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Diatoms as quantitative paleodepth indicators in coastal areas of the southeastern Beaufort Sea, Arctic Ocean

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Abstract

Surface sediment diatom assemblages in depth profiles along the southeastern Beaufort Sea coasts (Canada) were analysed to describe the relationship between species distribution and water depth of deposition. The 74 coastal stations sampled were distributed in several sedimentary environments, from salt marshes to the inner shelf. The relationship between diatom species distribution and water depth was examined using canonical correspondence analysis (CCA) and partial CCA. The water depth accounted for 9.7% of the variance in the data set. The diatom/water-depth relationship is believed to be controlled by the shoreface circulation which results in a shift in the relative abundance of the epipsammon, epipelon, and plankton along the water depth gradient. Upper shoreface assemblages are dominated mainly by epipellic species and a few number of epipsammic taxa, whereas deeper environments are dominated by planktonic species. A transfer function was derived using weighted averaging regression and calibration to reconstruct the water depth of deposition over the coastal interval from mean sea level to a maximum of 14 m depth on the coastal shelf of the southeastern Beaufort Sea. The transfer function allows relative sea level to be predicted from fossil diatom assemblages with a root mean square error of 1.43 m. This model is likely to produce reliable water depth inferences along the southeastern Beaufort Sea coasts and in other shallow sandy microtidal environments dominated by low energy waves and influenced by freshwater discharge. The transfer function was used to provide quantitative paleodepth inferences for late Holocene sediments from the Atkinson Point area based on fossil diatom assemblages. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Diatom analysis has been widely used at the interface of fresh and saline environments to identify lake isolation from the sea in areas of land up-

lift (e.g. Alhonen, 1971; Florin, 1977; Stabell, 1980, 1985, 1987; Kjemperud, 1981, 1986; Lie et al., 1983; Björck and Digerfeldt, 1986; Young and King, 1989; Williams, 1990; Pienitz et al., 1991; Wassell and Håkansson, 1992; Douglas et al., 1996), or to indicate marine and brackish water transgressions (e.g. Foged, 1970; Schaffel, 1971; Kabailiene, 1974; Digerfeldt, 1975; Alhonen et al., 1978; Denys, 1985;

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Long et al., 1996; Zong and Tooley, 1996). However, the potential for using diatom assemblages to quantitatively reconstruct past sea-level changes has rarely been explored, mainly because the distribution optima of individual taxa with respect to water depth are poorly documented. By determining the relationship between water depth and diatom species abundances in modern environments, diatom assemblages can be used to quantitatively infer past relative sea levels. This approach consists in collecting a set of surface samples covering the same range of water depths as represented by the fossil material. Fossil assemblages may then be compared with this set of modern samples using statistical techniques to derive a numerical function describing the response of taxa to water depth. The resulting transfer function may then be used to estimate past relative sea levels from fossil assemblages. This procedure has been applied to reconstruct past changes in lakewater pH and related variables (e.g. Birks et al., 1990), lake and estuarine salinities (e.g. Fritz et al., 1991; Juggins, 1992; Wilson et al., 1997) and lake phosphorus concentrations (e.g. Fritz et al., 1993) among others.

The development of a water depth transfer function is based on the assumption that the water depth is related to ecologically important variables in aquatic environments. In North American lakes, qualitative and quantitative differences between benthic diatom assemblages at different depths were reported by Stoermer (1968, 1975), Duthie and Sreenivasa (1972), Stevenson and Stoermer (1981), Kingston et al. (1983) and Yang and Duthie (1995). The latter authors have developed a transfer function to infer Holocene Lake Ontario water levels from fossil diatoms and found a good correlation ($r^2 > 0.9$) between measured and inferred water depth over the range 3 to 30 m. In coastal environments, studies conducted in the Baltic and North seas have shown qualitative differences in the vertical distribution of attached diatoms between the supralittoral, littoral, and sublittoral zones (Aleem, 1950; Simonsen, 1962; Edsbacke, 1965). In Antarctic fjords, Whitehead and McMinn (1997) observed five diatom depth zones between 0 and 35 m. The strongest diatom/water-depth relationship was observed in the intertidal zone along the North American and English coasts, in which intertidal diatoms showed well defined vertical zonations (e.g. Nelson and Kashima,

1993; Hemphill-Haley, 1995; Shennan et al., 1995, 1996; Zong, 1997). However, despite these efforts, no quantitative model has been developed to infer past sea levels.

In the Beaufort Sea, Vilks et al. (1979) made an attempt to assess paleodepth by calculating the weighted-averaged depth at which foraminiferal and molluscan species occur along the continental shelf. The inferred and measured water depths were significantly correlated. However, in shallow water the calculated depths were greater than the actual depths. The over-estimation of shallow depths both for molluscs and foraminifera indicated that distinct shallow water species were missing, and that species found at the shallowest localities were also important in the sediments of the inner shelf. Due to these discrepancies between the inferred and measured water depths, the paleodepth determinations conducted in core intervals were not conclusive and comparisons between molluscan and foraminiferal data showed little agreement. As a consequence of the lack of precise paleodepth determinations, reconstructions of past sea-level fluctuations in the Beaufort Sea area have been based mainly on radiocarbon dating of Holocene peats deposited in transgressed thermokarst lakes, freshwater ponds and salt marshes (Hill et al., 1985, 1993). In these studies, the assessment of the suitability of a sample for radiocarbon dating and the interpretation of the sedimentary environments have been accomplished mostly by means of palynological analysis and by counting of aquatic microflora, such as freshwater desmids, charophytes, freshwater ostracods and euryhaline dinoflagellates. With the exception of dinoflagellates, most of these indicators are present in environments well above the sea level and therefore provide little information on the position or the proximity of the shoreline. Diatoms could provide more accurate information in reconstructions of sea-level changes in the Beaufort Sea as they are present in most habitats (from lakes and peatlands to the open sea), and because they are sensitive to changes in salinity and water depth.

The objective of this paper is to assess the use of diatoms as quantitative indicators of past relative sea levels by identifying diatom species distribution optima with respect to the water depth of deposition, and to develop a transfer function for paleodepth inferences from fossil diatom assemblages.

2. The southeastern Canadian Beaufort Sea coasts

2.1. The Tuktoyaktuk Coastlands

The Beaufort Sea is the southernmost part of the Arctic Ocean. The southeastern Beaufort Sea is bordered by the Tuktoyaktuk Coastlands which are part of the Arctic coastal plain between the Mackenzie Delta and Amundsen Gulf (Rampton, 1988), and comprise the Tuktoyaktuk Peninsula and Richards Island (Fig. 1). The southwestern part of the Tuktoyaktuk Peninsula is primarily formed of ice-contact deposits, moraines or morainal veneer overlain by lacustrine sediments of Holocene age, while the northeastern part consists of glacial outwash sands which are in places covered by eolian or lacustrine sediments (Rampton, 1988). Richards Island forms an upland area between two of the major distributary channels of the Mackenzie River. The surficial geology of the island consists mainly of Wisconsinan

glaciogenic deposits covered in places by Holocene lacustrine sediments (Rampton, 1988).

The climate of the southern Beaufort Sea coastlands is characterized by short cool summers and long harsh winters. The mean annual temperature at Tuktoyaktuk is -10°C . Precipitation is low, with an annual mean of 142 mm, roughly half of which is accounted for by winter snowfall (Environment Canada, 1993). Cold climatic conditions during the Pleistocene have led to the formation of permafrost throughout the region. Permafrost is widespread beneath land areas, ranging from 200 to 500 m in thickness on the Tuktoyaktuk Peninsula, and over 700 m on Richards Island (Judge et al., 1987). Much of the topography in the area can be attributed to the presence of subsurface ground-ice. Thermokarst, which is the process of ground-ice melting and the accompanying collapse of the ground surface to form depressions, has been an active process during the Holocene and the latter part of the late Wisconsinan (Rampton, 1988). Thermokarst lakes cover about

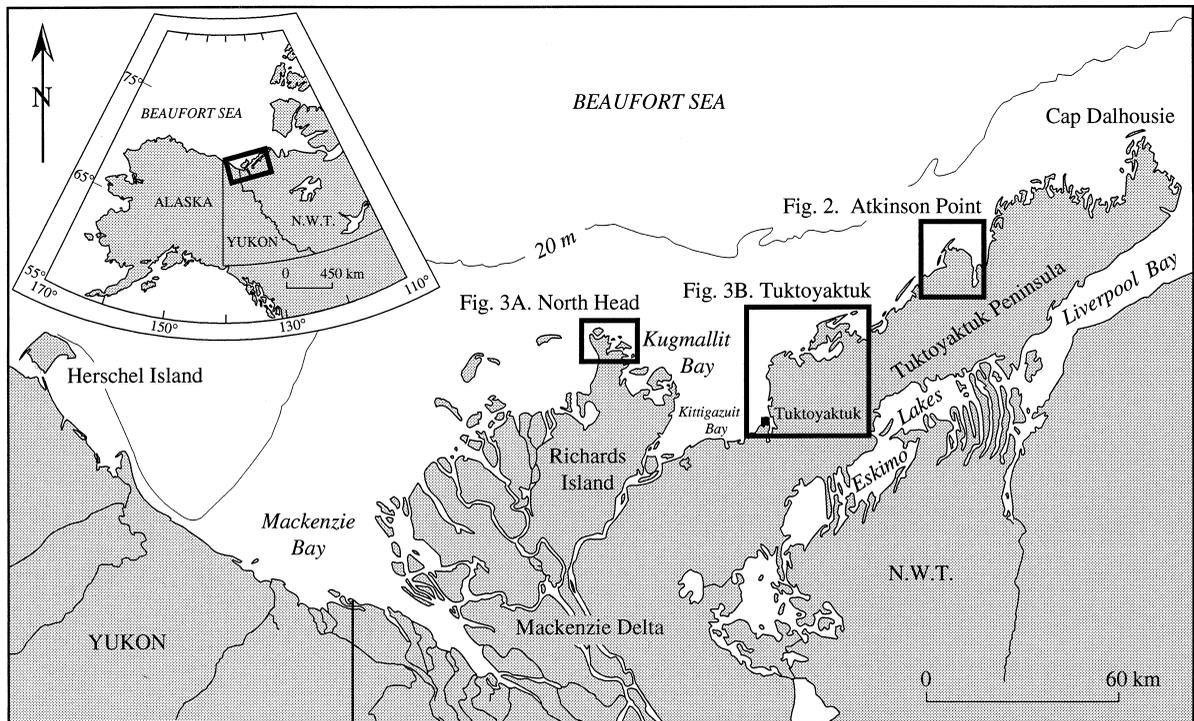


Fig. 1. The southeastern Beaufort Sea.

35% of Richards Island and the Tuktoyaktuk Peninsula, and nearly 70% of the northeastern part of the peninsula.

The coastal areas of the Tuktoyaktuk Peninsula and Richards Island are generally low lying with local relief less than 30 m. The coast consists mainly of bluffs developed in ice-bonded Quaternary sediments, and of barrier islands and spits enclosing, partially or completely, lagoons and embayments formed by the breaching of thermokarst lakes. Spits and barrier islands form approximately 30% of the length of the coastline east of the Mackenzie Delta (Harper, 1990). Héquette and Ruz (1991) calculated that barrier islands migrate onshore at a mean rate of 3.1 m yr^{-1} while spits are retreating at an average rate of 1.7 m yr^{-1} . On northern Richards Island, the coastline comprises a complex system of protected embayments, exposed headlands, and localized depocentres including spits and platforms. Coastal erosion of exposed headlands may exceed 5 m yr^{-1} , but other areas, such as the western shoreline of Richards Island, have been stable for the past 50 years. Causes of the widespread coastal retreat along the southeastern Beaufort Sea include: (1) wave-induced erosion; (2) thermal erosion (Harper, 1990); and (3) the ongoing relative sea-level rise (Hill et al., 1993).

The Canadian Beaufort Shelf extends offshore to 60–100 m water depth and is characterized by a very gentle gradient. The area is divided into three distinct physiographic regions: the narrow western shelf adjacent to the U.S. border, the Mackenzie Trough, and the broad eastern shelf. The fine surficial sediments (silts and clays) of the inner shelf are mainly derived from deposition of suspended sediments from the Mackenzie River.

The Tuktoyaktuk Coastlands are covered by low Arctic tundra vegetation. Upland sites are dominated by dwarf shrubs and lichens, whereas poorly drained peaty areas show ice-wedge polygon and frost hummock development with dominance by *Eriophorum vaginatum* and *Carex* stands (Corns, 1974). Sedge tussock flats occur around many lakes, on the bot-

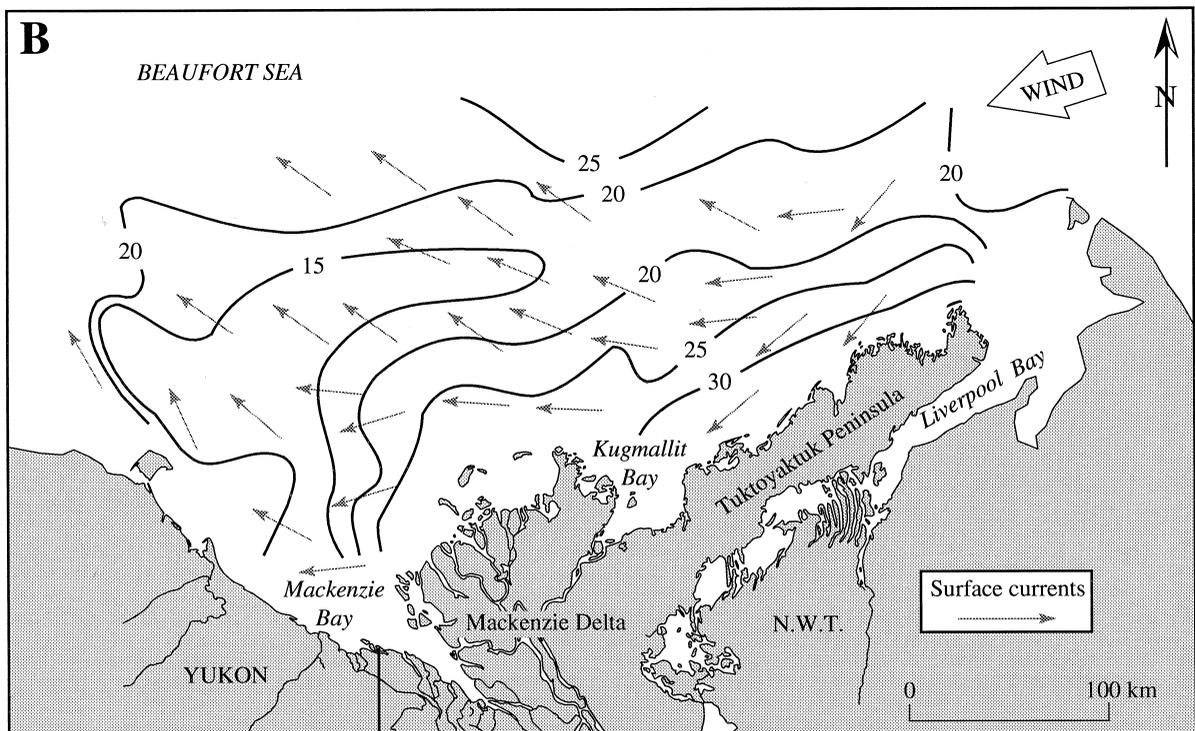
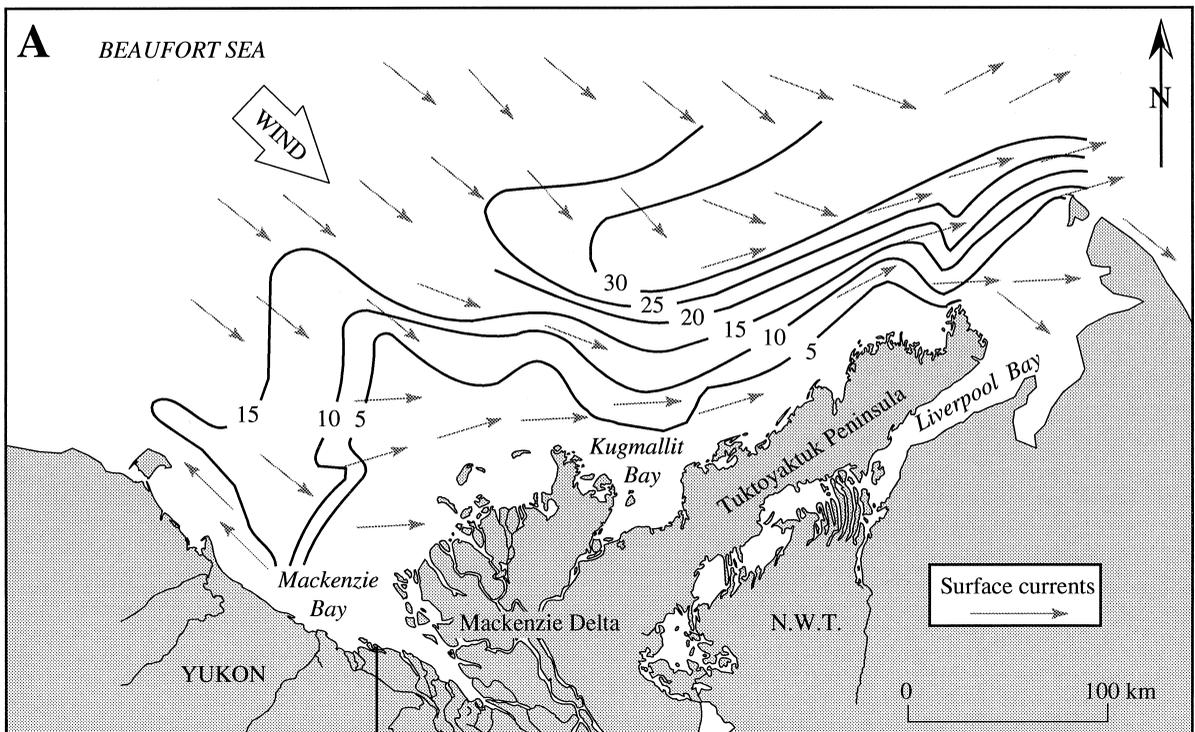
tom of drained lakes and along coastal lowlands (Mackay, 1963).

