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LATE QUATERNARY CHANGES IN SEDIMENT COMPOSITION IN THE CENTRAL ARCTIC OCEAN: FIRST RESULTS OF THE ARCTIC ´91 EXPEDITION

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ABSTRACT

First results of detailed sedimentological investigations of Late Quaternary ARCTIC ´91 sediments indicate that distinct changes in depositional environment occurred through space and time. Sedimentation processes in the major Arctic Ocean basins are mainly controlled by turbidity currents resulting in significant enrichment of organic carbon. On other hand, variations of biogenic and siliciclastic sediment components on the ridges and plateaus probably reflect glacial/interglacial variations in surface-water productivity, sea-ice cover, and/or oceanic circulation patterns. The decrease in abundance of biogenic calcareous and siliceous components during stage 2 suggests decreased glacial productivity because of more closed sea-ice cover, whereas during Holocene times productivity increased. In general, increased organic carbon contents are mainly caused by increased supply of terrigenous organic matter. Marine organic matter is only preserved in very minor amounts throughout the sedimentary sequences, reflecting the low-productivity environment of the central Arctic Ocean to be common through late Quaternary times.

INTRODUCTION

The Arctic Ocean and its marginal seas are key areas for understanding the global climate system and its change through time (for overviews see ARCSS Workshop Steering Committee, 1990; NAD Science Committee, 1992; and further references therein). In order to study this climatic history, the very successful international and multidisciplinary ARCTIC ´91 Expedition was carried out into the eastern central Arctic Ocean (Fig. 1; Anderson and Carlsson, 1991; Fütterer, 1992). Main goal of the ARCTIC ´91 marine geology programme is the reconstruction of the long-term as well as short-term glacial/interglacial changes in lithogenic, biogenic, and organogenic sediment supply in relation to changes in global climate, paleoceanic circulation, sea-ice cover, and paleoproductivity.

Methodology of shipboard and shorebased studies

To reach these objectives, a comprehensive geological sampling programme was performed at 60 stations and unique undisturbed surface-near samples and long sediment cores were obtained from major basins, ridges, and plateaus of the eastern Arctic Ocean (Fig. 1). Most of the sediment cores were already opened, described, and sampled onboard RV *Polarstern*. Furthermore, first microscopic investigations of smear slides and coarse fractions and deteminations of physical properties (water content, porosity, wet bulk density, and acoustic compressional wave velocity), magnetic susceptibility, and calcareous nannofossil abundances were also already performed during the cruise and allow a first - still preliminary - description of the depositional environment and its change through time and space. Details of these results obtained by the Shipboard Scientific Party during the ARCTIC ´91 Expedition are described in Fütterer (1992).

For our high-resolution study on stable isotope composition, organic geochemistry, and bulk and clay mineralogy of Arctic Ocean sediments, multicorer cores and kastenlot cores were sampled in detail. Here, we present first interpretations based on shipboard core description, smear slide, and coarse fraction data, and shorebased measurements of carbonate and total organic carbon. Total carbon and organic carbon contents were measured on ground bulk samples and HCl-treated carbonate-free samples, respectively, using a HERAEUS CHN analyser. Carbonate contents were calculated as (total carbon - total organic carbon) * 8.333. To get a first information about the composition of the organic matter, hydrogen index (HI) values have been determined: High HI values of 200 to 800 mg hydrocarbon / g organic carbon (mgHC/gC) suggest marine organic matter whereas HI values of < 100 (mgHC/gC) indicate a terrigenous source of the organic matter (Tissot and Welte, 1984). Further results including stable isotope and clay mineral data as well as more detailed description of methods will be published in more comprehensive papers elsewhere (Stein et al., 1993a, 1993b; Wahsner et al., 1993).

RESULTS

In Figs. 2 to 4, first results of the investigation of ARCTIC ´91 sediments from the Barents Sea - Nansen Basin - Gakkel Ridge - Amundsen Basin - Lomonosov Ridge - Makarov Basin profile and the Morris Jesup Rise - Amundsen Basin - Gakkel Ridge - Nansen Basin - Yermak Plateau profile (Fig. 1, A-B and C-D) are presented.

