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Biomonitoring past salinity changes in an athalassic subarctic lake

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Abstract

A short sediment core was taken from a small saline lake located on an intermontane plateau in the central Yukon Territory, Canada. In July 1990, chemical analyses indicated that, although the lake was shallow (Z_{max} = 1.1 m), it was also chemically stratified, with hyposaline (9.9 to 10.0 g L^{-1}) surface waters and slightly mesosaline (22.0 g L^{-1}) deeper waters. The surface water was dominated by Na^+ and HCO_3^-. To our knowledge, this is the northernmost athalassic saline lake yet recorded.

Quantification of algal (diatom, chrysophyte, and pigment) and invertebrate (chironomid, ceratopogonid, and Chaoborus*) fossils at four stratigraphic levels indicated that the lake sediments preserved numerous biological indicators that could be used to infer recent lake development. Many of the taxa are found in other athalassic salt lakes. The most striking stratigraphic change was a remarkable drop in the species richness of diatoms and invertebrates in the recent sediments, which parallels the elimination of species characteristic of less saline conditions. Halophilous taxa dominate the most recent sediments, indicating the development of more saline conditions. At the same time, a significant shift in chrysophyte cyst composition was observed. Fossil carotenoids and chlorophylls indicated a decrease in total algal abundance in recent sediments, as green and blue-green algae replaced diatoms and chrysophytes. Together, these paleolimnological data suggest a recent shift to drier conditions or increased evaporation in the central Yukon Territory.*

Introduction

Interest in modern and ancient athalassic (inland) saline lakes has grown significantly during recent years (e.g. Comín and Northcote, 1990; Hammer, 1983; Melack, 1988; Williams, 1981a; Williams, 1991). This acceleration in research is at least partly due to the sensitivity of athalassic systems to climatic change, as even modest changes in evaporation and precipitation can drastically affect the physical and chemical conditions of these lakes. Changes in water chemistry and lake depth will, in turn, control the distribution and abundance of aquatic organisms, as many taxa have defined optima and tolerances to both abiotic and biotic factors. Because many species leave identifiable fossils in lake sediments, paleolimnological approaches can be used to reconstruct past water balance, from which paleoclimatic inferences can be made (e.g. Bradbury *et al.*, 1981; Bradbury, Forester and Thompson, 1989; De Deckker and Forester, 1988; Gasse *et al.*, 1987; Last and Schweyen, 1983). Paleoclimatic studies provide vital information on long-term climatic trends, which are required to generate and test hypotheses and to validate climate models. Saline lake paleolimnology has already made important contributions to the study of past climatic trends (e.g. Fritz 1990; Hickman, Schweger and Hobgood, 1984; Last and Slezak, 1988; Roux, Servant-Vildary and Servant, 1991). However, these studies have generally focussed on temperate and equatorial lakes, where most athalassic systems are found. Therefore, we were surprised to find a saline lake in the central Yukon Territory while surveying a transect of 60 lakes in the western Canadian subarctic. To our knowledge, such systems are rare in these environments, and this site represents the northernmost athalassic salt lake thus far recorded. The hypersaline lacustrine brines recorded from the Canadian Arctic (e.g. Ouellet *et al.*, 1989) are not athalassic salt lakes (*sensu* Williams, 1981b), since their hypersaline water is derived from isostatically-trapped marine waters. In this paper, we describe the algal and invertebrate fossils preserved in the recent sediments of this potentially important reference site. A major objective of this study is to assess the composition, abundance, and preservation of biological indicators in these lake sediments, and to assess their potential as environmental markers of paleosalinity.

Study area

The small seepage lake discussed in this paper (surface area = 9.5 ha) is located near Pelly Crossing, central Yukon (62°45'N, 136°38'W), at an elevation of 600 m above sea-level (a.s.l.) (Fig. 1). The surrounding area belongs to the Yukon River Basin physiographic region, a 500–1,000 m high plateau that occupies the broad zone between the St Elias–Coast

Mountains in the southwest and the Mackenzie Mountains of the territory's interior (Canada, 1974).

The local bedrock consists of metamorphic rocks of Precambrian age, which are covered by glacial drift. Bostock (1966) recognized four major advances of the Cordilleran Ice Sheet in the central Yukon: Nansen (oldest), Klaza, Reid and McConnell (youngest). Maps showing the

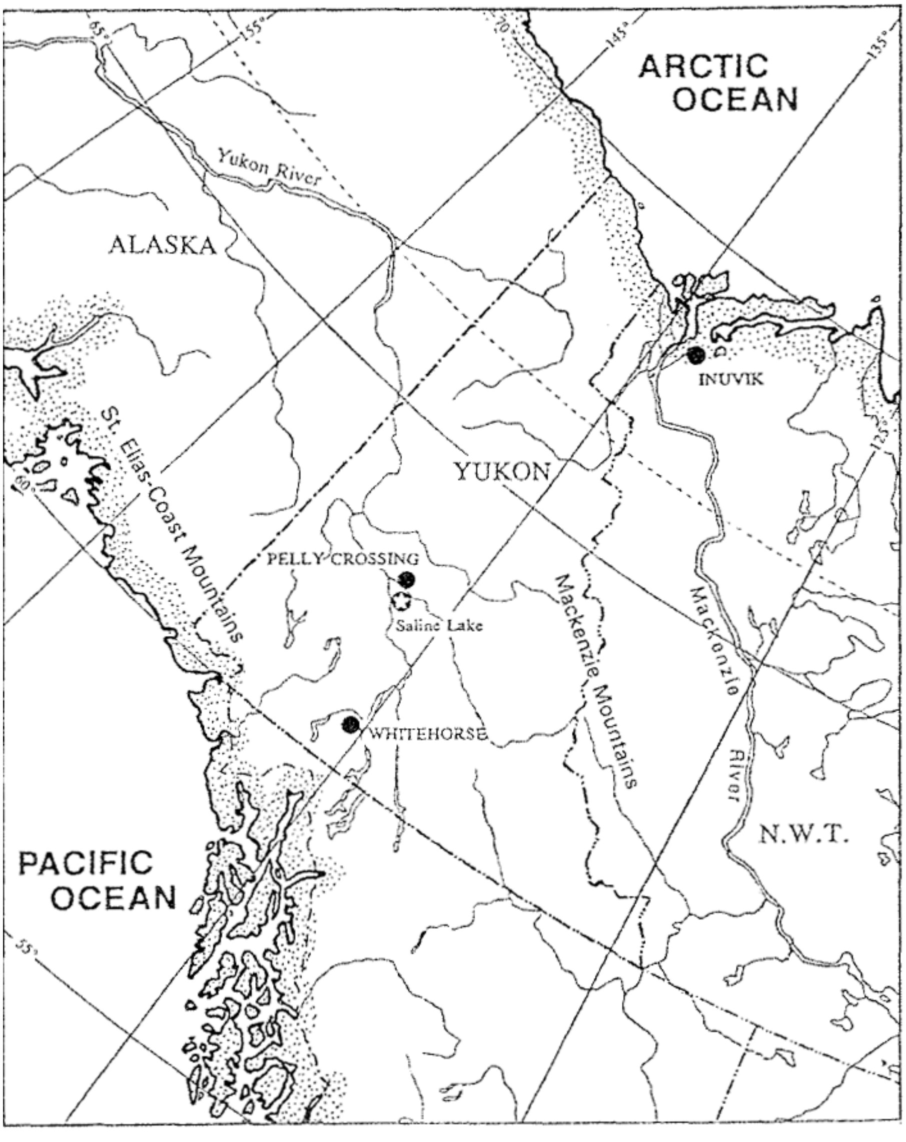


Fig. 1. Geographic location of the saline lake in the Yukon Territory.

distribution of glacial deposits (Duk-Rodkin, Jackson and Rodkin, 1986; Klassen, Morison and Duk-Rodkin, 1987) indicate that our site lies just beyond the limits of the last (McConnell) glacial advance. This suggests that the lodgement and ablation tills that cover bedrock in the area originated from the Reid Glaciation, considered to be of Illinoian age (Hughes, 1987). Deposits of the Reid Glaciation are more than 80,000 years old (Tarnocai, Smith and Hughes, 1985).

Our study site lies within the Central Climate Region of the Yukon (Wahl *et al.*, 1987), which is characterized by a subarctic continental climate. The area experiences extreme annual and daily temperature ranges, with warm summers and very cold winters. The annual mean daily temperature recorded at representative weather stations in Ft Selkirk and Carmacks is –4 to –5°C. The St Elias–Coast Mountains act as a formidable barrier to Pacific air masses, limiting their entry into the continent's interior. Thus, relative humidity and precipitation are low in the central Yukon (<300 mm yr^{-1}). Permafrost is discontinuous in the area. Regional vegetation is presently boreal forest dominated by white spruce (*Picea glauca*), black spruce (*P. mariana*), willow (*Salix*), and poplar (*Populus tremuloides*), with the regional treeline between 1,350 to 1,500 m a.s.l.

When the lake was sampled (July 1990), the watershed comprised a succession of distinct concentric zones surrounding a dense residual brine (Fig. 2). The dry, cracked, marginal lake mud grades in colour, with increasing distance from the lake, from white to pink or lavender, and finally to yellow or beige. Similar salt-encrusted mudflats surround saline lakes of interior British Columbia, and these flats are probably produced by annual shrinkage in lake volume during summer months (Renaut and Long, 1989; Renaut, 1990). In addition, the precipitation of salts could also take place in winter as a result of freeze-out processes. The role of seasonal frost in aiding the accumulation of soil and water salinity is known from saline lakes (Renaut and Long, 1987) and from a river delta in western Canada (Harris, 1990).

Evaporation of lake water, capillary evaporation from the exposed mud during summer months, and freeze-out processes during winter may account for the precipitation of salts and development of efflorescent crusts at the lake margin.

The vegetation in the lake's catchment also displays a pattern of concentric zonation. The innermost zone, comprising the cracked lake margin, is devoid of vascular plants and bryophytes. Halophytic plants (especially Chenopodiaceae) form an inner ring of treeless vegetation, followed by zones dominated by grasses and thin willows with increasing distance from the basin. The surrounding forest is composed predominantly of white spruce (*Picea glauca*) and trembling aspen (*Populus tremuloides*), with some balsam poplar (*Populus balsamifera*).

