# Freshwater chlorophycean algae in recent marine sediments of the Beaufort, Laptev and Kara Seas (Arctic Ocean) as indicators of river runoff

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ORIGINAL PAPER

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# Freshwater chlorophycean algae in recent marine sediments of the Beaufort, Laptev and Kara Seas (Arctic Ocean) as indicators of river runoff

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**Abstract** Freshwater chlorophycean algae are characteristic organic-walled microfossils in recent coastal and shelf sediments from the Beaufort, Laptev and Kara seas (Arctic Ocean). The persistent occurrence of the chlorophycean algae *Pediastrum* spp. and *Botryococcus* cf. *braunii* in marine palynomorph assemblages is related to the discharge of freshwater and suspended matter from the large Siberian and North American rivers into the Arctic shelf seas. The distribution patterns of these algae in the marine environments reflect the predominant deposition of riverine sediments and organic matter along the salinity gradient from the outer estuaries and prodeltas to the shelf break. Sedimentary processes overprint the primary distribution of these algae. Resuspension of sediments by waves and bottom currents may transport sediments in the bottom nepheloid layer along the submarine channels to the shelf break. Bottom sediments and microfossils may be incorporated into sea ice during freeze-up in autumn and winter leading to an export from the shelves into the deep sea. The presence of these freshwater algae in sea-ice and bottom sediments in the central Arctic Ocean confirm that transport in sea ice is an important process which leads to a redistribution of shallow water microfossils.

**Keywords** Arctic Ocean · Beaufort Sea · Laptev Sea · Kara Sea · Recent sediments · Chlorophyte distribution · Freshwater discharge

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## Introduction

Freshwater plays a key role in the hydrological cycle of the Arctic Ocean because it is essential for the maintenance of the low-salinity surface water layer and formation of sea ice (Aagaard and Carmack 1989). Changes in freshwater supply may have also a strong impact on the deep-water convection in the Arctic Ocean and Nordic seas. The freshwater budget of the Arctic Ocean is determined by three principal sources: river runoff, sea-ice formation and ice melt. Glacial meltwater discharge is of minor importance.

The Arctic Ocean receives approximately 3700 km$^3$ of freshwater from rivers which discharge annually into the circum-Arctic epicontinental seas: Eurasian rivers contribute approximately 2960 km$^3$ and the North American rivers 740 km$^3$ (Gordeev et al. 1996). Runoff to the Beaufort, Laptev and Kara seas (Fig. 1) alone makes up ca. 70% of the total annual discharge into the Arctic Ocean. This freshwater is mainly from the largest rivers: Mackenzie, Lena, Ob and Yenisei. Arctic rivers show a seasonal maximum of discharge in May to November with a flood peak period from May to June, whereas winter discharge (November to April) is less than 15% of the annual volume (e.g. Gordeev et al. 1996; Macdonald et al. 1998). The rivers transport enormous loads of particulate and dissolved matter which are deposited on the shelves or in the deep sea, mainly during the summer, particularly from May to August (Gordeev et al. 1996; Macdonald and Thomas 1991; Macdonald et al. 1998).

The summer discharge results in a strong salinity gradient from coast to shelf break (Fig. 1) which is associated with a pronounced decrease in temperature of the order of several degrees (Treshnikov 1985; Timokhov 1994; Burenkov and Vasil'kov 1995; Pavlov and Pfirman 1995; Burenkov et al. 1997). The shallow mixed layer (5–30 m) is strongly separated from the cold saline Arctic bottom waters. This decoupling of

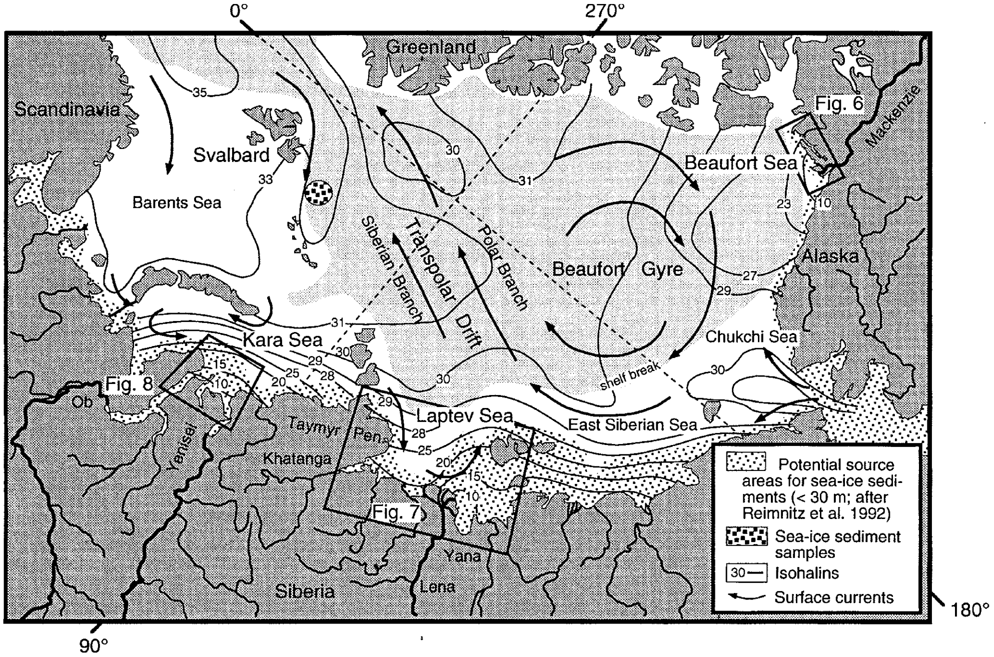


**Fig. 1** Location of the study areas (Beaufort, Laptev and Kara seas) in the Arctic Ocean. Water depths larger than 200 m are indicated by *grey shading*. Surface currents are shown schematically. The mean summer surface water salinity is indicated (Treshnikov 1985)

the surface layer makes it susceptible to wind forcing in the shelf regions (e.g. Johnson et al. 1997; Campeau et al. 1999) and the low-salinity plume may extend far to the north during high runoff and strong offshore winds. Strong salinity gradients may result in hydrographic fronts with differences of more than 10–20 psu over short distances (Burenkov and Vasil'kov 1995; Burenkov et al. 1997; Johnson et al. 1997).

Discharge rates and sediment supply vary considerably between the shelf regions. The Mackenzie River has a lower discharge rate than the Siberian rivers Lena, Ob and Yenisei, but the suspended particulate matter (SPM) load of the Mackenzie is three to four times larger than the three Siberian rivers combined (e.g. Gordeev et al. 1996). In contrast, the supply of total organic carbon (TOC) by the Eurasian rivers is much larger (>30% of SPM) than by the North American rivers (<5% of SPM) because of differences in the geology of the respective catchment areas (Pocklington 1987). The Mackenzie River erodes steeply sloping alluvial strata while the Siberian rivers deposit much of their SPM in the broad flat coastal lowlands. The SPM consists mainly of clays and silts, with minor amounts of fine sand (e.g. Hill et al. 1991; Lukashin et al. 1999). The particulate organic carbon (POC) is of variable importance in the river runoff. The TOC of the Mackenzie River consists mainly of POC, whereas it makes up less than 25% of the TOC in the Lena and Ob rivers (Gordeev et al. 1996; Macdonald et al. 1998; Stein, 2000).

The amount of SPM which finally reaches the shelf seas is variable. In the Beaufort Sea, approximately 50% of the fluvial sediments are trapped in the Mackenzie Delta (Macdonald et al. 1998), and most of the sediment load from the Lena River finally is deposited in the Laptev Sea (Rachold et al., 2000). In contrast to the Beaufort and Laptev seas, freshwater input to Kara Sea is discharged first into the Ob and Yenisei estuaries. Much SPM in both rivers is deposited in swamp and forest basins and coastal flood plains (Bobrovitskaya et al. 1996; Smith and Alsdorf 1998), and it is not known which amount of SPM finally reaches the Kara Sea.