Shipboard core description, smear slide, and coarse fraction data

Prominant changes in composition, texture, and grain size occur in the Quaternary sediment sequences from different locations. In general, sediments from the basin cores are characterized by fine-grained siliciclastic components with fining-upwards sequences, silt/clay alternations, and occasional cross-bedding, whereas sediments from the ridges and plateaus display distinct (cyclic) changes in color, grain size, and sediment composition (cf., Fütterer, 1992).

At almost all locations (i.e., in the basins as well as on the ridges), the upper 40 cm of the sedimentary sequences can clearly be divided into two very different lithologies (Fig. 3; Fütterer, 1992). The uppermost 5-15 cm thick (depending on the sedimentation rate) surface-near sediments are characterized by dark brown to brown clay with rare occurrence of nannofossils and a coarse fraction dominated by planktonic foraminifera. Benthic foraminifera and opal (sponge spicules) are present, however, only occur in minor amounts. In the sequences from shallower ridge and plateau positions, additionally shells, ostracodes, and echinoderms may occur. The underlain section consists of olive-gray to grayish-brown clay/silty clay; nannofossils are absent. In the coarse fraction, high amounts of quartz and rock fragments are typical, biogenic components such as planktonic foraminifera are of very minor importance. The siliciclastic particles are partly very coarse-grained (>> 1 mm). In the example shown in Fig. 3, these two units are underlain by a third unit which is similar to the uppermost one.

Carbonate and total organic carbon

In the surface sediments (Fig. 2), carbonate values are relatively low ranging from 0 to 17 %, with the higher values more typical for the ridges and the lower values more typical for the basins. At the Morris-Jesup-Rise, higher values of almost 30 % were measured. In sediment cores, maximum carbonate values are recorded in the uppermost part of the sequences corresponding to the Holocene, whereas the underlain grayish unit corresponding to glacial stage 2, has distinctly lower carbonate contents (Figs. 3 and 4; Stein et al., 1993b). Carbonate contents may again increase in isotope stage 3 (Fig. 3). At several cores, however, increased carbonate content is also obvious in stage 2 (such as, for example, in the Morris-Jesup-Rise area; Stein et al., 1993b).

At the long kastenlot cores from the Lomonosov Ridge as well as the Amundsen Basin, carbonate contents are generally less than 1% (Fig. 4). The very few intervals with some higher carbonate values may correspond to interglacial stages, as proven, for example, for the carbonate maxima in the uppermost interval and between about 200 and 230 cmbsf at Core PS2185-6. These carbonate peaks correlate with oxygen isotope stages 1 and 5, respectively, as indicated by stable isotope (Stein and Spielhagen, unpubl. data) and nannofossil (Gard, 1993) stratigraphies.

In general, total organic carbon (TOC) contents in surface sediments are higher in the basins (0.7 - 1.1 %) than on the ridges and plateaus (0.3 - 0.6 %) (Fig. 2). Maximum values of 1.2 to 1.9 % are reached at the Barents Sea Continental Margin and the Yermak Plateau. Hydrogen index values of < 100 mgHC/gC are dominant. Only in the Barents Sea Continental Margin area and in two samples from the deep Nansen Basin, HI values of 120 to 200 mgHC/gC were measured (Fig. 2; Stein et al., 1993a). At the multicorer cores, TOC increases from low values around 0.2 % occurring in the lower part to values of 0.5 to 0.7 % in the upper 5 to 10 cm (Fig.3; Stein et al., 1993b). This increase partly coincides with the carbonate increase and correlates with the Pleistocene/Holocene transition. In the example from the Gakkel Ridge, HI values are mainly < 100 mgHC/gC during oxygen isotope stage 1 and 3, whereas in stage 2 higher HI values of 150 to 200 mgHC/gC are typical (Fig. 3).

The two long-term records presented in Fig. 4 show distinct differences. Whereas the TOC record at Lomonosov Ridge Core PS2185-6 is characterized by very low values of dominantly 0.1 to 0.3 % (only the Holocene interval displays higher values of up to 0.6 %), high TOC values of 0.5 to 1.5 % are typical for the Amundsen Basin Core PS2176-3 (Fig. 4). The maximum values around 1.5 % are concentrated in the lower 4.5 m of the record. Average HI values are between 100 and 200 mgHC/gC (Fig. 4).

DISCUSSION AND CONCLUSIONS

Distinct changes in sedimentary facies of the ARCTIC 91 sediment sequences from different locations and different time intervals indicate that different mechanisms have controlled the sedimentation and that the relative importance of these mechanisms have changed through time.