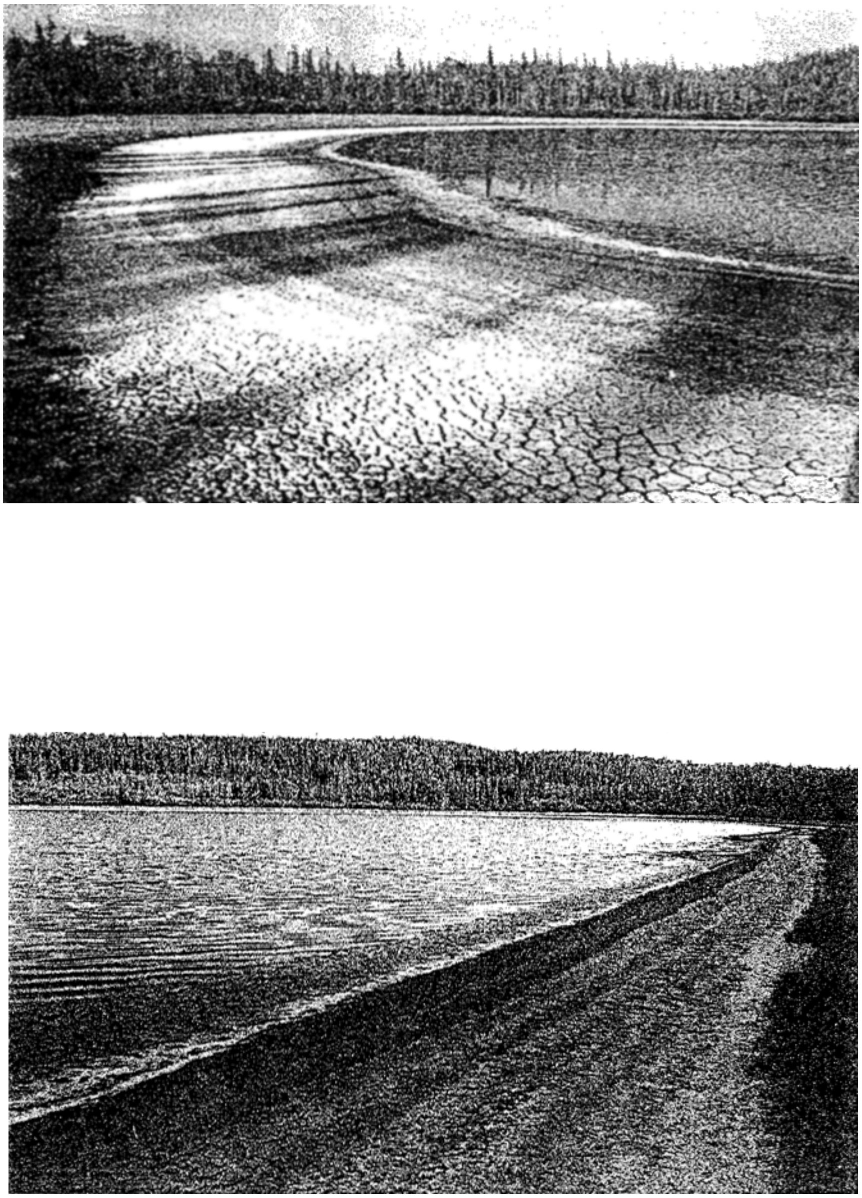


Fig. 2. Photographic views of the lake's margin showing pattern of concentric zonation.

Methods

The lake was sampled July 24, 1990, during a survey of 60 lakes between Whitehorse in the Yukon and Inuvik in the Northwest Territories. Measurements of water temperature, transparency, conductivity, salinity, pH and dissolved oxygen were taken in the field and surface water samples were collected in polyethylene bottles for laboratory analysis. Analyses for chlorophyll *a*, total phosphorus (TP), particulate organic carbon (POC) and nitrogen (PN), major ions, nutrients, and trace metals were carried out at the National Water Research Institute, Burlington, Ontario, following standard methods (Environment Canada, 1979).

For paleolimnological studies, a 35 cm long sediment core was taken from the deepest part of the basin using a miniature gravity corer (internal diameter of core tube = 3.8 cm) (Glew, 1991). Four core subsamples (0–1, 1–5, 25–26, and 30–31 cm) were sectioned from this short core and stored in Whirlpak® bags.

The preparation of samples for examination of siliceous algal microfossils (diatoms and chrysophycean cysts) followed standard techniques (Smol, 1983). Sediment samples (1 cm^3) were placed in 15 mL polypropylene centrifuge tubes and a concentrated solution of sulphuric (H_2SO_4) and chromic ($K_2Cr_2O_7$) acids was added to digest organic material. Digestion of organic matter proceeded over 5 to 6 days. In order to complete the digestion process, the samples were placed in a boiling water bath for two hours. Digested samples were then centrifuged and washed repeatedly with distilled water to remove acid. The prepared sediment was settled onto coverslips. Once dry, the coverslips were mounted on microscope slides with Hyrax®, a permanent mounting medium with high refractive index (RI = 1.71).

A minimum of 300 diatom valves was identified and counted along parallel transects from each sample. At depths of 0–1 and 1–5 cm, cysts were counted along parallel transects until at least 300 had been enumerated; due to lower abundances at 25 and 30 cm, counting of cysts was discontinued after 600 fields.

Light micrographs of diatoms and chrysophyte cysts were taken using a Nikon FX-35 photomicroscopy unit attached to a Nikon Optiphot microscope equipped with Nomarski optics and a Plan 100 DIC oil immersion lens (N.A. = 1.25).

Scanning electron microscopy (SEM) was also used to assist identification of the diatoms and chrysophyte cysts. For these studies, SEM stubs were prepared by evaporating some of the slurry used for light microscopy (LM) preparation onto aluminum foil. The foil was then affixed to aluminum SEM stubs with double-sided tape and trimmed to the 12 mm stub diameter. Each sample was coated with approximately 20 nm of gold using a Polaron Instruments Sputter Coater. A Hitachi-S-2500 SEM operating at 20 Kv was used for all scanning electron photomicrography.

Diatom identification was assisted by reference to Archibald and Schoeman (1984), Bérard-Therriault, Cardinal and Poulin (1986), Germain (1981), Krammer and Lange-Bertalot (1986, 1988, 1991a,b), and Schoeman and Archibald (1987). Chrysophyte cysts were described using the International Statospore Working Group (ISWG) guidelines (Cronberg and Sandgren, 1986).

Pigments were extracted from freeze-dried sediments following the procedures of Leavitt, Carpenter and Kitchell (1989). Pigment extracts were filtered, evaporated to dryness under nitrogen gas, and dissolved into an injection solution prior to quantification by high performance liquid chromatography, HPLC (Mantoura and Llewellyn, 1983, modified by Leavitt *et al.*, 1989). Pigment abundance was expressed as nmol pigment (g organic matter)$^{-1}$, where organic content was determined by loss-on-ignition at 500°C (Dean, 1974).

Carotenoid, chlorophyll and coloured derivatives isolated from sediments were compared to those obtained from unialgal cultures and other lake sediments. Spectral characteristics, chromatographic mobility and functional group assays were used to identify pigments from all sources (Leavitt *et al.*, 1989). Not all pigments were positively identified. We restricted our analysis to pigments characteristic of diatoms and chrysophytes in general (fucoxanthin), diatoms specifically (diatoxanthin), green algae (Chl *b*), chlorophytes and cyanophytes together (lutein-zeaxanthin), and total algal abundance (β-carotene). Lutein from green algae and zeaxanthin from cyanophytes were not separated on our HPLC and specific indicators of blue-green algae were rare (e.g. myxoxanthophyll). Consequently, we did not quantify cyanophytes separately.

For invertebrate analyses, 1 to 5 mL of wet sediment was treated with cold 10 per cent HCl to dissolve carbonates. The sediment was then deflocculated in warm 5 per cent KOH and sieved. Material retained on the 95 µm Nitex sieve was rinsed and examined in a Bogorov counting tray at 50x magnification for Chironomidae and Ceratopogonidae head capsules and mandibles of *Chaoborus*. Fossils were transferred to cover slips and mounted in Permount® on glass microscope slides for identification at 100 to 1,000x. The protocol for counting head capsule fragments followed that outlined by Walker *et al.* (1991). Identification was assisted by reference to Hirvenoja (1973), Merritt and Cummins (1978), Oliver and Roussel (1983), Simpson, Bode and Albu (1983), Uutala (1990), Walker (1988), and Wiederholm (1983).

Results and Discussion

Limnology and sediment description. Results of laboratory and field limnological measurements are summarized in Table 1. The lake is characterized by a Na/HCO_3-rich, hypo- to mesosaline brine during the summer months. The surface water is alkaline (pH = 8.6) and major ions are present in high concentrations, especially Na (919 mg L^{-1}) (Table 1). However, the chemical characterization must be regarded as tentative, because measured cation concentrations exceed anion values, thereby reflecting problems in applying standard freshwater analytical methods to brine analysis. Despite the lake's shallowness (Z_{max} = 1.1 m), a pronounced chemocline was observed, with hyposaline waters (salinity = 9.9 to 10.0 g L^{-1}) near the surface and mesosaline waters (salinity = 22.0 g L^{-1}) at the bottom (according to the classification of Hammer, Shamess and Haynes, 1983). The stratification probably has a cryogenic origin. During winter, freeze-out of dissolved salts from surface water can produce highly concentrated brines near the bottom of shallow, saline lakes (Wetzel, 1983). The concentrations of P and N appear to be very high, suggesting that the lake should be highly productive during the brief subarctic summer. This impression is reinforced by the massive occurrence of the cyanophyte *Chroococcus minutus* in July 1990 which, at the time, formed dense algal accumulations both on the lake bottom and floating on the lake surface.

Table 1. Summary of main physico-chemical features of the lake.

Latitude	62°45'N	SRP (mg L^{-1})	0.0341
Longitude	136°38'W	NH_3 (mg L^{-1})	1.04
Altitude a.s.l. (m)	600	DOC (mg L^{-1})	49
Maximum depth (Z_{max}) (m)	1.1	DIC (mg L^{-1})	89.7
Lake surface area (km^2)	0.095	TKN (mg L^{-1})	13.102
Transparency/Secchi depth (m)	0.5	POC (mg L^{-1})	2.61
Water temperature @ surface (°C)	22.5	PN (mg L^{-1})	0.416
@ Z_{max} (°C)	22.0	Na (mg L^{-1})	919.0
O_2 @ surface (mg L^{-1})	11.6	K (mg L^{-1})	277.0
@ Z_{max} (mg L^{-1})	0	Ca (mg L^{-1})	229.0
Conductivity @ surface (µS cm^{-1})	15,000	Cl (mg L^{-1})	31.4
@ Z_{max} (µS cm^{-1})	21,000–25,000	SO_4 (mg L^{-1})	9.1
Salinity @ surface (g L^{-1})	9.9–10.0	SiO_2 (mg L^{-1})	5.3
@ Z_{max} (g L^{-1})	22.0	Fe (mg L^{-1})	0.0089
Surface pH	8.6	Mn (mg L^{-1})	0.094
TP (unfiltered) (mg L^{-1})	0.1389	Chl *a* (uncorrected) (µg L^{-1})	4.7
(filtered) (mg L^{-1})	0.1019	(corrected) (µg L^{-1})	1.5
NO_2 (mg L^{-1})	0.0062	Main cation	Na^+
NO_3 (mg L^{-1})	0.027	Main anion	HCO_3^-

A single zooplankton net tow using a net of mesh aperture 50 µm revealed that two taxa, the rotifer *Brachionus plicatilis* and the copepod *Leptodiaptomus tyrreli*, were present in very high numbers (T. Nogrady, personal communication).

