THE DISTRIBUTION OF MODERN DIATOM ASSEMBLAGES IN COASTAL SEDIMENTARY ENVIRONMENTS OF THE CANADIAN BEAUFORT SEA: AN ACCURATE TOOL FOR MONITORING COASTAL CHANGES

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Abstract

The diatom assemblages preserved in the surface sediments of 11 coastal sub-environments were analysed to provide a modern analogue for the recognition of various sedimentary facies present in stratigraphic records of the Beaufort Sea coastal areas. The modern biofacies were defined using the relative abundance of different ecological groups, particularly the occurrence of marine/brackish epipsammic diatoms which are predominant. Other criteria, such as species richness values, the occurrence of diagnostic species and the relative abundance of chrysophycean statospores to diatom frustules were used. In addition to the classical nonmarine to marine gradient, the definition of these coastal biofacies lead to the recognition of a gradient in exposure to coastal processes, from restricted circulation in non-exposed breached lakes to more open coastal circulation in lagoons.

Résumé

Les assemblages de diatomées préservés dans les sédiments de surface de 11 sous-environnements côtiers furent analysés pour définir leurs biofaciès actuels et faciliter l'interprétation des unités stratigraphiques de la plate-forme continentale de la mer de Beaufort. Les biofaciès modernes furent définis selon l'abondance relative de différents groupes écologiques, particulièrement des diatomées épipsammiques d'eaux saumâtres qui sont les plus abondantes. D'autres critères, tels que le nombre d'espèces contenues dans les assemblages, la présence d'espèces diagnostiques et l'abondance relative des kystes de chrysophycées par rapport aux frustules de diatomées, furent également utilisés. Les biofaciès côtiers actuels mettent en évidence un gradient dans l'exposition des bassins aux processus côtiers, d'une circulation restreinte dans les lacs ouverts non exposés à une circulation plus intense dans les lagunes.

Introduction

Shoreline response is directly related to changes in sediment supply, climate and relative sea-level (RSL). There are therefore many valuable insights to be gained from being able to recognize a wide variety of clastic shorelines in the stratigraphic record. During the Holocene, the thermokarst activity and the rise of RSL have lead to the formation of various sedimentary basins in the coastal areas of the Tuktoyaktuk Peninsula (N.W.T.). The RSL of the Beaufort Sea rose from approximatly -70 m to its present position (Hill *et al.*, 1993). This rise induced coastal retreat and resulted in the formation of embayments formed by the breaching of thermokarst lakes. The transgression was also responsible for the development of spits and barrier islands. The landward migration of these transgressive coastal landforms contributed to the infilling of shallow breached lakes and lagoons during the late Holocene. High-resolution seismic profiles from the inner shelf of the Beaufort Sea suggest that this process of lagoon infilling also occurred during the middle Holocene (Héquette *et al.*, 1995). The interpretation of the sedimentary facies of these depositional environments may be complex due to the similarity of their sandy facies.

Diatoms have proven to be useful to reconstruct sedimentary facies and paleo-tide levels (Vos and de Wolf, 1988; Nelson and Kashima, 1993; Denys, 1994), sea-level change and related transgressive and regressive coastal lithozones (Stabell, 1982; Palmer and Abbott, 1986; Denys and Verbruggen, 1989; Palmer and Clague, 1991; Pienitz *et al.*, 1991) and paleo-salinity gradients (Moore and McIntire, 1977; Juggins, 1992).

In this report, the diatom assemblages preserved in the surface sediments of 11 coastal sub-environments were analysed to define the present biofacies of these sedimentary basins. Studies aiming at modelling the composition of contemporary biofacies in their modern environment may provide an accurate tool for the interpretation of the various sedimentary facies present in the stratigraphic record.

Thermokarst environments

Thermokarst lakes

More than 50% of the northeastern part of the Tuktoyaktuk Peninsula consists of thermokarst lakes (Fig. 1). In many lakes, a sandy shallow near-shore shelf surrounds a central deeper basin which rarely exceeds 5 m deep. Lakes are free of snow and ice for only a few weeks during the year (Hobbie, 1973), but small shallow lakes may be free of ice for a longer period. The water of the investigated lake is slightly alkaline (pH 7,7) and oligotrophic (total P = 8 µg/L). The surface-water temperature may reach 15°C in July. The proportions of the more abundant diatom taxa (>1%) are summarized in Fig. 2a. The diatom flora is dominated by small freshwater benthics with *Fragilaria pinnata* and *Amphora pediculus* being the most adundant species. The proportion of chrysophycean statospores to diatom frustules reaches up to 10%.