2.2. Coastal oceanography

The Mackenzie River represents a major influence on the oceanography of the shallow Beaufort Sea. During the summer months, its outflow introduces large quantities of freshwater into the sea influencing the physical and chemical properties of surface waters. The plume often extends completely across the shelf to the edge of the pack-ice during the open-water season (Harper and Penland, 1982). Temperature and salinity distribution patterns indicate relatively warm, low-salinity water flowing outward from the river mouth over colder, more saline water. The low salinity of the water creates a permanent pycnocline over the delta during summer months. Generally, the pycnocline decreases in depth in an offshore direction. Plume thickness, as defined by the pycnocline depth, can vary from 2 to 10 m. The water chemistry along the southeastern coasts depends mostly on the flow direction of the Mackenzie River plume, which in turn is controlled by surface winds. Under northwesterly winds, the surface and bottom currents set to the east and the Mackenzie River plume is deflected to the east along the Tuktoyaktuk Peninsula (Fig. 2A; Milne and Herlinveaux, 1977). Under easterly winds, a reversal in shelf circulation may occur and the position of the plume may shift further to the west (Fig. 2B). Consequently, the Tuktoyaktuk Peninsula coasts are subjected to strong water chemistry fluctuations. Under the influence of the plume, the salinity of the surface water tends to decrease and the supply of dissolved organic carbon (DOC) increases. Significant salinity fluctuations are also induced by the formation and melting of sea ice.

The Mackenzie River also acts as the major contributor of sediment to the southern Beaufort Sea system, contributing over 95% of the total (Harper and Penland, 1982). Annual sediment input is estimated at $150 \times 10^6 \text{ t}$, most of which is silt and clay

Fig. 2. Summer surface currents and salinities (‰) under northwesterly winds (A) and easterly winds (B) [after MacNeill and Garrett (1975) and Milne and Herlinveaux (1977)]. Note the deflection of the Mackenzie River plume along the Tuktoyaktuk Peninsula under northwesterly winds (A).



(Davies, 1975). The prodelta is thought to be the principal sediment sink with the major portion of the sediment being deposited in shallow water near the delta and lesser amounts distributed across the shelf (Harper and Penland, 1982).

The coastal ice regime is marked by four 'seasons': open water, freeze-up, winter and break-up. Coastal ice forms and becomes intermittently stationary during the freeze-up season, usually from October to mid-December. The winter season, usually from mid-January through May, is characterized by stable coastal ice (fast ice). The break-up season from June to mid-July is associated with deterioration of the fast ice. This period is followed by the open water season, from mid-July to early October. During the open-water season, winds originate mainly from the east, southeast and northwest quadrants. Storm winds ($>40 \text{ km h}^{-1}$) are usually from the northwest. The presence of sea ice during eight to nine months limits wave activity during most of the year and, even during the open-water season, wave generation is limited by the fetch-restricting pack ice. As a result, the Beaufort Sea is a moderate wave-energy environment and nearly 80% of deep-water waves are less than 1 m in height (Harper and Penland, 1982).

Tidal range is small in the Canadian Beaufort Sea. Typical ranges are 0.3 m for neap tides and 0.5 m for spring tides. Tidal currents are slow with velocities of less than 0.15 m s^{-1} for $>90\%$ of the time at most stations (Huggett et al., 1975, 1977; Fissel and Birch, 1984). In shallow waters, wave-induced currents are typically on the order of 0.5 m s^{-1} . Bottom currents in deeper waters ($>20 \text{ m}$) are much lower, typically less than 0.3 m s^{-1} (Anon, 1982). Storm surges are known to be significant in the Beaufort Sea. Surveys of log debris lines stranded on the tundra during these storm events indicate surge elevations up to 2.4 m above mean sea level in the Tuktoyaktuk area (Harper et al., 1988).

Forbes (1980) suggested that the relative sea level (RSL) of the Beaufort Sea has been rising over the last 15 ka. Hill et al. (1985) reported a number of additional ages and proposed a late Quaternary sea-level curve for the Canadian Beaufort Sea. According to this curve, the RSL rose from -140 m at 27 ka B.P. to a relative highstand of -40 m at approximately 15 ka B.P. and was then lowered to

a late Wisconsinan lowstand of -70 m . During the Holocene, the RSL rose from -70 m to its present position. The rate of RSL rise during the Holocene was further investigated by Hill et al. (1993). During the early Holocene, this rate was on the order of 4 to 5 mm yr^{-1} , and then increased to 7 to 14 mm yr^{-1} during the mid-Holocene. Over the last 3 ka, the rate of RSL rise slowed markedly. Recent radiocarbon dates on peats from modern coastal marshes on the Tuktoyaktuk Peninsula also suggest a slow rise in sea level during the last 1 ka (Hill et al., 1990). Although not statistically significant, tide-gauge data from Tuktoyaktuk suggest that relative mean sea level is still rising at a rate of about 1 mm yr^{-1} (Forbes, 1980). All these data suggest that the RSL of the Beaufort Sea has risen at a rate between 1.0 and 4.4 mm yr^{-1} during the late Holocene, but more precise data from coastal environments are required to determine if the RSL has risen, and is still rising, at or faster than the world average eustatic rate as determined by satellite altimeter data and tide gauge observations ($1\text{--}2 \text{ mm yr}^{-1}$; Gornitz, 1995; Nerem et al., 1997).

3. Methods

3.1. Surface samples

Surface sediment samples were collected at 74 stations along the southeastern Beaufort Sea coasts (Figs. 3 and 4). Sampling was assisted by using a 200 kHz depth recorder (Raytheon Fathometer[®]). The environmental raw data for the 74 sampling sites are given in Table 1, along with their coordinates, dates and techniques of sampling. Samples 1 to 59 and samples 61 and 62 were collected by the authors in July, August and September between 1987 and 1993. The remaining samples were collected by the Bedford Institute of Oceanography (Geological Survey of Canada) in April and July 1995. Surface grabs or top core sediments were collected. A Livingston coring system was utilized in the cases where sediments were unbonded and when they were anticipated to be very soft and highly organic (e.g. in breached lake basins). A portable vibracoring system was used in locations where sediments were unbonded and firmer than could be penetrated by the Livingston system.

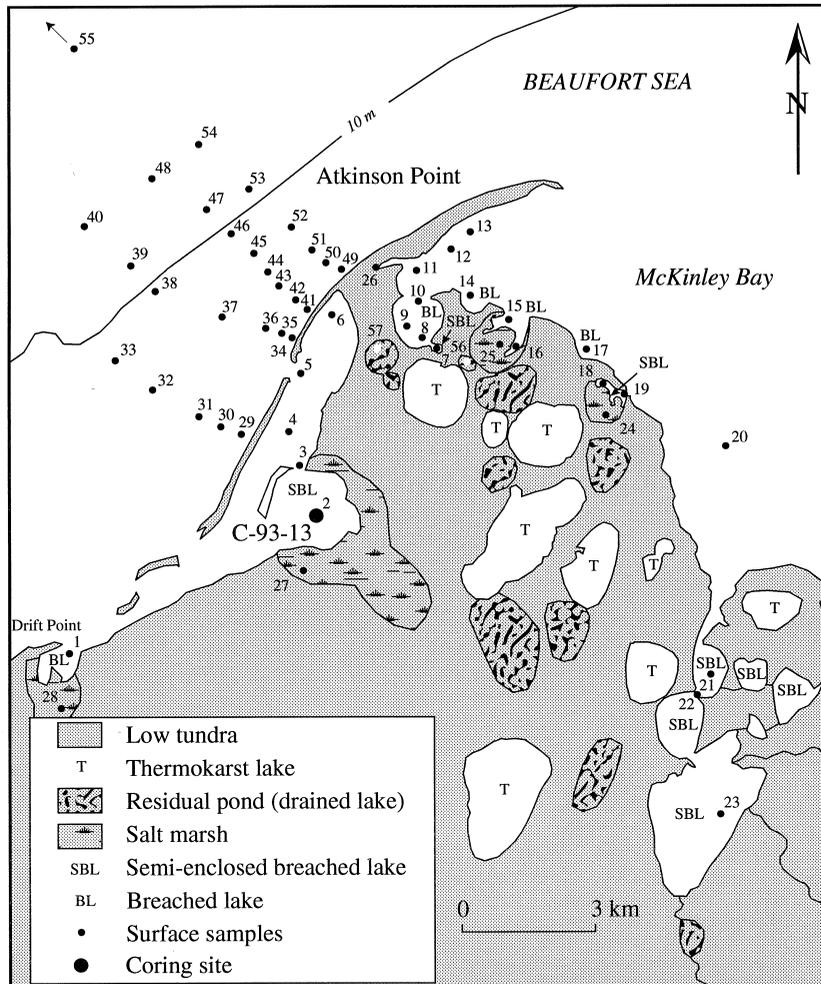


Fig. 3. The Atkinson Point area and location of sampling and coring sites.

Ice-bonded material was collected using a CRREL auger system with a Stihl power head mounted on a Winke Unipress drill stand.

The term 'surface sediments' is somewhat ambiguous. In this study, 'surface sediments' is used as a generic term to represent recent sediments collected between 1987 and 1995. In deep ocean studies, surface samples are usually those taken from the upper 1 to 2 cm of cores or surface grabs. These samples can represent a time span of 500 years or more (Maynard, 1976). In lake studies, surface samples are usually those taken from the upper few millimetres of cores which may represent a time span of one or a few growing seasons. Rao and

Lewin (1976) demonstrated that living epipelagic taxa in coastal environments are confined mostly to the upper 20 mm of surface sediments, whereas living epipsammic taxa may be found to depths of 180 mm. Furthermore, coastal environments have highly variable sedimentation rates depending on a number of factors, such as the rate of sediment supply and storm activity. A single storm, for example, may remove or deposit a layer of a few centimetres of sand. Consequently, the upper 2 to 5 cm of sediment in cores or surface grabs was used in this study. These surface sediments likely contain a time-averaged assemblage composed of diatoms deposited during a number of discrete events. The distributional patterns derived

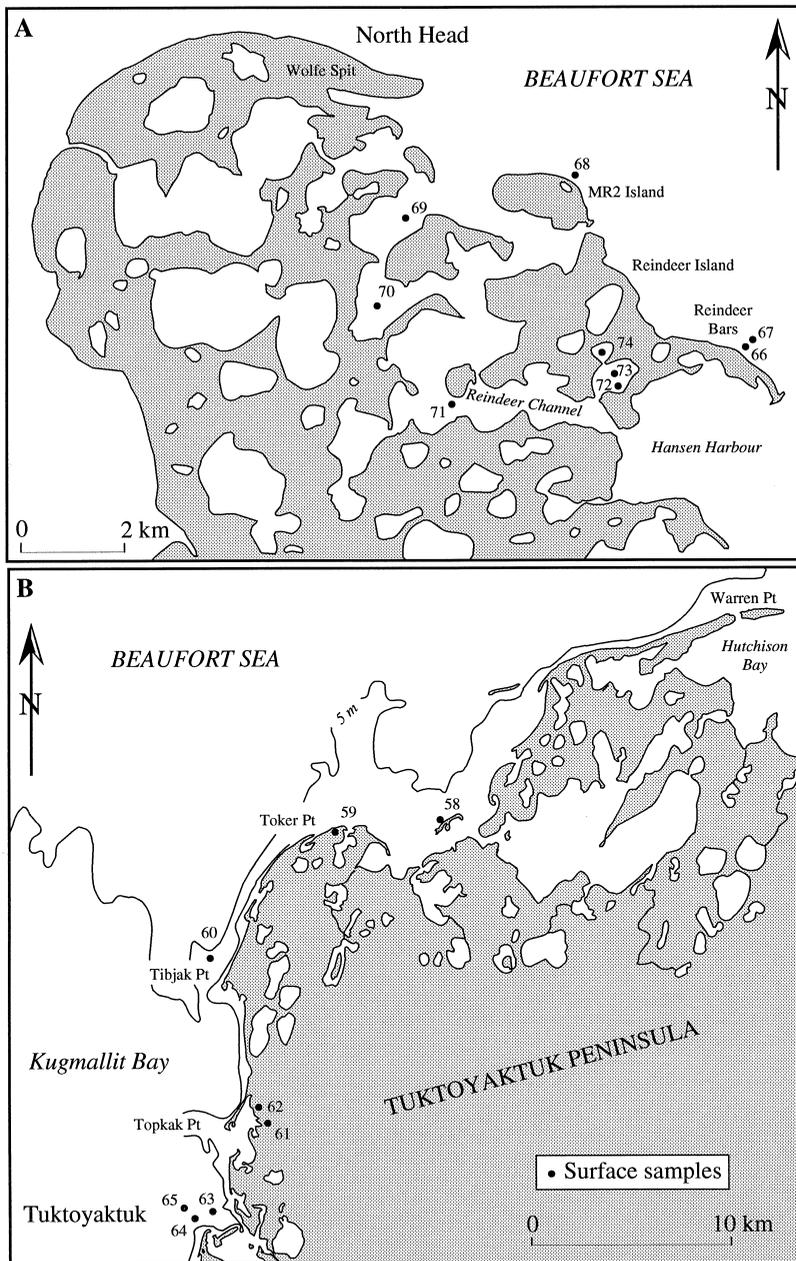


Fig. 4. The North Head (A) and Tuktoyaktuk (B) areas and location of sampling sites.

from these samples do not only represent the ecological preferences of each species of the biocenosis, but may also reflect processes that have led to the formation of the thanatocenosis. Seasonal variability in the composition of the biocenosis and discrete events responsible for the reworking of the assem-

blage may therefore be averaged out, but the time period represented by the sample will be unknown.

