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Organic matter deposition along the Kara and Laptev Seas continental margin (eastern Arctic Ocean) during last deglaciation and Holocene: evidence from organic–geochemical and petrographical data

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Abstract

Organic petrologic (maceral analysis) and bulk organic–geochemical studies were performed on five sediment cores from the Eurasian continental margin to reconstruct the environmental changes during the last ~13 000 yr. The core stratigraphy is based on AMS-^{14}C dating, and correlation by magnetic susceptibility and lithostratigraphic characteristics. Variations in terrigenous, freshwater, and marine organic matter deposition document paleoceanographic and paleoclimatic changes during the transition from the last deglaciation to the Holocene. Glacigenic diamictons deposited in the St. Anna Trough (northern Kara Sea) during the Last Glacial Maximum (LGM) are characterized by reworked terrigenous organic matter. In contrast, the Laptev Sea shelf was not covered by an ice-sheet, but was exposed by the lowered sea level. Increased deposition of marine organic matter (MOM) during deglaciation indicates enhanced surface-water productivity, possibly related to influence of Atlantic waters. The occurrence of freshwater alginite gives evidence for river discharge to the Kara and Laptev Seas after the LGM. At the eastern Laptev Sea slope, the first influence of Atlantic water masses is indicated by an increase in the contents of MOM and dinoflagellate cysts, with *Operculodinium centrocarpum* prior to ~10 000 yr BP. High sedimentation rates in the Kara and the Laptev Seas with the adjacent slope at the beginning of the Holocene are presumably related to increased freshwater and sediment discharge from the Siberian rivers. Evidence for elevated Holocene freshwater discharge to the Laptev Sea has been found between ~9.8 and 9 kyr BP, at ~5 kyr BP and at ~2.5 kyr BP. In the Kara Sea, an increased freshwater signal is obvious at ~8.5 kyr BP and at ~5 kyr BP. Higher portions of MOM were accumulated in the St. Anna Trough and at the Eurasian continental margin at several intervals during the Holocene. Increased primary productivity during these intervals is explained by seasonally ice-free conditions possibly associated with increased inflow of Atlantic waters.

Keywords: organic petrology; Kara Sea; Laptev Sea; deglaciation; Holocene

1. Introduction

The hydrographic system of the eastern Arctic Ocean is affected by the inflow of Atlantic water

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masses and the freshwater supply from rivers entering the Laptev and Kara Seas (e.g. Meincke et al., 1997; Aagaard and Carmack, 1989) (Fig. 1).

The Atlantic water system splits into two branches. One branch crosses the Barents and Kara Seas and enters the deep-sea Nansen Basin via the St. Anna Trough. The other branch continues along the western margin of the Barents Sea towards the Fram Strait, and then flows eastward along the continental slope (Rudels et al., 1994; Schauer et al., 1997; cf. Fig. 1). As a counterpart, low-saline polar water masses are transported via the Transpolar Drift and the East Greenland Current towards the Atlantic Ocean.

About 60% of the total Arctic continental runoff is supplied by rivers draining into the Laptev and Kara Seas. This supply of freshwater is essential for the sustainment of the strong stratification of near-surface water masses of the Arctic Ocean and for sea-ice formation (Aagaard and Carmack, 1989). The melting and freezing of sea ice affects the surface albedo, the energy balance, the moisture supply and thus, the ocean–ice–atmosphere interaction (Hibler, 1989; Carmack et al., 1995). Additionally, brine formation by salt enrichment during the freezing of sea water leads to water of high density, sinking as plumes into the deeper oceanic layers (Schauer et al., 1997). The St. Anna Trough and the region around Severnaya Zemlya are possible source areas for deep water formation by this mechanism (Jones et al., 1995).

The Siberian rivers transport large quantities of suspended and particulate organic matter (POM) into the Laptev and Kara seas (Martin et al., 1993; Gordeev et al., 1996; Rachold and Hubberten, 1999) where it is deposited and/or further transported by sea ice and turbidites towards the open ocean (Nürnberg et al., 1994; Lindemann, 1998; Stein et al., 1999).

Organic matter (OM), preserved in marine sediment records, reveal information about the environmental conditions, e.g. terrigenous supply and surface-water productivity. Studies on Quaternary marine sediments from the Norwegian–Greenland Sea (e.g. Hölemann and Henrich, 1994; Wagner and Henrich, 1994) and the Equatorial Atlantic (e.g. Wagner, 2000) have shown that organic petrography is a useful tool for characterization of the OM fraction in order to interpret paleoceanographic and paleoclimatic changes through time. Organic–geochemical analysis and organic petrography studies of sediments from the Kara and Laptev Seas have shown that the exclusive use of organic–geochemical parameters in these shelf sediments may reveal contradictory information about the organic-matter sources (Boucsein et al., 2000; Fahl and Stein, 1999). Thus, microscopical examinations are needed for a detailed characterization of the OM composition.

The OM in the Kara and Laptev Sea surface sediments and sediment records is mainly of terrigenous origin but, nevertheless, significant amounts of marine organic matter (MOM) indicate primary productivity in the water column (Fahl and Stein, 1997, 1999; Boucsein and Stein, 2000). Furthermore, the occurrence of chlorococcalean algae and pollen/spores, transported by rivers onto the shelf, can be used as an indicator for riverine inputs (Matthiessen et al., 2000; Kunz-Pirrung, 1999; Naidina and Bauch, 1999).

Several studies considering late Quaternary paleoenvironmental changes in the northern Barents Sea and the St. Anna Trough were performed during the last years (e.g. Lubinski et al., 1996; Polyak et al., 1997; Knies and Stein, 1998; Knies et al., 1999; Hald et al., 1999; Kleiber et al., 2000). In this study we compare the environments of the northern Kara Sea (St. Anna Trough) and the Laptev Sea during the last ~13 000 yr. New data from organic petrography (maceral analysis) and organic–geochemical bulk parameters (TOC, HI-values) are presented for cores located in the St. Anna Trough and along the northern Kara and Laptev Seas margin (Fig. 1). We show that maceral analysis gives detailed information about the OM composition (marine/freshwater/terrigenous) and enables the interpretation of paleoriver discharge, changes in the Atlantic water inflow, surface-water productivity, and the supply of terrigenous OM.

2. Material

Our study was performed on sediment Cores PL9408 and PL9460 taken during RV *Professor*

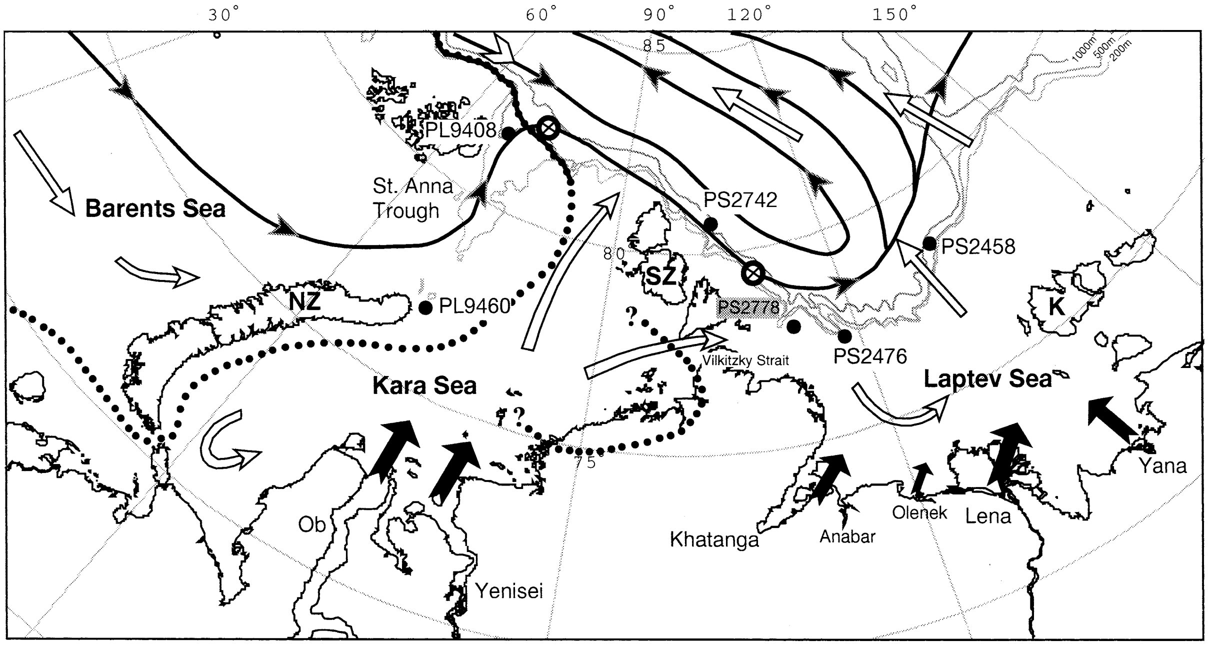
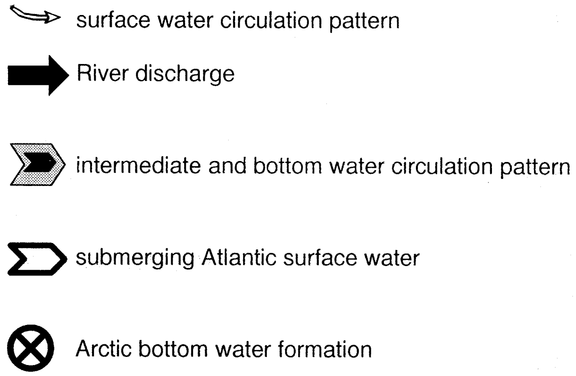