The sediments consisted of a very watery greyish, green and black gyttja, with a distinctive white band at 15 to 20 cm depth. Based on its stratigraphic position and the geographic location of the study site, it is presumed to be tephra, corresponding to the deposition of the White River volcanic ash approximately 1,250 years ago. As reported in previous investigations, this tephra layer was commonly found in terrestrial and lacustrine deposits at depths between 5 and 30 cm (e.g. Hughes, Rampton and Rutter, 1972; Stuart, Helmer and Hills, 1989; Wang and Geurts, 1991a,b). Our study site lies within a distinct belt of lakes in the central Yukon where values for total dissolved solids (TDS) exceed 0.2 g L^{-1} (Lindsey *et al.*, 1981). The volcanic eruption near the present Alaska–Yukon border spread ash over much of the Yukon Territory, and the deposits of White River tephra are particularly thick in the region of these high-TDS lakes (Lindsey *et al.*, 1981).

Fossil stratigraphies. The microfossil data obtained from diatom, chrysophyte and invertebrate analyses are presented as relative abundance diagrams (Figs 3, 4, 5). The results of fossil pigment analysis are summarized in Fig. 6. Paleoecological studies of saline lakes are sometimes plagued by poor preservation of siliceous fossils. However, in this lake, diatoms and chrysophytes were well preserved (Plates I-VI), indicating that dissolution of the frustules and stomatocysts in the sediment is minimal.

Diatoms. A total of 41 diatom taxa were recorded (Table 2). The sediments of the lowermost level (30 cm depth) contain a relatively diverse diatom assemblage, characterized by a mixture of euryhaline freshwater and saline taxa of benthic/periphytic affinity (Fig. 3). The flora is dominated by pennate forms, such as *Nitzschia* spp. (18.2 per cent),

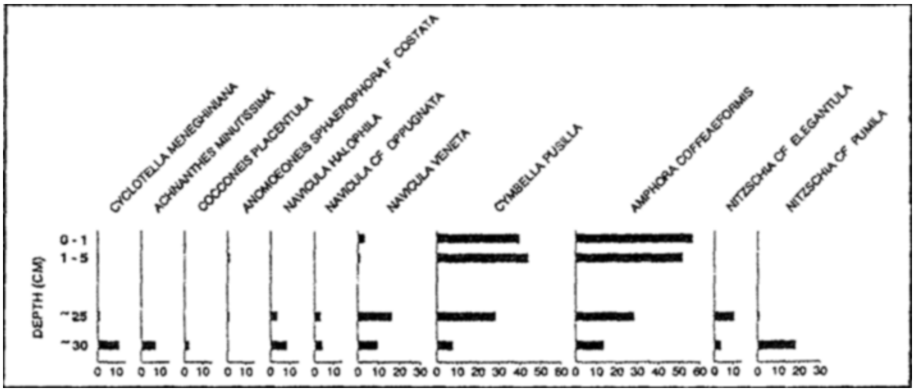


Fig. 3. Percentage diagram for dominant diatoms (relative abundance as per cent of total number of diatom valves).

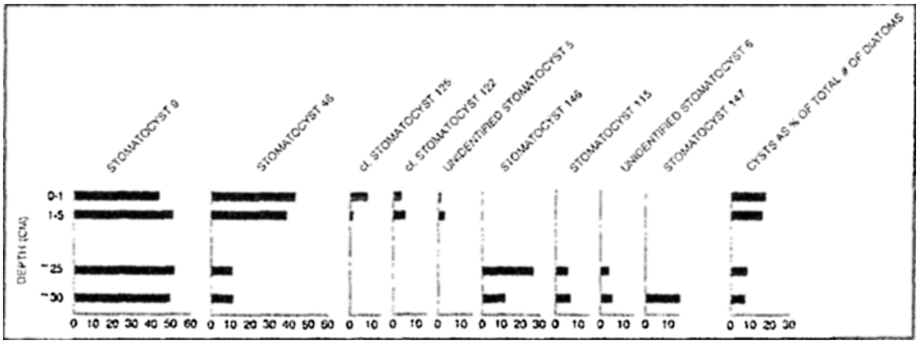


Fig. 4. Percentage diagram for dominant chrysophyte cysts (relative abunance as per cent of total number of chrysophyte cysts).

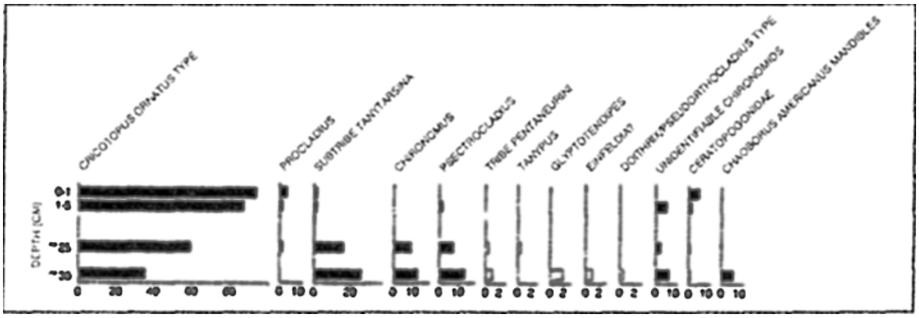


Fig. 5. Percentage diagram for dominant invertebrates (relative abundance as per cent of total number of chironomid head capsules).

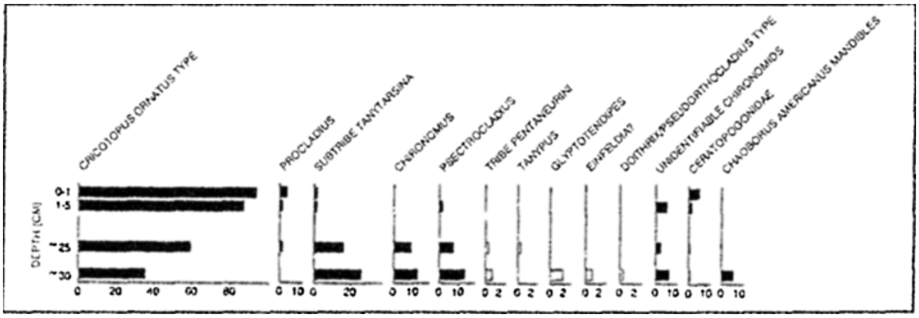


Fig. 6. Concentrations of selected fossil carotenoids and chlorophylls (nmoles pigment/ g organic matter).

Amphora coffeaeformis (13.6 per cent), *Navicula cryptocephala* var. *veneta* (9.3 per cent), *Navicula halophila* (8.3 per cent), *Cymbella pusilla* (7.6 per cent), *Achnanthes minutissima* (7.6 per cent), and the centric *Cyclotella meneghiniana* (11.3 per cent). *Cyclotella meneghiniana* is a euryhaline, tychoplanktonic species that can thrive both in pelagic habitats and very shallow waters. It has been found throughout a broad range of fresh and saline waters (Fritz, 1990). Gasse *et al.* (1987) described it as an eurytopic organism most commonly found in oligo- to polysaline waters, which corresponds to salinities ranging between 0.5 to 30 g L^{-1}. This taxon seems to be characteristic of eutrophic water with high concentrations of dissolved organic material (Bradbury *et al.*, 1981) as well as high pH (8–9) (Gasse *et al.*, 1987). Most of the other dominant taxa are also regarded as alkaliphilic and alkalibiontic forms with pH optima above 8, and thus also indicating highly eutrophic conditions (e.g. Cholnoky 1968; Gasse *et al.*, 1987; Krammer and Lange-Bertalot, 1986, 1988, 1991a,b). SEM and LM micrographs of the above taxa are presented in Plates I–IV.

The diatom assemblage preserved in this lowermost interval indicates the existence of a lake containing less saline waters than are present today, as evidenced by the presence of many freshwater species, such as *Achnanthes minutissima*, *Amphora veneta*, *Entomoneis alata*, *Epithemia adnata*, *Gomphonema* spp., *Navicula cuspidata*, *Pinnularia interrupta*, and *Rhopalodia gibba*. These taxa are only present in low numbers. According to the available autecological data on diatoms and their salt requirements and tolerances in African lakes (Gasse *et al.*, 1987), most of these taxa are tolerant of fresh to oligosaline waters with salinities ranging from 0 to 5 g L^{-1}. However, the abundance of halophytic species ('hard-water' species preferring water of high electrolyte content or brackish water), such as *Cyclotella meneghiniana*, *Navicula cryptocephala* var. *veneta*, and *Navicula halophila*, as well as saline diatoms like *Amphora coffeaeformis* and *Cymbella pusilla*, clearly indicates that the lake was slightly saline at the time of deposition.

The diatom community at the 25 cm level shows a decrease in species richness, which is mainly due to the increasing importance of the saline taxa, such as *Amphora coffeaeformis* (28.5 per cent) and *Cymbella pusilla* (28.5 per cent) (Fig. 3). The halophytic *Navicula cryptocephala* var. *veneta* reaches its maximum abundance of 16.5 per cent. The variety *veneta* (Kützing) Rabenhorst, which is abundant in electrolyte-rich, eutrophic waters (Krammer and Lange-Bertalot, 1986), is synonymous with *Navicula veneta* Kützing since it was raised to the rank of species by Lange-Bertalot (1979). According to Patrick and Reimer (1966), it prefers brackish waters or fresh water of high dissolved salt content.

The sediments from the two surficial subsamples (0–1 cm; 1–5 cm) contain well-preserved, but less diverse diatom assemblages. Higher salinities and low water levels in recent sediments are indicated by the overwhelming dominance of the two benthic saline taxa *Amphora coffeaeformis* and *Cymbella pusilla*, comprising 52 to 56 per cent and 39 to 44 per cent of the diatom assemblage, respectively (Fig. 3). Other pennate saline diatoms, such as *Navicula veneta*, *Navicula halophila*, *Anomoeoneis sphaerophora* f. *costata*, and *Nitzschia commutata*, occur only sporadically, whereas centric diatoms are extremely rare. *Cyclotella meneghiniana* disappears and only a few individuals of the planktonic species *Cyclotella striata* were found. This taxon is characteristic of inland saline lakes with salinities ranging from 5 to 16 g L^{-1} (Bradbury *et al.*, 1981).

Table 2. List of 41 diatom taxa recorded in the lake sediments.