Surface samples were split into two replicate samples. One sample was retained for sedimentological analysis and one for diatom analysis. Grain-size analyses were done by standard sieving techniques.

Organic matter contents were obtained by loss on ignition (550°C for 2 h).

3.2. Coring

A sediment core (C-93-13) was collected in the Atkinson Point area along the Tuktoyaktuk Peninsula (Fig. 3) in 1993. A modified Livingston corer was utilized from an inflatable boat. Sediment subsamples 1 cm thick were taken from the core at the boundaries of lithological zones and at varying intervals for diatom and sedimentological analysis. The sample submitted for accelerator mass spectrometry (AMS) dating was composed of organic sediments, and was selected because of its proximity to an isolation contact. The composition of the fossil diatom assemblage within this section suggests deposition in a salt marsh environment.

3.3. Cleaning and counting

In the Paleoecology laboratory at Laval University, a homogenized sediment subsample (ca. 1 cm³) from each of the surface and core samples was digested in hot acid (30% H₂O₂). The siliceous material was then repeatedly washed and decanted in order to remove acids. Coarse sand was removed by decanting. For samples with high proportions of clay-sized material, heavy-liquid separation with sodium polytungstate was used to concentrate diatom valves. An aliquot of the resulting slurry was evaporated onto coverslips, which were subsequently mounted onto glass slides with Naphrax[®]. Diatoms were identified and enumerated along transects using a Leica DMRB microscope under phase contrast illumination at a magnification of ×1000. When possible, 200–300 valves were counted per sample. Several slides had sometimes to be analysed to reach as high a number of diatom valves as possible, particularly in surface samples from shoreface environments. Broken valves consisting of more than half of the valve were counted as one valve. Diatom identifications were made to the lowest taxonomic level possible. The Shannon–Wiener diversity index (H') of the surface assemblages was calculated from the relative abundance data ($H' = -\sum p_i \log_e p_i$, where p_i is the proportion of species i in the assemblage). The ecology (salinity preferences and

life-forms), distribution and taxonomy of the Beaufort Sea coastal diatoms is presented in Campeau et al. (1998).

3.4. Model development

3.4.1. Ordinations

The strength of reconstruction models may be heightened when they are derived from environmental variables that account for a high and significant proportion of the species data. Canonical correspondence analysis (CCA) was used as a preliminary measure to determine whether the water depth, and thus the relative sea level, influences modern diatom assemblages to a great enough extent to substantiate the potential quantitative reconstruction of past sea levels from fossil diatoms. CCA detects patterns of variation in species data that can be explained by the observed environmental variables (Jongman et al., 1995). CCA was performed using the computer program CANOCO version 3.12 (Ter Braak, 1990), with downweighting of rare taxa. Diatom taxa that occurred in at least three of the 74 sampling sites with a relative abundance of ≥1% were included in the CCA. Of the 224 taxa identified in the surface sediments, 105 met the above criterion. In addition to the measured water depth at each station, the available environmental data consist of some sedimentological data, such as the percentage of sand (≥63 μm), mud (<63 μm) and organic matter, and the distance of the sampling stations from the Mackenzie Delta mouth. All variables had skewed distributions and were log-transformed [$\ln(x + 1)$] prior to statistical analyses. In addition, the nine main sedimentary environments occurring in our set of sampling sites, including the freshwater environments (ponds, salt ponds and coastal peats), salt marshes, semi-enclosed breached lakes, tidal channels, breached lakes and lagoons, shoreface, inner shelf, delta front and delta front lagoons, were included as dummy (value 0 or 1) passive variables. Summary statistics for the variables used in the CCA are given in Table 2.

The maximum depth at which a surface sample was collected was 14 m on the inner shelf, whereas the minimum depth was at the mean or above sea level in salt marshes and freshwater environments (coastal peats and ponds). As the tidal range is very small in the Beaufort Sea and no zonation has been

Table 1
Raw environmental data for the 74 sampling sites of the southeastern Beaufort Sea coasts

| Lab ID | Field ID | Location | Latitude | Longitude | Depth (m) | Sand (%) | Mud (%) | O.M. (%) | Dist. (km) | Env. | Date | Core type |
|--------|--------------|--------------------|-----------|------------|-----------|----------|---------|----------|------------|-------|--------|-----------|
| 1 | C-93-12 0-2 | Drift Point | 69°52'00" | 131°36'00" | 0.8 | 93.0 | 4.9 | 2.1 | 109.5 | BL | Jul-93 | VC |
| 2 | C-91-11 0-2 | Atkinson Point | 69°53'32" | 131°28'32" | 2.0 | 1.2 | 60.5 | 38.2 | 115.7 | SBL | Aug-91 | PC |
| 3 | C-91-11B 0-2 | Atkinson Point | 69°54'35" | 131°28'33" | 1.5 | 98.6 | 0.5 | 0.9 | 116.0 | TC | Aug-91 | PC |
| 4 | C-92-23 0-2 | Atkinson Point | 69°54'56" | 131°28'34" | 1.3 | 76.4 | 17.9 | 5.7 | 116.3 | BL | Aug-92 | Grab |
| 5 | C-91-4 0-2 | Atkinson Point | 69°55'40" | 131°28'33" | 0.4 | 99.9 | 0.0 | 0.0 | 117.0 | TC | Aug-91 | PC |
| 6 | C-91-10 0-2 | Atkinson Point | 69°55'54" | 131°27'39" | 1.0 | 96.5 | 2.0 | 1.5 | 118.5 | TC | Aug-91 | PC |
| 7 | C-91-7 0-2 | Atkinson Point | 69°55'56" | 131°23'33" | 0.4 | 95.3 | 2.9 | 1.8 | 120.8 | SBL | Aug-91 | PC |
| 8 | C-92-15 0-2 | Atkinson Point | 69°56'00" | 131°23'50" | 0.6 | 99.9 | 0.0 | 0.0 | 120.6 | TC | Aug-92 | PC |
| 9 | C-91-8 0-2 | Atkinson Point | 69°56'09" | 131°24'07" | 1.5 | 84.3 | 9.4 | 6.4 | 120.5 | BL | Aug-91 | PC |
| 10 | C-92-16 0-2 | Atkinson Point | 69°56'56" | 131°24'25" | 1.5 | 95.8 | 2.0 | 2.2 | 120.9 | BL | Aug-92 | VC |
| 11 | C-92-17 0-2 | Atkinson Point | 69°56'39" | 131°24'18" | 0.6 | 96.9 | 2.0 | 1.2 | 120.8 | BL | Aug-92 | |
| 12 | C-92-18 0-2 | Atkinson Point | 69°57'22" | 131°23'18" | 3.2 | 73.5 | 19.5 | 7.0 | 121.8 | BL | Aug-92 | VC |
| 13 | C-91-9 0-2 | Atkinson Point | 69°57'39" | 131°22'39" | 4.0 | 63.1 | 27.1 | 9.8 | 122.3 | BL | Aug-91 | PC |
| 14 | C-92-19S 0-2 | Atkinson Point | 69°56'40" | 131°21'30" | 1.6 | 94.9 | 2.9 | 2.2 | 122.3 | BL | Aug-92 | |
| 15 | C-92-20S 0-2 | Atkinson Point | 69°55'50" | 131°17'15" | 1.2 | 91.9 | 4.8 | 3.2 | 123.8 | BL | Aug-92 | Grab |
| 16 | C-91-14 0-2 | Atkinson Point | 69°55'00" | 131°20'00" | 0.8 | 26.5 | 41.4 | 32.2 | 122.4 | SBL | Aug-91 | PC |
| 17 | C-92-27 0-2 | Atkinson Point | 69°55'00" | 131°15'50" | 1.8 | 97.7 | 1.0 | 1.3 | 124.7 | BL | Aug-92 | Grab |
| 18 | C-92-28 0-2 | Atkinson Point | 69°55'25" | 131°15'40" | 1.0 | 31.5 | 47.2 | 21.3 | 124.6 | SBL | Aug-92 | Grab |
| 19 | C-92-21S 0-2 | Atkinson Point | 69°55'15" | 131°15'30" | 1.0 | 99.9 | 0.0 | 0.0 | 124.5 | TC | Aug-92 | |
| 20 | C-93-9A 0-2 | Mckinley Bay | 69°57'05" | 131°27'50" | 2.5 | 91.0 | 4.8 | 4.2 | 126.0 | BL | Jul-93 | VC |
| 21 | C-93-8 0-2 | Mckinley Bay | 69°52'22" | 131°12'26" | 1.2 | 66.9 | 28.7 | 4.5 | 121.5 | SBL | Jul-93 | VC |
| 22 | C-93-7 0-2 | Mckinley Bay | 69°52'19" | 131°12'22" | 4.0 | 96.8 | 2.0 | 1.2 | 120.9 | TC | Jul-93 | VC |
| 23 | C-93-6 0-2 | Mckinley Bay | 69°51'42" | 131°12'40" | 2.6 | 1.3 | 63.7 | 35.0 | 121.5 | SBL | Jul-93 | VC |
| 24 | C-92-22 0-2 | Atkinson Point | 69°53'10" | 131°27'50" | 0.0 | 38.9 | 29.4 | 31.7 | 124.5 | MARSH | Aug-92 | On site |
| 25 | C-91-3 0-2 | Atkinson Point | 69°55'00" | 131°21'00" | 0.0 | 36.4 | 36.4 | 27.2 | 121.8 | MARSH | Aug-91 | On site |
| 26 | C-92-25 0-2 | Atkinson Point | 69°56'56" | 131°25'30" | 0.0 | 16.5 | 38.4 | 45.2 | 120.9 | MARSH | Aug-92 | On site |
| 27 | C-92-26 0-2 | Atkinson Point | 69°53'15" | 131°28'32" | 0.0 | 17.3 | 40.3 | 42.4 | 115.0 | MARSH | Aug-92 | On site |
| 28 | C-92-24 0-2 | Drift Point | 69°51'45" | 131°36'15" | 0.0 | 39.1 | 39.1 | 21.9 | 108.5 | MARSH | Aug-92 | On site |
| 29 | B-92-84 | Off Atkinson Point | 69°54'53" | 131°29'59" | 2.2 | 99.3 | 0.5 | 0.2 | 115.7 | SHORE | Jul-92 | Grab |
| 30 | B-92-85 | Off Atkinson Point | 69°54'56" | 131°30'16" | 3.6 | 99.2 | 0.7 | 0.0 | 115.5 | SHORE | Jul-92 | Grab |
| 31 | B-92-87 | Off Atkinson Point | 69°55'04" | 131°31'17" | 5.0 | 99.2 | 0.5 | 0.2 | 115.5 | SHORE | Jul-92 | Grab |
| 32 | B-92-89 | Off Atkinson Point | 69°55'10" | 131°32'07" | 6.1 | 99.8 | 0.1 | 0.0 | 115.4 | SHORE | Jul-92 | Grab |
| 33 | B-92-91 | Off Atkinson Point | 69°55'18" | 131°33'20" | 7.9 | 72.4 | 25.4 | 2.2 | 115.5 | SHORE | Jul-92 | Grab |
| 34 | B-92-67 | Off Atkinson Point | 69°56'11" | 131°28'32" | 0.8 | 99.8 | 0.0 | 0.2 | 117.6 | SHORE | Jul-92 | Grab |
| 35 | B-92-66 | Off Atkinson Point | 69°56'12" | 131°28'41" | 2.5 | 99.6 | 0.3 | 0.1 | 117.6 | SHORE | Jul-92 | Grab |
| 36 | B-92-65 | Off Atkinson Point | 69°56'15" | 131°28'53" | 3.6 | 99.7 | 0.3 | 0.0 | 117.8 | SHORE | Jul-92 | Grab |
| 37 | B-92-62 | Off Atkinson Point | 69°56'23" | 131°30'18" | 7.0 | 99.7 | 0.2 | 0.0 | 117.5 | SHORE | Jul-92 | Grab |
| 38 | B-92-33 | Off Atkinson Point | 69°56'19" | 131°32'42" | 9.9 | 29.0 | 67.6 | 3.5 | 117.0 | SHELF | Jul-92 | Grab |
| 39 | B-92-32 | Off Atkinson Point | 69°56'31" | 131°33'45" | 11.0 | 21.1 | 74.7 | 4.2 | 117.2 | SHELF | Jul-92 | Grab |
| 40 | B-92-31b | Off Atkinson Point | 69°56'47" | 131°35'04" | 10.8 | 37.4 | 58.5 | 4.1 | 117.3 | SHELF | Jul-92 | Grab |
| 41 | B-92-19b | Off Atkinson Point | 69°56'24" | 131°28'18" | 1.1 | 99.2 | 0.7 | 0.1 | 118.2 | SHORE | Jul-92 | Grab |
| 42 | B-92-22 | Off Atkinson Point | 69°56'26" | 131°28'32" | 3.7 | 99.8 | 0.0 | 0.0 | 118.0 | SHORE | Jul-92 | Grab |
| 43 | B-92-24 | Off Atkinson Point | 69°56'33" | 131°29'01" | 6.7 | 99.4 | 0.5 | 0.0 | 118.0 | SHORE | Jul-92 | Grab |
| 44 | B-92-26 | Off Atkinson Point | 69°56'44" | 131°29'25" | 6.5 | 99.8 | 0.2 | 0.0 | 117.9 | SHORE | Jul-92 | Grab |
| 45 | B-92-27 | Off Atkinson Point | 69°56'54" | 131°30'05" | 8.3 | 85.1 | 12.3 | 2.7 | 117.4 | SHORE | Jul-92 | Grab |
| 46 | B-92-28 | Off Atkinson Point | 69°57'06" | 131°30'46" | 9.9 | 33.6 | 63.1 | 3.3 | 117.4 | SHELF | Jul-92 | Grab |
| 47 | B-92-30 | Off Atkinson Point | 69°57'12" | 131°31'30" | 11.1 | 20.9 | 74.8 | 4.3 | 117.4 | SHELF | Jul-92 | Grab |
| 48 | B-92-57 | Off Atkinson Point | 69°57'15" | 131°33'08" | 11.8 | 3.1 | 93.5 | 3.4 | 116.5 | SHELF | Jul-92 | Grab |
| 49 | B-92-40 | Off Atkinson Point | 69°56'56" | 131°27'01" | 0.9 | 99.7 | 0.0 | 0.2 | 120.2 | SHORE | Jul-92 | Grab |
| 50 | B-92-43 | Off Atkinson Point | 69°56'57" | 131°27'15" | 2.1 | 99.8 | 0.0 | 0.0 | 120.0 | SHORE | Jul-92 | Grab |
| 51 | B-92-47 | Off Atkinson Point | 69°57'01" | 131°27'47" | 5.3 | 99.9 | 0.0 | 0.0 | 120.0 | SHORE | Jul-92 | Grab |
| 52 | B-92-50 | Off Atkinson Point | 69°57'17" | 131°28'58" | 7.8 | 99.4 | 0.5 | 0.0 | 119.9 | SHORE | Jul-92 | Grab |