Fig. 1. Study area with core locations and schematically representation of (a) the surface-water circulation by white arrows (after Gordienko and Laktionov, 1969); (b) river discharge by black arrows; (c) the intermediate and bottom circulation pattern (Rudels et al., 1994; Jones et al., 1995); (d) submerging Atlantic surface water (after Gordienko and Laktionov, 1969); and (e) Arctic bottom water formation (Jones et al., 1995). The dotted line shows the maximum extend of the Late Weichselian Glaciation according to Svendsen et al. (1999), the black line the ice-sheet extend after Kleiber and Niessen (2000). SZ = Severnaya Zemlya, NZ = Novaya Zemlya, K = Kotelnyy.



Logachev expedition in 1994 (Ivanov et al., 1999), and sediment Cores PS2476-3, PS2458-4 and PS2742-5 recovered during RV *Polarstern* expeditions ARK-IX/4 in 1993 (Fütterer, 1994) and ARK-XI/1 in 1995 (Rachor, 1997) (Table 1). For detailed core descriptions we refer to AWI web page 'www.pangaea.de'.

3. Methods

3.1. Maceral analysis

According to the nomenclature described by Taylor et al. (1998), macerals are distinguished into three main groups: vitrinite/huminite, inertinite and liptinite, and several sub-groups. Since the classic maceral nomenclature was developed for coals and organic-rich sediments it has been modified for studying recent and mainly TOC-poor marine sediments (Wagner and Henrich, 1994; Wagner, 1999; Boucsein and Stein, 2000). With reference to the environment and different biological sources, we distinguished between terrigenous, freshwater and marine macerals (Boucsein and Stein, 2000).

Maceral analysis was performed on bulk-sediment samples in oil-immersion with a Zeiss-Axiophot microscope using incident light and, additionally, fluorescent light (wavelength: 395–440 nm, blue-light filter: Zeiss No. 05). At least 200–300 macerals were counted by 2D-scanning at 1000× magnification. The grain length of each maceral was estimated and normalized to 20 μm in order to prevent over-estimation of small particles. Nevertheless, quantification of macerals by counting has to be considered as semi-quantitative because the method depends on the resolution of light microscopes. We are only able to quantify particles >2 μm and quantification of finely disseminated OM is not possible. For a detailed discussion of this method we refer to Boucsein and Stein (2000).

3.2. Organic–geochemical bulk parameters

Total organic carbon (TOC) was determined on both ground bulk samples and HCl-treated carbonate-free sediment samples by means of a Heraeus CHN-O-RAPID element analyzer. For more details concerning this method see Stein (1991, and references therein). The Hydrogen index (HI) was determined using Rock-Eval Pyrolysis as described by Espitalié et al. (1977). The HI-value corresponds to the quantity of pyrolyzable hydrocarbons per gram TOC (mg HC/g TOC). In immature carbon-rich (TOC $>0.5\%$) sediments, HI values <100 mg HC/g TOC are typical for terrigenous organic matter (TOM) (kerogen type III), whereas HI values of 300–800 mg HC/g TOC (kerogen type II and I) result from alginites of marine and/or lacustrine origin mixed with terrestrial macerals (Tissot and Welte, 1984; Taylor et al., 1998).

3.3. Lithostratigraphy and chronology

High-resolution stratigraphic frameworks for Quaternary deposits in the eastern Arctic Ocean are rare because of limited occurrence of microfossils. Thus, detailed stable isotope records and radiocarbon dating are sparse (Knies et al., 2000). In this study, a combined stratigraphy based on AMS-^{14}C dating (taken from Bauch et al., 2001 and Stein and Fahl, 2000), magnetic susceptibility records, and lithological characteristics is used (Fig. 2). Magnetic susceptibility is a useful tool for core correlation within an area with coherent sedimentation history (e.g. Kleiber and Niessen, 2000). While the values of magnetic susceptibility are relatively high in sediments of the Last Glacial/post-glacial time from the Laptev Sea continental margin a distinct decrease is typical for the base of the Holocene and, thus, can be used for core correlation (e.g. Stein et al., 1999; Kleiber and Niessen, 2000). Moreover, we use the chronology and lithological characteristics of sediment records from the Kara Sea described in earlier publications (Polyak et al., 1997; Hald et al., 1999) for a correlation with the studied cores.

Based on X-ray radiographs three lithological units were distinguished in Core PL9408 and Core

Table 1
Site locations and water depths of the studied cores

Station	Latitude	Longitude	Depth (m)
PL9408 SL	81°77.1′N	67°45.6′E	617
PL9460 SL	76°99.4′N	70°06.2′E	572
PS2742-5 SL	80°78.8′N	103°82.6′E	1890
PS2476-3 SL	77°38.9′N	118°19.4′E	521
PS2458-4 KAL	78°16.6′N	133°39.8′E	983