Drained Thermokarst lakes

Many lakes have undergone at least partial drainage by erosion of ice-rich terrain at their outlets (Mackay, 1988). Once drained, the shelves may be covered by wet low center polygons and by residual ponds. Most of the plant cover consists of sedges, of which *Carex* and *Eriophorum* species are common (Corns, 1974). The diatom flora of the wet low center polygon is dominated by *Denticula kuetzingii* and by *Navicula tuscula* (Fig. 2b). This assemblage also contains a diagnostic species, *Hantzschia amphioxys*, which is an aerophilic taxon which may withstand drying (Bock, 1963). In residual ponds, the plant cover mainly consists of *Eriophorum angustifolium* ssp. *triste*, *Lemma trisulca*, *Caltha palustris* ssp. *arctica* and *Carex aquatilis*. The roots of these plants grow together, and as they die and decay, a quaking mat is formed (Corns, 1974). The diatom flora of these ponds is dominated by freshwater species (70%) of which *Eunotia praerupta* and *Navicula begerii* are the most abundant (Fig. 2c). These species are hydroterrestrial and are common in bogs and ponds. The rest of this assemblage consists of some euryhaline taxa. Species richness values, which were about 35 in thermokarst lakes, are reduced to 20 in both low center polygons and ponds.

Backbarrier environments

As the RSL rises and the coastline retreats, drained thermokarst lakes are breached and gradually flooded by sea water. These lakes are then affected by tidal currents and storm surges. The mean tidal range is 0.3 m at mean tides and 0.5 m at large tides. The coastline may occasionally be affected by positive storm surges up to 2.4 m above mean sea-level (Harper *et al.*, 1988). The chemistry of the coastal waters is particularly affected by the ice regime and the Mackenzie River plume. Coastal ice forms and becomes intermittently stationary during the freeze-up season, usually from October to mid-January. The period extending from mid-January through May is characterized by stable coastal ice (*fast ice*). The breakup season from June to mid-July is associated with deterioration of the fast ice. During the open water season, winds mainly originate from the east, southeast and northwest. However, most of the higher energy waves originate from the northwest in response to storm winds. As a result, the Mackenzie River plume usually reaches the Atkinson Point area in August due to an increased frequency of northwest winds. The Mackenzie River plume leads to an increase in the dissolved organic carbon (DOC) content of the coastal waters and to a decrease in their salinity (Table 1). Consequently, the diatom flora of the Beaufort Sea coastal waters is dominated by euryhaline species with a broad ecological tolerance. Moreover, the northeastern part of the peninsula is primarily formed of glacial outwash sands which are covered by eolian or lacustrine sediments (Rampton, 1988). Thus, the coastal basins mostly consist of sand with a variable content of organic matter. The diatom flora is consequently dominated by marine/brackish epipsammic (living attached to or between sand grains) species, excluding salt marsh assemblages which have a distinct species composition. *Achnanthes delicatula* ssp. *hauckiana* is the major component of coastal water assemblages and *Achnanthes lemmermannii, Martyana schulzii, Opephora olsenii* and *O. marina* are a significant part of the flora. Despite the dominance of epipsammic species, assemblages vary according to an exposure gradient to coastal processes, from non-exposed breached lakes with runoff input to open lagoons.

Table 1. Comparison of water chemistry before (mid-July) and after (mid-August) the occurrence of the Mackenzie River plume in the Atkinson Point area .

	Salinity ‰	T °C	DOC mg/L	SiO_2 mg/L	Cl^- mg/L	SO_4^{2-} mg/L	Na mg/L	Ca mg/L
Mid-July	23	13	0.2	0.04	16921	1555	9687	383
Mid-August	8.5	10	1.4	2.88	5200	718	2820	135

Salt marshes

Salt marshes may develop on former lake shelves, where periodic submergence by salt water occurs. Most of the plant cover of salt marshes consists of *Puccinellia* and *Carex* species (Corns, 1974). The diatom flora is marked by a dominance of fresh- and brackish aerophilous species of which *Diatoma vulgaris* and *Pinnularia borealis* are the most abundant (Fig. 4b). Other significant diatoms (>2%) of this assemblage include *Navicula mutica* and *Hantzschia amphioxys* which are aerophilous (supratidal) species typical of salt marshes and wet soils (Vos and de Wolf, 1988).

Non-exposed breached lakes

Some of the breached lakes are partly protected from coastal processes by submerged lake banks or by their inland situation (Fig. 3a, b). Breached lakes with runoff input have a low content of epipsammic species compared to exposed breached lakes and lagoons. They have a high content of brackish/freshwater species with a small amount of allochthonous freshwater species and chrysophytes cysts. These assemblages reflect a brackish environment influenced by freshwater runoff from inland areas. In breached lakes without runoff input, the percentage of brackish/freshwater species decreases, whereas the percentage of marine/brackish epipsammic species increases. The lack of allochthonous freshwater species and chrysophytes cysts is also a predominant feature of these assemblages.