Table 1 (continued)

| Lab ID | Field ID | Location | Latitude | Longitude | Depth (m) | Sand (%) | Mud (%) | O.M. (%) | Dist. (km) | Env. | Date | Core type |
|--------|-----------------|--------------------|-----------|------------|-----------|----------|---------|----------|------------|-------|--------|-----------|
| 53 | B-92-53 | Off Atkinson Point | 69°57'29" | 131°30'33" | 10.6 | 78.3 | 19.6 | 2.1 | 119.4 | SHELF | Jul-92 | Grab |
| 54 | B-92-56 | Off Atkinson Point | 69°57'41" | 131°32'00" | 12.0 | 3.9 | 92.9 | 3.3 | 118.5 | SHELF | Jul-92 | Grab |
| 55 | 87-35-8 | Off Atkinson Point | 70°02'49" | 131°25'08" | 14.0 | 3.8 | 89.2 | 7.0 | 124.5 | SHELF | Sep-87 | Grab |
| 56 | C-93-16 0-2 | Atkinson Point | 69°55'40" | 131°22'39" | 0.0 | 1.1 | 0.3 | 98.6 | 120.8 | FRESH | Aug-93 | On site |
| 57 | C-93-17 0-2 | Atkinson Point | 69°55'56" | 131°25'35" | 0.0 | 3.0 | 0.4 | 96.6 | 118.5 | FRESH | Aug-93 | On site |
| 58 | C-88-7 | Kukjuktuk Bay Is. | 69°39'00" | 132°41'12" | 0.0 | 4.1 | 0.7 | 95.2 | 62.3 | MARSH | Aug-88 | PC |
| 59 | C-88-5 | East Toker Point | 69°39'00" | 132°48'36" | 0.0 | 13.6 | 37.2 | 49.2 | 57.5 | MARSH | Aug-88 | PC |
| 60 | 95-301-029 | Off Tibjak Point | 69°35'52" | 133°00'25" | 4.8 | 0.5 | 90.9 | 8.6 | 47.6 | DELTA | Jul-95 | Grab |
| 61 | C-92-1 0-2 | Topkak Point | 69°30'31" | 132°57'17" | 0.0 | 2.3 | 0.3 | 97.4 | 45.1 | FRESH | Jul-92 | CRREL |
| 62 | C-88-1 | Topkak Point | 69°30'34" | 132°57'24" | 0.0 | 35.6 | 24.3 | 40.1 | 45.0 | MARSH | Aug-88 | PC |
| 63 | 95-301-001 | Tuk Island | 69°27'67" | 133°00'40" | 4.8 | 3.5 | 92.3 | 4.3 | 40.5 | DELTA | Jul-95 | Grab |
| 64 | 95-301-008 | Off Tuktoyaktuk | 69°27'33" | 133°02'28" | 3.2 | 1.0 | 96.2 | 2.8 | 39.8 | DELTA | Jul-95 | Grab |
| 65 | 95-301-006 | Off Tuktoyaktuk | 69°27'45" | 133°02'95" | 4.4 | 0.7 | 98.2 | 1.1 | 39.8 | DELTA | Jul-95 | Grab |
| 66 | 93-300-22 82-85 | Off North Head | 69°40'24" | 134°10'12" | 0.8 | 90.7 | 9.2 | 0.1 | 38.4 | SHORE | Apr-95 | CRREL |
| 67 | 93-300-21 82-84 | Off North Head | 69°40'25" | 134°10'00" | 0.8 | 77.3 | 22.6 | 0.1 | 38.4 | SHORE | Apr-95 | CRREL |
| 68 | 93-300-14 87-90 | Off North Head | 69°42'24" | 134°14'48" | 1.3 | 83.4 | 16.4 | 0.2 | 42.0 | SHORE | Apr-95 | CRREL |
| 69 | 93-300-12 89-91 | North Head | 69°41'36" | 134°19'00" | 0.9 | 4.9 | 94.3 | 0.9 | 42.0 | DLAG | Apr-95 | CRREL |
| 70 | 93-300-07 | North Head | 69°40'48" | 134°20'00" | 2.7 | 1.6 | 96.5 | 1.9 | 40.7 | DLAG | Apr-95 | LIV |
| 71 | 93-300-11 | North Head | 69°39'42" | 134°18'12" | 1.0 | 1.8 | 96.8 | 1.5 | 38.4 | DLAG | Apr-95 | CRREL |
| 72 | 93-300-02 0-4 | North Head | 69°39'59" | 134°12'48" | 2.4 | 3.8 | 94.3 | 1.9 | 37.8 | DLAG | Apr-95 | LIV |
| 73 | 93-300-03 0-2 | North Head | 69°40'00" | 134°12'48" | 7.9 | 2.0 | 96.2 | 1.8 | 37.8 | DLAG | Apr-95 | LIV |
| 74 | 93-300-4b 3-5 | North Head | 69°40'18" | 134°13'24" | 6.2 | 1.3 | 96.8 | 1.9 | 38.4 | DLAG | Apr-95 | LIV |

Sand: $\geq 63 \mu\text{m}$; Mud: $< 63 \mu\text{m}$; O.M. = organic matter (as determined by loss on ignition); Dist. = distance to the Mackenzie Delta mouth [southernmost part of Kittigazuit Bay (69°20'00"N, 134°00'00"W)]; Env. = Environments: FRESH: freshwater environments (tundra peat and ponds); MARSH = salt marshes; SBL = semi-enclosed breached lakes; BL = breached lakes and lagoons; TC = tidal channels; SHORE = shoreface; SHELF = inner shelf; DELTA = delta front; DLAG = delta front lagoons.

Core type: CRREL = CRREL auger; LIV = Livingston; PC = piston corer; VC = vibracorer; Grab = surface grab.

observed in the distribution of salt marsh assemblages, the same depth value (0 m) has been given to all salt marsh samples. The strongest water depth gradient was observed in shoreface environments (0 to 10 m). As mentioned above, the water chemistry of the southeastern Beaufort Sea is highly variable and depends mostly on the dispersion of the Mackenzie River plume. Diatoms are thus subjected to strong fluctuations in salinity, temperature, nutrients and light availability during the growing season. Near the Mackenzie Delta, populations are affected by low light penetration, low salinity, warm temperature and high nutrient content of the surface waters. Diatom populations of the Tuktoyaktuk Peninsula are on the other hand influenced by both the Mackenzie River plume and marine conditions depending on winds. To give an adequate picture of these fluctuations, it would have been necessary to analyse each station at different times of the year. Instead, we measured the distance of each sampling station from the Macken-

zie Delta mouth [southernmost part of Kittigazuit Bay (69°20'00"N; 134°00'00"W)]. Given the hydrographic conditions of the southeastern Beaufort Sea, this measure is thought to represent an integration of all the fluctuations in surface water chemistry arising from the wind-driven dispersion of the Mackenzie River plume. With respect to sedimentological data on a regional scale, sites closer to the Mackenzie Delta contained finer sediments than sites along the Tuktoyaktuk Peninsula. On a local scale, backbarrier environments and inner shelf contained finer sediments than sites on the shoreface. High organic contents occurred in subaerial environments and in semi-enclosed breached lakes.

The environmental variables in the CCA biplot are represented by arrows, whereas species and sampling sites are marked by numbers. Variables with high positive correlations have small angles between their biplot arrows, while high negative correlations are usually depicted by arrows pointing in opposite

Table 2
Summary statistics for the variables used in the canonical correspondence analysis

| Variable | Symbol | Minimum | Maximum | Median |
|---|--------|---------|---------|-------------------|
| Water depth (m) | DEPTH | 0 | 14 | 2.1 |
| Sand (%) | SAND | 0.5 | 99.9 | 74.9 |
| Mud (%) ^a | MUD | 0 | 98.2 | 14.3 |
| Organic matter (%) ^b | OM | 0 | 98.6 | 2.1 |
| Distance to the Mackenzie Delta (km) ^c | DIST | 37.8 | 126 | 117.5 |
| Sedimentary environments (dummy (value 0 or 1) passive variables) | | Symbol | | Number of samples |
| Freshwater environments ^d | | FRESH | | 3 |
| Salt marshes | | MARSH | | 8 |
| Semi-enclosed breached lakes | | SBL | | 6 |
| Breached lakes and lagoons | | BL | | 11 |
| Tidal channels | | TC | | 6 |
| Shoreface | | SHORE | | 21 |
| Inner shelf | | SHELF | | 9 |
| Delta front | | DELTA | | 4 |
| Delta front lagoons | | DLAG | | 6 |

^a Mud: <63 μ m.

^b As determined by loss on ignition.

^c Distance to the Mackenzie Delta mouth (southernmost part of Kittigazuit Bay (69°20'00"N, 134°00'00"W).

^d Coastal peats and ponds.

directions (Jongman et al., 1995). Variables with long arrows have high variance and their proximity to the axes summarizes the relative weight of each variable in determining each axis (Ter Braak, 1987). The direction of each arrow indicates ascending values for each environmental variable. Each taxon's position in the ordination space is an approximation of its weighted-average optimum in relation to other taxa and each explanatory variable (Jongman et al., 1995).

The contribution of water depth alone to the variability in diatom data was tested with CCA, with water depth as the only environmental variable constrained to the first axis (Ter Braak, 1987).

3.4.2. WA regression and calibration

Transfer functions may be based either on a linear or a unimodal response model (Ter Braak and Prentice, 1988). Species abundances may change linearly over a short range of an environmental gradient, but over longer gradients, species more often exhibit a unimodal response (Jongman et al., 1995). Examination of species distribution in Beaufort Sea environments indicates that this is the case for most diatom taxa along the water depth gradient, from salt

marshes to the inner shelf (Campeau et al., 1998). This observation has been confirmed by a detrended correspondence analysis (DCA) using the computer program CANOCO version 3.12 (Ter Braak, 1987). DCA is an indirect gradient method that reveals the maximum amount of variation in the species data. The length of the ordination axis, when detrended by segments, is equivalent to the range of the sample scores measured in standard deviation units as an estimate of tolerance. The lengths of the first axes can be used to determine whether a linear or a unimodal ordination technique is suitable for analysing the data. Gradient lengths that are less than two standard deviation units suggest that a linear approach should be used, while gradient lengths greater than four standard deviation units dictate that a unimodal approach should be used (Jongman et al., 1995). The present data showed considerable non-linearity as judged by the lengths of gradients extracted by DCA, with detrending by segments and non-linear rescaling (3–5 SD units in each of the first four axes of ordination). This indicates that a unimodal model of species response is appropriate for the Beaufort Sea data set.

Transfer functions for species exhibiting unimodal response curves are based either on maximum likelihood (ML) or weighted averaging (WA) techniques. Under certain conditions (see Ter Braak and Looman, 1986; Ter Braak and Barendregt, 1986), the computationally intensive method of ML may be approximated by the simpler method of WA. Previous studies have compared both methods and it was found that ML performed only slightly better than WA (Ter Braak and Van Dam, 1989) or even worse (Birks et al., 1990; Juggins, 1992) and was overly susceptible to ‘no-analogue’ conditions when applied to fossil data. Consequently, WA regression and calibration were used in this report to develop a water depth inference model based on diatom assemblages using the computer program WACALIB version 3.3 (Line et al., 1994). WA regression was used to describe the response of a species (optima and ranges) as a function of water depth. The optimum water depth of deposition is an estimate of the value along a water depth gradient at which a taxon achieves its highest abundance in surface sediments relative to other taxa. The optimum of a particular species is estimated by taking the average of all the measured water depths at the stations in which the taxon occurred, weighted by the taxon’s relative abundance at each station. Subsequently, WA calibration estimates paleodepth values from the optima and relative abundances of the diatom taxa present in sediment cores. The theory of WA is fully discussed in Ter Braak and Looman (1986), Ter Braak and Barendregt (1986) and Ter Braak and Prentice (1988).

Both WA and WA with tolerance downweighting [WA(tol)] were performed on the data set. WA and WA(tol) models with square-root transformation of species data were also executed. Finally, WA and WA(tol) models with classical and inverse deshrinking were performed. Deshrinking is necessary in WA reconstructions since averages are taken twice, once in WA regression and once in WA calibration. The strength of each of these models as a predictive tool was assessed by comparing the coefficient of determination (r^2) between measured and inferred water depths after bootstrapping, and the root-mean-square error (RMSE) of prediction after bootstrapping. The apparent RMSE of prediction is underestimated when it is based purely on the train-

ing set, because the model is being applied to the same sites from which it is derived (Ter Braak and Van Dam, 1989). Bootstrapping was employed as a cross-validation procedure to generate independent test sets from the original training set of sampling sites. The RMSE of prediction after bootstrapping is not as susceptible to errors created by rare or unique taxa in a given data set, making it a superior indicator of the model’s strength.

4. Diatom assemblages

A total of 224 diatom taxa representing 62 genera were identified in the 74 sediment samples. With respect to the salinity requirements, brackish-water forms were most abundant. The majority of the taxa had freshwater–brackish (42%) or brackish water (34%) affinities. Few had marine or marine–brackish (14%) or freshwater affinities (9%). In general, the relative abundance of freshwater–brackish species tended to increase towards the Mackenzie Delta front, while brackish and marine forms tended to increase towards the northeastern coasts of the Tuktoyaktuk Peninsula. Freshwater diatoms also reached greater abundances in some restricted areas along the peninsula, especially in lagoons influenced by freshwater inputs. The dominance of euryhaline taxa indicates important fluctuations in osmotic pressure due to the dispersion of the Mackenzie River plume along southeastern Beaufort Sea coasts. Benthic diatoms were predominant, with only 10.5% of planktonic or tychoplanktonic forms. The dominance of benthic species reflects the preponderance of shallow water habitats in our sample set. Of the 224 taxa identified, 47% were epipelagic, 19% epipelagic or epiphytic, 8.5% euplanktonic, 8.5% epipsammic, 7% epontic (sea ice diatoms), 7% aerophilic and 2% tychoplanktonic.

A detailed analysis of the diatom assemblages associated to the sedimentary environments of the southeastern Beaufort Sea is presented in Campeau et al. (1998). Figs. 5 and 6 summarize the distributional patterns of diatom life-forms, salinity preferences and some dominant diatom species. In coastal ponds, diatom assemblages were mostly dominated by epipelagic and epiphytic freshwater diatoms, such as *Eunotia praeurupta* and *Caloneis*

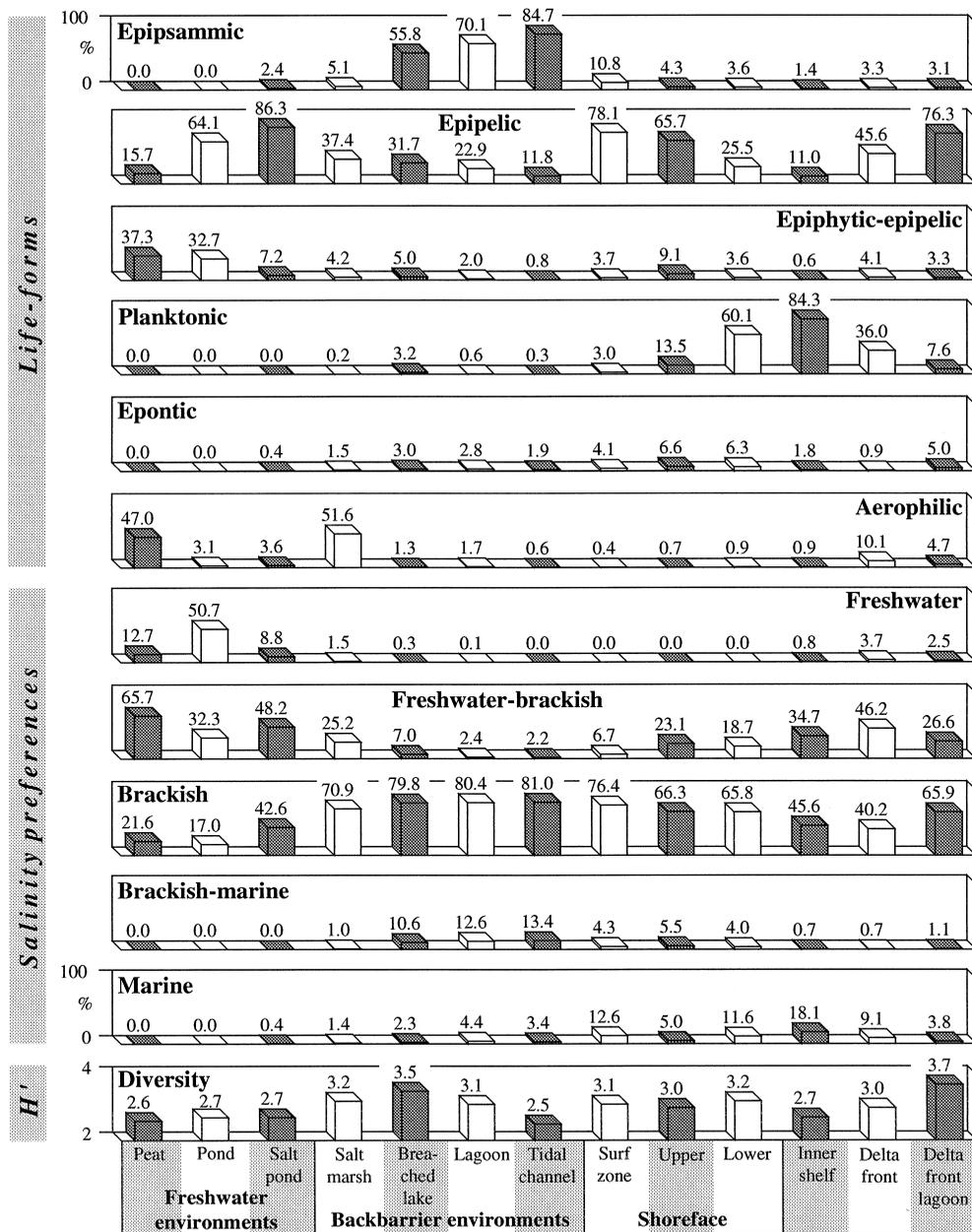


Fig. 5. Distribution of the mean relative abundance (%) of diatom life-forms and salinity preferences, and the Shannon–Wiener diversity index (H') in sedimentary environments of the southeastern Beaufort Sea.

tenuis. Coastal peat assemblages were dominated primarily by freshwater–brackish aerophilic and epiphytic diatoms, such as *Diatoma* cf. *vulgaris*, whereas salt marsh assemblages consisted mainly of brackish aerophilic and epipellic taxa, such as

Diploneis interrupta. As a consequence of the highly variable environmental conditions and the predominance of sandy material, breached lake and lagoon assemblages were dominated by euryhaline epipsammic diatoms with broad ecological tolerances.