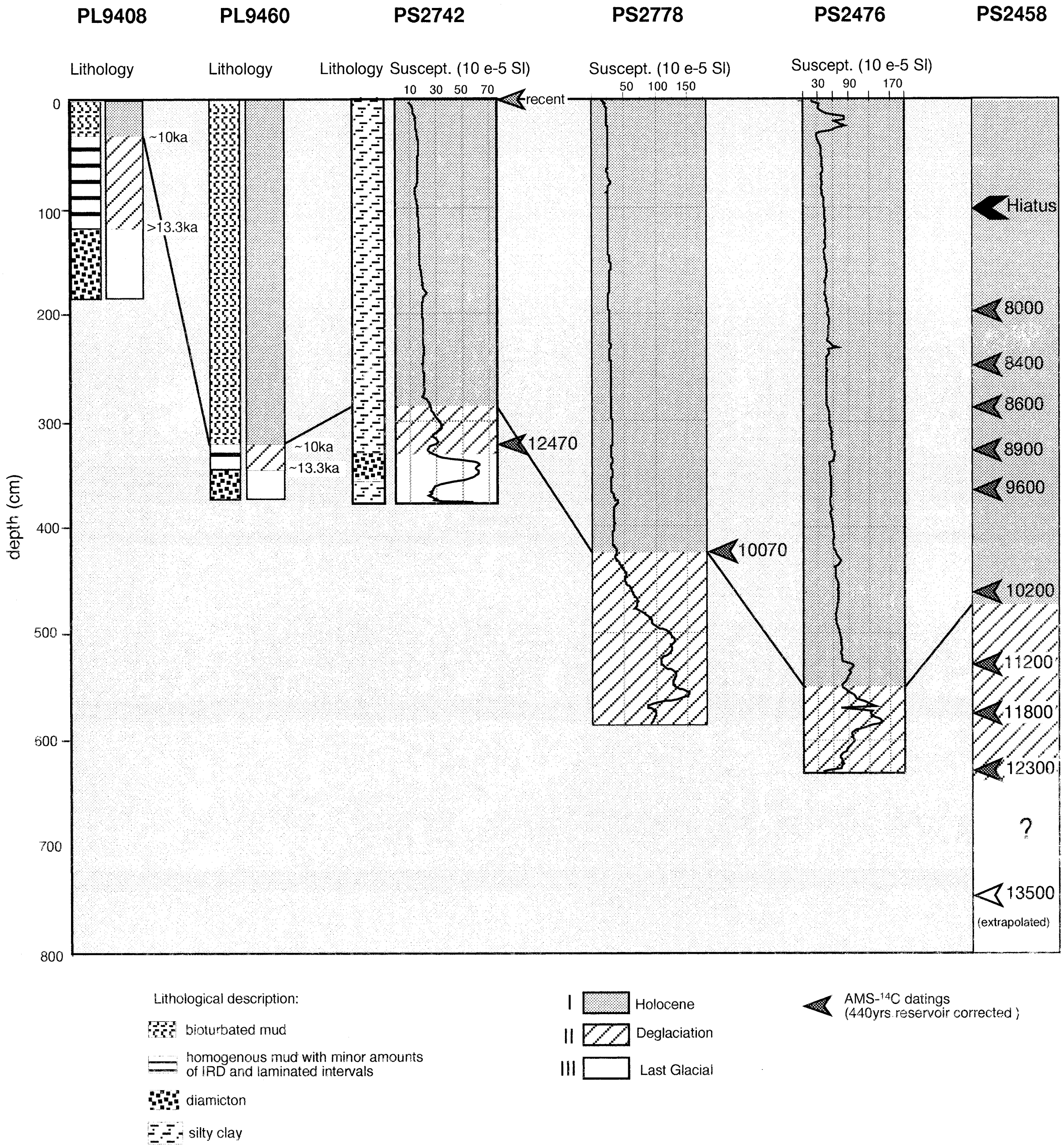
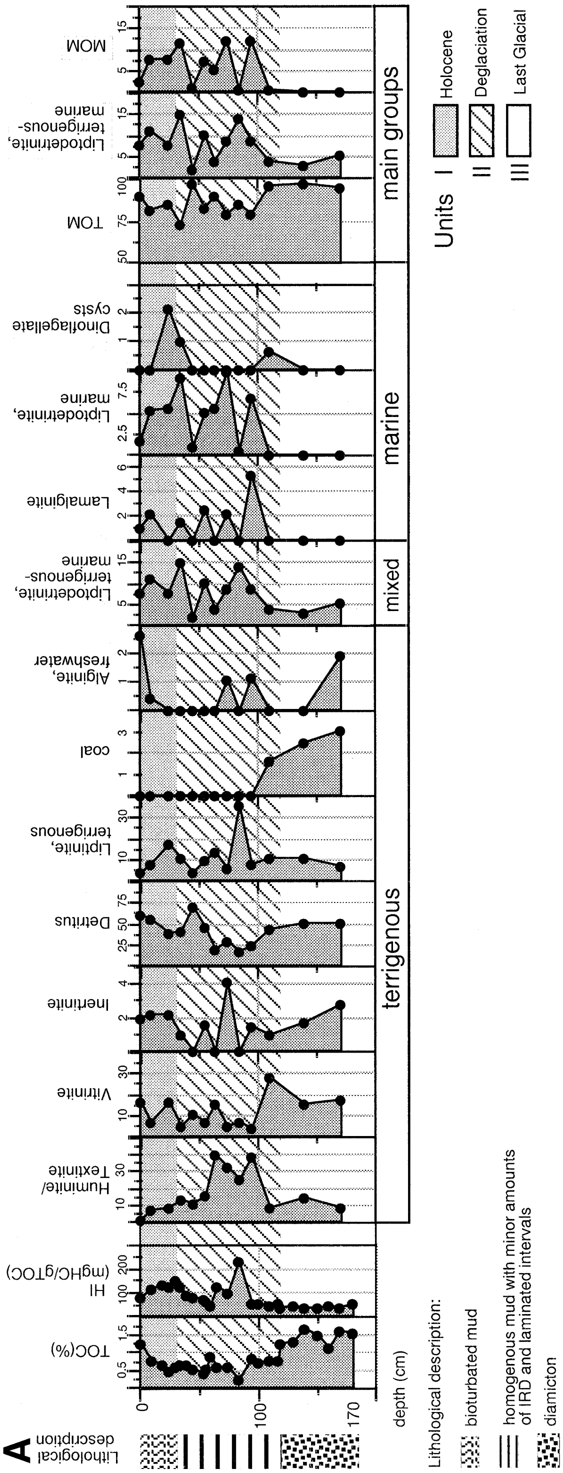


Fig. 2. Stratigraphy of the studied cores based on lithological characteristics, correlation of magnetic susceptibility and AMS-^{14}C dating (taken from Bauch et al., 2001; Stein and Fahl, 2000).


A
Lithological description
depth (cm)
TOC(%)
HI (mgHC/gTOC)
Huminite/ Textinite
Vitrinite
Inertinite
Detritus
Liptinite, terrigenous
coal
Alginite, freshwater
Liptodetrinite, terrigenous-marine
Lamalginite
Liptodetrinite, marine
Dinoflagellate cysts
TOM
MOM
terrigenous
mixed
marine
main groups
Units
I Holocene
II Deglaciation
III Last Glacial
Lithological description:
bioturbated mud
homogenous mud with minor amounts of IRD and laminated intervals
diamicton

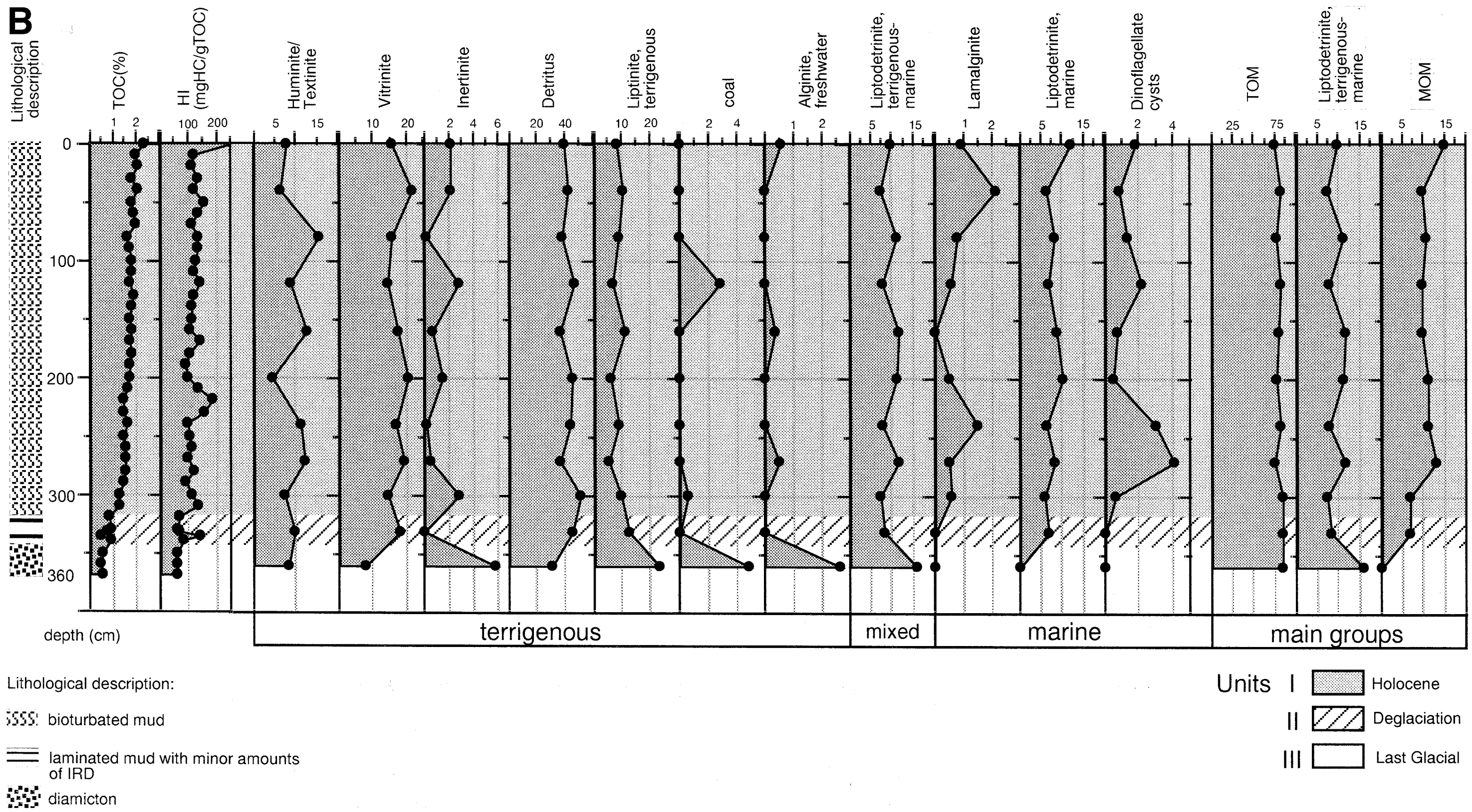


Fig. 3. (A) Maceral composition in grain %, bulk parameters (TOC (%), HI-values (mg HC/g TOC)) of core PL9408 from the St. Anna Trough. (B) Maceral composition in grain %, bulk parameters (TOC (%), HI-values (mg HC/g TOC)) of core PL9460 from the St. Anna Trough.