Various tracers have been used to characterise river runoff and associated SPM in recent sediments from the Eastern Arctic Ocean. Inorganic markers include major and minor elements as well as heavy and clay minerals (e.g. Schoster et al., 2000, and references therein). Biogenic components, including particulate organic matter (POM), may be characterised by geochemical and micropalaeontological tracers such as fatty acids, n-alkanes, diatoms, macerals and palynomorphs (e.g. Boucsein and Stein 2000; Cremer 1999; Fahl and Stein 1997, 1999; Kunz-Pirrung 1998; Mudie 1992; Polyakova 1999; Bauch et al. 2000). However, geochemical characterization of POM influx is limited by selective preservation of organic compounds and difficulties in sourcing biological origin and environments (e.g. Fahl and Stein 1997, 1999). In contrast, microfossils often can be identified to species level and to marine or freshwater environments. Most organic-walled palynomorphs also have an excellent preservation potential. In particular, the cell walls of some freshwater palynomorphs consist of highly aliphatic non-hydrolysable macromolecules, termed algaenans (e.g. Blokker et al. 1998; Gelin et al. 1999) which are very resistant to degradation (Derenne et al. 1991).

Palynomorphs that are transported by Arctic rivers into the shelf seas include terrestrial palynomorphs and phytoclasts (pollen and spores, plant debris) that are washed with sediments into the rivers, and aquatic palynomorphs which are remains of phyto- and zooplankton that lived in freshwater environments and are transported directly by runoff to the shelf seas (e.g. Vinogradov et al. 1995; Sorokin and Sorokin 1996; Matthiessen and Boucsein 1999). Among the freshwater palynomorphs the chlorophycean algae *Pediastrum* and *Botryococcus* are widespread in limnic and marine sediments throughout the Arctic region, in contrast to other algal spores (e.g. Zygnematales) which occur mainly in the deltaic areas. These chlorophycean algae have been recorded from recent Arctic Ocean sediments (Mudie 1992; Kunz-Pirrung 1998, 1999; Matthiessen 1999), circum-Arctic Holocene and Late Weichselian lake deposits and shelf sediments (e.g. Livingston et al. 1958; Fredskild 1973; Hill et al. 1985; Kunz-Pirrung 1998; Hahne and Melles 1999), and Pliocene and Pleistocene marine sediments from the high northern latitudes (Mudie 1985, 1989; de Vernal and Mudie 1989).

Freshwater palynomorphs have thus the potential to characterise the flux of freshwater and riverine sediments to the Arctic Ocean. The goals of this paper are (a) to review the present knowledge of the occurrence and distribution of these aquatic palynomorphs in the circum-Arctic shelf seas (Beaufort Sea, Laptev and Kara Sea), and (b) to evaluate their potential for reconstructions of palaeo-river discharge.

## Sea-floor morphology and surface sediments of the Beaufort, Laptev and Kara seas

The Beaufort, Laptev and Kara Sea shelves are part of the extensive shelf seas which cover approximately 35% of the Arctic Ocean surface area. The Beaufort Sea shelf (ca. $6.4\times10^4$ km$^2$) is much narrower than the Laptev (ca. $4.6\times10^4$ km$^2$) and the Kara shelves (ca. $8.83\times10^5$ km$^2$; Macdonald and Thomas 1991; Kleiber and Niessen 1999; Pavlov and Pfirman 1995). These shelf seas are relatively shallow, with relatively gentle gradients and water depths of approximately 50–100 m at the shelf break. Submarine channels, separated by shoals, cross the shelves and connect the river mouths with the shelf break or shelf troughs (Macdonald and Thomas 1991; Kleiber and Niessen 1999; Johnson and Milligan 1967). The Beaufort Sea is bissected by the deep Mackenzie Trough, a 200- to 300-m-deep glacial valley (Macdonald and Thomas 1991), whereas the Kara Sea is dissected by several deep (>400 m) shelf troughs.

The recent surface sediments of these shelves are mainly siliciclastic silty clays, clayey or sandy silts to sands (Fig. 2). Submarine channels are the main sinks for shelf sediments, with coarser sediments on banks and along the coasts (Hill et al. 1991; Kuptsov and Lisitsyn 1996). Biogenic components are subordinate in importance, and biogenic carbonate and opal contents are generally <2% (e.g. Stein 1996; Nürnberg 1996; Boucsein et al. 1999). Off the large Arctic rivers, TOC values are higher than in most oceanic areas (>0.5%; Romankevich 1984), and low hydrogen indices and high carbon/nitrogen ratios suggest a dominance of terrigenous organic matter (e.g. Stein 1996; Fahl and Stein 1997; Macdonald et al. 1998; Boucsein et al. 1999). However, the original proportions of terrestrial to marine organic matter are difficult to assess because labile marine organic matter is selectively degraded (e.g. Fahl and Stein 1997). High TOC contents are associated with fine-grained sediments (Fig. 3; e.g. Tyson 1995; Baskaran et al. 1996) which are preferentially deposited in the submarine channels (Fahl and Stein 1997; Hölemann et al. 1999).

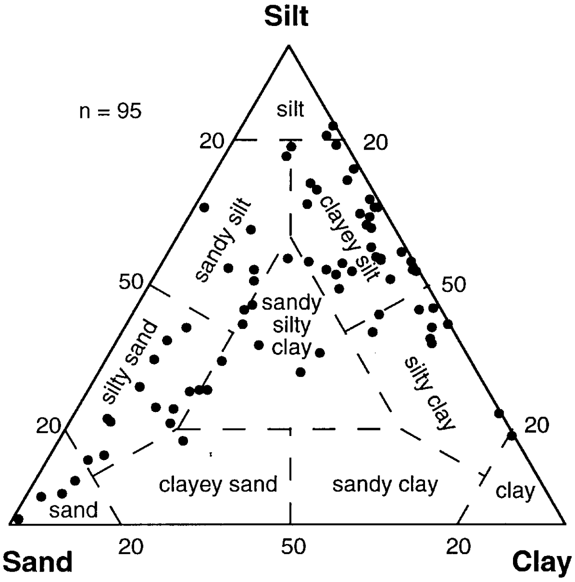


**Fig. 2** Granulometric composition (%) of shelf sediments in the Beaufort, Laptev and Kara seas (<60 m water depth). Sediment nomenclature after Shepard (1954). For sources of data see Table 1

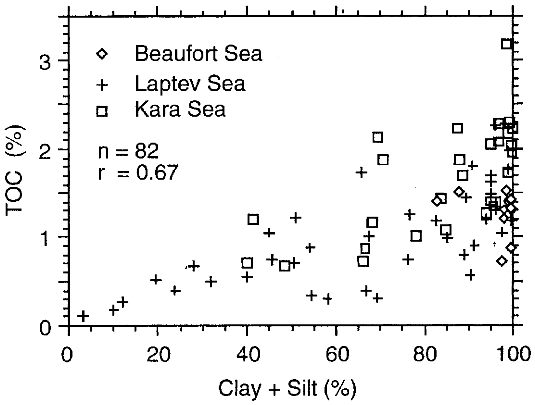


**Fig. 3** Relationship between TOC contents and granulometric composition of shelf sediments (<60 m water depth) in the Beaufort, Laptev and Kara seas. The linear correlation coefficient is indicated. For sources of data see Table 1

## Materials and methods

This review of the distribution of freshwater chlorophycean algae includes published results (Mudie 1992; Kunz-Pirrung 1998, 1999; Matthiessen 1999) as well as unpublished new data. Bottom sediments were sampled during various expeditions to the Arctic Ocean (Table 1).

Most of the western Beaufort shelf is covered by ice-gouged, current-swept relict sediments (Barnes et al. 1982) and is not included in this study. Also, the continental slope is very steep, with many gravity flow deposits; therefore, few slope samples are included here. Most of the samples come from the Canadian Beaufort Sea in the area between 141°W and 128°W longitude. The entire Laptev Sea was sampled for palynological investigations, whereas only samples from the estuaries of the Ob and Yenisei are included in this study (Fig. 1).