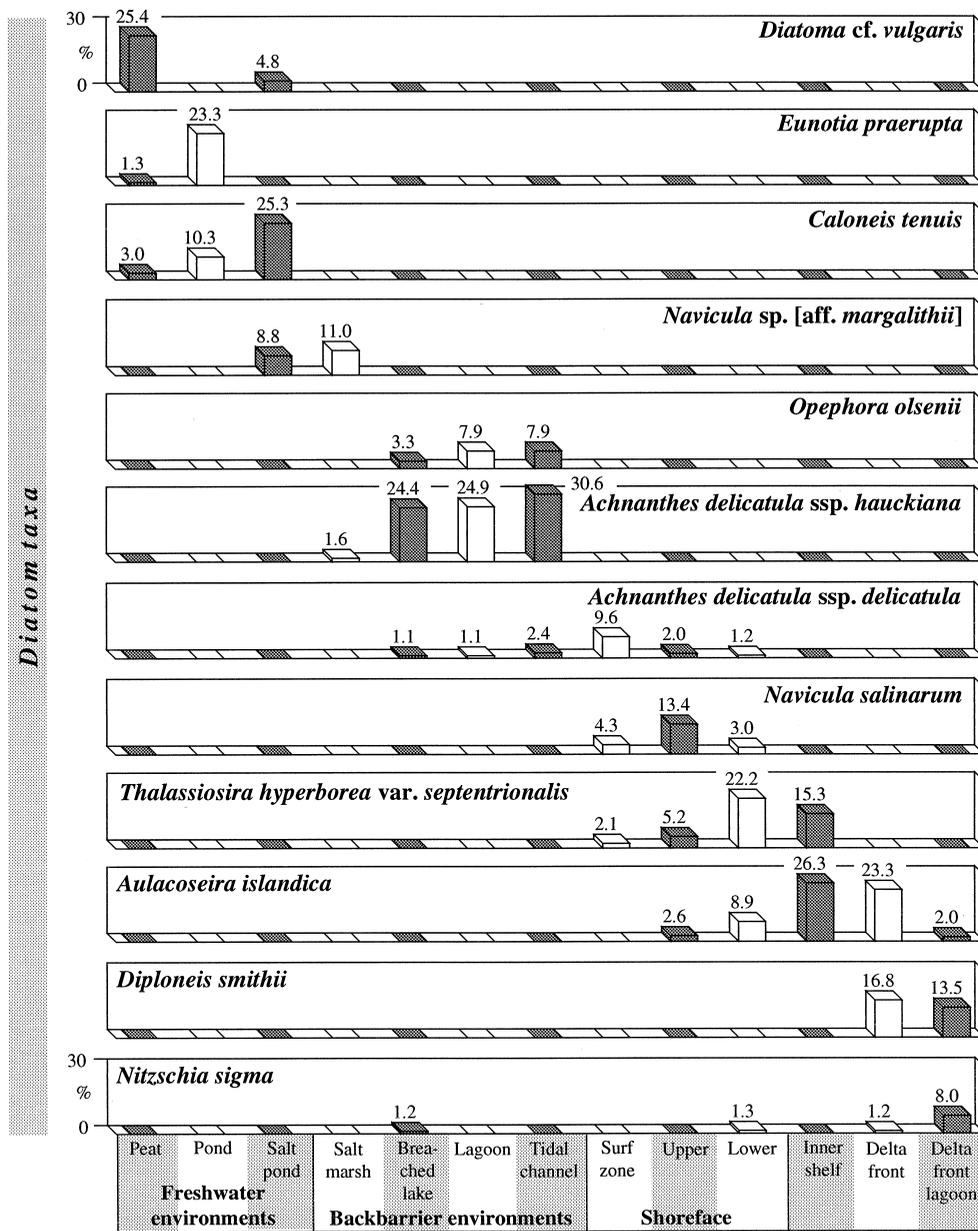


Fig. 6. Distribution of the mean relative abundance (%) of dominant diatom species in sedimentary environments of the southeastern Beaufort Sea.

The epipsammon consists of small appressed species or species with very short stalks, which occupy depressions in the surface of sand grains. Such epipsammic taxa occur generally in intertidal environments with pronounced currents and sediment displacement (De Jonge, 1985). Along the Tuktoyak-

tuk Peninsula, *Achnanthes delicatula ssp. hauckiana* was the dominant epipsammic diatom of backbarrier environments. The other epipsammic taxa of considerable abundance were *Achnanthes lemmermannii*, *Opephora olsenii*, *O. cf. parva*, *O. marina*, *Fragilaria cassubica*, *F. schulzii*, and *Navicula*

perminuta. Despite the dominance of epipsammic taxa, diatom assemblages varied according to an exposure gradient to coastal processes, from semi-enclosed breached lakes to tidal channels. Although dominated by epipsammic species, semi-enclosed breached lake assemblages contained more epipellic and epiphytic taxa than lagoons. Lagoonal assemblages were characterized by an increase in epipsammic diatoms and a decrease in species diversity. These tendencies were amplified in tidal channels which were almost entirely dominated by epipsammic taxa and had the lowest species diversity index (2.5) of all the environments investigated.

Both backbarrier and shoreface environments consisted mainly of sandy sediments. However, backbarrier sediments, although subjected to strong tidal currents, are little reworked by waves, whereas shoreface sediments are strongly reworked by breaking and shoaling waves. This results in a shift in diatom assemblage composition. Backbarrier environments were dominated by epipsammic species, while upper shoreface assemblages were dominated by motile epipellic taxa (Fig. 5), which are able to reposition themselves in the top layer of sediments on unstable wave-exposed sandy beaches. Lower shoreface assemblages contained mostly planktonic species that had settled out of the water column during fairweather conditions, as well as some epipellic and epipsammic diatoms. Inner shelf assemblages were primarily dominated by euplanktonic and tychoplanktonic forms that were able to settle owing to the low energy environment of the shelf.

Lower shoreface and inner shelf assemblages also contained a number of planktonic and tycho-planktonic forms with freshwater–brackish affinities (Fig. 5). The occurrence of these species in inner shelf sediments reflects the freshwater influence of the Mackenzie River plume along the Tuktoyaktuk Peninsula. For example, *Aulacoseira islandica*, the most common species of inner shelf assemblages, was also the dominant species of Mackenzie Delta front sediments (Fig. 6).

Delta front assemblages contained strongly silicified planktonic species, such as *Aulacoseira islandica* and the resting spores of *Chaetoceros* spp., and epipellic species. Due to the proximity of the Mackenzie River, delta front lagoons differ from the lagoons of the Tuktoyaktuk Peninsula through

their lower surface water salinities and finer sediments. Consequently, diatom assemblages contained less epipsammic species, more freshwater–brackish taxa, and more epipellic species adapted to muddy surfaces than lagoonal assemblages of the Tuktoyaktuk Peninsula (Fig. 5). The most common diatoms present were *Diploneis smithii*, *Nitzschia sigma*, and *Tryblionella acuminata*. Finally, although never abundant, sea ice (epontic) diatoms were a common component of the Beaufort Sea coastal assemblages.

5. Diatom/water-depth relationship

The CCA biplot presents a clear separation between shallow and deeper environments on the first axis, and between the sandy brackish–marine coastal environments of the Tuktoyaktuk Peninsula and the muddy freshwater–brackish environments of the delta front on the second axis (Fig. 7). Five main clusters can be easily distinguished (Fig. 7B) which regroup sites located in deep muddy environments (upper left quadrant), the delta front (uppermost part of the ordination), shallow or subaerial environments with high organic matter contents (upper right quadrant), sandy backbarrier environments (lower right quadrant) and the shoreface (lower left quadrant). Interset correlations of environmental variables with canonical axes (Table 3) show that water depth is highly correlated with axis 1, whereas axis 2 seems to represent a salinity and grain-size gradient. In general, as one moves from the top to the bottom of the biplot, the percentage of sand, the distance from the Mackenzie Delta and the salinity increase, whereas water depth increases from the right to the left. Diatom taxa that plot in the upper right quadrant (Fig. 7A) are mostly aerophilic forms that live in subaerial environments with high organic matter

Table 3
Interset correlations of environmental variables to canonical axes

| | Axis 1 | Axis 2 |
|---------------------------------|--------|--------|
| Water depth | –0.880 | 0.216 |
| Mud | –0.031 | 0.685 |
| Sand | –0.086 | –0.787 |
| Organic matter | 0.642 | 0.343 |
| Distance to the Mackenzie Delta | –0.127 | –0.705 |

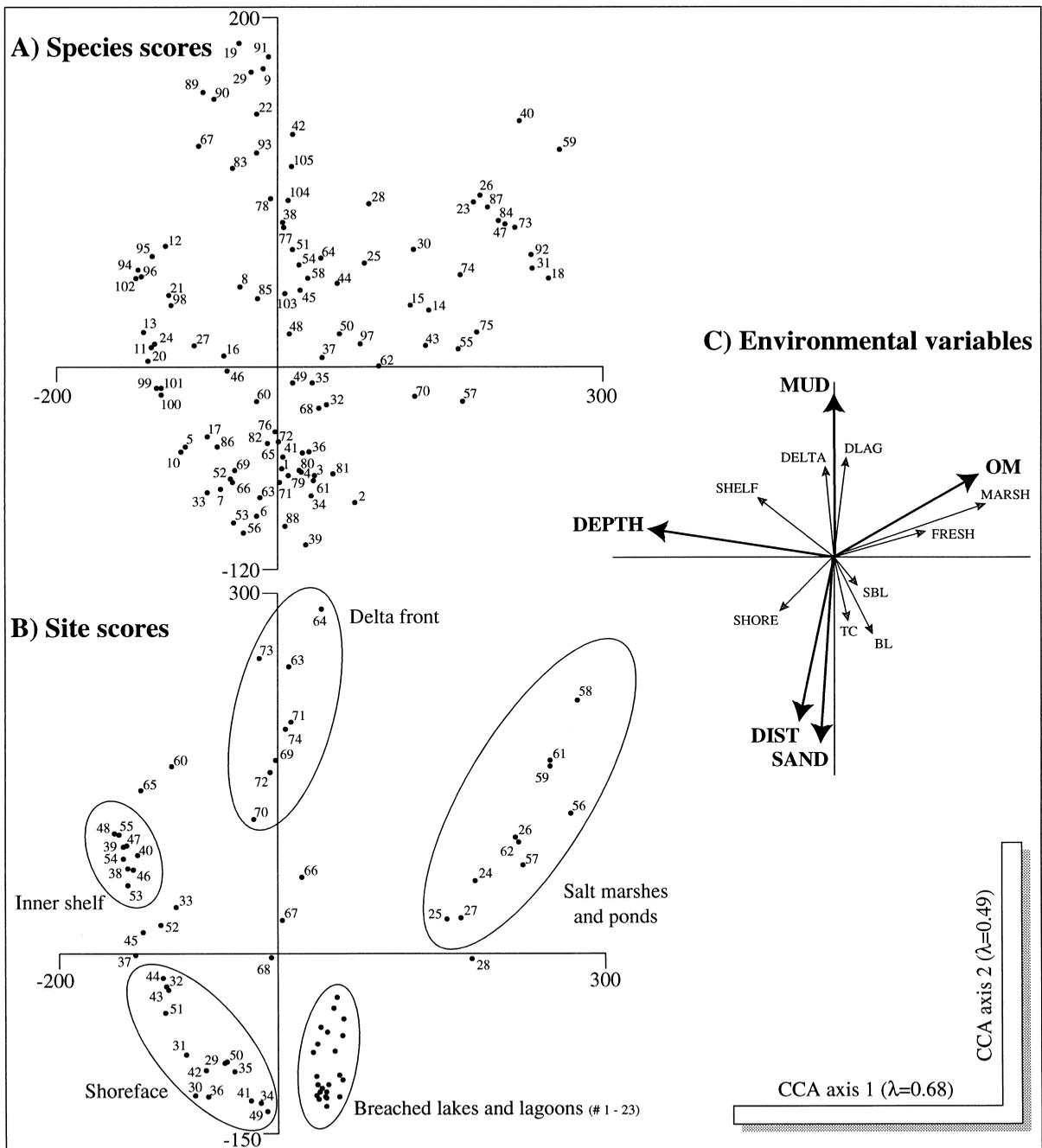


Fig. 7. Canonical correspondence analysis (CCA) for the 105 most common diatom taxa (A) and the 74 sampling sites (B). A list of the full diatom names with corresponding numbers used in the CCA is given in Table 6. Active variables: *DEPTH* = water depth (m); *SAND* = sand (%); *MUD* = mud (%); *OM* = organic matter (%); *DIST* = distance to the Mackenzie Delta (km). Sedimentary environments (dummy passive variables): *FRESH* = freshwater environments; *MARSH* = salt marshes; *SBL* = semi-enclosed breached lakes; *BL* = breached lakes and lagoons; *TC* = tidal channels; *SHORE* = shoreface; *SHELF* = inner shelf; *DELTA* = delta front; *DLAG* = delta front lagoons.

contents (salt marshes and ponds). Species plotting in the lower right quadrant are primarily epipsammic diatoms that prefer sandy shallow brackish environments, such as lagoons and breached lakes. Species plotting on the lower left quadrant are epipelagic, epipsammic and planktonic taxa present on the shoreface. Deeper sites are positioned in the upper left quadrant. Diatom taxa that plot in close proximity to these sites are mostly planktonic forms. Sites from the Mackenzie Delta front are plotted near the origin of the first axis as they have intermediate water depths. They contain species that are present both in shallow freshwater environments and in the inner shelf, but have few species in common with brackish backbarrier environments. Sites 60 and 65, located in the Mackenzie Delta front, have diatom assemblages closely related to those of the southeastern inner shelf. Stations 66 to 68 are located in shoreface environments from the Mackenzie Delta front and contain diatom assemblages closely related to shoreface assemblages of the Tuktoyaktuk Peninsula (lower left quadrant). Samples 33, 37, 45 and 52 have been collected from the lower shoreface. Their diatom assemblages share similarities both with stations from the shoreface and the inner shelf.

