution can be related to the polar surface water masses (HEBBELN & WEFER 1991, SAMTLEBEN & SCHRÖDER 1992). Furthermore, a perennial ice cover strongly restricts the productivity of planktic calcareous biota (HEBBELN & WEFER 1991). Thus, the low calcium carbonate contents in sediments of oxygen isotope stages 6, 4, 3 and 2 are due to the low calcium carbonate production in cold, often ice-covered surface water masses. Especially around 175 ka, 145-140 ka, 130-125 ka, and in the Norwegian Sea from 60-55 ka, production must have been reduced to a minimum as indicated by almost carbonate-free intervals (Figs. 2, 3). However, this may also be caused by increasing dilution of terrigenous material or by carbonate dissolution.

Highest carbonate values (>30 wt.-%) in all interglacial stages were observed only in sediments from the central Norwegian Sea. In the Iceland and Greenland Sea high carbonate contents were restricted to sediments of substage 5e and the Holocene (Figs. 2, 3). Thus, the interglacial environments were strongly variable throughout the last 350 ky. A strong Norwegian Current influencing the whole Norwegian-Greenland Sea area is limited to stage 5e and to the Holocene, while during isotope stages 9, 7, and the upper stage 5 a considerably weaker influx of Atlantic surface water is detected. However, a still existing influence of Atlantic water in the Greenland and Iceland Sea is documented by slight increases in carbonate and decreasing IRD values during these time intervals. Micropaleontological investigations also suggest a similar development of the Norwegian current (GARD 1988, BAUMANN 1990, BAUCH 1993).

Previous studies of marine sediments from high latitudes have shown that coarse terrigenous particles (>63 µm) can be interpreted as ice-rafted material (e. g. RUDDIMAN 1977, HEINRICH 1988, BISCHOF 1990, SPIELHAGEN 1991, GROUSSET et al. 1993), if other transport mechanisms (e. g. gravity flows, boundary currents) can be widely excluded. High amounts of coarse lithogenic material in our cores indicate that deposition from ice-rafting was the dominant sedimentation process in the Norwegian Sea during various intervals in the Late Quaternary. In turn, these high values imply a dense ice cover with little seasonal variations during those intervals. Because sea-ice sediments are mostly fine-grained and contain little or no terrigenous grains >63 µm (e. g. PFIRMAN et al. 1990), icebergs from land and fjord glaciers are proposed as the transport agents for the bulk of the sand-sized terrigenous material (MOLNIA 1972, CLARK & HANSON 1983, BISCHOF 1990). These icebergs discharged their sediment load in the deep ocean by melting and overturning.

Extensive IRD deposition occurred during glacials and deglaciations. From our results, highest numbers of icebergs can be inferred for the time intervals >310 ka, 260-240 ka, 185-125 ka and 60-10 ka (Fig. 4). Relative amounts of coarse terrigenous particles at all sites reached peak values during these intervals. However, somewhat more favourable conditions can be inferred in the Norwegian Sea for the interval 260-240 ka, where a lower amount of terrigenous particles suggests a less dense ice cover and sometimes (seasonally?) open waters. In the Greenland and Iceland Seas, IRD deposition was lower at about 180-125 ka, most probably due to a relative high "stability" of the Greenland Ice Sheet and little ice melting. This is also documented by higher IRD accumulation rates in the SE Norwegian Sea and decreasing values towards the west and the north (HENRICH et al. 1989, BAUMANN et al. 1993).

Investigations of the composition of the coarse terrigenous matter indicate that most of this debris was derived from Scandinavia (see also BISCHOF 1990). Therefore, variations in the terrigenous particle input must be the result of oscillations of the Scandinavian and the Svalbard/Barents Sea Ice Sheets. In general, the models of the ice sheet variations during the last 130 ky (MANGERUD 1991, MANGERUD & SVENDSEN 1992) correlate well with our marine data set (Fig. 4). However, there are significant offsets between peaks in the IRD records and the glacier advances and retreats. The main reason for this offset is probably that Lower and Middle Weichselian deposits have been clearly identified at only a very few onshore sites and have been dated with high uncertainties (ANDERSEN & MANGERUD 1989, MANGERUD & SVENDSEN 1992). In general, the stratigraphy of the last interglacial/glacial cycle in Scandinavia is mainly based on the correlation of the Eemian with