Cyclotella meneghiniana Kützing
C. stelligera Cleve & Grunow (in Van Heurck)
C. striata (Kützing) Grunow
Fragilaria pinnata Ehrenberg
F. vaucheriae (Kützing) Petersen
Achnanthes minutissima Kützing
Cocconeis neothumensis Krammer
C. placentula Ehrenberg
C. placentula var. *euglypta* (Ehrenberg) Grunow
Anomoeoneis sphaerophora f. *costata* (Kützing) Schmid
Navicula digitoradiata (Gregory) Ralfs
N. cuspidata (Kützing) Kützing
N. halophila (Grunow) Cleve
N. incertata Lange-Bertalot
N. cf. *oppugnata* Hustedt
N. veneta Kützing
Navicula sp.
Pinnularia interrupta W. Smith
Entomoneis alata (Ehrenberg) Ehrenberg
E. paludosa var. *subsalina* (Cleve) Krammer
Cymbella pusilla Grunow in A. Schmidt *et al.*
C. silesiaca Bleisch in Rabenhorst
Amphora coffeaeformis (Agardh) Kützing
A. veneta Kützing
Gomphonema clavatum Ehrenberg
G. gracile Ehrenberg
G. parvulum Kützing
Gomphonema sp.
Epithemia adnata (Kützing) Brébisson
E. turgida var. *granulata* (Ehrenberg) Brun
Rhopalodia gibba (Ehrenberg) O. Müller
Nitzschia cf. *amphibia* Grunow
N. commutata Grunow in Cleve & Grunow
N. diversa Hustedt
N. elegantula Grunow in Van Heurck
N. cf. *frustulum* (Kützing) Grunow in Cleve & Grunow
N. frustulum var. *bulnheimiana* (Rabenhorst) Grunow
N. incognita Legler & Krasske
N. pumila Hustedt
Nitzschia sp. 1
Nitzschia sp. 2

Both *Amphora coffeaeformis* and *Cymbella pusilla* are extremely eurytopic taxa that thrive in alkaline athalassic habitats (e.g. Cholnoky, 1968; Krammer and Lange-Bertalot, 1986; Patrick and Reimer, 1975), as well as brackish coastal or estuarine waters (e.g. Bérard-Therriault *et al.*, 1986; Germain 1981; Hendey 1964; Tynni 1978). *Cymbella pusilla* is the only *Cymbella* species known to occur in waters of high electrolyte content.

The diatom flora of this northerly saline lake can be best described as one characterized by eurytopic and widespread taxa. Most of these are particularly abundant in water-bodies which experience high fluctuations in salinity and osmotic pressure (Gasse *et al.*, 1987). The two dominant diatoms, *Amphora coffeaeformis* and *Cymbella pusilla*, as well as other important taxa, such as *Anomoeoneis sphaerophora* f. *costata*, *Cyclotella meneghiniana*, *Navicula halophila*, *Navicula veneta*, and *Nitzschia commutata*, are cosmopolitan taxa typical of assemblages observed in other saline habitats (e.g. salt lakes, thermal springs, estuaries, coastal environments) of temperate and tropical regions (e.g. Blinn, 1991; Gasse, 1986; Gasse, Talling and Kilham, 1983; Hammer *et al.*, 1983; Krammer and Lange-Bertalot, 1986, 1988; Patrick and Reimer 1966, 1975; Schoeman and Archibald, 1987). According to Blinn (1991), many diatoms found in athalassic saline environments in both northern and southern hemispheres are especially widespread.

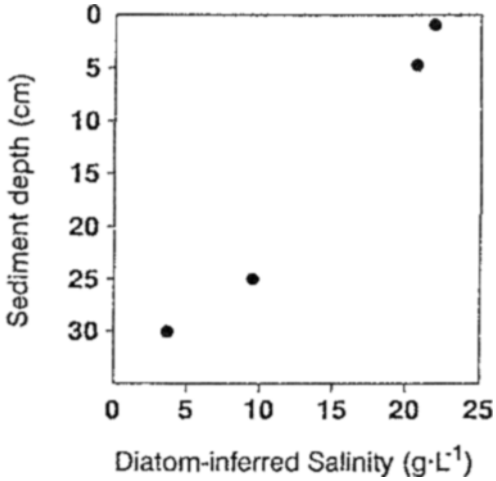
In general, the diatom species composition is very dissimilar from that found in freshwater Yukon lakes (the dominant taxa found in this lake were absent in all of the 60 freshwater lakes sampled in our survey). Assemblages of similar low species richness have been observed to occur typically in hyposaline lakes with equally high carbonate-bicarbonate (CO_3-HCO_3) concentrations (reviewed in Hammer *et al.*, 1983).

Only three species (*Amphora coffeaeformis*, *Cymbella pusilla*, and *Navicula veneta*) are numerically important and were present in all four subsamples. No apparently endemic species were found except for perhaps one undescribed *Navicula* sp. (Plate IV, Fig. 5) and some forms of *Anomoeoneis sphaerophora*.

In summary, the sedimentary diatom record documents a trend in paleosalinity from low, or moderate, salinities at the 30 and 25 cm levels, towards considerably higher salinities (>10 g L^{-1}) in the more recent sediments. Our qualitative interpretation of salinity changes is confirmed when using the closest available diatom calibration set for inferring lakewater salinity, which is one completed by S.E. Wilson (unpublished data) for a set of 45 lakes in British Columbia. Applying her transfer function to our data, we inferred a lakewater salinity of about 20 to 22 g L^{-1} in the lake's surficial sediments, and about 4 to 10 g L^{-1} in the deeper sediments (Fig. 7). Although these inferences should be viewed with caution, since the transfer functions were derived from more southern lakes, we note that our inferences for the recent sediments (i.e. 20 to 22 g L^{-1}) are almost identical to our measured lakewater salinity of 22 g L^{-1} in deeper waters.

The increase in salinity is paralleled by the replacement of a relatively diverse diatom flora by one dominated by only two taxa. It is interesting to note that slightly saline conditions existed prior to the deposition of the tephra. Thus, this event was not a major factor contributing to salinization. The latter may have originated during the early to mid-Holocene, when climatic conditions throughout most of northwestern Canada and Alaska are thought to have been warmest (Ritchie, 1987; Cwynar and Spear, 1991). During this time, several Yukon lakes seem to have dried up (J.V. Matthews Jr, personal communication).

Fig. 7. Diatom-inferred lakewater salinity using a transfer function developed for a 45 lake set in British Columbia (S.E. Wilson, unpublished data).



Chrysophytes. A total of nine stomatocyst morphotypes were found in the sediments of the saline lake (Plates V and VI). Using SEM, five of these were identified as previously described PEARL (Paleoecological Environmental Assessment and Research Laboratory) morphotypes, two were assigned new PEARL numbers, and the remaining two stomatocysts were observed only using LM. Descriptions of two morphotypes assigned new PEARL numbers (stomatocysts 146 and 147) and the two morphotypes observed with LM alone (unidentified stomatocysts 5 and 6) are given in Appendix I.

Two morphotypes, stomatocyst 9 (Duff and Smol, 1988) and stomatocyst 46 (Duff and Smol, 1991), dominated the assemblage, comprising 60 to 90 per cent at all levels (Fig. 4). Both of these morphotypes are smooth, unornamented cysts with no collar development, differing only in the latter having a deep conical pore. Stomatocyst 9 was present in high abundances (44–51 per cent) at all depths, and is probably salt-indifferent. It is a very common and widely distributed morphotype occurring in freshwater lakes (Duff and Smol, 1991), as well as the surficial sediments of this saline lake. In many lakes, it can only be separated from similar morphs on the basis of size, and is probably produced by a number of chrysophyte species (Duff and Smol, 1991; Duff, Douglas and Smol, 1992; Rybak, Rybak and Nicholls, 1991). Stomatocyst 46 increased fourfold, from 10 per cent relative abundance at the lower depths to over 40 per cent in the top two sediment levels. Since this morphotype occurs in the surficial sediment, it is obviously tolerant of saline conditions. Its greater abundance in the surficial mud, where halophilous diatoms and invertebrates indicate higher salinities, suggests that it may have a preference for saline waters.

Stomatocysts cf. 125 and 122 (Duff *et al.*, 1992), and unidentified cyst 5, are present only in the top sediments (Fig. 4). The biological affinities of the former two cysts have not been positively determined, but stomatocyst cf. 125 resembles the cyst produced by *Paraphysomonas antarctica* Takahashi, which is common in Antarctic marine waters (Takahashi, 1987).

Stomatocysts 146 and 115 (Zeeb, Duff and Smol, 1990), as well as unidentified cyst 6 and stomatocyst 147, are present only in the lower sediments of the saline lake (Fig. 4). Diatoms and invertebrates suggest that the lake was less saline at that time. Thus, the complete absence of these cysts in the surficial sediments suggests that they cannot tolerate highly saline conditions.

Ours is the first study to examine chrysophycean cysts from a saline lake environment, and therefore our interpretations cannot be verified with independent data sets. Clearly, there were major shifts in the stomatocyst assemblage. Based on other microfossil evidence in this study, we would suggest that cysts that were apparently intolerant of saline conditions (stomatocysts 146, 115, 147, and unidentified cyst 6) were succeeded by more salt-tolerant cysts 46, cf. 125, cf. 122, and unidentified cyst 5 in the upper two sediment levels. Only stomatocyst 9 showed little or no change in relative abundance in the four stratigraphic levels.

Invertebrates. Similar to the diatom community, the number of invertebrate species also decreases sharply in the lake's more recent sediments (Fig. 5). Ten taxa were identified from the 30 cm depth, whereas only four taxa were recorded in the surface sediments (0–1 cm). This significant decrease in species richness seems to confirm the inverse correlation between species numbers and salinity commonly recognized in salt lake faunas (e.g. Lancaster and Scudder, 1987; Timms, 1983; Williams, 1981b). Thus, the decrease in the number of species towards the top of the core might be attributable to increasing salinity. However, as pointed out by Williams, Boulton and Taaffe (1990), these relationships may become insignificant over intermediate ranges of salinity. As for the diatoms, the decrease in recent sediments may also be due, in part, to the absence of aquatic macrophytes, which limits habitat diversity in the shallow basin.

Fossils of *Cricotopus ornatus*-type (Meigen) chironomids dominate all samples and increase from about 35 per cent of the chironomid fauna at the 30 cm depth, to about 90 per cent in the surficial sediments (Fig. 5). *Procladius* and Ceratopogonidae head capsules are also relatively more abundant in the surficial sediments. *Chironomus, Psectrocladius* and the chironomid subtribe Tanytarsini are subdominant in the oldest sediments (25 and 30 cm depths). *Chironomus* and *Psectrocladius* have since disappeared, and the Tanytarsini are now rare. Pentaneurini, *Tanypus*, *Glyptotendipes*, *Einfeldia*?, *Doithrix* / *Pseudorthocladius*-type, and *Chaoborus americanus* (Johannsen) fossils are minor constituents of the fauna in the 25 and/or 30 cm levels, but were not recorded in more recent sediments.