Exposed breached lakes and lagoons

Exposed breached lakes and lagoons have similar assemblages (Figs. 4 and 5). The diatom community of these environments is composed of a small number of species compared to those from non-exposed areas. Besides, the number of epipsammic species increases, ranging from 55% to 85%. In lagoonal assemblages, the percentage of epipsammic species is slightly higher, whereas the species richness decreases significantly. The lowest number of taxa (12) occurs in sediments with low organic matter content which are subject to relatively strong tidal currents. The low number of taxa of which more than 85% are epipsammic diatoms could be explained by mechanical sediment reworking. The predominance of epipsammic species is consistent with the literature data describing diatom species composition in moderate- to high-energy coastal shallow environments (de Jonge 1985; Vos *et al.*, 1988).

Conclusion

The characteristic features of diatom assemblages with respect to their sedimentary environments are summarized in Table 2. The recognition of thermokarst lake sub-environment biofacies in the stratigraphic record should be facilitated by the distinct species composition of their fossil diatom assemblages. Thermokarst lakes are dominated by small freshwater benthic forms, whereas wet low center polygons and ponds are dominated by hydroterrestrial taxa. Salt marshes have also a particular diatom flora with a predominance of brackish aerophilous forms. In breached lake and lagoon basins, the dominance shifts to epipsammic species. Non-exposed breached lake assemblages are relatively diverse with species numbers ranging from 35 to 40 of which less then 50 % are epipsammic species. Exposed breached lakes and lagoons have a higher number of epipsammic species but species richness is poor. In addition to the classical nonmarine to marine gradient, the definition of these coastal biofacies leads to the recognition of a gradient in exposure to coastal processes, from restricted circulation in non-exposed breached lakes to more open coastal circulation in lagoons.

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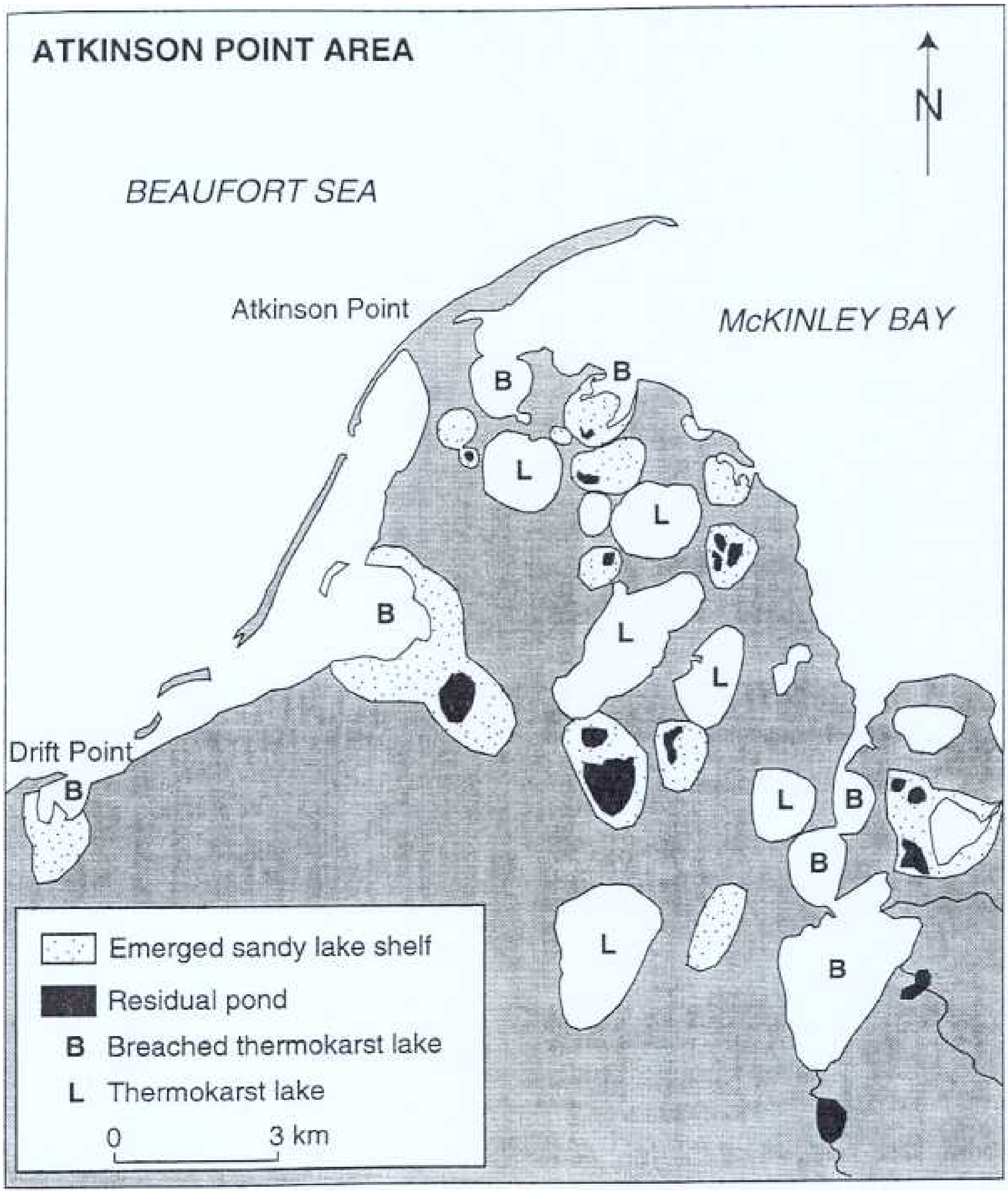
ATKINSON POINT AREA
N
BEAUFORT SEA
Atkinson Point
McKINLEY BAY
Drift Point
B
L
Emerged sandy lake shelf
Residual pond
B Breached thermokarst lake
L Thermokarst lake
0
3 km