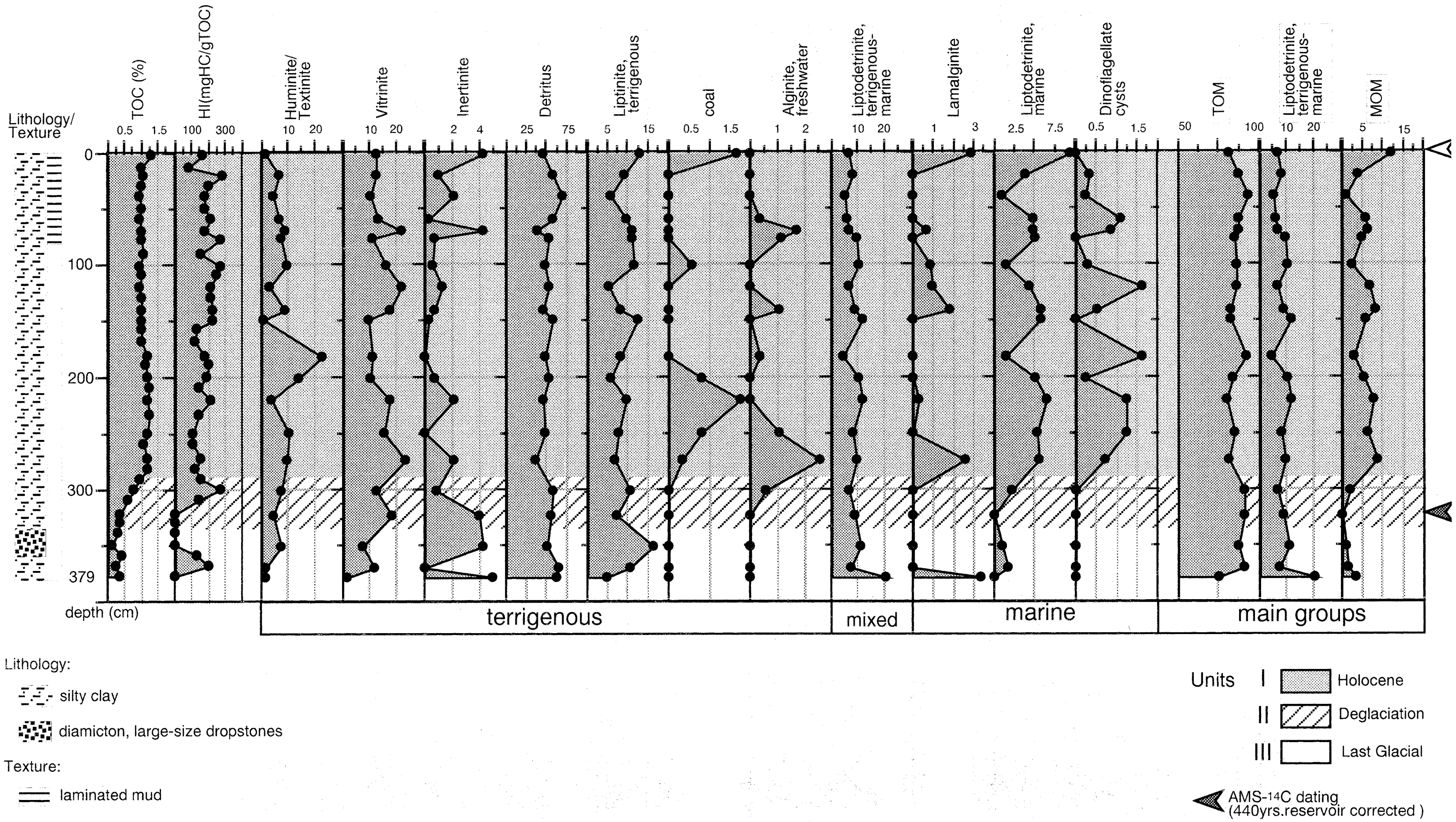


Fig. 4. Maceral composition in grain %, bulk parameters (TOC (%), HI-values (mg HC/g TOC)) of core PS2742-5 NE from Severnaya Zemlya.

PL9460 as shown in Figs. 2 and 3A,B. The cores can be correlated with nearby sediment cores studied and dated by Polyak et al. (1997); Hald et al. (1999) and Lubinski et al. (2001). According to these authors the diamictons in the St. Anna Trough reflect the late Weichselian glaciation. Deglaciation started prior to 13 300 yr BP and is documented in the deposition of the intermediate laminated sediment layer (Unit II, Fig. 2). A minimum age of 13 300 yr BP is supposed for the Unit III/II boundary. Unit I is interpreted to be deposited after the complete retreat of the ice-sheet at ~10 000 yr BP.

The stratigraphy of Core PS2742-5, Core PS2476-3, and Core PS2778-3 is based on AMS-^{14}C dating, a correlation of magnetic susceptibility records and lithological characteristics (as shown in Figs. 2, 4 and 5) (Stein and Fahl, 2000). The base of the Holocene is characterized by a distinct decrease in magnetic susceptibility dated at Core PS2778-2 to 10 070 yr BP (Fig. 2). The diamicton layer in Unit III of PS2742-5 (Figs. 2 and 4) characterized by large dropstones and maximum susceptibility values, is older than 12 470 yr BP and likely reflects the last glaciation.

Core PS2458-4 (Fig. 5B) consists of an 8-m-long sedimentary sequence of dominantly terrigenous sediments (Fütterer, 1994; Müller, 1999). Bivalves from several sub-bottom levels were used for ^{14}C dating (Fig. 2; Bauch et al., 2001). At a depth of 100 cm bsf a hiatus lasting 6000–8000 yr is supposed due to non-deposition or erosion (Bauch et al., 2001).

4. Results

Organic–geochemical bulk parameters (TOC values and HI values) are used to get first information about the content and composition of OM in the sediments. More detailed information about the different sources of the POM were acquired by means of maceral analysis.

In general, POM identified in incident light, mainly consist of terrigenous macerals, such as vitrinites/huminites, inertinites and detritus of these macerals (grain size < 10 μm). Also, liptinites of terrigenous origin, e.g. pollen grains, cutinites and freshwater alginite, are recorded. As freshwater alginite, we define chloroccocalean algae, such as *Pediastrum* and *Botryococcus* (cf. Batten and Grenfell, 1996a,b). In river-influenced shelf areas like the Eurasian shelf seas, these freshwater algae are useful tracers for river runoff (Matthiessen et al., 2000; Kunz-Pirrung, 1999). The marine macerals consist of lamalginite, dinoflagellate cysts and their fragments (marine liptodetrinite > 10 μm) and can be used as indicators for marine primary production (Boucsein and Stein, 2000). As shown by palynological studies of surface sediments from the Laptev Sea (Kunz-Pirrung, 1999) and of sediment records from the Norwegian–Greenland Sea (Matthiessen, 1995), dinoflagellate cysts can be used as indicators for environmental conditions. For example the dinoflagellate cysts *Operculodinium centrocarpum* (Deflandre and Cookson, 1955) in the Arctic is advected to warmer water masses and, thus, its occurrence in Holocene sediments at the continental slope of the Laptev Sea gives evidence for the influence of Atlantic water masses (Matthiessen et al., 2001).

4.1. St. Anna Trough (northern Kara Sea)

4.1.1. Cores PL9408 and PL9460

According to the organic–geochemical bulk parameters, the sedimentary sequence of Core PL9408 consists of two intervals (Fig. 3A). Below 120 cm bsf (Unit III), the TOC content is relatively high with values ranging from 1.1 to 1.7%, whereas the HI values are very low (< 60 mg HC/g TOC). In the upper part (Units II-I) TOC values vary between 0.4 and 0.9%, increasing to 1.3% at the surface. Furthermore, the HI values are elevated in the upper section, reaching a maximum of 233 mg HC/g TOC at 85 cm bsf. In the sediments of Core PL9460, TOC values are lowest in Unit III (< 0.6%), increasing up to 0.9% in Unit II, and reaching maximum values of 1.3–2.3% in Unit I (Fig. 3B). The HI values are low in the two lower units (< 80 mg HC/g TOC) and increase to values between 100 and 150 mg HC/g TOC in Unit I. A maximum value of 282 mg HC/g TOC occurs at the surface.