Surface sediment characteristics and modern environment

Because of its sea-ice coverage, the modern central Arctic Ocean is a low-productivity environment (Subba Rao and Platt, 1984) resulting in a very low flux of marine organic matter to the ocean floor. Despite of this low carbon flux, total organic carbon contents of surface sediments reach values of more than 1 % (Fig. 2) which are values distinctly higher than those typical for the modern open-ocean environment (about 0.3 %). This as well as the increase of organic carbon with increasing water depth (Fig. 2) (a correlation which is just the opposite to that recorded in normal marine pelagic environments; e.g. Suess, 1980) already suggest that other mechanisms than high primary productivity must have caused this enrichment of organic matter. In this case, the relatively high organic carbon contents are caused by supply of terrigenous organic matter, as clearly indicated by low hydrogen index values (Fig. 2) and high carbon/nitrogen ratios (Stein et al., 1993a). Part of this terrigenous material is very probable derived from the Sibirian shelf areas and transported by sea ice via the Transpolar Drift, the dominant surface-current system in the eastern central Arctic Ocean (e.g., Pfirman et al., 1989; Bischof et al., 1990). In the central Nansen Basin, high TOC values partly coincide with high kaolinite values. The kaolinite is probably derived from the Barents Sea shelf area and/or Franz-Josef-Land and transported via turbidity currents into the deep basins (Stein et al., 1993a; Wahsner et al., 1993). In these turbidites, increased amounts of (marine and terrigenous) organic matter are preserved in the oxic deep-sea environment of the Nansen Basin. Since the organic matter in turbidites is rapidly buried after redeposition in the deep sea, the residence time in zones of bioturbation and oxic decomposition is short, resulting in elevated quantities of (more hydrogen-rich) organic matter in these sediments.

The very high TOC values close to the Barents Sea Continental Margin which coincide with increased hydrogen indices (Fig. 2) indicating increased preservation of marine organic matter, probably reflect some increased productivity controlled by the inflow of warm Atlantic waters (cf., Stein et al., 1993a).

Late Quaternary changes in depositional environment

In the late Quaternary sedimentary sequences from the Nansen Basin as well as the Amundsen Basin fine-grained siliciclastic components with fining-upwards sequences and silt/clay alternations commonly occur (Fütterer, 1992). These deposits are interpreted as (distal) turbidites dominating the sedimentation in the basins. In several cases, the Sibirian shelf areas are probably the source area of these sediments as suggested from shallow-water benthic foraminifera and bivalves. Some of the turbidites are characterized by distinctly increased terrigenous organic carbon contents as indicated by TOC values of 1.5 % and HI values around 100 mgHC/gC (Fig. 4).

On the other hand, the (hemi-) pelagic sediments from the ridges and plateaus are characterized by (cyclic) changes in color and sedimentary facies (Fütterer, 1992). These differences in biogenic and siliciclastic sediment composition suggest major paleoenvironmental (glacial/interglacial) changes in the Central Arctic Ocean during Quaternary times, such as changes in bioproductivity, sea-ice cover, and/or transport mechanisms of sediment particles. Common amounts of planktonic foraminifers as well as coccoliths (Gard, 1993) were recorded, for example, in surface-near sediments and between 200 and 230 cmbsf at Core PS2185-6, suggesting at least seasonally ice-free conditions and some increased carbonate productivity during interglacial stages 1 and 5 (Fig. 4). Very low organic carbon and biogenic carbonate contents recorded in the pelagic sedimentary sequence from the Lomonosov Ridge, however, indicate generally low bioproductivity throughout late Quaternary times.

Because of this very low carbonate content, it is still difficult to get a precise stratigraphic framwork from the Arctic Ocean sedimentary sequences, which is necessary for a detailed paleoenvironmental interpretation of the data. At the Lomonosov Ridge Core PS2185-6, the development of a stable isotope stratigraphy on planktonic foraminifer *N. pachyderma sin.* was possible for the upper 5 m probably representing oxygen isotope stages 1 to 7 (Stein and Spielhagen, unpubl.), whereas below 5 m the amounts of planktonic foraminifera are too low for isotope measurements. These dating problems are even more drastic in the almost carbonate-free basin cores (such as, for example, Core PS2176-3; Fig. 4).