A significance test (Monte Carlo test with 999 permutations, $P = 0.01$) of the first two axes demonstrated that both were statistically significant. These axes, with eigenvalues of $\lambda_1 = 0.68$ and $\lambda_2 = 0.49$, accounted for 17.7% of the cumulative variance of the diatom taxa and captured 61% of the variance in the diatom–environmental relationship (Table 4). The species–environment correlations for CCA axis 1 (0.96) and axis 2 (0.90) were high, indicating a strong relationship between diatom distribution and the explanatory variables. With forward selection and unrestricted Monte Carlo permutation tests (99 permutations), CCA showed that all 5 active variables explained significant proportions ($P \leq 0.01$) of the variance in the diatom data.

This CCA explains a slightly smaller proportion of the taxon variance than is explained by the DCA (Table 4). According to Jongman et al. (1995), small differences in the eigenvalues of DCA and CCA indicate that most of the variance explained by all influencing factors is explained by the factors selected in the CCA. To test directly the hypothesis of an effect of water depth on diatom deposition

Table 4

Summary statistics for detrended correspondence analysis (DCA), canonical correspondence analysis (CCA), and CCA constrained to water depth

| | Axis 1 | Axis 2 |
|--|--------|--------|
| <i>DCA</i> | | |
| Eigenvalue | 0.81 | 0.63 |
| Cumulative percentage variance of species data | 12.1 | 21.6 |
| <i>Unconstrained CCA</i> | | |
| Eigenvalue | 0.68 | 0.49 |
| Species–environment correlation | 0.96 | 0.90 |
| Cumulative percentage variance: | | |
| of species data | 10.5 | 17.7 |
| of species–environment relation | 35.9 | 61.0 |
| <i>Constrained CCA (water depth)</i> | | |
| Eigenvalue | 0.65 | 0.71 |
| Species–environment correlation | 0.93 | 0.0 |
| Cumulative percentage variance: | | |
| of species data | 9.7 | 20.3 |
| of species–environment relation | 100.0 | 0.0 |

and distribution, we performed a CCA with water depth as the sole explanatory environmental variable (i.e. species composition was constrained to water depth). When species data are constrained to one environmental variable in a CCA, a high ratio of the first constrained eigenvalue (λ_1) to the second unconstrained eigenvalue (λ_2) indicates the relative importance of that environmental variable in explaining the species data (Ter Braak, 1986). Environmental variables with high λ_1/λ_2 are potentially strong candidates for developing inference models. The constrained CCA indicated that the water depth of deposition explained 9.7% of the variance in the diatom data (Table 4). The eigenvalues for the first two axes were 0.65 and 0.71, respectively, and were found to be significant (Monte Carlo test with 999 unrestricted permutations, $P \leq 0.01$). The λ_1/λ_2 ratio was very high (0.92) indicating that water depth was an important variable in explaining the diatom distribution and was thus considered to be a strong candidate for weighted-averaging reconstruction.

6. Water-depth transfer function

A series of weighted-averaging (WA) models were performed on the data set (74 sites, 105 species) to

Table 5

333Summary statistics of the performance of simple weighted averaging (WA) and tolerance-downweighted WA (WA-tol) models for water depth with square-root transformation of species data and no transformation, using classical and inverse deshrinking methods. See text for explanation of performance statistics

| | No transformation | | | | Square-root transformation of species data | | | |
|----------------------|-----------------------|----------|---------------------|----------|--|----------|---------------------|----------|
| | classical deshrinking | | inverse deshrinking | | classical deshrinking | | inverse deshrinking | |
| | WA | WA (tol) | WA | WA (tol) | WA | WA (tol) | WA | WA (tol) |
| r_{boot}^2 | 0.87 | 0.89 | 0.87 | 0.89 | 0.83 | 0.86 | 0.83 | 0.86 |
| RMSE _{boot} | 0.365 | 0.467 | 0.360 | 0.442 | 0.404 | 0.522 | 0.390 | 0.484 |

estimate the optimum water depth of deposition of each species and to test the strength of each model as a predictive tool. When the bootstrapped values of r^2 and RMSE of prediction of the different WA methods are compared, the model with no transformation of species data gave better results than the model with square-root transformation of species data (Table 5). Furthermore, the simple WA model (i.e. with no tolerance downweighting) provided similar r^2 but a lower RMSE than the WA(tol) model. Finally, inverse deshrinking provided a lower RMSE than classical deshrinking. The chosen model is thus a simple WA model with inverse deshrinking and without transformation of the species data ($r_{boot}^2 = 0.87$ and $RMSE_{boot} = 0.360$). A weighted averaging partial least squares (WA-PLS) (Ter Braak and Juggins, 1993) water depth model was also developed. It produced an r^2 and RMSE of prediction after jack-knifing comparable to the simple WA model ($r_{jack}^2 = 0.83$ and $RMSE_{jack} = 0.333$ for both models). The WA-PLS model is therefore not presented here. The weighted-averaging optima of water depth of deposition and the weighted-averaging ranges of the 105 most abundant diatom taxa are listed in Table 6. The maximum relative abundance of each taxon, its number of occurrences and effective number of occurrences (Hill's $N2$) are also listed. The effective number of occurrences (i.e. Hill's $N2 = 1/\text{Simpson's diversity index}$; Hill, 1973) is used as an estimate of the number of samples that influence the weighted average of each species. Optima estimated for taxa with a low $N2$ should be interpreted with caution. The relationship between measured and diatom-inferred water depth are shown in Fig. 8. This transfer function allows relative sea level to be predicted with a root mean square error (after bootstrapping) of 1.43 m.

7. The diatom/water-depth relationship along the southeastern Beaufort Sea coasts

Our results show a strong relationship between modern diatom assemblages and the measured water depth of deposition. However, some discrepancies were observed (Fig. 8) between the water depth values inferred by the model and the measured values. First, the model failed in discriminating between the shallow lagoons of the Atkinson Point area and deeper lagoons located in the Mackenzie Delta front

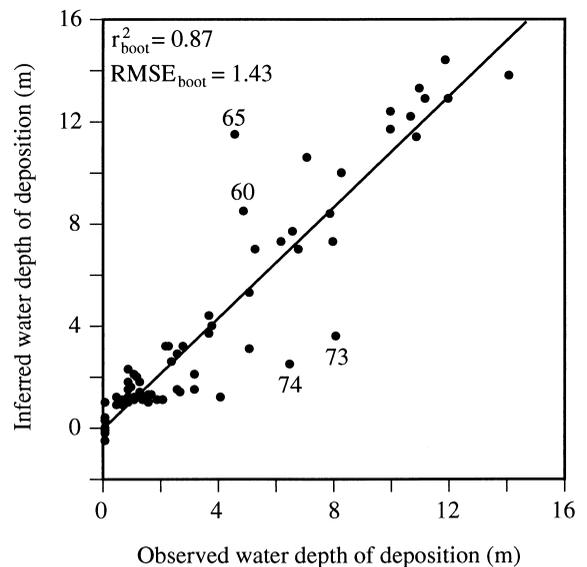


Fig. 8. The relationship between observed and diatom-inferred water depths of deposition from the simple WA model with no species transformation and inverse deshrinking. Inferred water depths are back-transformed \log_e values. Indicated points 60 and 65 represent over-estimates whereas points 73 and 74 represent under-estimates; see text for details.

Table 6

Weighted-averaging optima of water depth of deposition (WA Opt.) and ranges (WA Rg.) of the 105 most abundant diatom taxa, their maximum relative abundances (Max.), their number of occurrences (Num. Occ.) and effective number of occurrences (Hill's N2), as well as their numbers used in CCA (No.). Listed optima and ranges are back-transformed \log_e values

| No. | Taxon | Max. (%) | WA Opt. (m) | WA Rg. (m) | Num. Occ. | Hill's N2 |
|-----|--|-------------|----------------|---------------|--------------|--------------|
| 18 | <i>Caloneis tenuis</i> (Gregory) Krammer | 25.3 | 0.0 | 1.1 | 3 | 2 |
| 57 | <i>Navicula</i> sp. (aff. <i>margalithii</i> Lange-Bertalot) | 38 | 0.0 | 1.1 | 9 | 4.4 |
| 75 | <i>Nitzschia clausii</i> Hantzsch | 8.1 | 0.0 | 1.2 | 12 | 7.2 |
| 31 | <i>Eunotia praerupta</i> Ehrenberg | 23.3 | 0.1 | 1.9 | 5 | 1.2 |
| 47 | <i>Navicula cincta</i> (Ehrenberg) Ralfs in Pritchard | 14.7 | 0.1 | 1.4 | 12 | 6.1 |
| 59 | <i>Navicula</i> cf. <i>microdigitoradiata</i> Lange-Bertalot | 20.4 | 0.1 | 2.5 | 4 | 1.1 |
| 92 | <i>Stauroneis phoenicenteron</i> (Nitzsch) Ehrenberg | 10.8 | 0.1 | 2.1 | 5 | 1.5 |
| 55 | <i>Navicula gregaria</i> Donkin | 18.8 | 0.2 | 1.4 | 18 | 8.4 |
| 73 | <i>Neidium ampliatus</i> (Ehrenberg) Krammer | 5.4 | 0.2 | 2.4 | 4 | 1.7 |
| 84 | <i>Pinnularia lundii</i> Hustedt | 11.2 | 0.2 | 1.9 | 9 | 2.9 |
| 43 | <i>Mastogloia exigua</i> Lewis | 1.6 | 0.2 | 1.7 | 5 | 4.7 |
| 40 | <i>Luticola mutica</i> (Kützing) Mann | 9.3 | 0.3 | 1.8 | 8 | 2 |
| 26 | <i>Diploneis interrupta</i> (Kützing) Cleve | 74.1 | 0.3 | 2.0 | 28 | 5.8 |
| 23 | <i>Cosmioneis pusilla</i> (Smith) Mann and Stickle | 4.4 | 0.4 | 2.0 | 11 | 6 |
| 74 | <i>Nitzschia bilobata</i> Smith | 1.6 | 0.4 | 1.8 | 10 | 8.2 |
| 70 | <i>Navicula</i> sp. (aff. <i>subadnata</i> Hustedt) | 4.9 | 0.4 | 1.6 | 12 | 6.2 |
| 14 | <i>Berkeleya rutilans</i> (Trentepohl) Grunow | 15.7 | 0.4 | 1.7 | 18 | 5.1 |
| 87 | <i>Pinnularia</i> cf. <i>streptoraphe</i> Cleve | 5.8 | 0.5 | 2.4 | 4 | 3 |
| 15 | <i>Caloneis bacillum</i> (Grunow) Cleve | 11.7 | 0.5 | 2.2 | 20 | 9.3 |
| 2 | <i>Achnanthes delicatula</i> fo. 2 | 4.1 | 0.6 | 1.1 | 3 | 2.8 |
| 30 | <i>Diploneis stroemii</i> Hustedt | 1.6 | 0.7 | 2.8 | 7 | 5.2 |
| 62 | <i>Navicula phyllepta</i> Kützing | 10 | 0.9 | 1.8 | 36 | 17.5 |
| 81 | <i>Opephora</i> cf. <i>parva</i> (van Heurck) Krasske | 12.7 | 1.0 | 1.5 | 26 | 12.2 |
| 39 | <i>Licmophora</i> sp. 1 | 1.7 | 1.0 | 1.3 | 5 | 4.3 |
| 58 | <i>Navicula meniscus</i> Schumann | 23.1 | 1.0 | 1.3 | 12 | 3.6 |
| 97 | <i>Tabularia fasciculata</i> (Agardh) Williams and Round | 3.4 | 1.1 | 1.9 | 28 | 21.9 |
| 88 | <i>Placoneis clementis</i> (Grunow) Cox | 33.7 | 1.1 | 1.3 | 22 | 5.2 |
| 28 | <i>Diploneis ovalis</i> (Hilse) Cleve | 5.3 | 1.1 | 2.4 | 14 | 9.1 |
| 32 | <i>Fallacia pygmaea</i> (Kützing) Stickle and Mann | 7.9 | 1.1 | 1.5 | 20 | 10 |
| 34 | <i>Fragilaria cassubica</i> Witkowski and Lange-Bertalot | 22.5 | 1.2 | 1.5 | 34 | 17.4 |
| 61 | <i>Navicula perminuta</i> Grunow in van Heurck | 17 | 1.3 | 1.4 | 25 | 16.7 |
| 3 | <i>Achnanthes delicatula</i> ssp. <i>hauckiana</i> (Grunow) Lange-Bertalot in Lange-Bertalot and Ruppel | 45.5 | 1.3 | 1.5 | 432 | 1.9 |
| 45 | <i>Navicula bipustulata</i> Mann | 34.6 | 1.4 | 1.9 | 39 | 5.6 |
| 54 | <i>Navicula flantica</i> Grunow | 15.8 | 1.4 | 1.8 | 34 | 11.5 |
| 1 | <i>Achnanthes delicatula</i> (Kützing) Grunow ssp. <i>delicatula</i> | 25.3 | 1.5 | 1.7 | 57 | 15 |
| 41 | <i>Fragilaria schulzii</i> Brockmann | 9.8 | 1.5 | 1.6 | 38 | 20.8 |
| 4 | <i>Achnanthes lemmermannii</i> Hustedt | 23.1 | 1.5 | 1.6 | 42 | 20.9 |
| 48 | <i>Navicula cruciculoides</i> Brockmann | 3.9 | 1.5 | 1.5 | 19 | 10.3 |
| 50 | <i>Navicula cryptotenella</i> Lange-Bertalot | 2.4 | 1.6 | 1.4 | 6 | 3.6 |
| 68 | <i>Navicula</i> sp. 1 | 3.7 | 1.6 | 1.4 | 8 | 6.5 |
| 25 | <i>Denticula kuetzingii</i> Grunow | 4 | 1.6 | 3.4 | 10 | 3.9 |
| 80 | <i>Opephora olseni</i> Møller | 16.2 | 1.6 | 1.6 | 35 | 19.2 |
| 51 | <i>Navicula digitoradiata</i> (Gregory) Ralfs in Pritchard | 12.6 | 1.7 | 2.0 | 46 | 16.7 |
| 36 | <i>Fragilariforma virescens</i> var. <i>exigua</i> (Grunow) Poulin | 39.2 | 1.8 | 1.6 | 17 | 3.4 |
| 71 | <i>Navicula subinflata</i> Grunow in Cleve | 2.6 | 1.8 | 1.9 | 24 | 15.9 |
| 65 | <i>Navicula rhynchocephala</i> Kützing | 7.3 | 1.8 | 2.2 | 25 | 11.7 |
| 104 | <i>Tryblionella acuminata</i> Smith | 15 | 1.8 | 1.7 | 27 | 8.1 |
| 49 | <i>Navicula</i> sp. 2 | 4.5 | 1.8 | 1.7 | 21 | 12.3 |
| 37 | <i>Fragilaria pinnata</i> f. 1 | 6.5 | 1.8 | 1.4 | 11 | 4.3 |
| 103 | <i>Tryblionella apiculata</i> Gregory | 2.8 | 1.8 | 1.9 | 10 | 6.6 |
| 64 | <i>Navicula rhynchocephala</i> var. <i>elongata</i> Grunow | 2.5 | 1.9 | 2.4 | 10 | 7.9 |