Half the samples used to study the Beaufort Sea palynomorphs (Table 2, no. 1–21) were from push cores or gravity cores obtained on Richards Island (Solomon et al. 1992) and in the outer active delta (Robbi Burns, unpublished data). All of these samples contain a modern sediment layer. Most offshore samples are from gravity cores collected during cruises from CCGS Nahidik or Shelby tube cores provided by exploration companies. The amount of sediment missing from these core tops is unknown. Samples 34 and 35, however, are surface samples from box cores collected during cruises of CCGS Louis St. Laurent.

The palynological data are listed in Table 2, except those of the Laptev Sea which were previously published by Kunz-Pirrung (1998, 1999). The sedimentological and geochemical data that were used in this study are from various sources (Table 1). Most grain-size and TOC (reported as weight percent) data are from the same samples as those used for palynological studies. Sediment data of samples 19–35 are from nearby samples studied by Pellitier (1975, 1984). Data used in this paper can be retrieved from the databank PANGAEA at AWI (http://www.pangaea.de; e-mail: sepan@awi-bremerhaven.de/ info.pangaea.de).

Refrigerated (4 °C) or freeze-dried samples from the surface (0–1 cm) sediments were processed with standard palynological preparation methods (Mudie 1992; Matthiessen 1995; Kunz-Pirrung 1998). The sea-ice samples were not processed quantitatively and comprise only the wet fraction <63 µm that was not used for analysis of benthic foraminifers. The processing method includes use of cold hydrochloric and hydrofluoric acids to dissolve carbonates and silicates. Most of the fine organic matter is removed by wet sieving to enrich the POM larger than 6 µm (or 10 µm for Beaufort Sea). Concentrations of palynomorphs were calculated according to the marker grain method of Stockmarr (1971), where the number of *Lycopodium* spores per tablet is 12.542±2081. Palynomorphs were only counted when more than half of a specimen was seen. Counts of *Botryococcus* are only estimates because colonies have variable sizes and may easily fall apart. Variable numbers of freshwater palynomorphs and *Lycopodium* spores have been counted, ranging from less than 10 to more than 200 specimens, and from 5 to more than 100 specimens, respectively. Thus, the statistical error may be as large as 30% for samples with low counts (Stockmarr 1971), but these are mainly located at the continental margins where abundances of freshwater palynomorphs are low; therefore, contours were only drawn on relatively broad intervals.

## Results

### Freshwater palynomorphs in Arctic shelf sediments

Most surface sediments of the Beaufort, Laptev and Kara seas contain chlorophytes (green algae) that usually are absent in marine environments. In addition to the chlorophycean algae *Pediastrum* spp. and *Botryococcus* cf. *braunii*, several other taxa of green algae are abundant in inner shelf and delta front assemblages from the Beaufort and Kara seas, includ-

**Table 1** Sources of surface sediment data used in this study

| Region | Year | Expedition | Granulometry | TOC | Palynomorphs |
|---|---|---|---|---|---|
| Beaufort Sea | 1989-1985 | CCGS Nahidik (1) | 1 | 1 | 13 |
| | 1991 | ARTOS 91 (1) | 1 | 1 | 13 |
| | 1997 | CCGS Louis St. Laurent | | | 13 |
| | 1999 | CCGS Louis St. Laurent | | | 13 |
| Laptev Sea | 1993 | RV Polarstern (2) | 7 | 10 | 14 |
| | 1993 | RV Ivan Kireyev (3) | 8 | 10 | 14 |
| | 1994 | RV Prof. Multanowskiy (4) | | | 14 |
| | 1995 | RV Kapitan Dranitsyn (5) | | 11 | 14 |
| Kara Sea | 1997 | RV Akademik Boris Petrov (6) | 9 | 12 | 13,15 |

References: *1* Solomon et al. (1992); *2* Fütterer (1994); *3* Kassens and Karpiy (1994); *4* Kassens and Dmitrenko (1995); *5* Kassens et al. (1997); *6* Matthiessen and Stepanets (1998); *7* M. Wahsner et al., unpubished data; *8* Rossak (1995); *9* Müller and Stein (1999); *10* Fahl and Stein (1997); *11* R. Stein, unpublished data; *12* Boucsein et al. (1999); *13* this paper; *14* Kunz-Pirrung (1998, 1999); *15* Matthiessen (1999)

**Table 2** Sample numbers, environmental data and palynomorph concentrations per gram dry sediment of surface sediments from the Beaufort and Kara seas

| Sample no. | Station | Expedition | Environment | Elevation | Salinity | *Botryococcus* g$^{-1}$ | *Pediastrum* g$^{-1}$ | Desmidiaceae g$^{-1}$ | Zygnemataceae g$^{-1}$ | Dinoflagellate Cysts g$^{-1}$ | Pollen and spores g$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Beaufort Sea (Fig. 6) | | | | | | | | | | | |
| Richard Island Inactive Delta Front | | | | | | | | | | | |
| 1 | 24A | Ark91 | Polygon pond | 8 | 0 | 0 | 0 | 0 | 197 | 0 | 1542 |
| 2 | 24B | Ark91 | Basin lake | 6 | 0 | 63 | 63 | 0 | 253 | 0 | 4183 |
| 3 | 10B | Ark91 | Breached pond | 4 | 1 | 0 | 0 | 15655 | 388 | 259 | 5435 |
| 4 | 11C | Ark91 | Breached pond | 3.5 | 2 | 0 | 0 | 9894 | 371 | 124 | 10506 |
| 5 | 12C | Ark91 | Low saltmarsh | 1.5 | 5 | 0 | 0 | 822 | 617 | 0 | 44815 |
| 6 | 20A | Ark91 | Thermokarst lagoon | 1.5 | 9 | 0 | 0 | 435 | 0 | 0 | 25724 |
| 7 | 17A | Ark91 | Thermokarst lagoon | 1 | 9–29 | 153 | 697 | 0 | 77 | 77 | 11997 |
| 8 | 1A | Ark91 | Barrier high marsh | 2 | 5–30 | 0 | 350 | 0 | 0 | 0 | 38139 |
| 9 | 2A | Ark91 | Barrier high marsh | 2 | 5–30 | 0 | 0 | 0 | 64 | 0 | 312 |
| 10 | 3A | Ark91 | Barrier high marsh | 2 | 5–30 | 0 | 0 | 0 | 25 | 0 | 1021 |
| 11 | 1B | Ark91 | Barrier low marsh | 1 | 5–30 | 0 | 26 | 0 | 0 | 27 | 1757 |
| 12 | 2B | Ark91 | Barrier low marsh | 1 | 5–30 | 0 | 0 | 0 | 86 | 0 | 5319 |
| 13 | 6B | Ark91 | Barrier low marsh | 1 | 5–30 | 0 | 1108 | 0 | 0 | 277 | 47920 |
| 14 | 15A | Ark91 | Barrier low marsh | 1 | 5–30 | 0 | 24 | 0 | 49 | 0 | 1706 |
| 15 | 1C | Ark91 | Tidal flat | 0 | 5–30 | 0 | 24 | 0 | 16 | 16 | 792 |
| 16 | 6C | Ark91 | Tidal flat | 0 | 5–30 | 0 | 64 | 0 | 16 | 32 | 1865 |
| 17 | 7C | Ark91 | Tidal flat | 0 | 5–30 | 0 | 0 | 0 | 869 | 310 | 7123 |
| 18 | 91N19 | Nahidik | Nearshore | 2 | 5–30 | 0 | 357 | 0 | 357 | 1315 | 46663 |
| Active Delta | | | | | | | | | | | |
| 19 | 9101 | C91 | Outer channel | 0 | 0–5 | 0 | 0 | 0 | 71 | 284 | 7374 |
| 20 | 9105 | C91 | Middle channel | 0.5 | 0–5 | 0 | 0 | 0 | 0 | 0 | 7472 |
| 21 | 9106 | C91 | Inner channel | 0 | 0–5 | 0 | 0 | 0 | 0 | 0 | 11216 |
| 22 | 87N114 | Nahidik | Delta front | –2 | 5–15 | 15 | 5 | 0 | 15 | 65 | 70 |
| 23 | 87N04 | Nahidik | Plume front | –17 | 15–20 | 198 | 0 | 0 | n.d. | 491 | 1700 |
| Shelf | | | | | | | | | | | |
| 24 | Her18 | | Hershel Basin | –52 | 5–15 | 0 | 155 | 0 | 120 | 10 | 90 |
| 25 | 87N86 | Nahidik | Midshelf scour zone | –9.5 | 5–15 | 0 | 308 | 0 | 51 | 410 | 2565 |
| 26 | 87N56 | Nahidik | Midshelf scour zone | –8.9 | 5–15 | 0 | 0 | 0 | 0 | 1403 | 1737 |
| 27 | SK8211 | Sauvrak | Midshelf scour zone | –19 | 5–15 | 0 | 334 | 30 | n.d. | 365 | 5107 |
| 28 | S1A | Amauligak | Midshelf | –30 | 5–15 | 0 | 59 | 0 | 0 | 59 | 6844 |
| 29 | 82N07 | Nahidik | Outer shelf, trough | –75 | 5–15 | 0 | 0 | 30 | 0 | 638 | 912 |
| 30 | FNAT | Natiak | Outer shelf, trough | –48 | 5–15 | 51 | 153 | 0 | 102 | 1327 | 2092 |
| 31 | KPLF | Tarsiut | Outer shelf, pingo | –20 | 5–15 | 0 | 43 | 43 | n.d. | 3269 | 3356 |
| 32 | 144 | Tarsiut | Outer shelf, pingo | –58 | 5–15 | 0 | 0 | 0 | 87 | 2622 | 2360 |
| 33 | BNER | Nerlek | Outer shelf, pingo | –55 | 5–15 | 17 | 86 | 69 | 86 | 823 | 1372 |
| 34 | 9710 | SHEBA | Outer shelf, trough | –70 | 5–15 | 0 | 15 | 0 | 0 | 2059 | 920 |
| 35 | L99–2 | TNW99 | Outer shelf, trough | –33 | 5–15 | 0 | 363 | 91 | 0 | 9080 | 2906 |