Because of a more precise stratigraphic framwork of the uppermost about 40 cm of the sedimentary records, a more detailed (although also still preliminary) interpretation of the depositional history is possible. Based on AMS^{14}C dating and stable isotope and carbonate stratigraphy (Stein et al., 1993b) as well as nannofossil abundances (Gard, 1993), these records probably represent the latest Pleistocene and Holocene (i.e., mainly oxygen isotope stages 1 and 2). According to Figure 3, the glacial interval is characterized by low content of carbonate and organic carbon and low amounts of biogenic coarse fraction (i.e., planktonic and benthic foraminifera, ostracodes, and opal). The coarse fraction is dominated by quartz grains. Furthermore, calcareous nannofossils are absent in this interval (Gard, 1993). On the other hand, all major biogenic components (i.e., foraminifers, ostracodes, coccoliths, and opal) as well as carbonate and organic carbon contents distinctly increase towards the Holocene. The decrease in abundance of biogenic calcareous components and biogenic opal during stage 2 may indicate decreased glacial productivity because of an extented sea-ice cover, whereas during

Holocene times, productivity increased. Changes in carbonate dissolution as controlling factor for the changes in carbonate content can be neglected as shown by carbonate dissolution studies on planktonic foraminifera from the Nansen Basin and Gakkel Ridge areas across the glacial/interglacial transition (Pagels, 1991). Increased Holocene productivity is also suggested from the ARCTIC ´91 ostracode assemblages (Cronin et al., 1993). During oxygen isotope stage 3, the situation was probably more similar to that of Holocene times.

Although the increase in biogenic components towards the Holocene is paralled by an increase in organic carbon, the latter is probably not a productivity signal, as indicated by the decreased hydrogen index values. That means, major proportions of the organic matter is of terrigenous origin. The flux of marine organic matter might have been increased during the Holocene, however, because of the oxic deep-water conditions (shown by the homogenous brown sediments) and low sedimentation rates of about 0.5 cm/ky (Fig. 3) almost nothing of this material is preserved in the sediments. On the other hand, during stage 2 the marine organic carbon flux was probably distinctly reduced (see above). Nevertheless, some higher amounts of marine organic matter seems to be preserved as suggested from the increased hydrogen index values. This increased preservation of hydrogen-rich organic matter during the last glacial interval may have been caused by reduced ventilation of deep-water masses which is probably also reflected in the dominantly olive gray to grayish colors of glacial sediments and the absence of benthic foraminifera. Because of the low TOC content, this first interpretation of the hydrogen index values has to be regarded as still very preliminary and has to be proven by a more detailed organic geochemical study using gaschromatography and kerogen microscopy (Schubert and Stein, in prep.). The change from olive-gray and grayish brown late glacial to dark brown to brown Holocene sediment colors interpreted as increased oxygenation of deep waters, however, is supported by a distinct change in ostracode assemblages which is also explained by increased inflow of well-oxygenated Atlantic water masses near the stage 1/2 transition (Cronin et al., 1993).

At the present stage of work on ARCTIC ´91 material, it should be finally mentioned that for more precise paleoenvironmental interpretations of the unique ARCTIC ´91 sedimentary records, much more detailed data on absolute ages, stratigraphy, organic and inorganic geochemistry, paleontology, and sedimentology are necessary and will be produced in major international multidisciplinary projects in the coming months and years. The results of these future studies will hopefully help to decipher the still mostly unknown history of the central Arctic Ocean environment and its relationships to the global climate system.

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Figure Caption

Fig. 1. Position of ARCTIC ´91 geological stations with profiles A-B and C-D (cf. Fig. 2). Position of cores PS2163, PS2176, and PS2185 are marked by asterisks (cf. Figs. 3 and 4).

Fig. 2. Profiles A-B and C-D (see Fig. 1 for position) with carbonate and total organic carbon (TOC) contents (%) and hydrogen index (HI) values (mgHC/gC).

Fig. 3. Data of Core PS2163-3 at the Gakkel Ridge: Composition of biogenic coarse fraction (solid dots: planktonic foraminifera; open dots: benthic foraminifera; crosses: biogenic opal), as based on rough estimates performed onboard POLARSTERN; carbonate and total organic carbon contents; and HI values (mgHC/gC). Because of the low TOC values, HI values have been determined twice. Nevertheless, the HI values from the organic-carbon-poor (< 0.4 %) intervals have to be interpreted with caution. Lithologic units 1, 2, and 3 approximately correspond to oxygen stable isotope stages 1, 2, and 3, respectively. Absolute ages (ky BP) and sedimentation rates (cm/ky) are based on AMS ^{14}C dating (Stein et al., 1993b).