Figure 1.

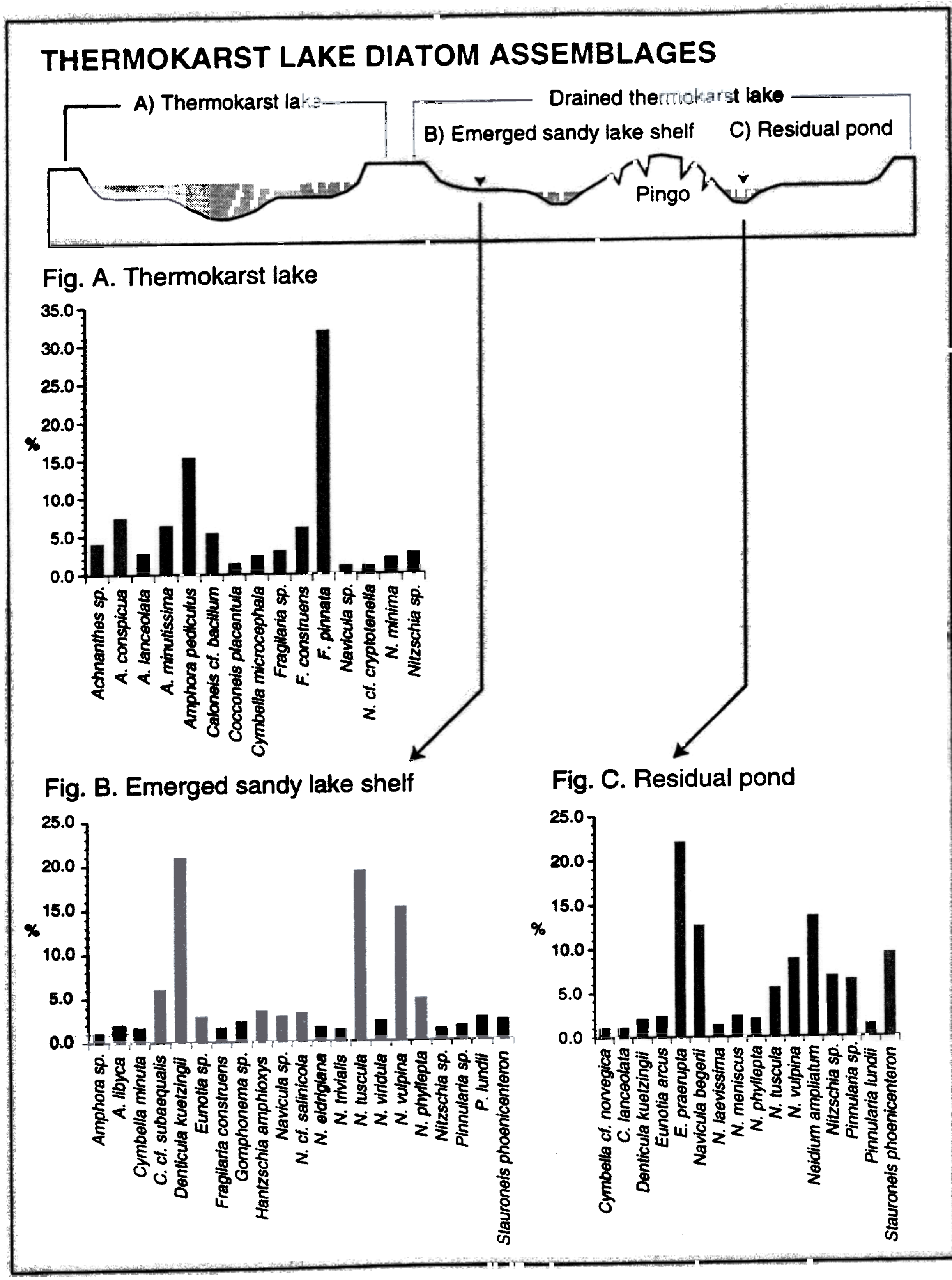
THERMOKARST LAKE DIATOM ASSEMBLAGES
A) Thermokarst lake
Drained thermokarst lake
B) Emerged sandy lake shelf
C) Residual pond
Pingo
Fig. A. Thermokarst lake
%
Achnanthes sp.
A. conspicua
A. lanceolata
A. minutissima
Amphora pediculus
Caloneis cf. bacillum
Cocconeis placentula
Cymbella microcephala
Fragilaria sp.
F. construens
F. pinnata
Navicula sp.
N. cf. cryptotenella
N. minima
Nitzschia sp.
Fig. B. Emerged sandy lake shelf
Amphora sp.
A. libyca
Cymbella minuta
C. cf. subaequalis
Denticula kuetzingii
Eunotia sp.
Fragilaria construens
Gomphonema sp.
Hantzschia amphioxys
Navicula sp.
N. cf. salinicola
N. eldrigiana
N. trivialis
N. tuscula
N. viridula
N. vulpina
N. phyllepta
Nitzschia sp.
Pinnularia sp.
P. lundii
Stauroneis phoenicenteron
Fig. C. Residual pond
Cymbella cf. norvegica
C. lanceolata
Denticula kuetzingii
Eunotia arcus
E. praerupta
Navicula begerii
N. laevissima
N. meniscus
N. phyllepta
N. tuscula
N. vulpina
Neidium ampliatum
Nitzschia sp.
Pinnularia sp.
Pinnularia lundii
Stauroneis phoenicenteron