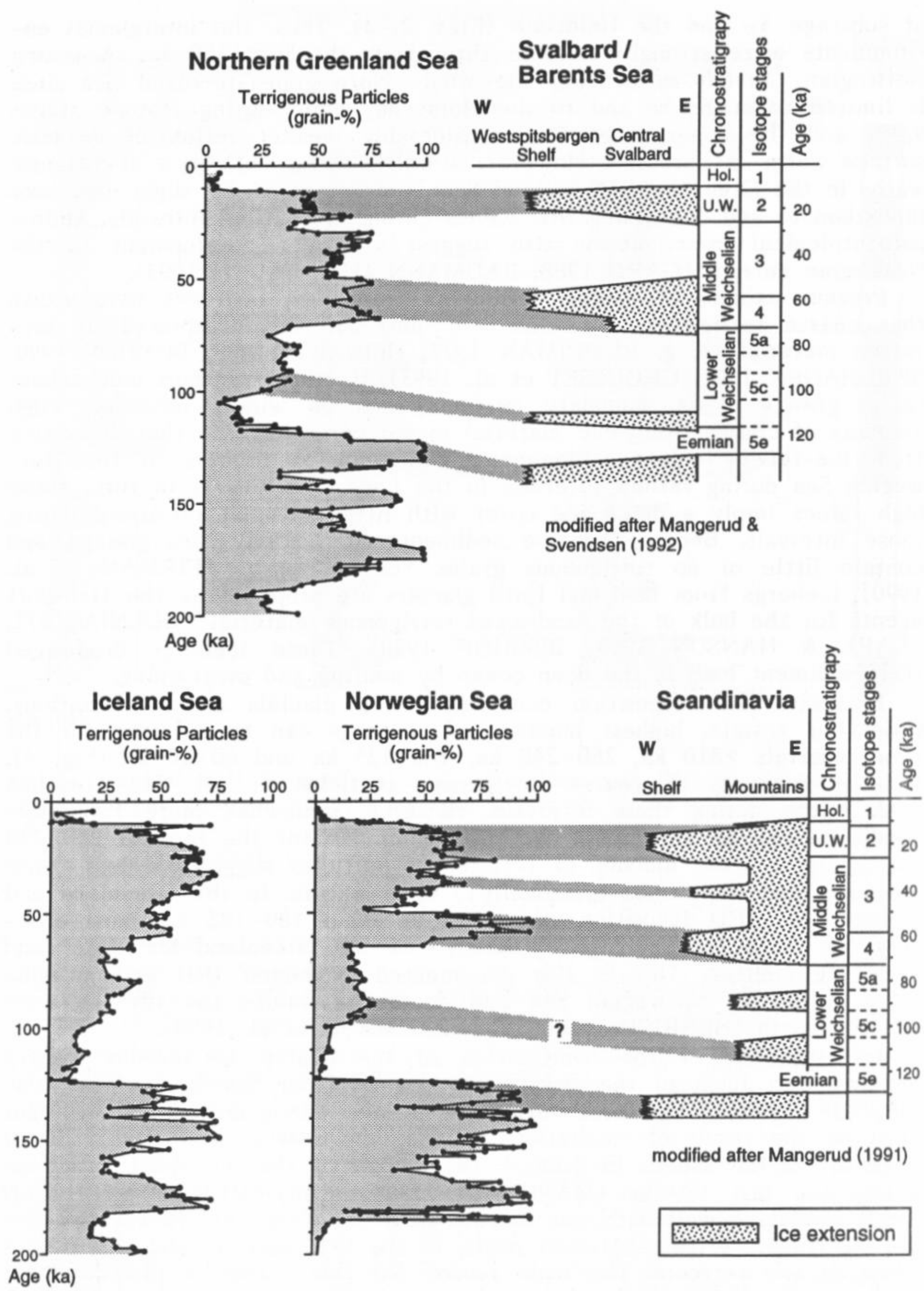

Fig. 4. Stacked and 3-point average smoothed records of terrigenous detritus (grain-%) in cores from the northern Greenland (23230, 1900, 1910, 17728), Norwegian (23065, 643A, 23199, 23359), and Iceland Sea (1852, 23353, 23357). Proposed correlation to ice extension of Svalbard/Barents Sea and Scandinavian ice sheet is indicated. For explanation of the stratigraphic offset see discussion in the text.

marine substage 5e (MANGERUD 1989). Thus, the Weichselian started around the substage 5e/5d boundary (117 ka). The Middle Weichselian deposits were correlated to marine stages 3 and 4, while the Weichselian glacial maximum roughly corresponds to isotope stage 2 (MANGERUD 1989). In addition to the terrestrial record, the limited resolution between stratigraphical fixpoints in the marine record does not allow to determine the exact duration of deglacial events with sufficient accuracy. Thus, the timing of glacial terminations (e. g. at the stage 6/5 boundary) contains uncertainties also in the marine record. Nevertheless, there is a fairly good general agreement between the terrestrial and marine data sets, which shows that it is possible to reconstruct the history of continental ice sheets from marine data sets.

Conclusions

The different records permit the following conclusions:

- Coarse sediment deposition is primarily related to glacial intervals. Maxima in the input of ice-rafted lithic fragments were observed especially at the end of glaciations close to the terminations, indicating massive melting of icebergs in the western Norwegian-Greenland Sea.
- The high input events of ice-rafted detritus were followed by an increase in calcium carbonate production caused by maximum intrusion of temperate Atlantic surface waters. Changes in calcium carbonate contents indicate a variable contribution of Atlantic surface water to the Greenland and Iceland Seas.
- The inflow of temperate Atlantic surface water was strongest in the Norwegian Sea, as reflected by highest $CaCO_3$ values in cores from this area. $CaCO_3$ decreases towards the north and the west and indicates a weakening of the warm current. Low but constant values in the westernmost cores document a relatively stable environment, which was weakly influenced by relatively warm surface water masses during the last 350 ka.
- A strong intruding Norwegian Current is limited to stage 5e and to the Holocene, while during isotope stages 9, 7, and the upper stage 5 a considerably weaker influx of Atlantic surface water is detected.
- There is a fairly good comparison of the terrestrial and marine data sets, indicating that variations in the terrigenous particle input are the result of oscillations of the Scandinavian and the Svalbard/Barents Sea Ice Sheets.

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