Fig. 4. Carbonate and total organic carbon records as well as average HI values (mgHC/gC) of Lomonosov Ridge Core PS2185-6 (A) and Amundsen Basin Core PS2176-3 (B). Oxygen stable isotope stage boundaries 1/2 and 5/6 at Core PS2185-6 are based on oxygen isotope record determined on planktonic foraminifera *N. pachyderma sin.* (Stein and Spielhagen, unpubl.). Solid triangles mark occurrence of turbidites at Core PS2176-3. For HI values see also Fig. 3.

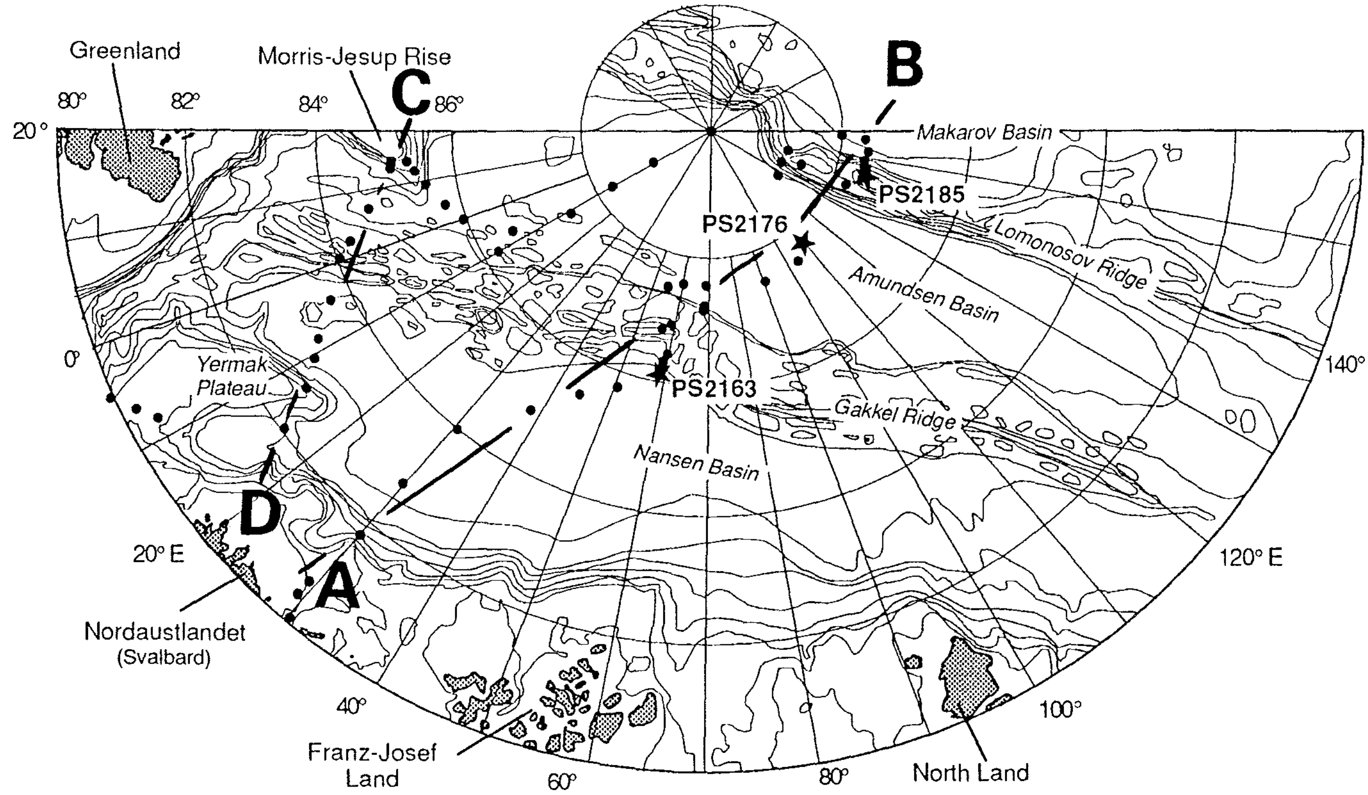
Greenland
Morris-Jesup Rise
80°
82°
84°
86°
20°
B
C
Makarov Basin
PS2185
PS2176
Lomonosov Ridge
Amundsen Basin
0°
Yermak
Plateau
140°
PS2163
Gakkel Ridge
Nansen Basin
D
20° E
A
120° E
Nordaustlandet
(Svalbard)
40°
100°
Franz-Josef
Land
60°
80°
North Land