Figure 2.

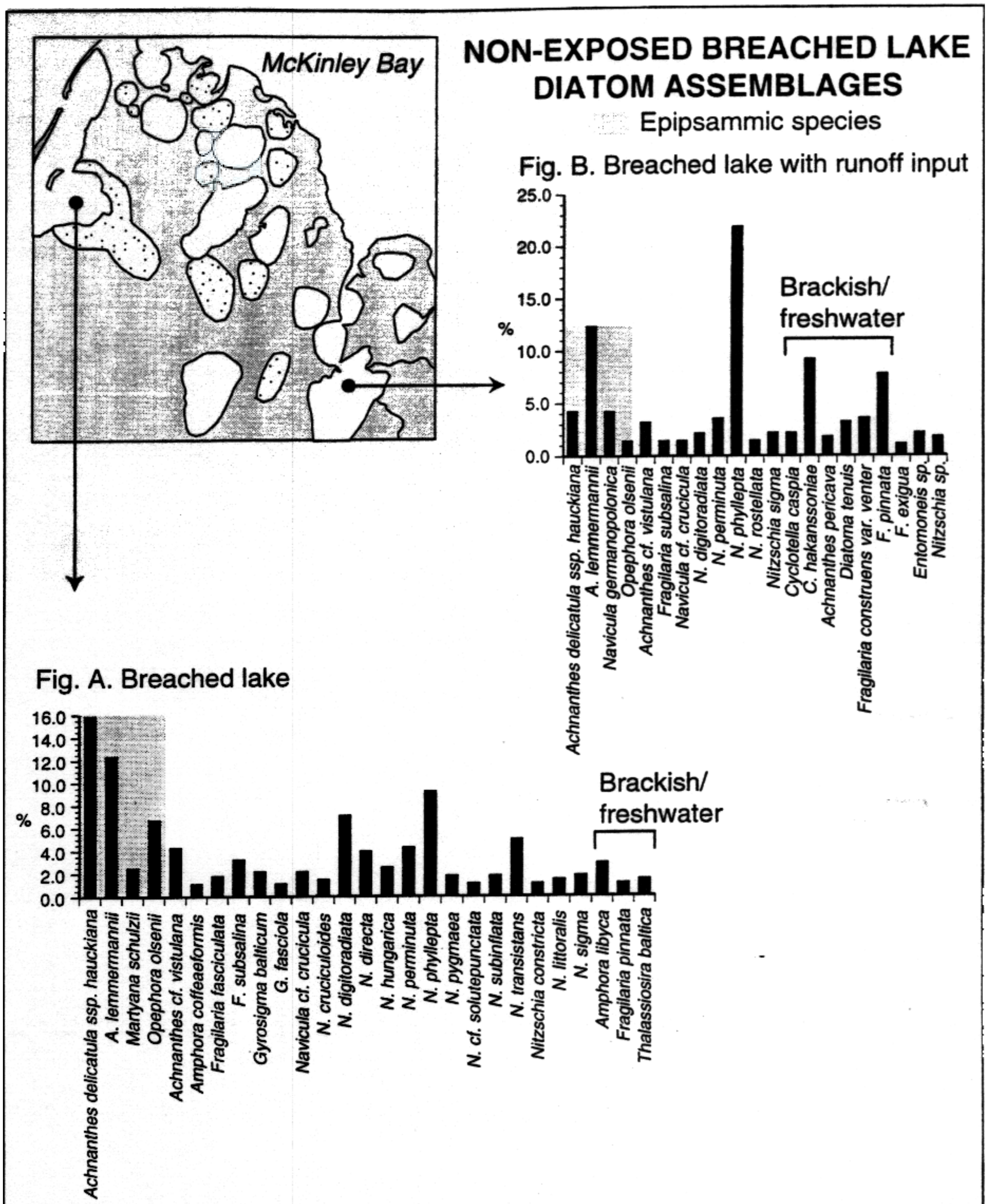
NON-EXPOSED BREACHED LAKE DIATOM ASSEMBLAGES
Epipsammic species
McKinley Bay
Fig. B. Breached lake with runoff input
25.0
20.0
15.0
10.0
5.0
0.0
%
Brackish/ freshwater
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Navicula germanopolonica
Opephora olsenii
Achnanthes cf. vistulana
Fragilaria subsalina
Navicula cf. crucicula
N. digitoradiata
N. perminuta
N. phyllepta
N. rostellata
Nitzschia sigma
Cyclotella caspia
C. hakanssoniae
Achnanthes pericava
Diatoma tenuis
Fragilaria construens var. venter
F. pinnata
F. exigua
Entomoneis sp.
Nitzschia sp.
Fig. A. Breached lake
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
%
Brackish/ freshwater
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Martyana schulzii
Opephora olsenii
Achnanthes cf. vistulana
Amphora coffeaeformis
Fragilaria fasciculata
F. subsalina
Gyrosigma balticum
G. fasciola
Navicula cf. crucicula
N. cruciculoides
N. digitoradiata
N. directa
N. hungarica
N. perminuta
N. phyllepta
N. pygmaea
N. cf. solutepunctata
N. subinflata
N. transistans
Nitzschia constricta
N. littoralis
N. sigma
Amphora libyca
Fragilaria pinnata
Thalassiosira baltica

Figure 3.