Maceral analysis shows that the POM in the

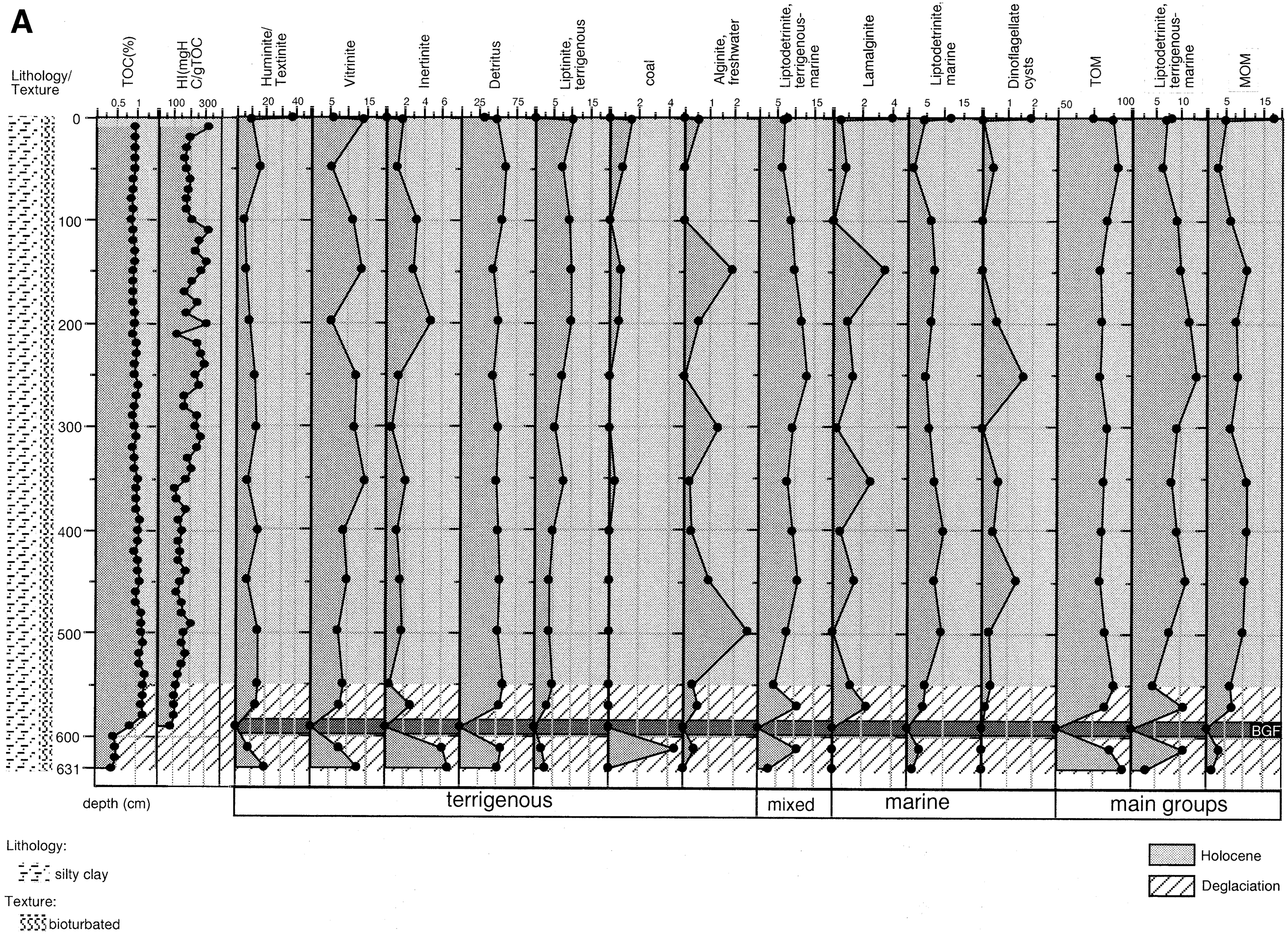


Fig. 5. (A) Maceral composition in grain % of core PS2476-4 from the western Laptev Sea margin. Bulk parameters (TOC (%), HI-values (mg HC/g TOC)) and stratigraphy is taken from Stein and Fahl (2000). (B) Maceral composition in grain % and bulk parameters (TOC (%), HI-values (mg HC/g TOC)) of core PS2458-4 from the eastern Laptev Sea margin. AMS ^{14}C-datings are taken from Bauch et al. (2001).

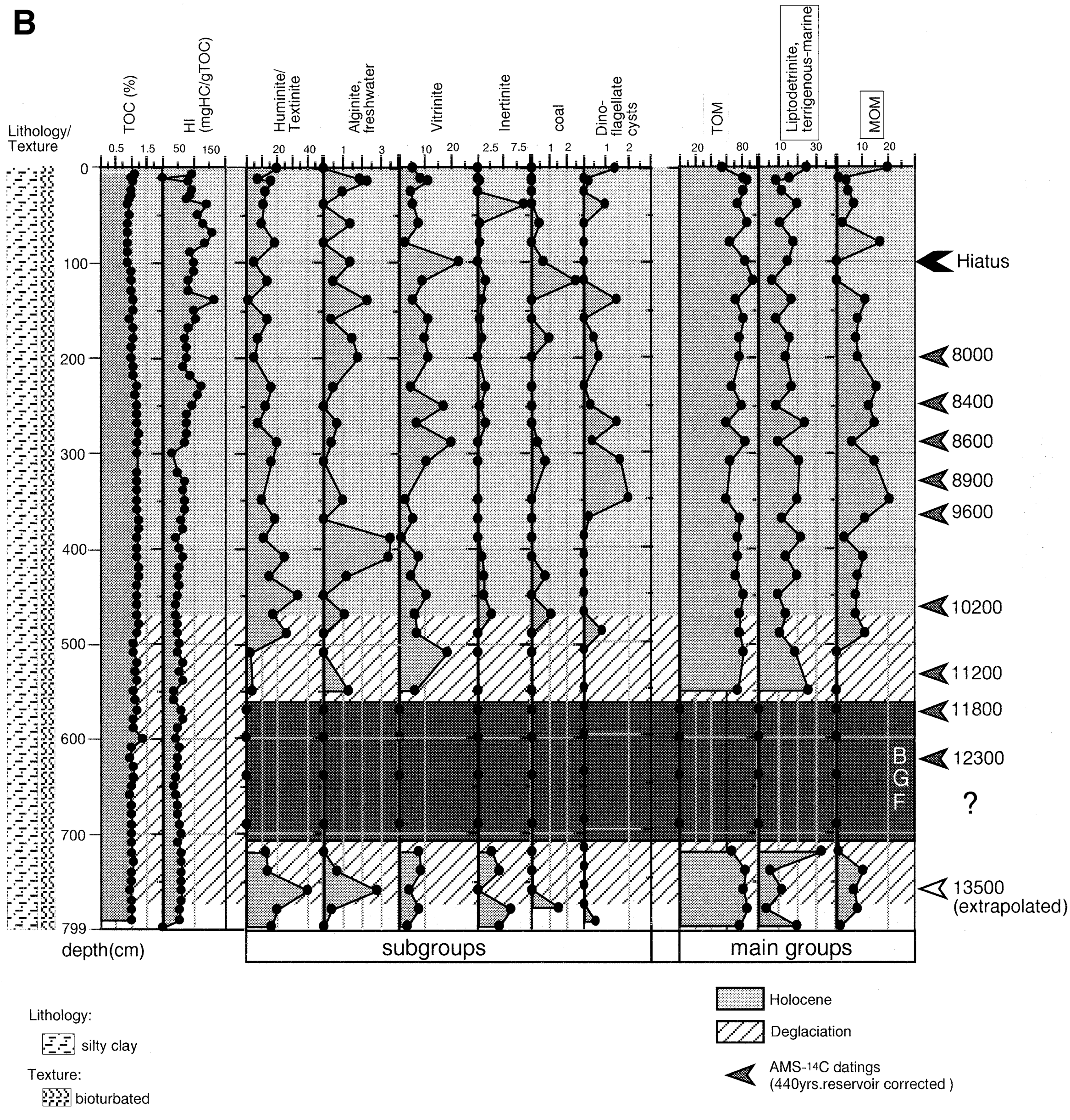


Fig. 5 (*Continued*).

sediments of Cores PL9460 and PL9408 is mainly of terrigenous origin (Ø: 80–85%) (Fig. 3A,B). Variations exist, however, when looking at the distribution of specific maceral groups. The POM in the basal diamicton (Unit III) is characterized by relatively high amounts of coal fragments (PL9460: 5%/PL9408: 3%) and inertinite (5.9%/2.8%). Additionally, freshwater alginite occur (2.7%/2%). Relatively high amounts of liptodetrinite (16%) were observed in Core PL9460. MOM is absent in Unit III of both cores. Marine macerals including lamalginite, marine liptinite