FIG. 1

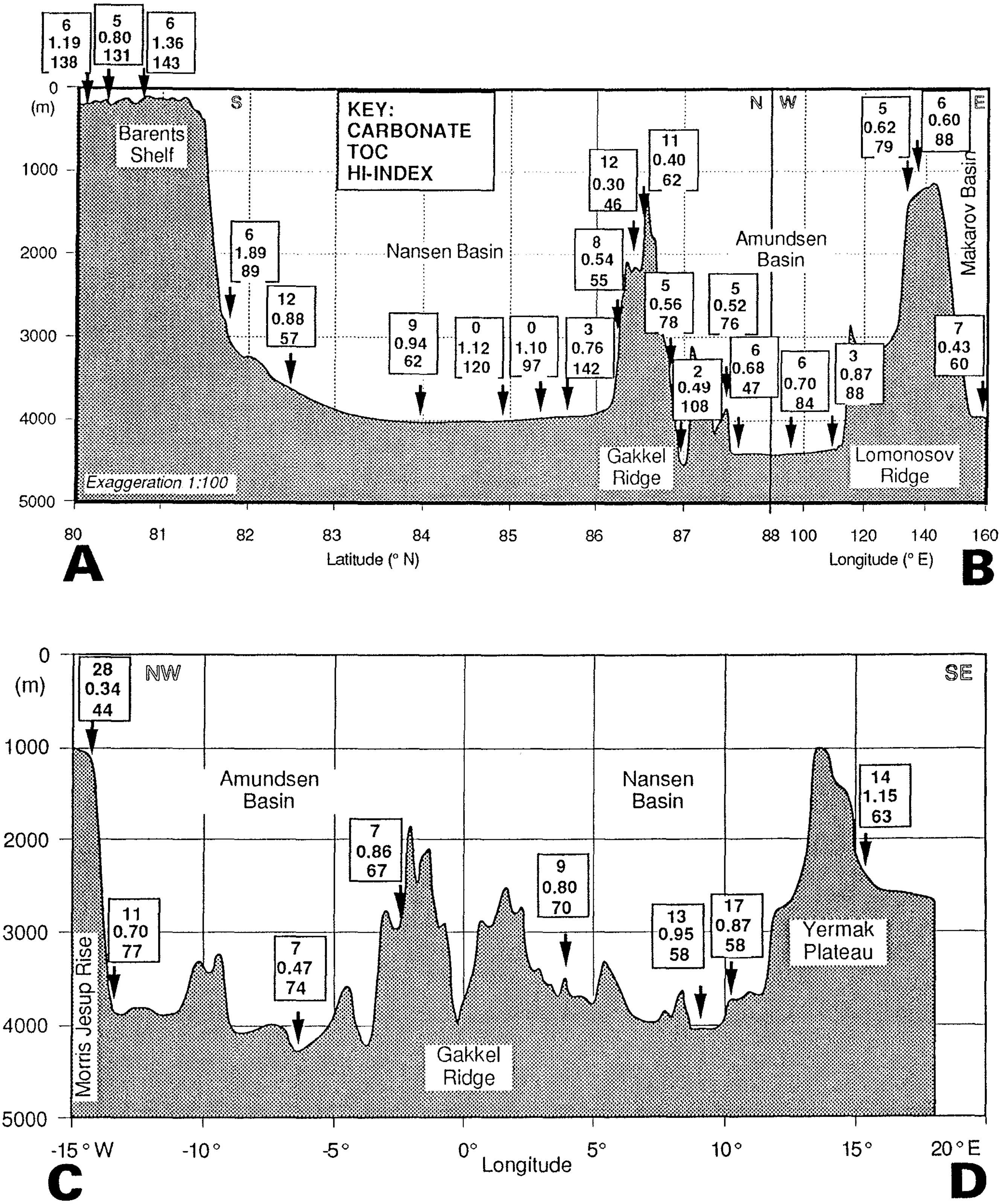
KEY:
CARBONATE
TOC
HI-INDEX
Barents Shelf
Nansen Basin
Gakkel Ridge
Amundsen Basin
Lomonosov Ridge
Makarov Basin
S
N
W
E
(m)
Exaggeration 1:100
Latitude (° N)
Longitude (° E)
A
B
6 1.19 138
5 0.80 131
6 1.36 143
6 1.89 89
12 0.88 57
9 0.94 62
0 1.12 120
0 1.10 97
3 0.76 142
8 0.54 55
12 0.30 46
11 0.40 62
5 0.56 78
2 0.49 108
5 0.52 76
6 0.68 47
6 0.70 84
3 0.87 88
5 0.62 79
6 0.60 88
7 0.43 60
NW
SE
Amundsen Basin
Nansen Basin
Gakkel Ridge
Yermak Plateau
Morris Jesup Rise
Longitude
C
D
28 0.34 44
11 0.70 77
7 0.47 74
7 0.86 67
9 0.80 70
13 0.95 58
17 0.87 58
14 1.15 63