Cricotopus ornatus is the midge most characteristic of North American saline lakes, occurring at salinities ranging from 5 to 61 g L^{-1} (Hammer, Sheard and Kranabetter, 1990; Timms, Hammer and Sheard, 1986). Other *Cricotopus* species (e.g. *C. abanus* (Curran), *C. flavibasis* (Malloch), and *C. trifasciatus* (Panzer)) are known from less concentrated (<5.4 g L^{-1}) brines (Cannings and Scudder, 1978), and some of these species are not readily separated from *C. ornatus* during fossil identification. Despite this uncertainty, the midge assemblage in the 0–1 and 1–5 cm samples is completely unlike that of any North American freshwater habitat, but is strikingly similar to that of moderately saline lakes in adjacent provinces (Hammer *et al.*, 1990; Timms *et al.*, 1986; Walker 1990; I.R. Walker, unpublished data).

The known salinity ranges in North America for the other taxa are ≤9.8 g L^{-1} for *Einfeldia*, *Glyptotendipes*, and *Psectrocladius*, ≤24.7 g L^{-1} for Pentaneurini, ≤26.0 g L^{-1} for Tanytarsini, ≤36.8 g L^{-1} for *Chironomus* and *Procladius*, ≤43 g L^{-1} for *Tanypus*, and ≤50 g L^{-1} for Ceratopogonidae (Cannings and Scudder, 1978; Hammer *et al.*, 1990; Timms *et al.*, 1986). *Chaoborus americanus* has not been reported from saline lakes. Its presence at the base of the core indicates that less saline conditions formerly existed.

The salinity (10 g L^{-1}) recorded from the lake surface on July 24, 1990, is only slightly greater than, or within, the salinity range of most of these taxa, but the bottom water was more saline (22 g L^{-1}). Chironomidae and Ceratopogonidae are predominantly benthic, whereas *Chaoborus americanus* is pelagic. Since *Einfeldia*, *Glyptotendipes*, and *Psectrocladius* are not known to occur at salinities greater than 10 g L^{-1}, their absence is probably attributable to the present bottom-water salinity.

The July salinity measurements do not portray the annual range in this variable. The salinity of the water may become higher during late summer with continued evaporation from the warm lake surface. Also, during winter, the formation of ice at the lake surface will exclude salts. The lake is only 1.1 m deep. Since ice is often 1 m thick on subarctic freshwater lakes, the salinity of the bottom water may be highest during mid- to late winter when the ice is thickest. Since most midges will have life cycles of about 1 year (or more) in subarctic lakes, they must be able to tolerate the entire annual lakewater salinity range. Shallow areas of the lake will freeze in winter; thus, chironomids may also have to tolerate ice formation and sub-zero temperatures in the surficial sediments.

Chaoborus americanus is intolerant of fish predation (Johnson *et al.*, 1990; Uutala, 1990). Thus, fish did not occur when sediments at the 30 cm depth were deposited, nor are fish known to occur in the lake today. The lake is presently a closed basin. If this has always been true, then fish may never have been able to colonize the lake. In addition, in shallow, productive lakes, fish are often killed by anoxic conditions during winter. Alternatively, the lake may already have been too saline for fish survival. The disappearance of *Chaoborus americanus* is probably due to increasing salinities rather than to the progressive decrease in water depth.

The chironomid assemblage is unusual, with low diversity and dominance by *Cricotopus ornatus*-type fossils throughout. The fauna is unlike that of freshwater lakes; thus, the lake has probably been somewhat saline over the period represented by the core. The increasing relative abundance of *C. ornatus*-type fossils and the disappearance of several midges intolerant of moderately saline conditions suggests a progressive increase in the lake's salinity over the interval represented in the 30 cm-long sediment core. Before more quantitative reconstructions of lakewater salinity can be made, the salinity tolerance of individual midge taxa must be more accurately quantified.

Pigments. Preservation of all fossil pigments was unusually good. Sedimentary concentrations of pigments from green algae were within the range characteristic of eutrophic lakes (Sanger, 1988; P.R. Leavitt, unpublished data). Sediments were also dominated by labile chlorophylls, rather than the stable pheopigment derivatives. Ratios of undegraded Chl *b* to pheophytin *b* ranged from 3.9 to 9.9, while Chl *a* was 1.5 to 3.2 times more abundant than pheophytin *a*. Undegraded chlorophylls generally predominate in fossil deposits only when algal remains are rapidly buried in an anoxic environment (Leavitt and Carpenter, 1989; Leavitt *et al.*, 1989). High concentrations of undegraded carotenoids and chlorophylls are consistent with other paleolimnological analyses that show excellent pigment preservation in sediments from saline lakes in Alberta and British Columbia (P.R. Leavitt and others, unpublished data).

The presence of benthic algal mats, combined with relatively low water column Chl concentrations (Table 1), suggested that high sedimentary pigment concentrations are derived from epipelic production, rather than from phytoplankton. This interpretation is supported by the observation that concentrations of alloxanthin were generally lower than those obtained in sediments from temperate lakes. Cryptophyceae have a strictly planktonic habit and may be limited by the shallow nature of the lake.

Stratigraphies of sedimentary carotenoids and chlorophylls indicate that total algal abundance declined in recent times (Fig. 6). Concentrations of β-carotene and pheophytin *a* (not shown) were both lower in recent sediments than in deep samples, consistent with a reduction in algal biomass or production. These stable compounds are ubiquitous among plants and have been recommended as sedimentary indicators of total algal abundance (Leavitt and Carpenter, 1989; Leavitt *et al.*, 1989). Chl *a* is also ubiquitous, but its propensity for degradation in surface sediments obscures stratigraphic patterns (Leavitt and Carpenter, 1989). Unusually high concentrations of Chl *a* (120 to 470 nmol Chl *a* (g organic matter)$^{-1}$) in the 0–1 cm sample were observed in this study.

Algal community composition also changed through the period of time encompassed by the core. Pigments from diatoms (fucoxanthin, diatoxanthin) were less abundant in surface sediments than in deep core samples (Fig. 6). Similarly, alloxanthin from cryptophytes was most abundant in the 30 cm sample. In contrast, concentrations of undegraded Chl *b* and lutein-zeaxanthin from green (Chl *b*, lutein) and blue-green algae (zeaxanthin) were greatest in the 0–1 cm interval. Taken together, these data suggest that green algae, and perhaps blue-greens, have partly replaced the diatoms and/or chrysophytes as the dominant algal group. We did not recover any common cyanophyte-specific pigments (e.g. myxoxanthophyll) from any lake sediments, despite an abundance of benthic taxa.

Changes in fossil pigment composition were consistent with the inferred increase in lakewater salinity in recent times. Diatom communities in surface samples were comparatively depauperate, and dominated by two benthic halophilic taxa (see above). Similarly, diatoxanthin (from diatoms) and fucoxanthin (from all diatoms and chrysophytes) were in low concentration in surface muds, unlike in most temperate lakes (Leavitt *et al.*, 1989). In contrast, pigments from green and blue-green algae were more abundant in recent sediments. Surveys of surface sediments from 110 saline lakes in British Columbia, spanning a salinity gradient from 0 to 200 g L^{-1}, show that lutein-zeaxanthin generally replaced fucoxanthin as the dominant sedimentary carotenoid in the high salinity lakes (P.R. Leavitt and others, unpublished data). These changes are also consistent with casual observations that cyanophytes and chlorophytes predominate the algae in saline lakes (Hammer *et al.*, 1983; Hammer, 1986).

Conclusions

The major objectives of this paper were to document the presence of an athalassic saline lake from this northern location in the Yukon and to evaluate preservation of biological fossils in its sediments. Interestingly, many of the taxa encountered are also found in other athalassic salt lakes of temperate and tropical regions, suggesting that water chemistry may be more important than biogeographic factors in determining species occurrences.

The biostratigraphic information yields a history of salinity changes which may be related to climatic change in the central Yukon. However, these interpretations must remain speculative because of the preliminary nature of our study. The shift towards salt-tolerant taxa, observed in both algal and faunal assemblages, shows that the basin was formerly occupied by a lake of low to moderate salinity. Changes in evaporation/precipitation ratios may have resulted in increased salinity and abundant carbonate precipitation in the basin in recent times.

It seems possible that the presence of mixed assemblages of freshwater and saline diatom taxa in the basal two samples could have resulted from short periods of freshwater inputs, allowing a temporary development of a freshwater flora, followed by subsequent periods of evaporative concentration and salinities as high as those found in the upper two samples. The relatively high concentration of alloxanthin from cryptophytes in the 30 cm sample is consistent with a 'fresher' lake and deeper water column. Gasse *et al.* (1987) argued that mixtures of environmental indicators (e.g. freshwater and saline) commonly observed in African saline lakes '...may reflect either a spatial juxtaposition of microhabitats (e.g. stratified waters with a surficial lense of dilute waters, and a saline hypolimnion), or short-term fluctuations of the palaeosystems'. Thus, the shifts observed in the composition of the biotic communities could also have resulted from greater seasonal fluctuations rather than changes in maximum salinity. Because we do not have strong geochronostratigraphic control of past sedimentation rates, little can be said of the temporal duration of these changes.

The combined evidence from all fossil remains suggests that an extrinsic shift towards drier climate has strongly affected the lake. Detailed paleoecological data are especially important in high latitude regions where projected greenhouse warming is expected to be greater than the global average temperature change (e.g. Luckman, 1989; Roots, 1989). As a consequence, the Yukon has been identified as an important reference area for climate impact studies in the western Canadian subarctic (e.g. CGCCP guidelines). In addition, we feel this study has provided some interesting biogeographical and ecological data on various indicators from saline lake systems.

The promising results from this reconnaissance study encourage us to examine other such northerly saline lakes in order to determine their suitability as reference sites for paleolimnological and paleoclimatic studies. Our results thus far suggest that these lakes have considerable potential for providing high resolution proxy data of past climatic changes in high latitude regions. The use of contemporary algal and faunal assemblages and associated water chemistry data represents a potentially useful approach for developing transfer functions for the quantitative reconstruction of salinity and water-level change in Yukon saline lakes.

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References

Archibald, R.E.M. and Schoeman, F.R., 1984. *Amphora coffeaeformis* (Agardh) Kützing: a revision of the species under light and electron microscopy. *South African Journal of Botany* **3**: 83–102.

Bérard-Therriault, L., Cardinal, A. and Poulin, M., 1986. Les diatomées (Bacillariophyceae) benthiques de substrats durs des eaux marines et saumâtres du Québec. 6. Naviculales: Cymbellaceae et Gomphonemaceae. *Naturaliste canadien* **113**: 405–429.