Table 6 (continued)

| No. | Taxon | Max. (%) | WA Opt. (m) | WA Rg. (m) | Num. Occ. | Hill's N/2 |
|-----|---|-------------|----------------|---------------|--------------|---------------|
| 77 | <i>Nitzschia sigma</i> (Kützing) Smith | 17.3 | 1.9 | 2.0 | 49 | 12.8 |
| 79 | <i>Opephora marina</i> (Gregory) Petit | 8.9 | 1.9 | 1.5 | 19 | 9.9 |
| 38 | <i>Gyrosigma</i> cf. <i>balticum</i> (Ehrenberg) Rabenhorst | 3.2 | 1.9 | 1.7 | 7 | 4.9 |
| 44 | <i>Navicula abscondita</i> Hustedt | 4.4 | 2.0 | 1.3 | 4 | 3 |
| 6 | <i>Amphora acutiuscula</i> Kützing | 2.9 | 2.0 | 1.6 | 14 | 7.7 |
| 105 | <i>Tryblionella levidensis</i> Smith | 4.5 | 2.0 | 1.9 | 19 | 11.5 |
| 72 | <i>Navicula transitans</i> Cleve | 5.8 | 2.1 | 2.0 | 45 | 26.1 |
| 63 | <i>Navicula ramosissima</i> (Agardh) Cleve | 5.1 | 2.1 | 1.2 | 5 | 3.6 |
| 60 | <i>Navicula oestrupii</i> Schulz | 23.7 | 2.1 | 1.6 | 33 | 12.3 |
| 56 | <i>Navicula jamalinensis</i> Cleve in Cleve and Grunow | 8.8 | 2.1 | 1.5 | 14 | 8.8 |
| 35 | <i>Fragilariopsis cylindrus</i> (Grunow) Krieger | 3.3 | 2.2 | 1.4 | 7 | 4.9 |
| 76 | <i>Nitzschia dissipata</i> (Kützing) Grunow | 2.2 | 2.3 | 1.3 | 9 | 7.3 |
| 85 | <i>Pinnularia quadratarea</i> (Schmidt) Cleve | 9.1 | 2.4 | 2.3 | 23 | 7.9 |
| 42 | <i>Mastogloia elliptica</i> (Agardh) Cleve | 6 | 2.5 | 3.1 | 5 | 2.8 |
| 53 | <i>Navicula finmarchica</i> (Cleve and Grunow) Cleve | 2.3 | 2.5 | 1.6 | 9 | 6.9 |
| 82 | <i>Petronis humerosa</i> (Brébisson) Stickle and Mann | 1.6 | 2.6 | 2.0 | 18 | 14.8 |
| 78 | <i>Opephora gemmata</i> (Grunow) Hustedt | 2.6 | 2.6 | 1.7 | 6 | 5.4 |
| 69 | <i>Navicula</i> cf. <i>starmachii</i> Witkowski and Lange-Bertalot | 7.1 | 2.6 | 1.5 | 12 | 5.7 |
| 52 | <i>Navicula directa</i> var. <i>javanica</i> Cleve | 6.7 | 2.8 | 1.6 | 15 | 6.2 |
| 66 | <i>Navicula salinarum</i> Grunow in Cleve and Grunow | 25.4 | 3.0 | 1.8 | 45 | 13.7 |
| 29 | <i>Diploneis smithii</i> var. <i>dilatata</i> (Peragallo) Terry | 52.6 | 3.2 | 1.8 | 26 | 6.2 |
| 8 | <i>Amphora copulata</i> (Kützing) Schoeman and Archibald | 20 | 3.3 | 1.8 | 47 | 14.1 |
| 91 | <i>Fragilaria leptostauron</i> (Ehrenberg) Hustedt | 2 | 3.3 | 2.1 | 7 | 5.3 |
| 46 | <i>Navicula cancellata</i> Donkin | 11.4 | 3.3 | 2.1 | 28 | 7.5 |
| 7 | <i>Amphora coffeaeformis</i> (Agardh) Kützing | 12.3 | 3.3 | 1.6 | 30 | 15.3 |
| 86 | <i>Pinnularia</i> sp. 1 | 2.5 | 3.5 | 2.0 | 20 | 13.9 |
| 93 | <i>Fragilaria pinnata</i> Ehrenberg | 13.1 | 3.5 | 1.8 | 35 | 11.3 |
| 19 | <i>Caloneis westii</i> (Smith) Hendey | 2 | 3.6 | 2.0 | 6 | 4.3 |
| 22 | <i>Cocconeis placentula</i> Ehrenberg | 1 | 3.6 | 2.4 | 12 | 9.6 |
| 9 | <i>Amphora pediculus</i> (Kützing) Grunow in Schmidt et al. | 2.5 | 3.6 | 1.7 | 7 | 4.9 |
| 16 | <i>Caloneis crassa</i> (Gregory) Ross in Hartley | 4.6 | 3.6 | 2.1 | 34 | 21.1 |
| 33 | <i>Fallacia soluteopunctata</i> (Hustedt) Mann | 23.1 | 3.7 | 1.4 | 19 | 7.2 |
| 17 | <i>Caloneis schumanniana</i> (Grunow) Cleve | 33.1 | 4.0 | 1.7 | 36 | 15.1 |
| 83 | <i>Petronis marina</i> (Ralfs) Mann | 15 | 4.3 | 2.1 | 24 | 4.7 |
| 5 | <i>Achnanthes taeniata</i> Grunow in Cleve and Grunow | 11.4 | 5.2 | 1.3 | 16 | 9.2 |
| 10 | <i>Amphora</i> sp. (aff. <i>ocellata</i> sensu Peragallo and Peragallo) | 5 | 5.8 | 1.2 | 9 | 5.8 |
| 27 | <i>Diploneis litoralis</i> (Donkin) Cleve | 1.2 | 5.8 | 1.7 | 15 | 11.3 |
| 90 | <i>Fragilaria construens</i> (Ehrenberg) Hustedt | 6 | 5.9 | 1.8 | 15 | 6.8 |
| 67 | <i>Navicula scutelloides</i> Smith in Gregory | 2.4 | 6.0 | 1.9 | 12 | 9.9 |
| 89 | <i>Fragilaria brevistriata</i> Grunow in van Heurck | 4.5 | 6.4 | 1.6 | 14 | 6.3 |
| 99 | <i>Thalassiosira hyperborea</i> var. <i>septentrionalis</i> (Grunow) Hasle 1989 | 47.6 | 7.5 | 1.5 | 32 | 15.7 |
| 21 | <i>Chaetoceros</i> sp. 1 | 19.4 | 7.5 | 1.6 | 33 | 17 |
| 98 | <i>Thalassiosira baltica</i> (Grunow) Ostfeld | 17.8 | 7.5 | 1.7 | 31 | 14.2 |
| 100 | <i>Thalassiosira hyperborea</i> (Grunow) Hasle | 8.6 | 7.6 | 1.3 | 19 | 13.1 |
| 101 | cf. <i>Thalassiosira</i> sp. 1 | 9.3 | 7.8 | 1.3 | 19 | 10.2 |
| 12 | <i>Aulacoseira islandica</i> (Müller) Simonsen | 54.9 | 8.0 | 1.5 | 32 | 16 |
| 20 | <i>Chaetoceros diadema</i> (Ehrenberg) Gran | 4.1 | 8.8 | 1.3 | 15 | 8.5 |
| 24 | <i>Craspedopleura kryophila</i> (Cleve) Poulin | 1.4 | 8.8 | 1.3 | 7 | 6.2 |
| 11 | <i>Aulacoseira alpigena</i> (Grunow) Krammer | 2.2 | 8.8 | 1.3 | 14 | 11.6 |
| 95 | <i>Stephanodiscus</i> sp. 1 | 15.2 | 9.1 | 1.5 | 22 | 13.9 |
| 13 | <i>Aulacoseira</i> cf. <i>italica</i> var. <i>tenuissima</i> (Grunow) Simonsen | 3.6 | 9.5 | 1.3 | 15 | 12.3 |
| 94 | <i>Stephanodiscus</i> sp. [cf. <i>rotula</i> (Kützing) Hendey] | 4.3 | 10.4 | 1.4 | 13 | 8.2 |
| 96 | <i>Synedra ulna</i> (Nitzsch) Ehrenberg | 1.5 | 10.8 | 1.2 | 8 | 6.6 |
| 102 | <i>Thalassionema nitzschioides</i> (Grunow) Grunow ex Hustedt | 11.9 | 11.0 | 1.2 | 14 | 7.7 |

(e.g. sites #73 and 74). Most of the water depth values inferred from lagoonal assemblages approximate 1 m, which is in close agreement with the mean water depth of the shallow lagoons of the Atkinson Point area. However, there is a considerable gap between inferred and observed values in lagoons of the Mackenzie Delta front.

Secondly, the model over-estimated the water depth of some samples located in Kugmallit Bay, in the Mackenzie Delta front. The inferred water depths at stations 65 and 60 are about twice the measured values. These anomalies may be attributed to the similar composition of diatom assemblages in the delta front and the inner shelf. These environments contain a number of planktonic and tycho-planktonic forms with freshwater–brackish affinities. The occurrence of these species reflects the freshwater influence of the Mackenzie River plume along the Tuktoyaktuk Peninsula and has an important impact on the model. *Aulacoseira islandica*, for example, is the dominant species in both the Mackenzie Delta front sites and on the southeastern inner shelf. However, *A. islandica* occurs at lower water depths in the delta than along the peninsula due to the greater influence of freshwater discharges near the delta. Because of the small number of sampling stations in the delta front, the WA optimum water depth of deposition reflects more adequately the distribution of this taxon along the southeastern coast where there are more stations. In order to more accurately reflect the vertical distribution of diatom species in the entire Beaufort Sea, our training set should be enlarged to integrate the heterogeneous hydrographic conditions produced by the dispersion of the Mackenzie River plume along the eastern, central and western parts of the shelf.

Besides these anomalies, the model is powerful in inferring the water depth of shoreface environments. Fig. 9 presents some morphological features and processes that could explain the strong diatom/water-depth relationship in these environments, which is believed to be related to the shoreface circulation. Along the southeastern Beaufort Sea coasts, the surf zone, which is the most dynamic environment of the upper shoreface, is dominated by brackish epipellic diatoms, such as *Placoneis clementis*, *Navicula meniscus*, *N. oestrupii* and *N. bipustulata*, and by few epipsammic species,

dominated by *Achnanthes delicatula* ssp. *delicatula*. Besides the surf zone, the remaining part of the upper shoreface, which is not affected by breaking waves but still influenced by shoaling waves, is also dominated by epipellic taxa but differs with respect to the dominant species. Planktonic diatoms are unable to deposit on the constantly reworked sediments of the surf zone. They begin to settle in the lower part of the upper shoreface becoming progressively the dominant diatoms deposited in lower shoreface and inner shelf sediments. On the lower shoreface, the wave influence is lower and only effective during storm events. However, during northwesterly storms, strong seaward-directed near-bottom currents associated with downwelling have been observed (Héquette and Hill, 1993; Desrosiers, 1997). Because medium- to fine-grained sands prevail on the shoreface, a significant sediment transport load is probably moved down the shoreface by such currents during major events, thus contributing to offshore sediment dispersal. The mechanisms that distribute sediment particles also influence the density and composition of diatom populations. Since bottom currents may dislocate shallow-water forms and transport them in deeper areas, diatom assemblages of the lower shoreface may contain representatives of both the neritic and oceanic plankton as well as a number of sessile and vagile forms. Consequently, lower shoreface assemblages contain mostly planktonic species that have settled out of the water column during fairweather conditions and some epipellic and epipsammic diatoms. The latter live in the upper sediments or have been transported from the upper shoreface by seaward-directed bottom currents during storm events. Inner shelf assemblages are primarily dominated by euplanktonic and tycho-planktonic forms that are able to settle owing to the low energy environment of the shelf.

In summary, the strong diatom/water-depth relationship in the surface sediments of the southeastern Beaufort Sea coasts is mostly explained by a shift in the relative abundance of the epipsammic, epipellic, and plankton along the water depth gradient of the shoreface (Fig. 9). Upper shoreface assemblages are dominated mainly by epipellic species and some epipsammic taxa, whereas deeper environments are dominated by planktonic species. This strong water depth signal is partially due to its close

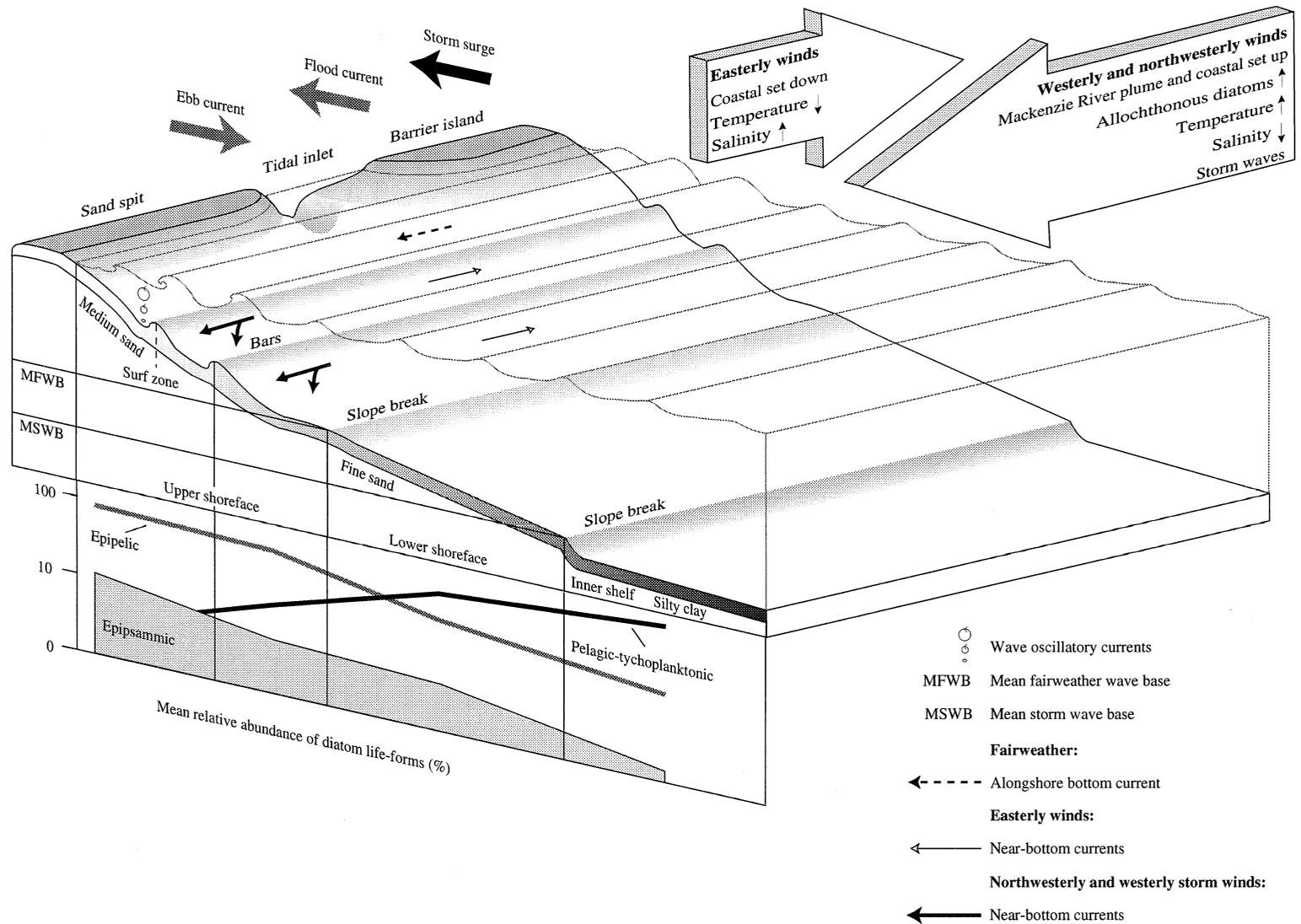


Fig. 9. Some morphological features and processes controlling the distribution of shoreface and inner shelf diatom assemblages, and distribution of the mean relative abundance (%) of diatom life-forms along the water depth gradient.

relationship to other environmental variables, and it may therefore be difficult to separate diatom-preferred depth from oceanic processes influencing the distribution of the assemblages. Consequently, it is argued that the transfer function derived from this calibration set does not necessarily reflect the water depth preferences of diatom taxa, but rather a depositional pattern specific to each water depth resulting from all processes acting on their distribution. Depending on their size, shape and life-form, diatoms are more or less easily transported by currents. As a consequence, sediments deposited below the water column contain a mixture of autochthonous and allochthonous valves. The term allochthonous refers to those individuals transported away from their life position before burial, whereas autochthonous individuals are those incorporated into the deposit directly from their source communities. As for diatoms, it has been considered important to differentiate between allochthonous valves and those belonging to the local assemblage, as only the latter were considered to give precise information on the local paleoenvironment (Beyens and Denys, 1982; Vos and De Wolf, 1988). Based on the results of the present study, it is argued that allochthonous valves should rather be considered as a valuable source of additional information. The occurrence of certain allochthonous taxa in sedimentary environments has previously been used to infer former tidal influence, the presence of other habitats adjacent to the site of deposition, as well as patterns of sediment transport. In the Beaufort Sea, the distribution of allochthonous valves reflects the hydrological regime of surface waters by marking the extent of the Mackenzie River plume. In shoreface environments, allochthonous valves provide information on the intensity of the hydrological processes and the source of eroded and transported materials. The separation between upper and lower shoreface assemblages was possible due to the distinct processes acting on the distribution of diatom valves in these environments. By considering the whole assemblage, one can get a synoptic view of the processes acting on an environment. From that point of view, few inferences can be made on the ecological preferences of each species in an assemblage. On the other hand, valuable insights can be obtained on the processes that have led to the formation of a particular deposit. However, to adequately interpret the

environmental significance of allochthonous valves, it is imperative to analyse the composition of surficial sediments to establish the relationships between modern assemblages and sedimentary environments. The knowledge of these relationships allows more accurate paleoenvironmental interpretations of fossil diatom assemblages.