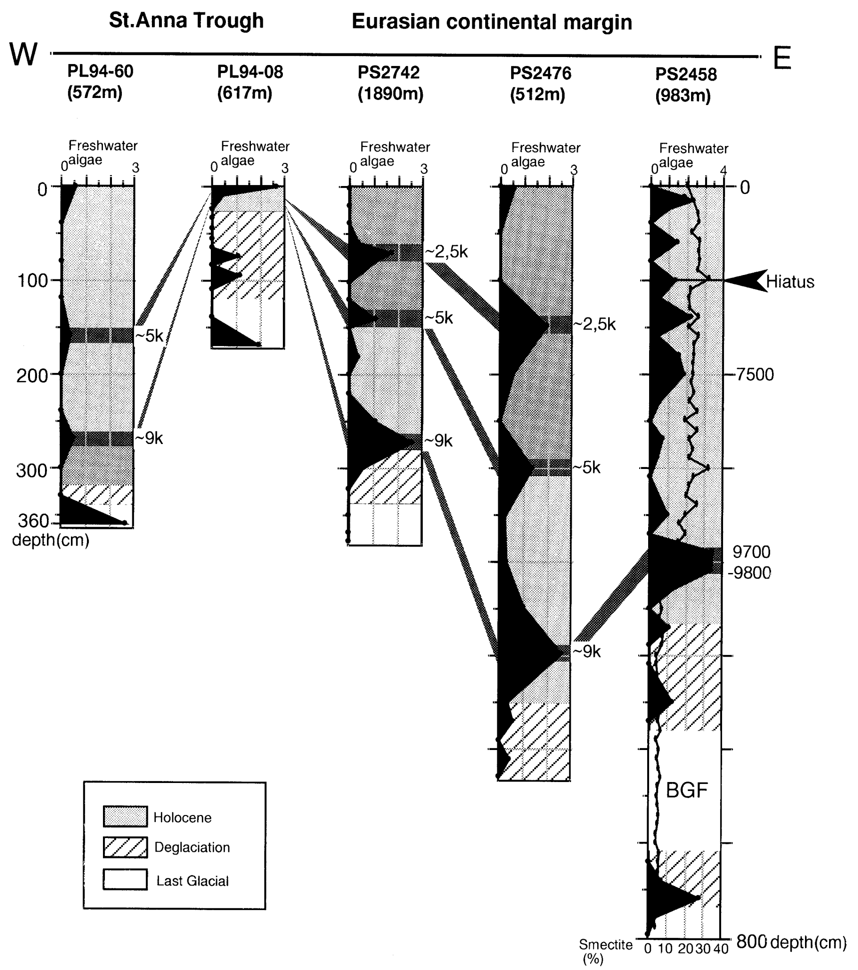


Fig. 6. Distribution of freshwater alginite (grain %) in the studied cores. Smectite data of core PS2458-4 is taken from Müller (1999). Ages are estimated based on stratigraphy as shown in Fig. 2, ages from Core PS2458-4 are interpolated.

and partially dinoflagellate cysts appear first in the sediments of Unit II with values up to 12% in Core PL9408.

In both cores, the amounts of freshwater alginite in Unit II are relatively small (< 1%). Textinites and huminites, which originate from immature landplant material, occur throughout the sedimentary sequences, showing a remarkable increase in the sediments of Unit II of Core PL9408 (up to 39%).

In the Holocene sediments of Core PL9408, the amounts of MOM are relatively small (8%) further decreasing towards the surface. On the other hand, the portions of freshwater alginite increase up to a value of 2.7% at the surface. In comparison, the amounts of MOM are about 10% in the Holocene sediments of Core PL9460, increasing towards the surface to a value of 15%.

4.2. Continental slope NE Severnaya Zemlya

4.2.1. Core PS2742-5

Unit III (Fig. 4) is characterized by very low TOC contents (< 0.3%) which increase in Unit II to values between 0.4 and 1.0%. The highest TOC values were found in Unit I (1–1.3%). The HI values are relatively high in Units II-I, reaching maxima of > 250 mg HC/g TOC at 300, 111, 102,

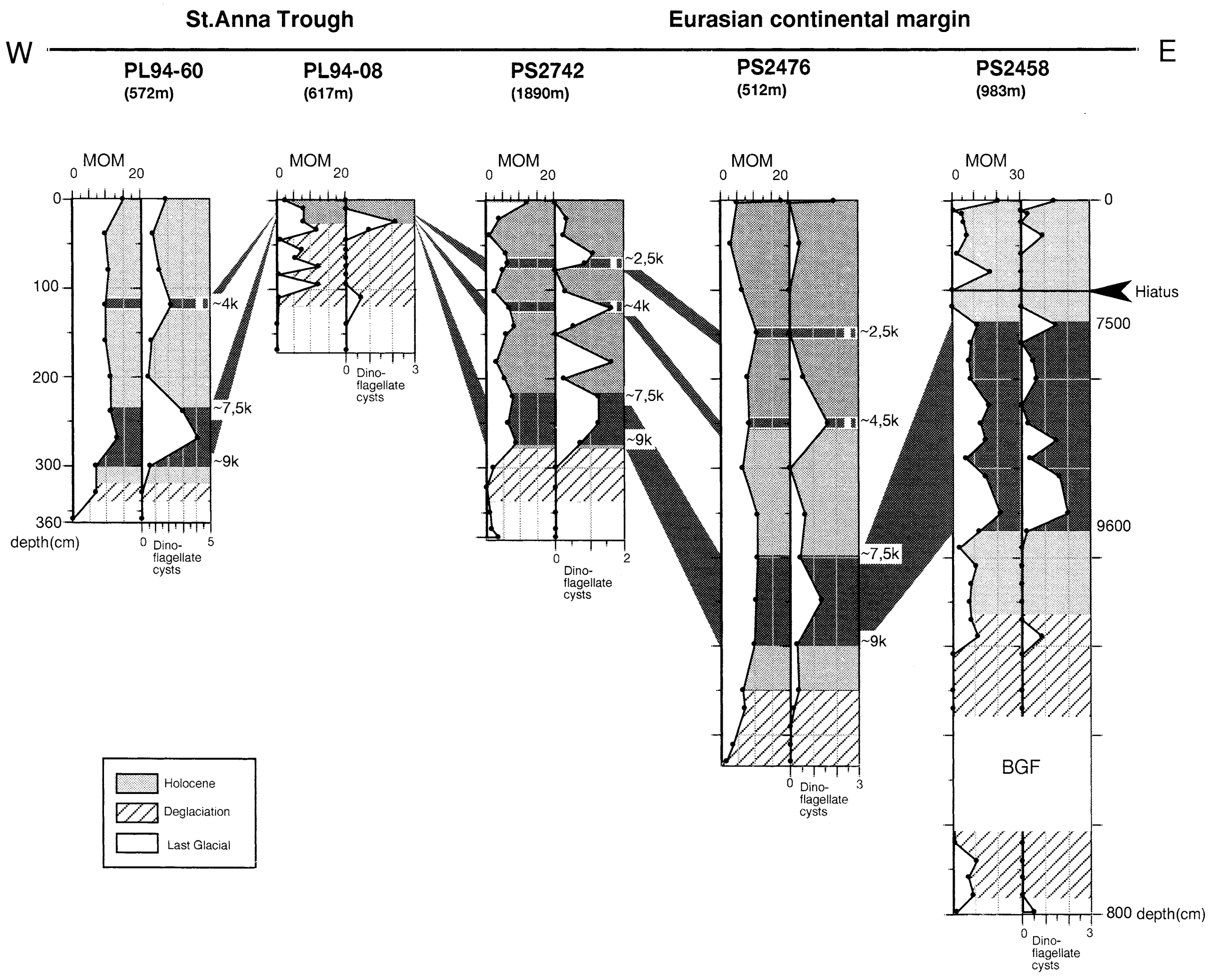


Fig. 7. Distribution of MOM and dinoflagellate cysts (grain %) in the studied cores. Ages are estimated based on stratigraphy as shown in Fig. 2, ages from Core PS2458-4 are interpolated.

78 and, 21 cm bsf. The amounts of terrigenous macerals in the sediment record (Fig. 4) range from 76 to 94%. In the diamicton (Unit III) higher amounts of resistant OM (inertinite: 4–5%) are found, but coal fragments are absent. In the lowest section of Unit III and Unit II MOM only occurs in minor portions ($< 3\%$).

At the boundary between Unit II and the Holocene sediments (Unit I) a remarkable increase in freshwater alginite (up to 2.6%) and MOM (up to 9%) (Fig. 4) co-occurs with a decrease in magnetic susceptibility (Fig. 2). Additionally, the amounts of textinite and huminite increase in Unit I at 182 cm bsf (22%). Higher portions of coal fragments (1.7%) are recorded at 221 cm bsf and at the surface.