Blinn, D.W., 1991. The diatom flora of Lake Eyre South: a large episodically filled salt lake in South Australia. *Hydrobiologia* **210**: 101–104.

Bostock, H.S., 1966. Notes on glaciation in central Yukon Territory. *Geological Survey of Canada, Paper* **65–36**: 1–18.

Bradbury, J.P., Leyden, B., Salgado-Labouriav, M., Lewis, W.M., Scubert, C., Binford, M.W., Frey, D.G., Whitehead, D.R. and Weibezahn, F.H., 1981. Late-Quaternary environmental history of Lake Valencia, Venezuela. *Science* **214**: 1299–1305.

Bradbury, J.P., Forester, R.M. and Thompson, R.S., 1989. Late Quaternary paleolimnology of Walker Lake, Nevada. *Journal of Paleolimnology* **1**: 249–267.

Canada, 1974. **The National Atlas of Canada.** Department of Energy, Mines and Resources, Ottawa.

Cannings, R.A. and Scudder, G.G.E., 1978. The littoral Chironomidae (Diptera) of saline lakes in central British Columbia. *Canadian Journal of Zoology* **56**: 1144–1155.

Cholnoky, B.J., 1968. **Die Ökologie der Diatomeen in Binnengewässern.** Cramer, Berlin.

Comín, F.A., and Northcote, T.G., (Eds) 1990. Proceedings of the Fourth International Symposium on Athlassic (Inland) Saline Lakes, Banyoles, Spain, May 1988. *Hydrobiologia* **197**.

Cronberg, G. and Sandgren, C., 1986. A proposal for the development of standardized nomenclature and terminology for chrysophycean statospores. In: J. Kristiansen and R.A. Andersen (Eds) **Chrysophytes: Aspects and Problems.** pp. 317–328. C.U.P.

Cwynar, L.C., and Spear, R.W., 1991. Reversion of forest to tundra in the central Yukon. *Ecology* **72**: 202–212.

De Deckker, P., and Forester, R.M., 1988. The use of ostracods to reconstruct continental palaeoenvironmental records. In: P. De Deckker, J.-P. Colin and J.-P. Peypouquet (Eds) **Ostracoda in the Earth Sciences**. Elsevier, Amsterdam.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition. *Journal of Sedimentary Petrology* **44**: 242–248.

Duff, K.E. and Smol, J.P., 1988. Chrysophycean stomatocysts from the postglacial sediments of a high Arctic lake. *Canadian Journal of Botany* **66**: 1117–1128.

Duff, K.E. and Smol, J.P., 1991. Morphological descriptions and stratigraphic distributions of the chrysophycean stomatocysts from a recently acidified lake (Adirondack Park, N.Y.). *Journal of Paleolimnology* **5**: 73-113.

Duff, K.E., Douglas, M.S.V. and Smol, J., 1992. Chrysophycean cysts in Canadian high Arctic ponds. *Nordic Journal of Botany* **12**: 471–499.

Duk-Rodkin, A., Jackson, L.E. and Rodkin, O., 1986. A composite profile of the Cordilleran ice sheet during McConnell Glaciation, Glenlyon and Tay River map areas, Yukon Territory. *Current Research, Geological Survey of Canada, Paper* **86–1B**: 257–262.

Environment Canada, 1979. **Analytical Methods Manual.** Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Fritz, S.C., 1990. Twentieth-century salinity and water-level fluctuations in Devils Lake, North Dakota: A test of a diatom-based transfer function. *Limnology and Oceanography* **35**: 1771–1781.

Gasse, F., 1986. East African diatoms. *Bibliotheca Diatomologica*, Vol. **11**. Cramer, Berlin.

Gasse, F., Talling, J.F. and Kilham, P., 1983. Diatom assemblages in East Africa: Classification, distribution and ecology. *Revue d'Hydrobiologie tropicale* **16**(1): 3–34.

Gasse, F., Fontes, J.C., Plaziat, J.C., Carbonel, P., Kaczmarska, I., De Deckker, P., Soulié-Marsche, I., Callot, Y. and Dupeuble, P.A., 1987. Biological remains, geochemistry and stable isotopes for the reconstruction of environmental and hydrological changes in the Holocene lakes from North Sahara. *Palaeogeography, Palaeoclimatology, Palaeoecology* **60**: 1–46.

Germain, H., 1981. **Flore des diatomées.** Boubée, Paris.

Glew, J., 1991. Miniature gravity corer for recovering short sediment cores. *Journal of Paleolimnology* **5**: 285–287.

Hammer, U.T., (Ed.) 1983. Proceedings of the Second International Symposium on Athalassic (Inland) Saline Lakes, Saskatchewan, Canada, June 1982. *Hydrobiologia* **105**.

Hammer, U.T., 1986. **Saline Lake Ecosystems of the World.** *Monographiae Biologicae* **59.** Junk, Dordrecht.

Hammer, U.T., Shamess, J.,and Haynes, R.C., 1983. The distribution and abundance of algae in saline lakes of Saskatchewan, Canada. *Hydrobiologia* **105**: 1–26.

Hammer, U.T., Sheard, J.S. and Kranabetter, J., 1990. Distribution and abundance of littoral benthic fauna in Canadian prairie saline lakes. *Hydrobiologia* **197**: 173–192.

Harris, S.A., 1990. Dynamics and origin of saline soils on the Slims River Delta, Kluane National Park, Yukon Territory. *Arctic* **43**: 159–175.

Hendey, N.I., 1964. An introductory account of the smaller algae of British coastal waters. Part V: Bacillariophyceae. *Fishery Investigations, Series* **IV.** Ministry of Agriculture, Fisheries and Food, London.

Hickman, M., Schweger, C.E. and Habgood, T., 1984. Lake Wabamun, Alberta: A paleoenvironmental study. *Canadian Journal of Botany* **62**: 1438–1465.

Hirvenoja, M., 1973. Revision der Gattung *Cricotopus* van der Wulp und ihrer Verwandten (Diptera, Chironomidae). *Annales Zoologici Fennici* **10**: 1–363.

Hughes, O.L., Rampton, V.N. and Rutter, N.W., 1972. **Quaternary Geology and Geomorphology, Southern and Central Yukon (Northern Canada).** Guidebook, Field Excursion All, International Geological Congress, Session **24**, pp. 12–16.

Hughes, O.L., 1987. Quaternary geology. In: S.R. Morison and C.A.S. Smith (Eds) **Guide Book for Quaternary Research in the Yukon.** pp. 12–16. XII INQUA Congress, Ottawa, Canada. National Research Council of Canada, Ottawa.

Johnson, M.G, Kelso, J.R.M., McNeil, O.C. and Morton, W.B., 1990. Fossil midge associations and the historical status of fish in acidified lakes. *Journal of Paleolimnology* 3: 113–127.

Klassen, R.W., Morison, S.R. and Duk-Rodkin, A., 1987. Surficial geology, Carmacks, Yukon Territory. *Geological Survey of Canada*, Map **9**–1985, scale 1:250 000.

Krammer, K., and Lange-Bertalot, H. 1986. Bacillariophyceae. Part I: Naviculaceae. In: H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (Eds) **Süßwasserflora von Mitteleuropa.** Gustav Fischer Verlag, Stuttgart.

Krammer, K. and Lange-Bertalot, H., 1988. Bacillariophyceae. Part II: Bacillariaceae, Epithemiaceae, Surirellaceae. In: H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (Eds) **Süßwasserflora von Mitteleuropa.** Gustav Fischer Verlag, Stuttgart.

Krammer, K. and Lange-Bertalot, H., 1991a. Bacillariophyceae. Part III: Centrales, Fragilariaceae, Eunotiaceae. In: H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (Eds) **Süßwasserflora von Mitteleuropa.** Gustav Fischer Verlag, Stuttgart/Jena.

Krammer, K. and Lange-Bertalot, H., 1991b. Bacillariophyceae. Part IV: Achnanthaceae. In: H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (Eds) **Süßwasserflora von Mitteleuropa.** Gustav Fischer Verlag, Stuttgart/Jena.

Lancaster, J. and Scudder, G.G.E., 1987. Aquatic Coleoptera and Hemiptera in some Canadian saline lakes: patterns in community structure. *Canadian Journal of Zoology* **65**: 1383–1390.

Lange-Bertalot, H., 1979. Toleranzgrenzen und Populationsdynamik benthischer Diatomeen bei unterschiedlich starker Abwasserbelastung. *Archiv für Hydrobiologie, Supplement* **56**:184–219.

Last, W.M. and Schweyen, T.H., 1983. Sedimentology and geochemistry of saline lakes of the Great Plains. *Hydrobiologia* **105**: 245–263.

Last, W.M. and Slezak, L.A., 1988. The salt lakes of western Canada: A paleolimnological overview. *Hydrobiologia* **158**: 301–316.

Leavitt, P.R. and Carpenter, S.R., 1989. Effects of sediment mixing and benthic algal production on fossil pigment stratigraphies. *Journal of Paleolimnology* **2**: 147–158.

Leavitt, P.R., Carpenter, S.R. and Kitchell, J.F., 1989. Whole-lake experiments: The annual record of fossil pigments and zooplankton. *Limnology and Oceanography* **34**: 700–717.

Lindsey, C.C., Patalas, K., Bodaly, R.A. and Archibald, C.P., 1981. Glaciation and the physical, chemical and biological limnology of Yukon lakes. *Canadian Technical Report, Fisheries and Aquatic Sciences* **966**: 1–37.

Luckman, B.H., 1989. Global change and the record of the past. Energy, Mines and Resources Canada. *GEOS* **18**: 1–8.

Mantoura, R.F.C. and Llewellyn, C.A., 1983. The rapid determination of algal chlorophyll and carotenoid pigments and their breakdown products in natural waters by reversed phase high-performance liquid chromatography. *Analytica chimica Acta* **151**: 297–314.

Melack, J.M., (Ed.) 1988. Proceedings of the Third International Symposium on Inland Saline Lakes, Nairobi, Kenya, August 1985. *Hydrobiologia* **158**.

Merritt, R.W. and Cummins, K.W., (Eds) 1978. **An Introduction to the Aquatic Insects of North America.** Kendall/Hunt, Dubuque, Iowa.

Oliver, D.R. and Roussel, M.E., 1983. The insects and arachnids of Canada. Part 11. The genera of larval midges of Canada; Diptera: Chironomidae. *Agriculture Canada, Publication* **1746**, 1–263.

Ouellet, M., Dickman, M., Bisson, M. and Pagé, P., 1989. Physico-chemical characteristics and origin of hypersaline meromictic Lake Garrow in the Canadian High Arctic. *Hydrobiologia* **172**: 215–234.