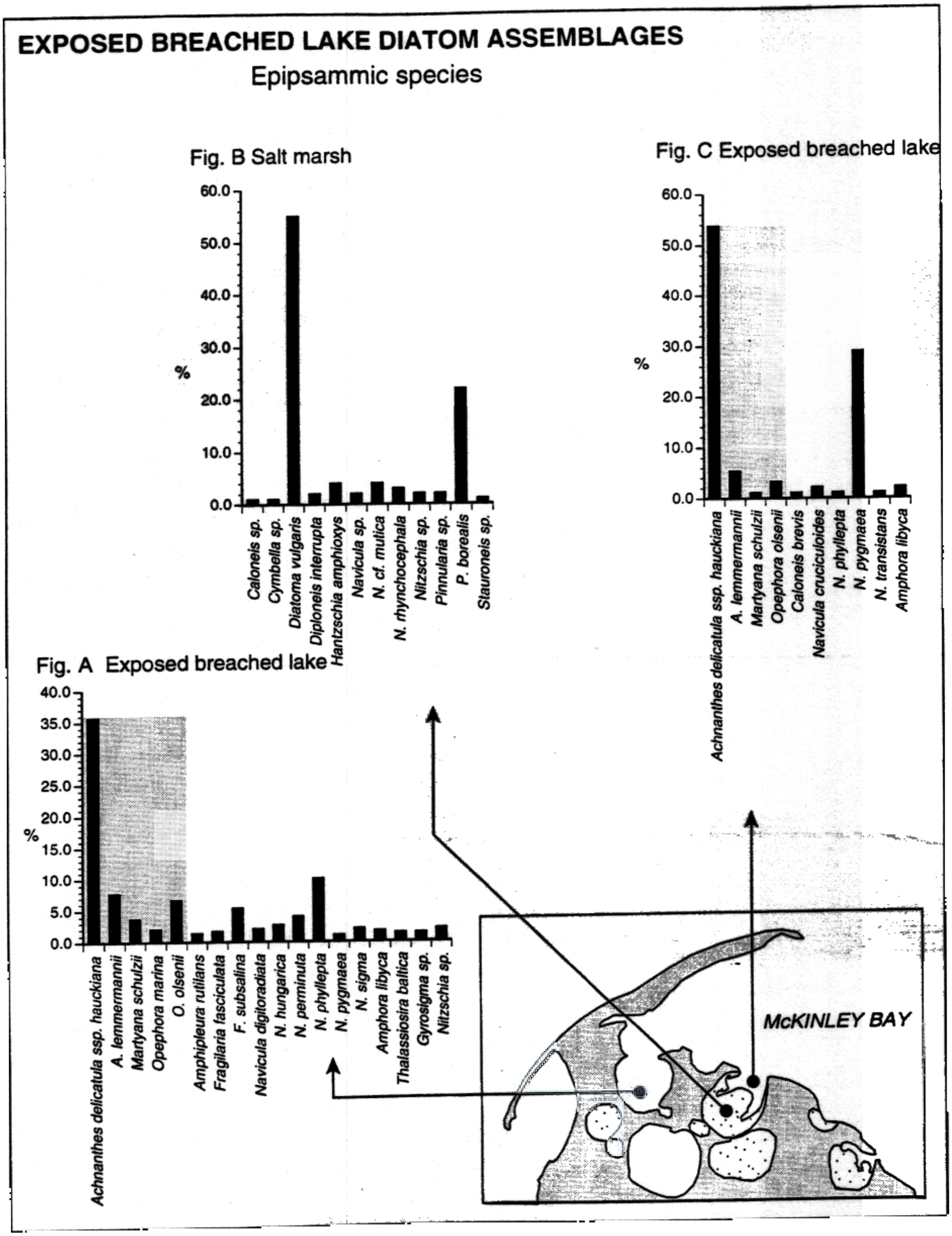
EXPOSED BREACHED LAKE DIATOM ASSEMBLAGES
Epipsammic species
Fig. B Salt marsh
60.0
50.0
40.0
30.0
20.0
10.0
0.0
%
Caloneis sp.
Cymbella sp.
Diatoma vulgaris
Diploneis interrupta
Hantzschia amphioxys
Navicula sp.
N. cf. mutica
N. rhynchocephala
Nitzschia sp.
Pinnularia sp.
P. borealis
Stauroneis sp.
Fig. C Exposed breached lake
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Martyana schulzii
Opephora olsenii
Caloneis brevis
Navicula cruciculoides
N. phyllepta
N. pygmaea
N. transistans
Amphora libyca
Fig. A Exposed breached lake
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Martyana schulzii
Opephora marina
O. olsenii
Amphipleura rutilans
Fragilaria fasciculata
F. subsalina
Navicula digitoradiata
N. hungarica
N. perminuta
N. phyllepta
N. pygmaea
N. sigma
Amphora libyca
Thalassiosira baltica
Gyrosigma sp.
Nitzschia sp.
McKINLEY BAY