4.3. Laptev Sea continental margin

4.3.1. Core PS2476-4

The sediments of Core PS2476-4 from the western Laptev Sea continental slope represent the transition from the last glaciation to the Holocene (bottom to 550 cm bsf) and the Holocene (550 cm bsf to the surface) (Fig. 5A). In the lowest core section (bottom to 600 cm bsf) TOC values are very low (< 0.5%) increasing at 580 cm bsf to values about 1%. Furthermore, the HI values are relatively high with values up to 300 mg HC/g TOC.

Maceral analysis shows that the POM in the lowest core section is dominated by terrigenous macerals (up to 95%) including relatively high amounts of vitrinite (maximum: 13%) and inertinite (maximum: 7%). MOM occurs only in minor amounts (2–6%). At 591 cm bsf, background fluorescence (BGF) caused by a dominance of liptodetrinite was observed. Here, a quantification of macerals by counting is not possible because major portions of the liptinitic particles are too small. At the base of the Holocene (550 cm bsf), a distinct increase in MOM to about 10% and in freshwater alginite (to 2.6%) co-occurs with a decrease in magnetic susceptibility, similar to the results from Core PS2742-5. Throughout the Holocene sediments MOM constitutes about 10%, but decreases towards the surface. At depths of 499, 301 and 149 cm bsf freshwater alginite show distinct peaks.

4.3.2. Core PS2458-4

The results from organic–geochemical analysis (bulk parameters, biomarker) and organic petrography of Core PS2458-4 from the eastern Laptev Sea continental margin are described in detail by Fahl and Stein (1999) and Boucsein et al. (2000). In this study, we concentrate on the distribution of distinct macerals and bulk parameters as shown in Fig. 5B for a comparison with the sediment cores described above. The TOC values in this core are relatively high, ranging from 1 to 1.5%. In the lower core section, the HI values are low (< 100 mg HC/g TOC), but increased values occur in the upper part. Maceral composition shows more variations. In the lower core sections at a depth of 760 cm bsf increased amounts of freshwater alginite, textinite/huminite and MOM are determined. At the depth of 690–570 cm bsf the OM is dominated by fluorescing liptinitic particles, causing BGF. The portions of freshwater alginite and textinite/ huminite increase at the depth of 470–390 cm bsf. The upper core section (370 cm bsf to surface) is characterized by increased portions of MOM and dinoflagellate cysts.

5. Discussion

5.1. Late Weichselian glacial history of the Eurasian shelves

According to Svendsen et al. (1999, and references therein) the extent of the Svalbard–Barents Sea ice-sheet (SBIS) was restricted to the western part of the Kara Sea and the Barents Sea (Fig. 1). The St. Anna Trough (northwestern Kara Sea) was likely filled with grounded glacier ice (Polyak et al., 1997; Hald et al., 1999 and references therein), while the southern extent of ice in the Kara Sea is still under discussion (e.g. Siegert et al., 1999; Velichko et al., 1997). Severnaya Zemlya (SZ) was presumably covered only by local ice caps as suggested from IRD records from the northern Severnaya Zemlya continental margin (Knies et al., 2000) and radiocarbon dating of mammoth tusks from Severnaya Zemlya (Bolshiyanov and Makeyev, 1995).

For the Laptev Sea, the post-glacial sea-level rise can be considered as eustatic due to the lack of a major ice sheet (e.g. Hahne and Melles, 1997; Kleiber and Niessen, 1999). Thus, the global sea-level curve (Fairbanks, 1989) is applicable, showing that the shallow Laptev Sea shelf (average water depth: 50–60 m) was exposed during the Last Glacial because of the lowered sea level of about 120 m. Although the discharge of the Siberian rivers Olenek, Lena and Yana was reduced during the Last Glaciation, freshwater and sediment was delivered to the Laptev Sea and into the Arctic Ocean (Nørgaard-Petersen et al., 1998; Kleiber and Niessen, 1999).

5.2. Paleoenvironmental conditions during the Last Glacial

In the St. Anna Trough, the distribution of a glacigenic diamicton, such as in Cores PL9408 and PL9460, provides evidence for grounded glacier ice, which may have reached the shelf edge during the LGM (Polyak et al., 1997). Based on ^{14}C-ages, the minimum age for the retreat of the grounded ice from the central deep St. Anna Trough is about 13 300 yr BP (Polyak et al., 1997).

The diamicton in Cores PL9408 and PL9460 is characterized by reworked terrigenous OM, including high-matured coal fragments and inertinite, and framboid pyrite. This OM composition can be compared with organofacies types described by Wagner and Henrich (1994) for diamictons in sediment records from the Norwegian–Greenland Sea. Reworked OM is also common in diamictons of the Barents Sea and can be related to redeposition of Mesozoic bedrocks (Elverhoi et al., 1989; Polyak and Solheim, 1994; Polyak et al., 1997). Additionally, we found freshwater alginite (Fig. 3A,B). These macerals are originated from chloroccocalean algae living in freshwater to brackish waters (e.g. Batten and Grenfell, 1996a,b) and, thus, indicate freshwater discharge into marine systems (Kunz-Pirrung, 1999). Moreover, they can be well preserved in geological records, which enable their use in environmental reconstructions (Matthiessen et al., 2000). We believe, however, that the observed freshwater alginite in the diamicton in Cores PL9408 and PL9460 does not indicate freshwater supply to the Kara Sea during the Last Glacial. The accumulation within a diamicton facies and the absence of lamination do not support a fluvial deposition. We suppose that the freshwater algae are originated from meltwater pools occurring during summer periods on top of the glacier rather than from river discharge.

Environmental conditions during the Last Glacial at the continental slope of the Laptev Sea are different from the St. Anna Trough because this region was probably not covered by a large ice-sheet (Svendsen et al., 1999, and references therein). We found a diamicton layer with large dropstones at the base of Core PS2742-5, but IRD is almost absent in the Upper Weichselian sediment records from the Laptev Sea continental margin (Müller, 1999). Therefore, we assume that the diamicton in Core PS2742-5 reflects the retreat of local ice caps on Severnaya Zemlya during the Last Glacial. The OM in the diamicton is characterized by very low TOC-contents, and microscopical studies show a dominance of resistant terrigenous OM like inertinites, vitrinites and fragments of terrigenous liptinites (cutinites, resinites, reworked alginites). This composition is comparable with the POM in the diamictons of the St. Anna Trough.

5.3. Deglaciation

After Hald et al. (1999) and Polyak et al. (1997), deglaciation of the St. Anna Trough started prior to ~13 300 yr BP and was completed by ~10 000 yr BP. Occurrences of lamalginite, marine liptodetrinite and dinoflagellate cysts in Unit II of Cores PL9408 and PL9460 (Fig. 3A,B) indicate accumulation of MOM during deglaciation. The accumulation of MOM can be interpreted as a signal for marine primary productivity, which was possibly triggered by the influence of Atlantic water masses. This conclusion is supported by foraminiferal fauna recorded in sediment records of the St. Anna Trough, which implies an episodic presence of biota during deglaciation (Polyak et al., 1997). Moreover, foraminiferal assemblages occurring at 13 300 yr BP are related to subsurface Atlantic water masses and/or relatively increased surface-water productivity (Polyak et al., 1997). A significant increase in the contents of immature land-plant material (huminite/textinite) is found in the sediments of Unit II in Core PL9408 together with higher concentrations of freshwater alginite (Figs. 3A and 6). Even if the concentration of freshwater alginite is relatively small, this OM composition may be the first signal of fluvial inputs to the northern Kara Sea after the LGM. Evidence for open water conditions or freshwater discharge is not given by the OM composition in the sediments of Core PS2742-5. The OM is dominated by terrigenous OM with high concentrations of inertinites (Fig. 4) while the TOC contents are low.