Patrick, R. and Reimer, C., 1966. **The Diatoms of the United States.** Vol. **1**: **Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae.** The Academy of Natural Sciences of Philadelphia, Philadelphia.

Patrick, R. and Reimer, C., 1975. **The Diatoms of the United States.** Vol. 2. **Entomoneidaceae, Cymbellaceae, Gomphonemaceae, Epithemiaceae.** The Academy of Natural Sciences of Philadelphia, Philadelphia.

Renaut, R.W., 1990. Recent carbonate sedimentation and brine evolution in the saline lake basins of the Cariboo Plateau, British Columbia, Canada. *Hydrobiologia* **197**: 67–81.

Renaut, R.W. and Long, P.R., 1987. Freeze-out precipitation of salts in saline lakes—examples from western Canada. In: G.L. Strathdee, M.O. Klein and L.A. Melis (Eds) **Crystallization and Precipitation.** pp. 33–34. Pergamon, Oxford.

Renaut, R.W. and Long, P.R., 1989. Sedimentology of the saline lakes of the Cariboo Plateau, Interior British Columbia, Canada. *Sedimentary Geology* **64**: 239–264.

Ritchie, J.C. 1987. **Postglacial Vegetation of Canada.** Cambridge University Press, Cambridge.

Roots, E.F., 1989. Climate change: High-latitude regions. *Climatic Change* **15**: 223–253

Roux, M., Servant-Vildary, S. and Servant, M., 1991. Inferred ionic composition and salinity of a Bolivian Quaternary lake, as estimated from fossil diatoms in the sediments. *Hydrobiologia* **210**: 3–18.

Rybak, M., Rybak, I. and Nicholls, K., 1991. Sedimentary chrysophycean cyst assemblages as paleoindicators in acid sensitive lakes. *Journal of Paleolimnology* **5**: 19–72.

Sandgren, C.D. and Carney, H.J., 1983. A flora of fossil Chrysophycean cysts from the recent sediments of Frains Lake, Michigan, U.S.A. *Nova Hedwigia* **38**: 129–163.

Sanger, J.E., 1988. Fossil pigments in paleoecology and paleolimnology. *Palaeogeography, Palaeoclimatology, Palaeoecology* **62**: 343–359.

Schoeman, F.R. and Archibald, R.E.M., 1987. Observations on *Amphora* species (Bacillariophyceae) in the British Museum (Natural History). *Nova Hedwigia* **44**: 377–398.

Simpson, K.W., Bode, R.W. and Albu, P. 1983. Keys for the genus *Cricotopus* adapted from 'Revision der Gattung *Cricotopus* van der Wulp und ihrer Verwandten (Diptera, Chironomidae)' by Hirvenoja. *Bulletin New York State Museum* **450**: 1–133.

Smol, J.P., 1983. Paleophycology of a high arctic lake near Cape Herschel, Ellesmere Island. *Canadian Journal of Botany* **61**: 2195–2204.

Stuart, G.S.L., Helmer, J.W. and Hills, L.V. 1989. The Holocene paleoecology of Jenny Lake area, southwest Yukon, and its implications for prehistory. *Arctic* **42**: 347–353.

Takahashi, E., 1987. Loricate and scale-bearing protists from Lützhow-Holm Bay, Antarctica II. Four marine species of *Paraphysomonas* (Chrysophyceae) including two new species from the fast-ice covered coastal area. *Japanese Journal of Phycology* **35**: 155–166.

Tarnocai, C., Smith, S. and Hughes, O.L., 1985. Soil development on Quaternary deposits of various ages in the central Yukon Territory. Current Research, Part A. *Geological Survey of Canada*, Paper **85-1A**: 229–238.

Timms, B.V., 1983. A study of benthic communities in some shallow saline lakes of western Victoria, Australia. *Hydrobiologia* **105**: 165–177.

Timms, B.V., Hammer, U.T. and Sheard, J.W., 1986. A study of benthic communities in some saline lakes in Saskatchewan and Alberta, Canada. *Internationale Revue der gesamten Hydrobiologie und Hydrographie* **71**: 759–777.

Tynni, R., 1978. Über Finnlands rezente und subfossile Diatomeen. Part X. *Geological Survey of Finland, Bulletin* **296**.

Uutala, A.J., 1990. *Chaoborus* (Diptera: Chaoboridae) mandibles—paleolimnological indicators of the historical status of fish populations in acid-sensitive lakes. *Journal of Paleolimnology* **4**: 139–151.

Wahl, H.E., Fraser, D.B., Harvey, R.C. and Maxwell, J.B., 1987. Climate of Yukon. *Climatological Studies*, No. **40**, Atmospheric Environment Service, Environment Canada, Ottawa.

Walker, I.R., 1988. Late-Quaternary Palaeoecology of Chironomidae (Diptera: Insecta) from Lake Sediments in British Columbia. Ph.D. Thesis, Simon Fraser University, Burnaby, British Columbia, Canada.

Walker, I.R., 1990. Modern assemblages of arctic and alpine Chironomidae as analogues for late-glacial communities. *Hydrobiologia* **214**: 223–227.

Walker, I.R., Smol, J.P., Engstrom, D.R. and Birks, H.J.B., 1991. An assessment of Chironomidae as quantitative indicators of past climatic change. *Canadian Journal of Fisheries and Aquatic Sciences* **48**: 975–987.

Wang, X.-C. and Geurts, M.-A., 1991a. Post-glacial vegetation history of the Ittlemit Lake basin, southwest Yukon Territory. *Arctic* **44**: 23–30.

Wang, X.-C., and Geurts, M.-A., 1991b. Late Quaternary pollen records and vegetation history of the southwest Yukon Territory: A review. *Géographie physique et Quaternaire* **45**: 175–193.

Wetzel, R.G., 1983. **Limnology.** Saunders College Publishing, Philadelphia.

Wiederholm, T., (Ed.) 1983. Chironomidae of the Holarctic region. Keys and diagnoses. Part 1—Larvae. *Entomologica Scandinavica, Supplement* **19**: 1–457.

Williams, W.D., (Ed.) 1981a. Salt Lakes. Proceedings of the International Symposium on Athalassic (Inland) Salt Lakes, Adelaide, Australia, October 1979. *Hydrobiologia* **81**.

Williams, W.D., 1981b. Inland salt lakes: An introduction. *Hydrobiologia* **81**: 1–14.

Williams, W.D., (Ed.) 1991. **Salt Lakes and Salinity.** *Hydrobiologia* **210**, nos 1–2.

Williams, W.D., Boulton, A.J. and Taaffe, R.G., 1990. Salinity as a determinant of salt lake fauna: a question of scale. *Hydrobiologia* **197**: 257–266.

Zeeb, B.A., Duff, K.E. and Smol, J.P., 1990. Morphological descriptions and stratigraphic profiles of chrysophycean stomatocysts from the recent sediments of Little Round Lake, Ontario. *Nova Hedwigia* **51**: 361–380.

Appendix I

Saline Lake Cyst Descriptions. Seven morphotypes were identified from the saline lake sediments using the SEM. Five of these stomatocysts have been previously described elsewhere by at least one of the authors: stomatocyst 9 (Duff and Smol, 1988), stomatocyst 46 (Duff and Smol, 1991), stomatocyst 115 (Zeeb *et al.*, 1990), and stomatocysts cf. 122 and cf. 125 (Duff *et al.*, 1992). All seven morphotypes could be distinguished using LM, and we have included scanning electron micrographs as well as light micrographs (Plates V and VI). Description of our two new morphotypes follow the ISWG guidelines published by Cronberg and Sandgren (1986). The number in parentheses following the authors' names indicates the number of scanning electron micrographs on which the description is based. The negative number, locality information, and first figure refer to the characteristic SEM specimen of that morphotype. Cyst numbering follows consecutively from Duff *et al.* (1992). We have also included light micrographs of two cysts that could be distinguished using the LM, but were not observed with the SEM. In accordance with ISWG guidelines, which require SEM identification, we have not included a formal description of these cysts and their informal descriptions are preceded by the word, 'Unidentified'. They are also numbered consecutively from Duff *et al.* (1992).

Stomatocyst 146, Zeeb and Smol (3) Plate VI
Negative #: J.P. Smol 451, Plate VI, Fig. 1 Figs 1 and 2
Locality: YUK-Saline Lake (U60), Yukon, core depth 25 cm

This spherical cyst is 6.6–7.4 μm in diameter, and has a smooth to psilate surface. The collar is short (*ca.* 0.6 μm) and cylindrical, with abrupt inner and outer margins of the apex. The annulus (diameter *ca.* 2.0 μm) is conical and slopes toward the regular pore (diameter 0.6–0.7 μm). This morphotype is identical to Sandgren and Carney's (1983) cyst #11, but these authors report that some of their specimens have a bipartite distinction of the annulus where the distal portion is planar. This cyst may be produced by an *Ochromonas* sp. (Sandgren and Carney, 1983).

Stomatocyst 147, Zeeb and Smol (2) Plate VI
Negative #: J.P. Smol 453, Plate VI, Fig. 5 Figs 5 and 6
Locality: YUK-Saline Lake (U60), Yukon, core depth 30 cm

This smooth spherical cyst is *ca.* 5.5 μm in diameter. The small conical pore (diameter *ca.* 0.4 μm) is set in a planar annulus and surrounded by an acute conical collar (diameter 2.3 μm). This morphotype is identical to cyst #19 (Rybak *et al.*, 1991). Its biological affinity is unknown.

Unidentified Stomatocyst 5, Zeeb and Smol Plate VI
Negative #: Yukon cysts, BZ-1, Plate VI, Fig. 7 Fig. 7
Locality: YUK-Saline Lake (U60), Yukon, core depth 1–5 cm

This is a very small cyst (2–3.5 μm diameter), and is therefore difficult to describe. It is spherical in shape and has no distinct collar. A tiny pore is sometimes visible using LM. Although specimens appear smooth using LM, the one SEM we obtained, that is of similar size and shape, has a psilate surface with long, very low ridges running along its surface. We hesitate to make a definite connection between LM and SEM because the pore is not plainly visible in the latter, and because ridges could not be seen on the LM specimens.

Unidentified Stomatocyst 6, Zeeb and Smol Plate VI
Negative #: Yukon cysts, BZ-1, Plate VI, Fig. 8 Fig. 8
Locality: YUK-Saline Lake (U60), Yukon, core depth 30 cm

This stomatocyst is spherical and has a diameter of *ca.* 4–6 μm. It appears to be smooth-walled, with no surface ornamentation. It is easily distinguished using LM because it has a distinct cylindrical collar rising *ca.* 0.5 μm above the cyst surface. A SEM of this morphotype was not obtained.