FIG. 2

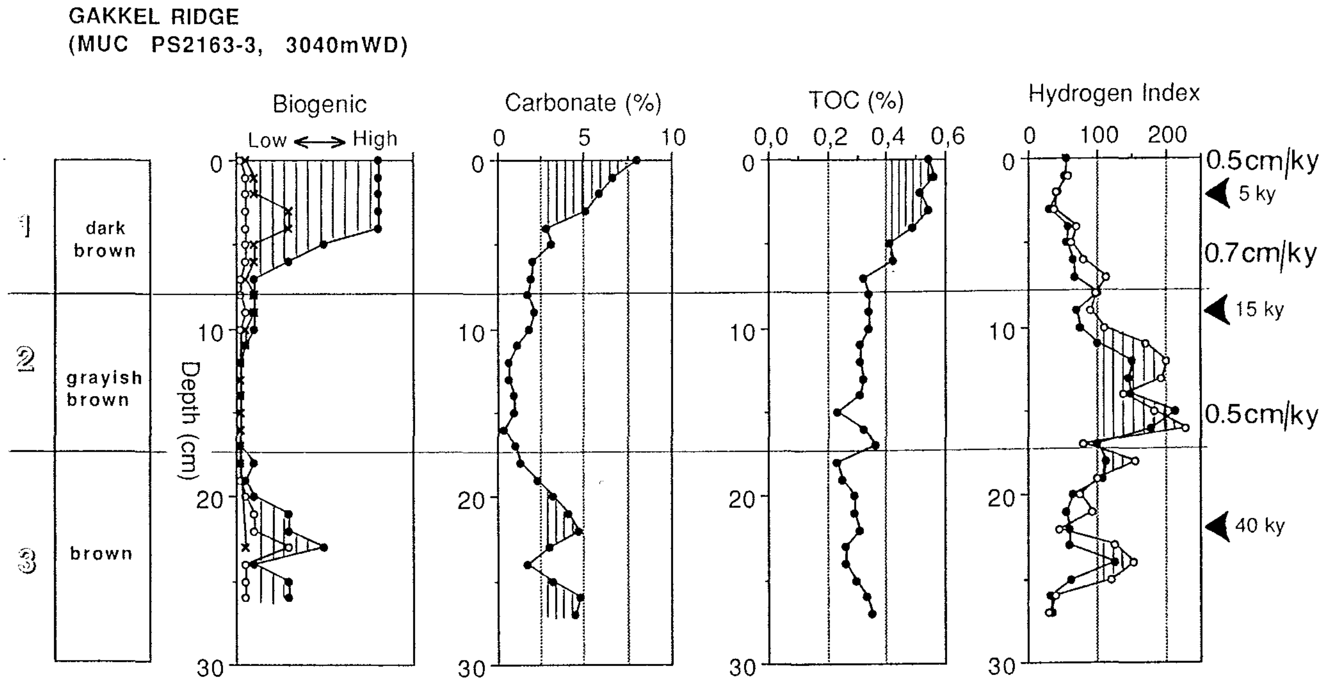
GAKKEL RIDGE
(MUC PS2163-3, 3040mWD)
Biogenic
Low ⟷ High
Carbonate (%)
TOC (%)
Hydrogen Index
dark brown
grayish brown
brown
Depth (cm)
0.5cm/ky
5 ky
0.7cm/ky
15 ky
0.5cm/ky
40 ky