More variations in OM composition were found in Core PS2458-4 from the eastern Laptev Sea margin (Fig. 5B). Relatively high estimated sedimentation rates ($\sim$60 cm/kyr) allow a detailed investigation of environmental changes. At $\sim$13.5 kyr BP (extrapolated age) a first indication for primary productivity and freshwater supply in the Laptev Sea shelf is provided by the deposition of MOM and an increase in the amounts of freshwater alginite (Figs. 6 and 7). Here, primary production of MOM is possibly related to a reduction in sea-ice cover caused by the increasing insolation at the end of marine isotope stage 2 (MIS2) (Berger, 1978). During that time, the Lena River Delta was supposedly located near the continental slope about 300 km north-west of the present delta because of the lowered sea-level (Holmes and Creager, 1974). The position near the slope (where Core PS2458-4 is located) explains the deposition of fluvial material far from the modern coastline although the river discharge was supposedly low during glacial times. Between $\sim$13 kyr and $\sim$12 kyr BP the OM sources must have changed. The macerals are dominated by immature liptinitic (fluorescing) material, in this case, textinites, liptinites and liptodetrinite (detritus <10 μm), causing BGF (Fig. 5B). Nevertheless, reworked alginites of freshwater and marine origin, reworked pollen grains, inertinite and vitrinite indicate resuspension of OM. Well-preserved textinite indicates short distance transport of the OM. The occurrence of recent freshwater alginite (showing green fluorescence colors) verifies the fluvial influence. Possible sources for this OM are plants of the tundra vegetation on the exposed shelf and shelf sediments (Boucsein et al., 2000). The release of OM by defrosting of the permafrost soils and freshwater discharge by melting of glaciers and snowfields in the Siberian hinterland may have caused transport and sedimentation of immature liptinitic and reworked material. After this first warming, the environmental conditions at the eastern Laptev Sea slope presumably changed. Low primary productivity and river-runoff during the time from $\sim$12 to 11 kyr BP is documented by a dominance of terrigenous macerals ($>80\%$) in the OM composition and the absence of MOM and freshwater material. At an interpolated age of approximately 10.4 kyr BP, we found increased concentrations of MOM together with the dinoflagellate cyst *O. centrocarpum* (Fig. 7). This OM composition is interpreted as the first post-glacial influence of warmer Atlantic water masses at the eastern continental slope (Boucsein et al., 2000).

Small portions of freshwater alginite and BGF found in the deglacial section of Core PS2476-3 (western Laptev Sea slope) (Fig. 5A) indicates riverine inputs of OM comparable with the results from the eastern Laptev Sea margin.

5.4. Holocene ($\sim$10 000 yr BP)

5.4.1. Freshwater signal

At the beginning of the Holocene a voluminous freshwater discharge to the Eurasian continental margin is indicated by the occurrence of freshwater alginite in Cores PS2742-5, PS2476-4 and PS2458-4 (Fig. 6). Average amounts of freshwater alginite in surface samples from the inner Laptev Sea are about 2% and reaches maximum values of 8% close to the mouth of the Anabar river (Boucsein and Stein, 2000). Thus, we interpret the freshwater alginite in the studied cores as a signal for freshwater supply, although the concentrations are small ($<4\%$). Based on radiocarbon dating from Core PS2458, this event took place at $\sim$9.8–9.7 kyr BP. In Cores PS2476-4 and PS2742-5, further west maximum values of freshwater alginite are recorded near $\sim$9 kyr BP. The related enhanced river discharge to the slope is also supported by an increase of smectite (Müller, 1999) (Fig. 6) and by heavy mineral distribution (Behrends, 1999). As a source for the voluminous freshwater supply we consider melting of glaciers and snow fields in the Siberian hinterland caused by the post-glacial warming together with the increased precipitation during Holocene (Monserud et al., 1998). Additionally, the post-glacial sea-level rise may have amplified the defrosting of permafrost soils on the shallow Laptev Sea shelf, leading to a release of large quantities of meltwater. High sedimentation rates (up to 200 cm/1 kyr) and high accumulation rates of organic carbon (up to 2.0 g C/cm^2/kyr) at the eastern Laptev Sea continental slope in the early Holocene (Boucsein et al., 2000; Stein and Fahl, 2000) can be related to the increased fluvial supply of sediments and OM.

The Kara Sea is suggested as a possible source for freshwater alginite in Holocene sediments of Core PS2742-5. Knies et al. (2000) discussed the Kara Sea as source for high smectite contents in Holocene sediments of Core PS2741 at the continental slope northeast of Severnaya Zemlya. The formation of dense brines cascading downslope and carry fine-grained suspension in contour current along the continental slope was discussed as a possible explanation for the eastward transport of the Kara Sea material (Knies et al., 2000). This pathway may explain the transportation of freshwater alginite to Core PS2742-5 from the Ob and Yenisei rivers via the Kara Sea.

During the Holocene, further increase in the amounts of freshwater alginite is recorded in Cores PS2476-3 and PS2742-5. This increase probably reflects the intensification of freshwater supply from the Kara and western Laptev Sea towards the continental margin at about ∼5 and ∼2.5 kyr BP.

Between ∼8 and 9 kyr BP, extremely high sedimentation rates of 100–500 cm/kyr were reported for the inner parts of the St. Anna Trough and explained by an increased sediment input from the Siberian rivers and/or coastal erosion during postglacial sea-level rise (Herlihy, 1996; Kolstad, 1996; Polyak et al., 1997). However, in Cores PL9408 and PL9460 from the St. Anna Trough, the signal for freshwater supply is relatively small. Palynological studies on surface sediments from the southern Kara Sea (Matthiessen, 1999; Polyakova, 1999) have shown that freshwater algae and diatoms are mainly deposited in the estuaries of the Ob and Yenisei rivers, decreasing in abundance towards the open seas. This distribution can explain the reduced freshwater signal in the cores from the St. Anna Trough.

5.4.2. *Marine signal*

Knies et al. (2000) suggested the intensification of Atlantic water inflow at the northern Barents Sea margin in the Holocene, as indicated by peaks in the accumulation of MOM. Our data show that this signal can be traced towards the eastern Laptev Sea margin.

In the early Holocene, a remarkable increase in the amounts of MOM (up to 20%) and dinoflagellate cysts (Fig. 7) occurred in the sediments of the Laptev Sea margin. We interpret these OM characteristics as enhanced surface-water productivity triggered by the inflow of warmer Atlantic water masses, partly ice-free conditions and nutrient supply by the Siberian rivers. For a comparison, relatively high modern summer productivity rates (200 mg/cm^2/day) are reported for the ice-free area of the Laptev Sea and, especially, near the ice-edge at the shelf break (Boetius and Damm, 1998). This primary productivity signal is preserved in surface sediments as reported from organic–geochemical and palynological studies (e.g. Boetius et al., 1996; Fahl and Stein, 1997; Kunz-Pirrung, 1999). Maceral data reveal that 20–40% of the POM preserved in surface sediments near the Laptev Sea margin is of marine origin (Boucsein and Stein, 2000).

In Core PS2458-4, the increase in primary productivity took place during the time interval from ∼9.5 to ∼7.5 kyr BP. In cores further west, an increase in the amounts of MOM occurred between about ∼9 and ∼7.5 kyr BP. The enhanced primary productivity recorded in sediments from the eastern Laptev Sea slope is confirmed by organic–geochemical data, showing a distinct increase in the concentrations of marine biomarkers (i.e., short-chain fatty acids, dinosterols, brassicasterol) (Fahl and Stein, 1999). In the Holocene sediments from Cores PS2476-3 and PS2742-5, two further events of enhanced primary productivity are indicated by increased concentrations of MOM and dinoflagellate cysts (at about ∼4 kyr BP and ∼2.5 kyr BP) (Fig. 7). Unfortunately, these signals are not recorded in the sediments of Core PS2458-4 due to a hiatus lasting 6–8 kyr.

In the sediments from the St. Anna Trough, higher concentrations of MOM since deglaciation time are explained by a continuous influence of Atlantic water. In the southernmost Core PL9460, maximum values of MOM are reached at the beginning of the Holocene (Fig. 7) and can be interpreted as an intensification of Atlantic water inflow and seasonally ice-free conditions similar to the environmental conditions inferred for the Eurasian continental margin further east.

6. Summary and conclusions

The OM in sediment cores from the St. Anna Trough and the Eurasian continental margin is characterized by a dominance of terrigenous particulate OM. Variations in OM composition document freshwater and Atlantic water influence to the Kara and Laptev Seas and paleoenvironmental changes from the last deglaciation to the Holocene.

During deglaciation, increased deposition of MOM in the St. Anna Trough indicates enhanced surface-water productivity, possibly related to the influence of Atlantic waters. At the eastern Laptev Sea slope, we suggest Atlantic water inflow for the first time after the LGM at ~10 400 yr BP as indicated by an increase of MOM and dinoflagellate cysts, with *O. centrocarpum*. Freshwater alginite gives evidence for active draining of rivers into the Kara and Laptev Seas.

At the beginning of the Holocene, enlarged fluvial supply to the Kara and Laptev Seas is indicated by a distinct increase in freshwater alginite content. This increase co-occurs with high sedimentation rates in the Kara and Laptev seas, which can be explained by higher discharge from the Siberian rivers.

Heightened surface-water productivity presumably caused by an intensification of Atlantic water inflow, temporary ice-free conditions and/or fluvial nutrient supply is reflected in the increased accumulation of MOM and dinoflagellate cysts and can be followed along the Kara and Laptev Sea margin at several intervals during the Holocene.

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