*n.d.* No data; + above mean sea level; – below mean sea level

**Table 2** (continued)

| Sample no. | Station | Expedition | Environment | Elevation | Salinity | *Botryococcus* $g^{-1}$ | *Pediastrum* $g^{-1}$ | Desmidiaceae $g^{-1}$ | Zygnemataceae $g^{-1}$ | Dinoflagellate Cysts $g^{-1}$ | Pollen and spores $g^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Kara Sea (Fig. 8) | | | | | | | | | | | |
| Ob Transect | | | | | | | | | | | |
| 36 | 12 | BP97 | Estuary | –13 | 0–5 | 147 | 3182 | 236 | 0 | 301 | 4331 |
| 37 | 10 | BP97 | Estuary | –15 | 0–5 | 236 | 3380 | 419 | 0 | 341 | 8606 |
| 38 | 47 | BP97 | Estuary | –18 | 0–5 | 156 | 2671 | 182 | 0 | 78 | 3942 |
| 39 | 17 | BP97 | Estuary | –20 | 0–5 | 212 | 1635 | 135 | 0 | 404 | 3742 |
| 40 | 48 | BP97 | Estuary | –29 | 0–5 | 122 | 977 | 92 | 0 | 427 | 2770 |
| 41 | 49 | BP97 | Shelf | –29 | 5–10 | 70 | 961 | 14 | 0 | 752 | 4309 |
| 42 | 50 | BP97 | Shelf | –28 | 5–10 | 192 | 1317 | 48 | 0 | 1868 | 3952 |
| 43 | 52 | BP97 | Shelf | –30 | 10–15 | 97 | 1015 | 0 | 0 | 2635 | 2260 |
| Yenisei Transect | | | | | | | | | | | |
| 44 | 32 | BP97 | Estuary | –10 | 0–5 | 86 | 2244 | 1122 | 0 | 173 | 53991 |
| 45 | 35 | BP97 | Estuary | –14 | 0–5 | 58 | 1852 | 1042 | 0 | 116 | 80086 |
| 46 | 27 | BP97 | Estuary | –19 | 0–5 | 58 | 1544 | 772 | 0 | 251 | 18514 |
| 47 | 39 | BP97 | Shelf | –40 | 5–10 | 50 | 502 | 113 | 0 | 978 | 3872 |
| 48 | 21 | BP97 | Shelf | –41 | 10–15 | 35 | 555 | 81 | 0 | 728 | 2432 |
| Inner Kara Sea | | | | | | | | | | | |
| 49 | 42 | BP97 | Shelf | –32 | 10–15 | 35 | 164 | 0 | 0 | 456 | n.d. |
| 50 | 43 | BP97 | Shelf | –31 | 10–15 | 35 | 154 | 59 | 0 | 177 | n.d. |
| 51 | 19 | BP97 | Shelf | –30 | 10–15 | 0 | 848 | 0 | 0 | 2322 | n.d. |
| 52 | 46 | BP97 | Shelf | –27 | 10–15 | 71 | 389 | 71 | 0 | 2616 | n.d. |
| Gydanskii Transect | | | | | | | | | | | |
| 53 | 56 | BP97 | Estuary | –14 | 0–5 | 75 | 2387 | 25 | 0 | 224 | n.d. |
| 54 | 55 | BP97 | Estuary | –14 | 5–10 | 77 | 2145 | 96 | 0 | 441 | n.d. |
| 55 | 58 | BP97 | Shelf | –23 | 10–15 | 14 | 292 | 36 | 0 | 590 | n.d. |

*n.d.* No data; + above mean sea level; – below mean sea level ing desmidiacean (*Cosmarium*, *Staurastrum*) and zygnematacean algae (*Spirogyra*, *Gelinacysta*).

Acritarchs can be additionally abundant in the same environments (Mudie 1992; Kunz-Pirrung 1998). These organic-walled microfossils of uncertain biological affinity are not further considered in this study because it is uncertain whether they live in shelf environments or are transported in river water. The distribution patterns of some taxa (*Halodinium* spp., *Beringiella* spp., *Radiosperma corbiferum*, *Sigmopollis* spp.) suggest an authochthonous occurrence in freshwater delta ponds or inner shelf environments with reduced sea-surface salinities (Mudie 1992; Solomon et al. 1992; Kunz-Pirrung 1998).

For this study, the chlorophycean algae are identified only to genera except for specimens of *Botryococcus*. A more detailed taxonomy is not required because the green algae are considered to be transported into the marine environment. Most green algae live in freshwater environments, such as lakes, ponds, bogs, rivers and streams, although species of *Botryococcus*, *Pediastrum* and *Staurastrum* may be found in low-salinity environments (e.g. Tyson 1995; Matthiessen and Brenner 1996; Batten 1996; Batten and Grenfell 1996). Specimens of *Botryococcus* in recent sediments have commonly been assigned to *B.* cf. *braunii* (Matthiessen and Brenner 1996; Kunz-Pirrung 1998) because morphological features that are used to distinguish extant taxa may not be preserved on fossil specimens. Thus, several extant species of *Botryococcus* might be lumped in fossil specimens of *B. braunii* (Tyson 1995; Batten and Grenfell 1996). Basic taxonomic references for identification of species are Batten (1996), Batten and Grenfell (1996), Parra Barrientos (1979), Komárek and Fott (1983) and Head (1992, 1993). Useful reviews of the biology of the green algae are provided by Hoshaw and McCourt (1988), Head (1992), Gerrath (1993), Tyson (1995), Batten (1996), and Batten and Grenfell (1996). The recorded taxa have a largely cosmopolitan distribution and have been recorded from freshwater environments in the circum-arctic region (e.g. Croasdale 1973; Rawson 1956; Børgesen 1910).