8. Application of the model in other coastal areas

As it was derived from one specific geographic location, the applicability of the Beaufort Sea model in other coastal areas will have to be tested. As surface sediment diatom assemblages are modelled by hydrodynamic conditions, it is likely that the diatom/water-depth relationship may vary from one coastal area to another. For example, the storm-generated shoreface circulation observed along the Tuktoyaktuk Peninsula seems to affect shallower depths compared to other shoreface environments, because the Beaufort Sea is characterized by lower energy waves (Héquette and Hill, 1993; Desrosiers, 1997). Accordingly, the surf zone characteristically does not exceed 2 m depth (Héquette and Barnes, 1990) depending on weather conditions, whereas it may extend, for example, to a depth of 5 m along the Atlantic shores (Swift et al., 1985). Similarly, the boundary between the upper shoreface and the lower shoreface is not absolute and depends on the intensity of waves and currents; with regards to the effects of waves on the bottom, depths of 10–15 m are considered as a valid generalized division (Swift et al., 1985). That boundary is of great importance as it is associated, in the Beaufort Sea, with shifts in diatom abundances from benthic to planktonic species. These shifts, which occur gradually in the Atkinson Point area from 3 to 10 m, will occur at different depths depending on the dynamic conditions of a particular coast. In the southern Baltic Sea, for example, they occur only at stations deeper than 15 to 20 m (Witkowski, 1991).

A further limitation on the applicability of the Beaufort Sea model in other coastal areas is imposed by the tidal range. The vertical range of salt marsh zones and the relations of their boundaries to tide levels differ from one region to another. Consequently, the optimum water depth of deposition of a

particular salt marsh species is likely to vary from microtidal to macrotidal environments.

However, apart from these dissimilarities, comparison with diatom studies of coastal deposits from northern temperate regions shows that most diatom species encountered in the surface sediments of the Beaufort Sea are worldwide in distribution. Most of the Beaufort Sea diatoms have also been observed, for example, in the Baltic and North seas (Hendey, 1964; Pankow, 1976; König, 1982; Sundbäck, 1983, 1987; Thulin, 1987; Witkowski, 1991, 1994), Belgium (Denys, 1991), The Netherlands (Sabbe and Vyverman, 1991; Vos and De Wolf, 1993), and along the northeast Pacific coasts (Nelson and Kashima, 1993; Hemphill-Haley, 1996). The apparently wide distribution of many coastal diatoms in northern seas suggests that the Beaufort Sea data set could be merged with data sets from other coastal areas to develop a more universal transfer function. A larger calibration data set would increase the number of taxa in the inference model, increase our understanding of the relationship between diatom assemblages and water depth, and provide more analogues appropriate for paleoreconstructions. Merging of regional data sets generates new transfer functions without decreasing their predictive ability and has proven to provide suitable analogues for fossil assemblages, even though they may be geographically distant (Gasse et al., 1995; Wilson et al., 1996). Otherwise, the present calibration function will generate reliable data only when applied in coastal areas with hydrographic conditions similar to those of the Beaufort Sea, i.e. in shallow sandy microtidal environments with low wave energy and strong freshwater influences.

9. Paleodepth reconstruction

Fossil diatoms were analysed from a 1.08 m core from the Atkinson Point area (Fig. 3), and the water depth transfer function was used to infer the history of late Holocene relative sea-level change in this area. The results of the diatom analysis have been synthesized in the form of percentage diagrams (Fig. 10). WA calibration was performed based on the species optima previously calculated to directly infer the position of past relative sea levels from fos-

sil core diatom assemblages. The \log_e -inferred water depths were back-transformed to the original unit (m). Core assemblages contained some taxa absent in the modern data set and vice versa. Only taxa present in both sets were included in the analyses, which represent 75–95% of the total diatom count per core sample. The high similarities between fossil and recent diatom assemblages allowed to produce reliable paleodepth inferences.

The base of core C-93-13 consists of an organic-rich silty sand layer overlain by muddy peat (Fig. 10). The middle section of the core is composed of organic-rich silty sand between 66 and 72 cm followed by a clean sand layer at 59–66 cm. The uppermost zone of the core consists of muddy peat. Comparison of core diatom assemblages with contemporary assemblages of the Beaufort Sea coast (Campeau et al., 1998) allowed to identify three diatom zones, each of them corresponding to a modern analogue. The lowermost diatom zone (A) is largely dominated by oligohalobian-indifferent species, such as *Fragilaria pinnata* and its varieties, *F. construens*, *F. brevistriata*, *Amphora pediculus* and *Achnanthes minutissima*. These benthic species dominate the modern assemblages of thermokarst lakes on the Tuktoyaktuk Peninsula. They may withstand slightly brackish water conditions, which reflects the maritime character of these lakes. Benthic algal growths are favoured by the shallowness of the lakes and the resulting high levels of available light reaching the bottom. The lower boundary of this zone only contains fragments of freshwater diatoms, which may reflect the initial phase of a lake. Lake diatom assemblages were not included in our modern data set. Consequently, no paleodepth values have been inferred in the bottom section of the core. The transition between zones A and B is marked by a gradual contact, as all the freshwater species occurring in zone A are also present in zone B. The lower boundary of zone B is distinguished by the appearance of epipsammic and aerophilic species, the latter including *Diploneis interrupta*, *Navicula eidrigiana*, *N. aff. marginalithii*, and *Caloneis bacillum*, which are characteristic species of salt marsh assemblages. Salt marshes commonly develop on drained lake shelves along the southeastern Beaufort Sea coasts. This assemblage indicates that the thermokarst lake has been breached and was periodically, but not fre-

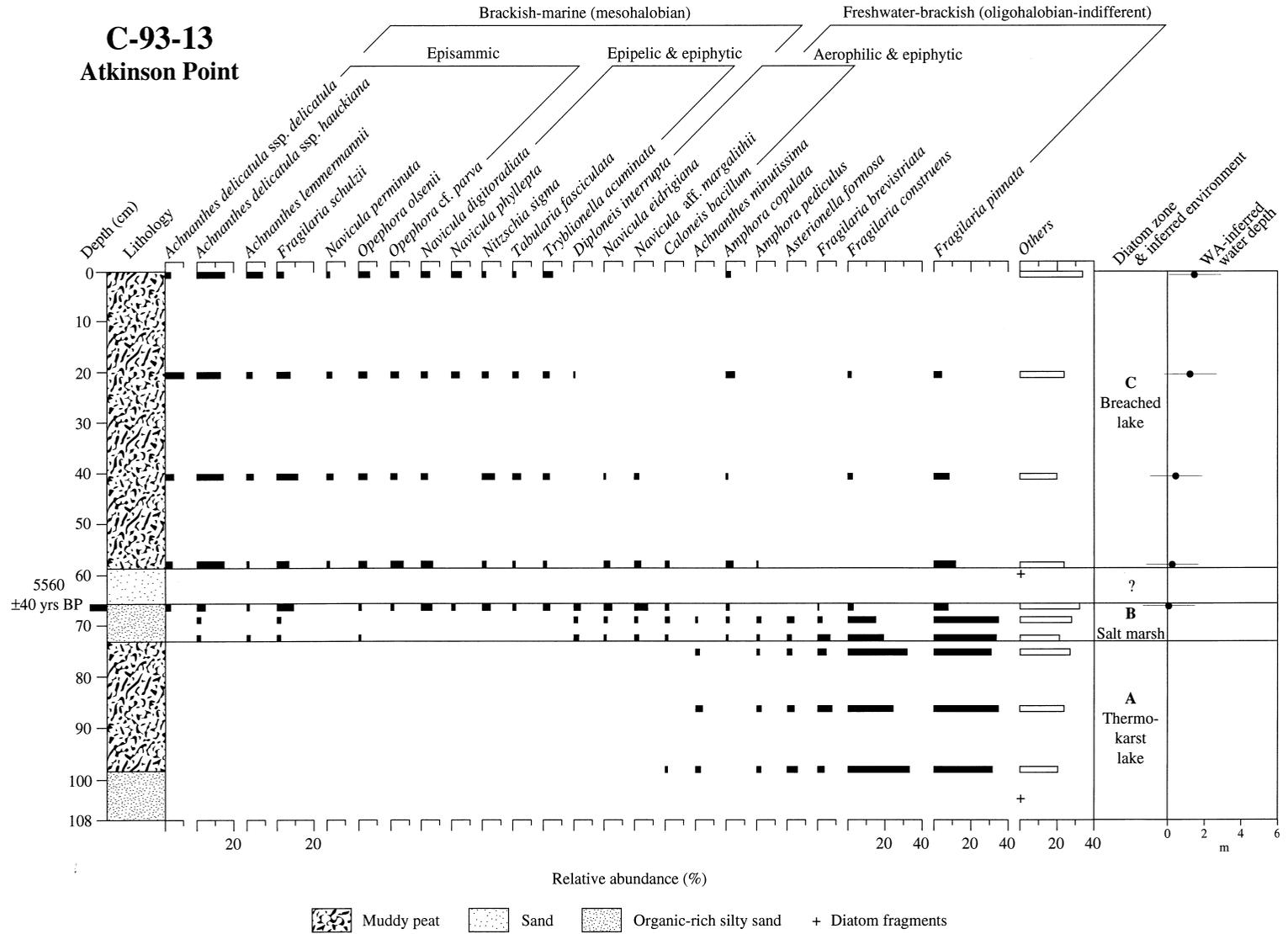


Fig. 10. Diatom diagram for core C-93-13 (Atkinson Point). Diatoms are classified according to their salinity preferences and life-forms. The biostatigraphic zones were defined based on a detailed analysis of the contemporary diatom assemblages associated with modern sedimentary environments of the southeastern Beaufort Sea coast (Campeau et al., 1998). Paleodepth values were inferred from the diatom-based transfer function presented in this paper.

quently, inundated by sea water. The low abundance of epipsammic taxa and the dominance of *Fragilaria* species suggest that the basin was influenced only by high tide levels and storm surges. The upper boundary of zone B shows an increase in epipsammic and aerophilic taxa, the appearance of epipellic diatoms, and a drastic decline in freshwater species. This indicates that the mean sea level reached the basin. The WA-inferred water depth is close to zero. The abundance of mesohalobian taxa and the drop in oligohalobian species clearly indicate that this assemblage was permanently tidally influenced. The sand layer, between zones B and C, which contains only fragments of mesohalobian diatoms, probably originates from an intensification of sea influence and may be interpreted as a storm deposit.

Diatom zone C is marked by an increase in mesohalobian epipsammic species and a further decline in freshwater taxa. The most prominent feature of this zone is the dominance of mesohalobian epipsammic diatoms, including *Achnanthes delicatula* ssp. *hauckiana*, *A. lemmermannii*, *Opephora* cf. *parva*, *O. olsenii*, *Fragilaria schulzii* and *Navicula perminuta*. These species, accompanied by some epipellic and epiphytic taxa, are characteristic of modern lagoonal assemblages. As mentioned in Section 2.1, lagoonal environments along the southeastern Beaufort Sea are usually made of embayments formed by the breaching of thermokarst lakes. Although present at the boundary between the sand layer and zone C, aerophilic species decrease upwards, as the water depth increased. The entire sedimentary sequence therefore represents a lagoonal environment that has transgressed over a thermokarst lake. The dated sample from the uppermost part of zone B provided an age of 5560 ± 40 yr B.P. (Beta-110638).

The dated sample, associated with the water-depth value inferred by the WA model, represents a sea-level index point. The vertical component of this index point, i.e. its indicative meaning (sensu Van de Plassche, 1986), was calculated by adding the depth (0.66 m) of the dated core section to the water depth at the core station (2.0 m), and by subtracting the WA-inferred water depth (0.07 m) from this value. As coring was conducted from an inflatable boat and tidal range is small, the reference datum-level used was the local mean sea level. The vertical error associated with the index point was thus cal-

culated by adding the range of spring tides (± 0.25 m) to the error associated with the WA-inferred water depth (± 1.43 m) for the dated level. As sand is little subjected to compaction (over a geologically short period of a few thousand years and at shallow depths; Greensmith and Tucker, 1986) and coastal sediments of the Atkinson Point area rest on clay-deficient Pleistocene sands, no correction was made for sediment compaction. Thus, the diatom paleodepth record indicates that the relative sea level was 2.59 ± 1.66 m lower during the mid-Holocene and has continuously increased since then. However, these results are preliminary and a more complete investigation involving a greater number of cores is presently underway to accurately reconstruct the late Holocene RSL fluctuations in the southeastern Beaufort Sea.

The use of a water-depth transfer function represents an improvement over traditional methods of sea-level reconstructions which usually provided qualitative estimates of past RSL. Traditional approaches mostly relied on the identification and analysis of transgressive and regressive overlaps by analysing stratigraphic boundaries between terrestrial freshwater sediments and marine littoral facies. In these studies, diatom analysis was used to validate sea-level index points by considering changes in the composition of diatom groups of different salinity preferences. Most of these paleo-sea-level reconstructions were constrained by the lack of well-established quantitative relationships between modern diatom assemblages and sea level, and therefore none of the index points used were direct sea-level indicators. The radiocarbon dates used in these studies only yielded minimum or maximum ages, depending on which side of the isolation contact they were obtained. By determining the relationship between water depth and diatom species distributions and abundances in modern environments, it is possible to overcome the limitations of traditional approaches and quantitatively infer past relative sea levels. The water-depth model could be especially useful in incomplete sequences in which the transition between the lacustrine and marine zones is marked by an erosional contact. The water depth transfer function actually eliminates the need of a freshwater–marine contact. Any section of the brackish–marine sequence may thus be dated and serve as a sea-level

index point, as long as datable material is available and water-depth inferences are based on reliable modern analogues.

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