FIG. 3

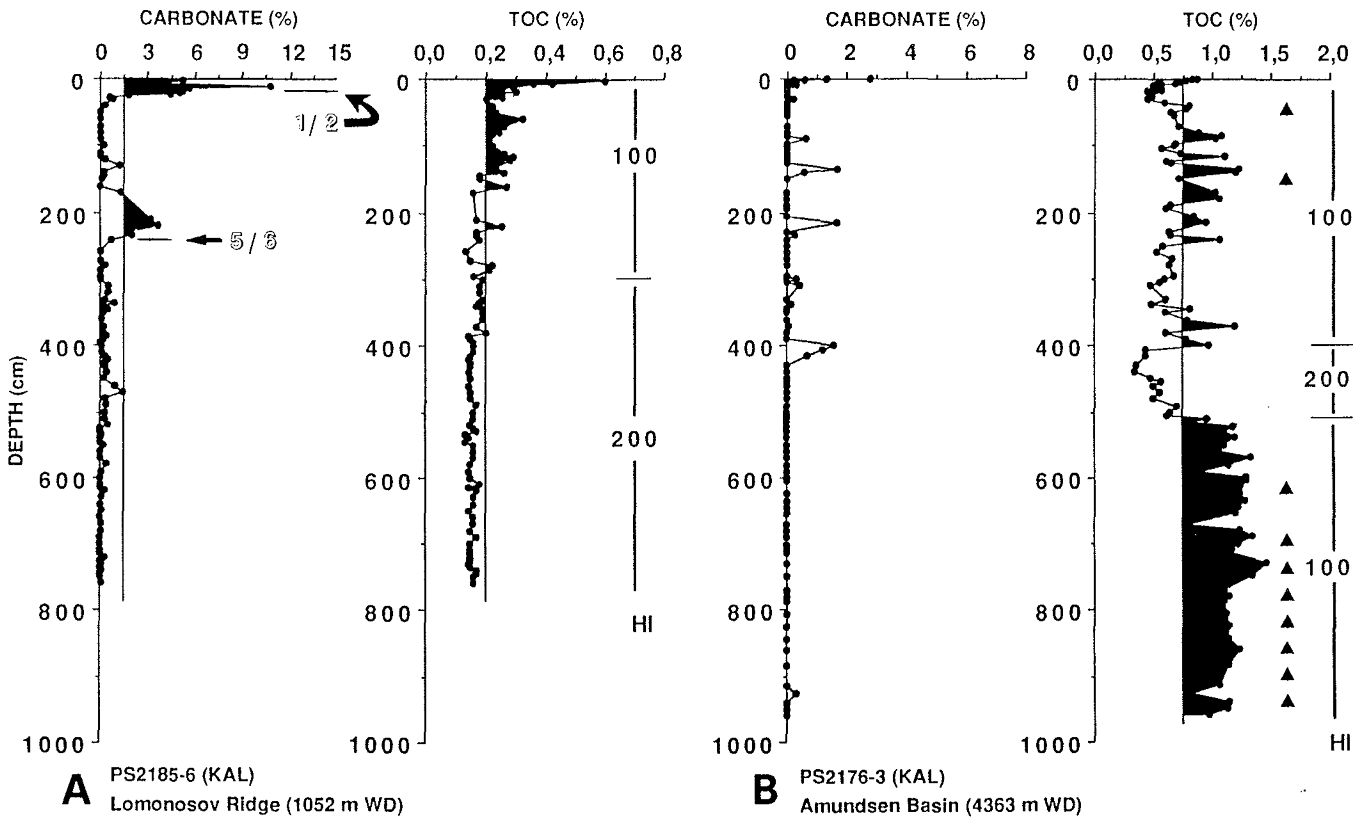
CARBONATE (%)
TOC (%)
CARBONATE (%)
TOC (%)
DEPTH (cm)
1/2
5/6
100
200
HI
100
200
100
HI
A
PS2185-6 (KAL)
Lomonosov Ridge (1052 m WD)
B
PS2176-3 (KAL)
Amundsen Basin (4363 m WD)

FIG. 4