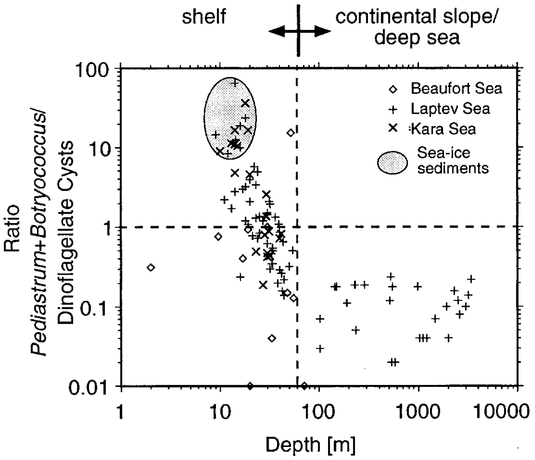


**Fig. 4** Ratio of *Pediastrum* spp. and *Botryococcus* cf. *braunii* to dinoflagellate cysts vs water depth in surface sediments from the Arctic Ocean. The range of ratios in sea-ice sediment samples is indicated

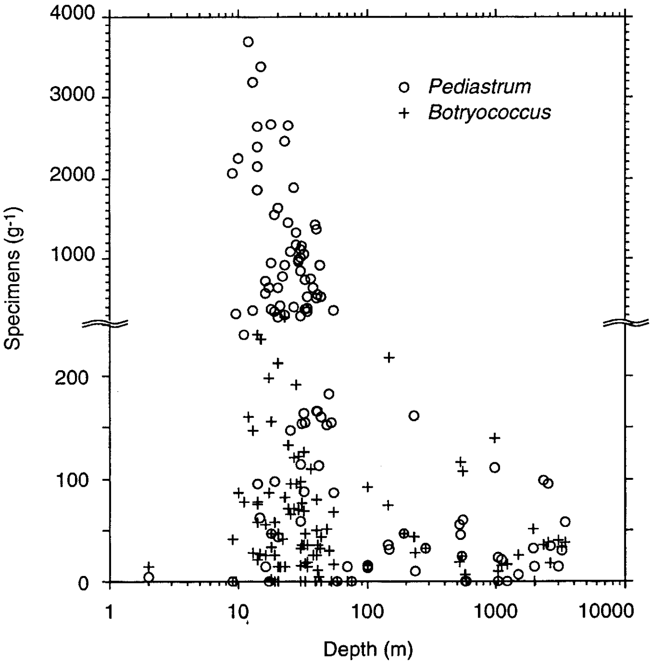


**Fig. 5** Sediment concentrations of *Pediastrum* spp. and *Botryococcus* cf. *braunii* vs water depth of samples in the Arctic Ocean

## *Distribution of chlorophycean algae in shelf sediments*

Species of *Pediastrum* and *Botryococcus* cf. *braunii* are almost ubiquitous in the Arctic shelf and delta samples. They may be more abundant than marine dinoflagellate cysts in water depths of <50–60 m, and they are rare to common in continental slope and deep-sea sediments (Fig. 4). Four sea-ice sediment samples collected from ice floes north of Svalbard (Fig. 1) have chlorophycean to dinoflagellate cyst ratios similar to inner shelf samples (7, 14, 45, 92). *Pediastrum* spp. (mainly *Pediastrum boryanum* and *P. kawraiskyi*) are generally more abundant than *Botryococcus* cf. *braunii*, and *Pediastrum* concentrations decrease from the shelves to the deep sea while *B.* cf. *braunii* is more uniformly distributed (Fig. 5).

Concentrations of *Pediastrum* spp. and *Botryococcus* (Figs. 6, 7, 8) are less than 500 specimens per gram of dry sediment in most shelf samples. Elevated concentrations are associated mainly with the rivers and extend from the river mouths offshore. This distribution pattern is most clear in the eastern Laptev Sea (Fig. 7) where >3000 specimens/g are found. In the Kara Sea, concentrations decrease similarly from the Ob and Yenisei estuaries to <500 specimens/g in

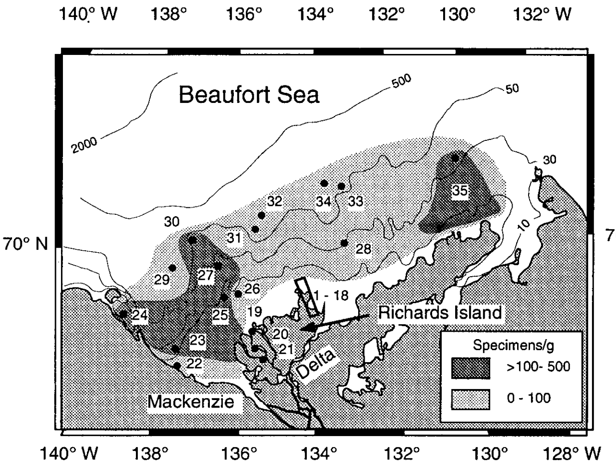


**Fig. 6** Sediment concentrations of *Pediastrum* spp. and *Botryococcus* cf. *braunii* in the Beaufort Sea. Additional data for various environments in the Mackenzie Delta (stations 1–18) are listed in Table 2. Depth contours in metres are indicated

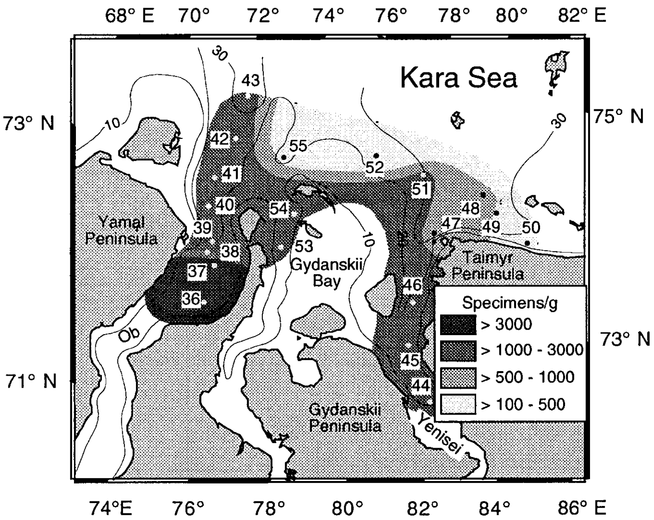
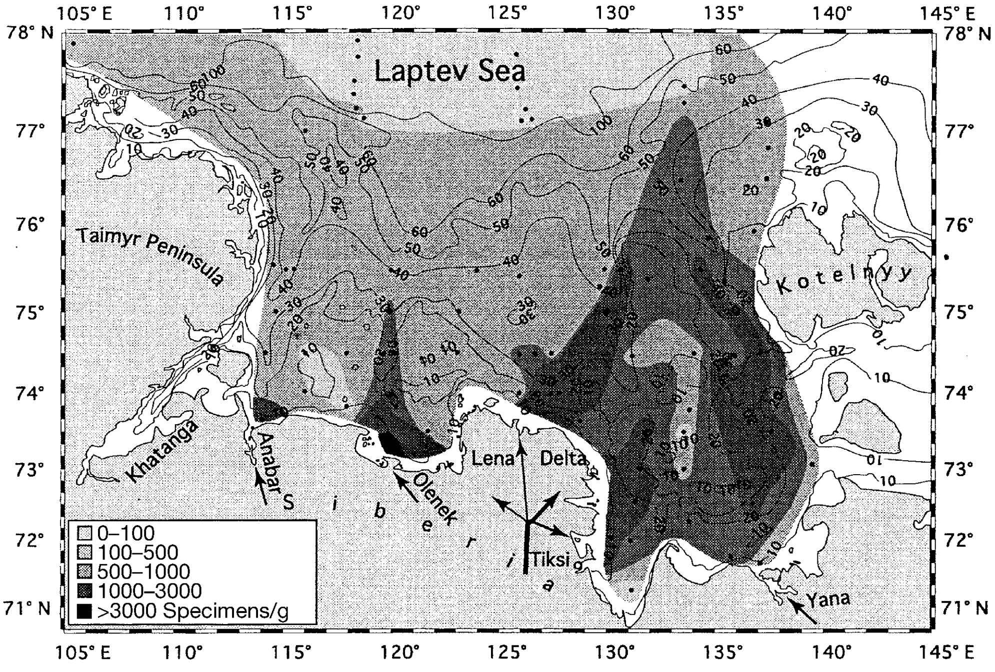


**Fig. 8** Sediment concentrations of *Pediastrum* spp. and *Botryococcus* cf. *braunii* in the Kara Sea. Depth contours in metres are indicated

the inner Kara Sea (Fig. 8). In the Beaufort Sea, concentrations are mostly low, with maximum of >100 specimens/g off the Mackenzie Delta (Fig. 6).