Figure 4

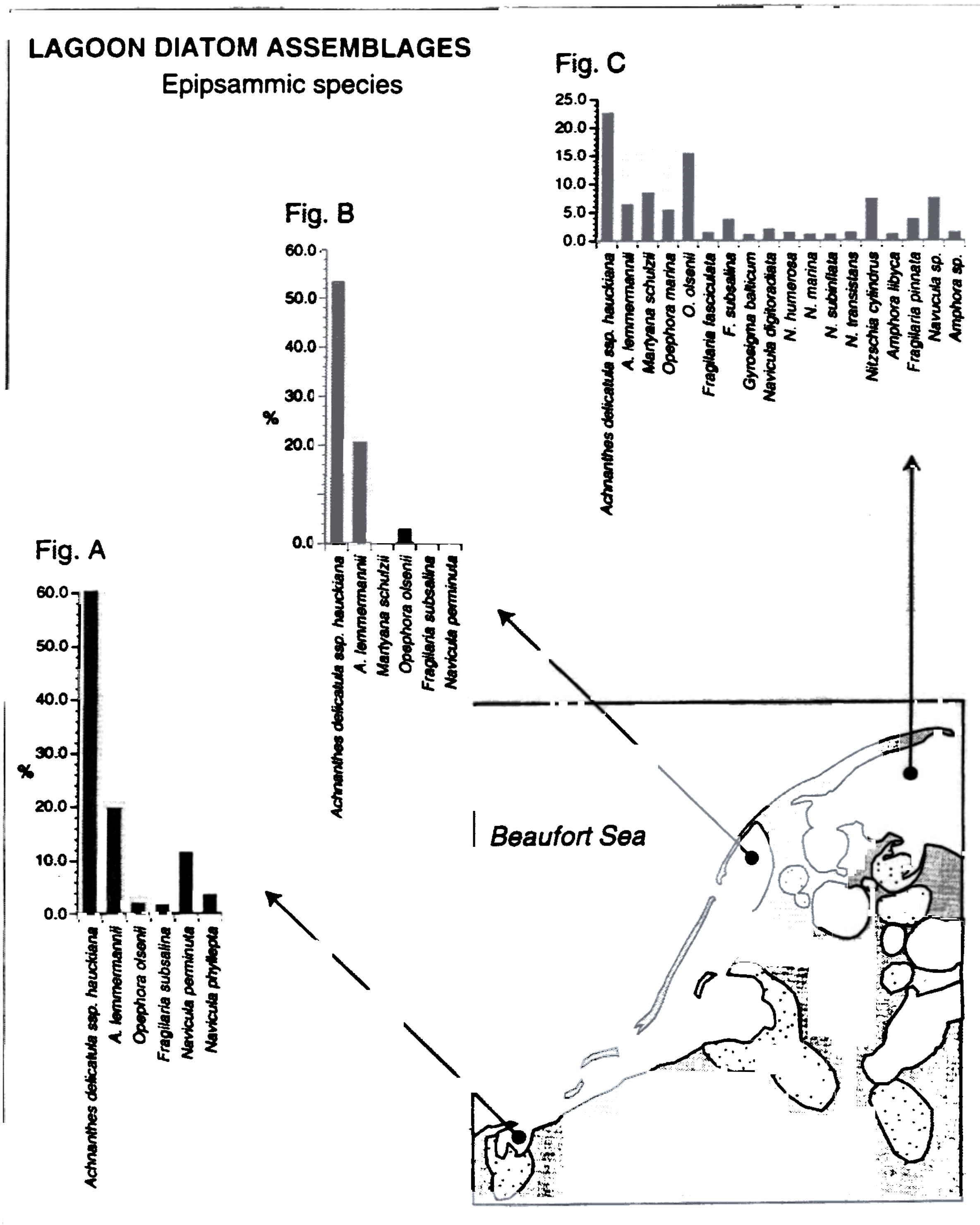
LAGOON DIATOM ASSEMBLAGES
Epipsammic species
Fig. A
%
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Opephora olsenii
Fragilaria subsalina
Navicula perminuta
Navicula phyllepta
Fig. B
%
0.0
20.0
30.0
40.0
50.0
60.0
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Martyana schulzii
Opephora olsenii
Fragilaria subsalina
Navicula perminuta
Fig. C
0.0
5.0
10.0
15.0
20.0
25.0
Achnanthes delicatula ssp. hauckiana
A. lemmermannii
Martyana schulzii
Opephora marina
O. olsenii
Fragilaria fasciculata
F. subsalina
Gyrosigma balticum
Navicula digitoradiata
N. humerosa
N. marina
N. subinflata
N. transistans
Nitzschia cylindrus
Amphora libyca
Fragilaria pinnata
Navucula sp.
Amphora sp.
Beaufort Sea

Figure 5.

Table 2. Relation between some characteristic features of diatom assemblages and sedimentary environments

Thermokarst lake environments						Chrysophyte cysts** (%)
Thermokarst lake	0	0	100	35	*Fragilaria* *Amphora* *Fragilaria*	10
Emerged sandy lake shelf	0	30	70	20	*Denticula kuetzingii* *Navicula tuscula* *Hantzschia amphioxys*	10
Residual pond	0	10	90	20	*Eunotia praerupta* *Neidium ampliatum*	15
Backbarrier environments						
Salt marsh	0	45	55		*Diatoma vulgaris* *Pinnularia borealis* *Diploneis interrupta*	20
Non-exposed breached lake:						
A) Breached lake with runoff input	25	30	0 - 5	35	*Navicula phyllepta* *Cyclotella hakanssoniae*	10
B) Breached lake without runoff input	40	5	0	40	*Navicula phyllepta* *N. digitoradiata*	
Exposed breached lake	55 - 65	0 - 5	0	15 - 30	*Navicula phyllepta* *Fragilaria subsalina* *Navicula pygmaea*	
Lagoon	60 - 85	0 - 5	0	15 - 30	*Navicula perminuta* *Fragilaria subsalina* *Nitzschia cylindrus*	

* Exclusive of epipsammic species
** Relative proportion of chrysophycean statospores to diatom frustules