Palynomorph assemblages from freshwater ponds and lagoons in the Beaufort Sea region are marked by abundant desmidiacean algae (*Cosmarium* spp.), and common zygnematacean spores (mostly *Gelinacysta* and *Spirogyra*) characterise the intertidal assemblages (Table 2). Stations 1–21 are deltaic environments at or above extreme low water (set at 0 m in Table 2). Stations 22–35 are arranged roughly according to distance offshore. Deltaic environments are generally marked by very high concentrations of Quaternary pollen and terrestrial spores (>5000 grains/g), together with common green algae (>350 specimens/g). Samples 1 to 4 represent supratidal delta pond environments with little or no marine influence (Table 2) and are marked by abundant desmidiacean and zygnematacean algae. *Pediastrum* and *Botryococcus* are more common in larger barrier lagoons. Pollen concentrations are also high on the inner Beaufort Shelf, and dinoflagellate cysts become more abundant offshore. Concentrations of desmidiacean algae and pollen also decrease with increasing salinity in the Ob and Yenisei estuaries, and pollen are common in the inner Kara Sea. In con-

**Fig. 7** Sediment concentrations of *Pediastrum* spp. and *Botryococcus* cf. *braunii* in the Laptev Sea (from Kunz-Pirrung 1998). Depth contours in metres are indicated



trast to the delta environments, dinoflagellate cysts are consistently present in all shelf samples (Table 2).

## Discussion

Previous studies have shown that chlorophycean algae, such as *Botryococcus* and *Pediastrum*, are transported in river water into adjacent shelf environments and may even occur in low abundances in deep-sea environments (e.g. Tyson 1995, and references therein). The other recorded green algae are not of importance in Arctic shelf sediments but are highly diagnostic of deltaic and near-shore facies, and may be important for interpreting Holocene prodelta environments (e.g. Hill et al. 1985). The distribution patterns are interesting because *Pediastrum* and *Botryococcus* may be more abundant than marine dinoflagellate cysts in inner shelf sediments (Fig. 4). Despite the dominance of chlorophycean algae, however, the continuous presence of dinoflagellate cysts indicates some marine influence, even close to river mouths and in intertidal delta sites.

The distribution of freshwater palynomorphs in surface sediments from the Arctic seas does not simply reflect the source of river water discharge. In estuaries and deltas, large amounts of riverine sediments may be deposited, resuspended and transported with bottom currents or incorporated into sea ice. The remaining suspension load may be further dispersed by wind-driven currents and major flooding. Knowledge of the processes that influence the dispersal and sedimentation of riverine sediments in the shelf seas is therefore important for understanding the distribution patterns of freshwater palynomorphs.

## Transport of freshwater palynomorphs by rivers

The discharge of fresh water and sediments into the Arctic shelf seas is a seasonal process, occurring mainly in the short summers. The Beaufort, Laptev and Kara seas are usually ice-covered for 8–9 months per year (Macdonald and Thomas 1991; Reimnitz et al. 1994; Timokhov 1994; Pavlov and Pfirman 1995; Gordeev et al. 1996; Macdonald et al. 1998). The SPM in runoff may be discharged onto the ice in June/July because the ice breaks up earliest in the estuaries. These sediments are released mainly in place in the inner shelves during melting of the fast ice in the summer (Hill et al. 1991; Pavlov and Pfirman 1995; Pfirman et al. 1995; Bareiss et al. 1999).

Unfortunately, there are few data on occurrences of freshwater palynomorphs in the Arctic river discharge because they are reported only occasionally during plankton surveys (e.g. Druzhkov and Makarevich 1999). The chlorophycean algae *Pediastrum* spp., *Scenedesmus* spp. and *Botryococcus* cf. *braunii* occur in the plankton of the southeastern Laptev Sea, in particular close to the mouths of the rivers Lena and Yana (Kisselev 1932; Tuschling 2000). Reports of chlorophycean and desmidiacean algae in the Mackenzie River plume and in the Mackenzie River are also rare except in the Eskimo Lakes of the eastern delta (e.g. Hsiao 1976; Moore 1981). Plankton samples (mesh size >10 μm) from the surface water (0–2 m) in the outer Ob and Yenisei estuaries contained species of *Pediastrum* and *Scenedesmus* (Matthiessen and Boucsein 1999). The chlorophyll in the cells of numerous specimens of *Pediastrum* showed that they lived in the rivers or other limnic environments before being transported into the Kara Sea. These algae were most abundant in the river plume south of 73°N in the Ob and Yenisei estuaries in September 1997 where SPM and POC concentrations were high (Fig. 9).

It appears that the transport of freshwater algae is related to the supply of POM and POC. The estimated abundances of chlorophycean algae in the river plume of the rivers Ob and Yenisei are probably directly related to the SPM and POC concentrations in summer (Fig. 9). However, more water-column investigations are needed to prove the possible relationship between freshwater discharge, SPM, POC and concentrations of algae, and sediment trap data are needed to determine the seasonal cycles of freshwater algae influx in relation to sediment supply.

Sediment supply from the coastal regions may overprint this freshwater discharge signal significantly. In the Mackenzie Delta, fossilisable green algae are fairly abundant in different types of fresh and brackish water sediments (Table 2). These deposits could be eroded and the algae redistributed into the shelf seas. In the Beaufort Sea this contribution would be small because it amounts to less than 5% of the SPM discharge (Macdonald et al. 1998). This is also supported by sporadic occurrences of zygnematacean and desmidiacean algae in shelf sediments from the Beaufort Sea (Table 2). In contrast, coastal erosion could be an important source of SPM and POC in the Siberian shelf seas, being probably more important than river discharge (Rachold et al., 2000). However, the distribution patterns of *Pediastrum* spp. and *Botryococcus* cf. *braunii*, with highest concentrations extending off the river mouths, suggest a predominant riverine influx (Figs. 7, 8). The regular occurrence of fresh coenobia with chlorophyll in the surface waters of the estuaries and sediments of the Kara and Laptev seas also supports the assumption that primary riverine influx is more important for discharge of POM than coastal erosion (Kunz-Pirrung 1998; Matthiessen and Boucsein 1999). In contrast, fresh coenobia are rarely found in Beaufort Shelf environments.

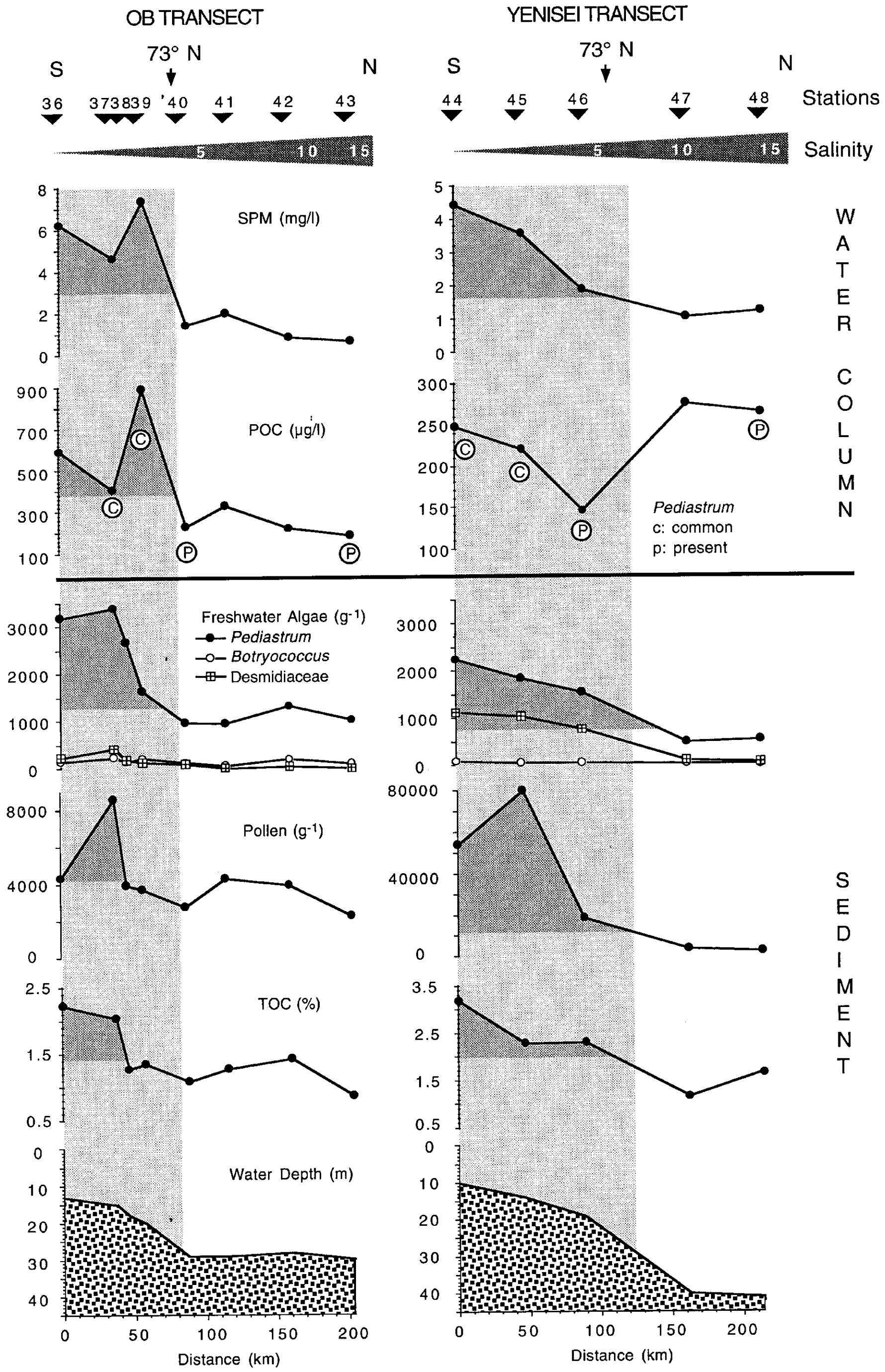


**Fig. 9** Distribution of selected palynomorphs in surface waters and surface sediments along the salinity gradient from the Ob and Yenisei estuaries to the Kara Sea. The riverine SPM and POC are predominantely deposited south of 73° N. Mean sea-surface salinities are from Burenkov and Vasil'kov (1995). The SPM and POC data are from Lukashin et al. (1999)

## Dispersal and sedimentation of freshwater palynomorphs in the shelf environments

The final distribution of green algae in the shelf sediments is the result of various sedimentary processes. Chlorophyte concentrations increase with increasing clay and silt contents (Fig. 10) showing that transport and sedimentation of green algae is associated with the settling of fine-grained sediments. Since TOC contents are positively related to the clay and silt fractions of sediments (Fig. 3), concentrations of green algae are also related to TOC contents (Fig. 11; see also Fig. 9). This relationship is not certain, however, because palynomorphs were only studied in the grain-size fraction larger than 6 μm; thus, finer organic matter that may account for some TOC is neglected. On the other hand, autochthonous production of organic matter is also included in bulk TOC contents. This is reflected by presence of dinoflagellate cysts, tintinnid loricae, ciliate cysts and organic linings of foraminifers (Kunz-Pirrung 1998, 1999; Matthiessen 1999; Solomon et al., 2000).

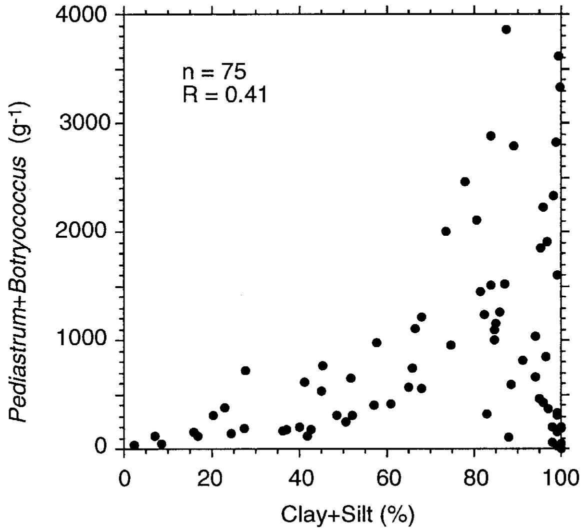


**Fig. 10** Sediment concentrations of *Pediastrum* spp. and *Botryococcus* cf. *braunii* vs clay and silt contents in Beaufort, Laptev and Kara sea shelf sediments (<60 m water depth). The linear correlation coefficient is indicated

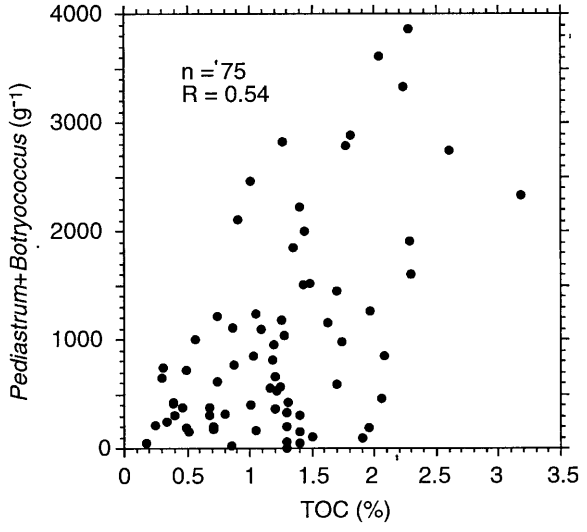


**Fig. 11** Sediment concentrations of *Pediastrum* spp. and *Botryococcus* cf. *braunii* vs TOC contents in the Beaufort, Laptev and Kara sea shelf sediments (<60 m water depth). The linear correlation coefficient is indicated

The concentration gradients suggest that deposition of chlorophycean algae is higher in the zone where riverine and marine waters mix (Figs. 7, 8, 9). Therefore, maximum concentrations of *Pediastrum* and *Botryococcus* may indicate the average location of the mixing zones ("marginal filter" of Lisitsyn 1995) where most riverine sediments are deposited. In this zone, biogeochemical and physical properties of waters change leading to a flocculation of colloids and particulates and adsorption of dissolved elements (see Tyson 1995, and references therein).

The distribution of chlorophycean algae appears to match the mean distribution of the river plumes as reflected in the salinity gradient of the Laptev Sea (compare Figs. 1, 7). Dispersal of fluvial SPM in a thin surface layer (<10 m) is highly variable, but it is usually transported further offshore (up to 500 km) in the eastern region off the Lena Delta than in the western Laptev Sea because of stronger discharge and prevailing offshore currents (Timokhov 1994; Burenkov et al. 1997). Based on this assumption, the Lena and Yana plumes clearly stand out against the other river plumes. The relatively low chlorophycean algae concentrations in sediments underlying the central part of the plume reflects dilution by the higher amount of coarse-grained sediments.

In contrast, there is not a close correspondence between sediment plume and algal distribution off the Khatanga River (Fig. 7). This might reflect either the coarse sample coverage in the estuarine environment or low abundances of *Pediastrum* and *Botryococcus* in the Khatanga River and the freshwater environments of its catchment area (Kunz-Pirrung 1998).

In the sediments from the Ob and Yenisei estuaries, concentrations of chlorophycean algae, pollen and TOC contents decrease rapidly along the salinity gradient in the outer estuaries (Fig. 8, 9); thus, a large part of the riverine POM is deposited at low salinities (Fig. 9; <5 psu, see Lukashin et al. 1999), as also indicated by the strong gradient in particle fluxes offshore (Lisitsyn et al. 1995). The sharp decrease of palynomorphs also indicates that, on average, the river plumes are confined to the coastal zone in the Kara Sea south of ca. 74°N, as shown by turbidity and diatom data (Burenkov et al. 1995; Polyakova 1999).

In the Beaufort Sea there is a strong decrease in chlorophycean and desmidiacean algae across the outer Mackenzie Delta, from supratidal ponds to intratidal flat environments (Solomon et al. 1992, 2000). The freshwater plume, with high concentrations of SPM, may extend over much of the shelf, but is most persistent east of the delta (Hill et al. 1991). The distribution of the chlorophycean algae do not reflect this trend clearly (Fig. 6). This may partly reflect the low sample coverage in the coastal zone, which includes the mean location of the river plume. Chlorophycean algae, however, are not abundant in the tributaries of the Mackenzie River and lakes of the delta and hinterland (Hsiao 1976; Moore 1981; Table 2) which suggests a lower influx of chlorophycean algae in river water. Also, POC makes up less than 5% of SPM of the Mackenzie River (Macdonald et al. 1998), being highly diluted by inorganic sediment; therefore, concentrations of freshwater algae might be much lower in the SPM of the Mackenzie River than in the rivers entering the Kara and Laptev seas.

## Resuspension of bottom sediments and palynomorphs

The primary distribution patterns of freshwater algae may be blurred by various processes. In shallow parts of the shelf and coastal areas, sediments and chlorophycean algae are easily resuspended by waves and tidal currents. Maximum wave heights during storms in the Beaufort, Kara and Laptev seas are in the range of 4–6 m (Hill et al. 1991; Are 1996; Timokhov 1994; Pavlov and Pfirman 1995). Resuspension of sediments results in the formation of a bottom nepheloid layer which has high concentrations of SPM and POC, similar to the surface water plume, in the Laptev and Kara seas (e.g. Aleksandrova and Shevchenko 1997; Burenkov et al. 1995; Burenkov et al. 1997; Kuptsov et al. 1999). The resuspended sediments might also be preferentially transported in the submarine channels which are the main depocentres of muds (e.g. Kuptsov and Lisitsyn 1996; Kuptsov et al. 1999). Thus, the high concentrations of freshwater algae might not only reflect settling from the surface plume but also resedimentation from the bottom nepheloid layer in the channels (Figs. 6, 7, 8).

High saline brines released from the sea surface during ice formation may also trigger sediment transport in the bottom nepheloid layer in autumn to winter (Lisitsyn 1995). The brines and resuspended sediments flow along the submarine channels to the shelf break and transport the sediments into the deep sea. Resuspended sediments may be also incorporated in the ice cover of flaw leads and transported offshore (Pfirman et al. 1995). The bulldozing of sediment by ridge ice scour and further current transport of the resuspended sediments may affect the Beaufort shelf in water depths of 15–45 m (Macdonald and Thomas 1991). This process is probably negligible in the Laptev and Kara seas.

## Transport of sediments and freshwater palynomorphs by sea ice

Resuspended sediments and freshwater algae may be exported from the circum-Arctic shelf seas not only along the submarine channels but also in newly formed sea ice (e.g. Nürnberg et al. 1994; Mudie 1992; Dethleff et al., 2000). The ice is formed mainly in the shallow parts of the shelves (<30 m; Fig. 1); hence, the sediments incorporated in newly formed sea ice should be similar to inner shelf sediments (cf. Reimnitz et al. 1992, 1998). Sedimentological and palaeontological data have been used to define the geographic location and facies of source areas, e.g. sea ice in the western Beaufort Sea contain shallow water microfossils such as diatoms, benthic foraminifers, molluscs and ostracods, and high percentages of the clay mineral illite (Reimnitz et al. 1992, 1993a, 1993b, 1998).

The composition of sediments in sea ice of the central Arctic Ocean allows the reconstruction of transport pathways. For example, sediments from ice floes in the Siberian Branch of the Transpolar Drift north of Svalbard which contained high abundances of the clay mineral smectite (>40%; Nürnberg et al. 1994; Dethleff et al., 2000) and planktic freshwater diatoms (>70%; Abelmann 1992) were tracked back to the inner Kara Sea off the rivers Ob and Yenisei by Pfirmann et al. (1997). Freshwater palynomorphs are an additional tool to reconstruct facies of source areas of sea-ice sediments. The chlorophyte to dinoflagellate cyst ratio of four sediment samples (7, 14, 45, 92) from ice floes which were collected north of Svalbard (Fig. 1) close to those with a high smectite content (Dethleff et al., 2000) suggest a shallow water origin (<30 m; Fig. 4). Possible source area is the inner Kara Sea because bottom sediments from the estuaries of Ob and Yenisei have a unique composition for the Eurasian Arctic shelfs with higher abundances of both freshwater palynomorphs and smectite (Schoster et al., 2000; Dethleff et al., 2000) confirming the ice drift reconstruction of Pfirman et al. (1997). Abundant Quaternary pollen and moss leaves in sea-ice sediments in the Eastern Arctic Ocean also suggest that the shallow shelves are the source areas (Pfirman et al. 1989).

The occurrence of displaced freshwater palynomorphs in deep-sea sediments may therefore be easily explained as a result of sea-ice transport (cf. Mudie 1992; Matthiessen 1995; Kunz-Pirrung 1998, 1999). Previous investigations have shown that *Pediastrum* is an important component in recent deep-sea sediment assemblages from the Gakkel Ridge below the present Polar Branch of the Transpolar Drift (Mudie 1992). The relatively low smectite and high illite contents in both sea ice and surface sediments in this region suggest the eastern Laptev Sea as source area (Schoster et al., 2000; Dethlef et al., 2000). In the Pleistocene, increased *Pediastrum* on the Alpha Ridge may also indicate greater runoff and transport in sea ice (Mudie 1985).

## Conclusion

The marginal shelf seas of the Arctic Ocean (Beaufort, Laptev and Kara seas) are characterised by the common occurrence of organic-walled freshwater algae in bottom sediments. Among other chlorophycean algae, *Pediastrum* spp. and *Botryococcus* cf. *braunii* are the most conspicuous freshwater taxa in the marine palynomorph assemblages, usually being more abundant than marine dinoflagellate cysts in sediments from shallow depths and below delta plumes. The distribution of these algae is clearly related to the discharge of fresh water and suspended matter by the large rivers into the shelf seas. Relatively high concentrations of algae may extend from the river mouths over 100 to 500 km offshore, e.g. in the eastern Laptev Sea and may mark the average distribution of the river plumes.

There are few observations on transport, dispersal and depositional processes, because these chlorophycean algae are usually not counted during routine water-column studies. The supply of these algae is probably a seasonal signal and might be attributable to the peak discharge of fresh water and sediments, including the particulate organic matter load, during the summer months. Because concentrations correlate with the clay and silt fractions, freshwater algae are probably dispersed mainly with the fine-grained sediments supplied by the rivers. Dispersal of the algae appears to be controlled by surface circulation, which is wind driven, and by the intensity of freshwater discharge. Highest concentrations in bottom sediments are found where fresh water mixes with marine water and most riverine SPM is deposited. The distribution of the chlorophycean algae, grain size data and TOC contents suggest that most riverine SPM is deposited on the shelves; however, additional studies are required to verify these proposed relationships between freshwater discharge, sediment supply and organic carbon load.

The primary distribution patterns of freshwater palynomorphs in sediments may be blurred by the resuspension of sediments by waves and bottom currents, by ice-ridge scouring in the Beaufort Sea and by export of sediments from the shelves in sea ice. Resuspended sediments might be preferentially transported in the bottom nepheloid layer and in the large submarine channels. These channels cross the shelves and may act as transport pathways for resuspended sediments to the continental slope. During freeze-up in autumn, and sea-ice formation in winter, freshwater palynomorphs may be incorporated into sea ice and transported by the Transpolar Drift into the central Arctic Ocean. The occurrence of *Pediastrum* and *B.* cf. *braunii* in sea-ice sediments and bottom sediments from the Arctic Ocean confirms previous observations that sediments are frozen into sea ice in the shallow inner shelves; therefore, these algae might be another valuable indicator for the facies of source regions of sea-ice sediments.

Freshwater palynomorphs are thus both useful tracers of river runoff and SPM supply, allowing application for reconstructing palaeo-river discharge and also for the determination of source areas of sea-ice sediments.

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