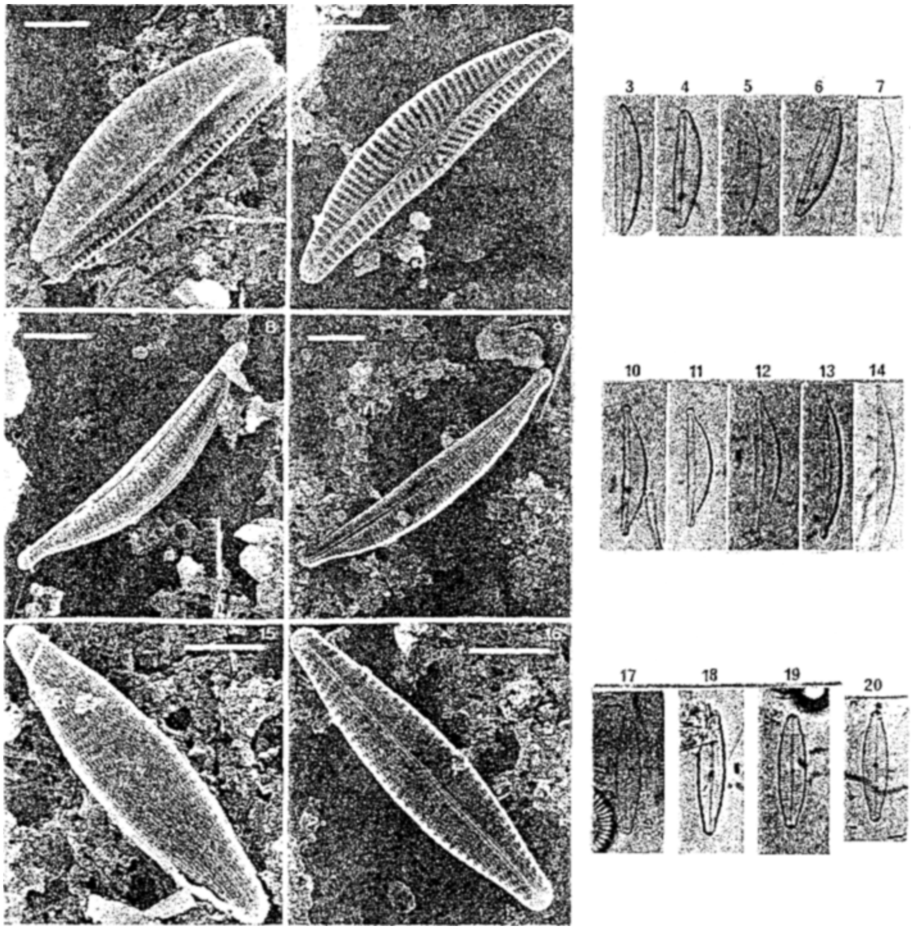

Plate I. Figs 1–7, *Cymbella pusilla* Grunow. [1] external view of valve (SEM). [2] internal view of valve (SEM). [3–7] valve views (LM). Figs 8–14, *Amphora coffeaeformis* Kützing. [8] external view of valve (SEM). [9] internal view of valve (SEM). [10–14] valve views (LM). Figs 15–20, *Navicula veneta* Kützing. [15] external view of valve (SEM). [16] internal view of valve (SEM). [17–20] valve views (LM). (all scale bars = 5 µm).

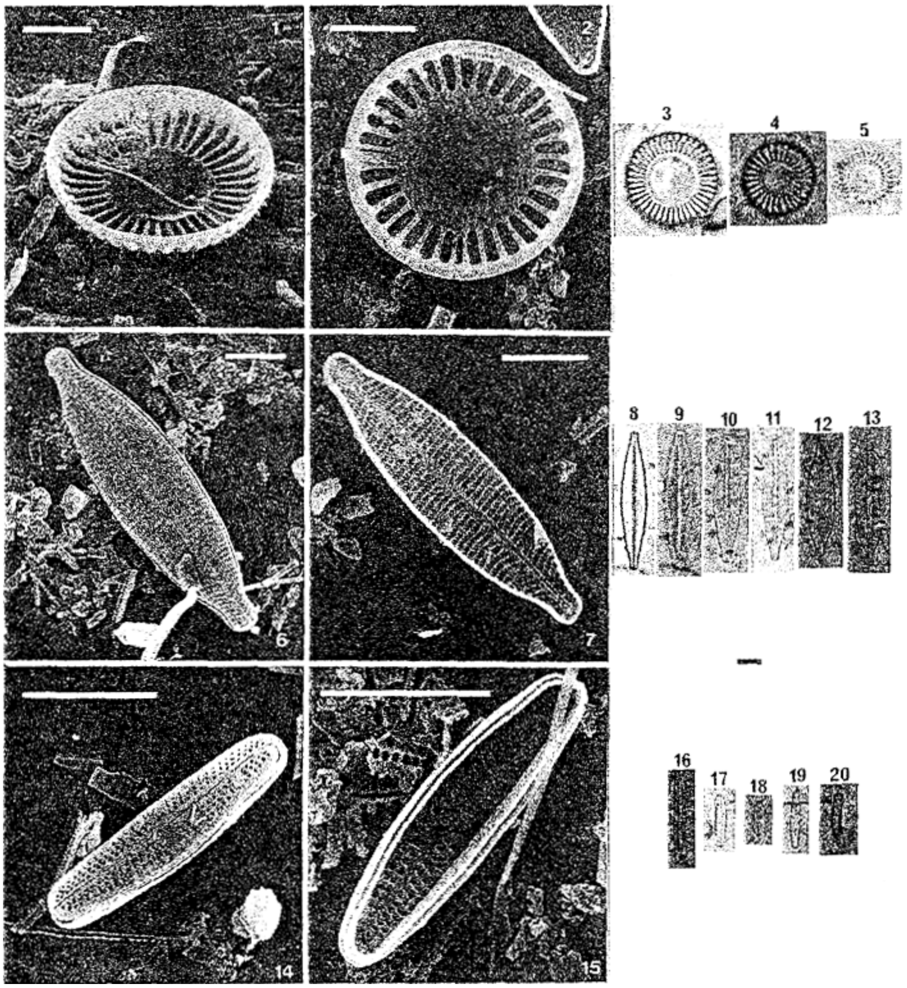

Plate II. Figs 1–5, *Cyclotella meneghiniana* Kützing. [1] internal view of valve (SEM). Note internal openings of marginal strutted processes as well as single central strutted process. [2] internal view of valve (SEM). Note inner opening of two central strutted processes, each with three struts. [3-5] valve views (LM). Figs 6–13, *Navicula halophila* (Grunow) Cleve. [6] external view of valve (SEM). [7] internal view of valve (SEM). [8-13] valve views (LM). Figs 14–20, *Achnanthes minutissima* var. *minutissima* Kützing. [14] external view of raphe valve (SEM). [15] internal view of rapheless valve (SEM). [16–19] valve views (LM). [20] girdle view of frustule (LM). (all scale bars = 5 μm).

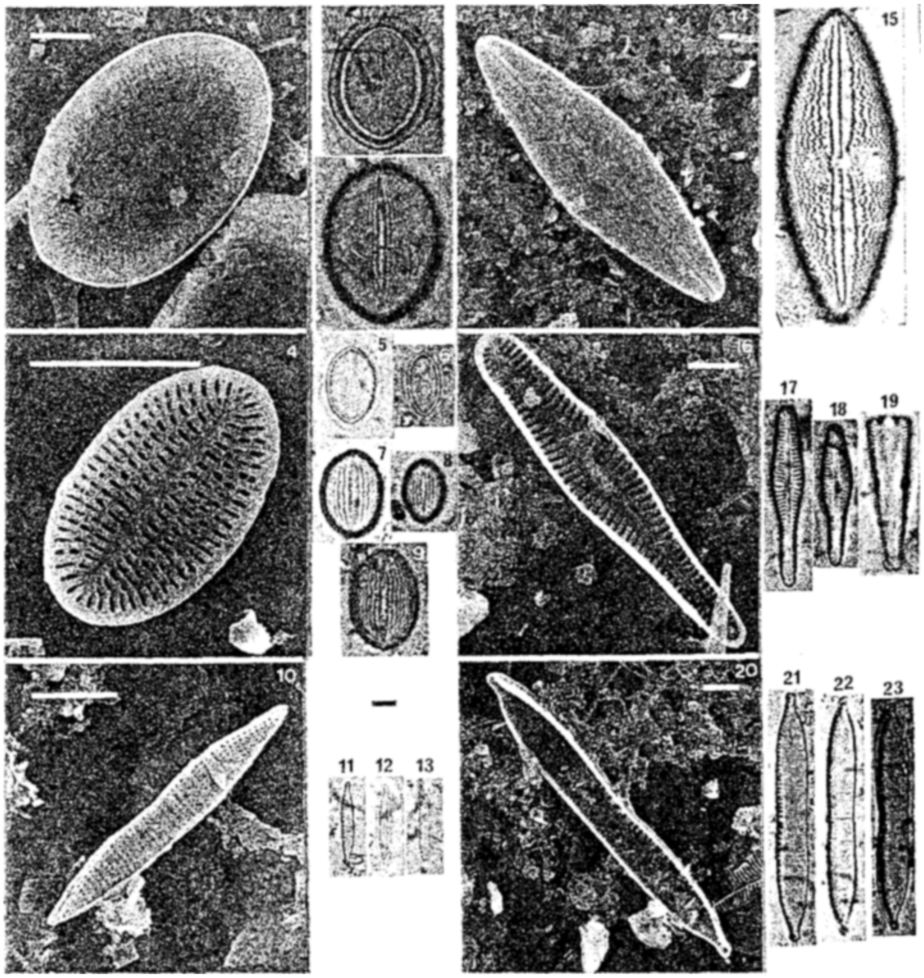

Plate III. Figs 1–3, *Cocconeis placentula* var. *placentula* Ehrenberg. [1] raphe valve (SEM). [2] raphe valve (LM). [3] rapheless valve (LM). Fig. 4, rapheless valve of *Cocconeis neothumensis* Krammer (SEM). Figs 5–9, *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow. [5,6] raphe valve (LM). [7–9] rapheless valve (LM). Figs 10–13, *Nitzschia* sp. (10, 13 = *Nitzschia* cf. *frustulum*?). [10] valve view (SEM). [11–13] valve views (LM). Figs 14 and 15, *Anomoeoneis sphaerophora* f. *costata* (Kützing) Schmid. Note 'ghost areolae' (= shallow pits) in central area. [14] external view of valve (SEM). [15] valve view (LM). Figs 16–19, *Gomphonema clavatum* Ehrenberg. [16] internal view of valve (SEM). [17, 18] valve views (LM). [19] girdle view of frustule (LM). Figs 20–23, *Nitzschia commutata* Grunow in Cleve and Grunow. [20] internal view of valve (SEM). [21–23] valve views (LM). (all scale bars = 5 μm).

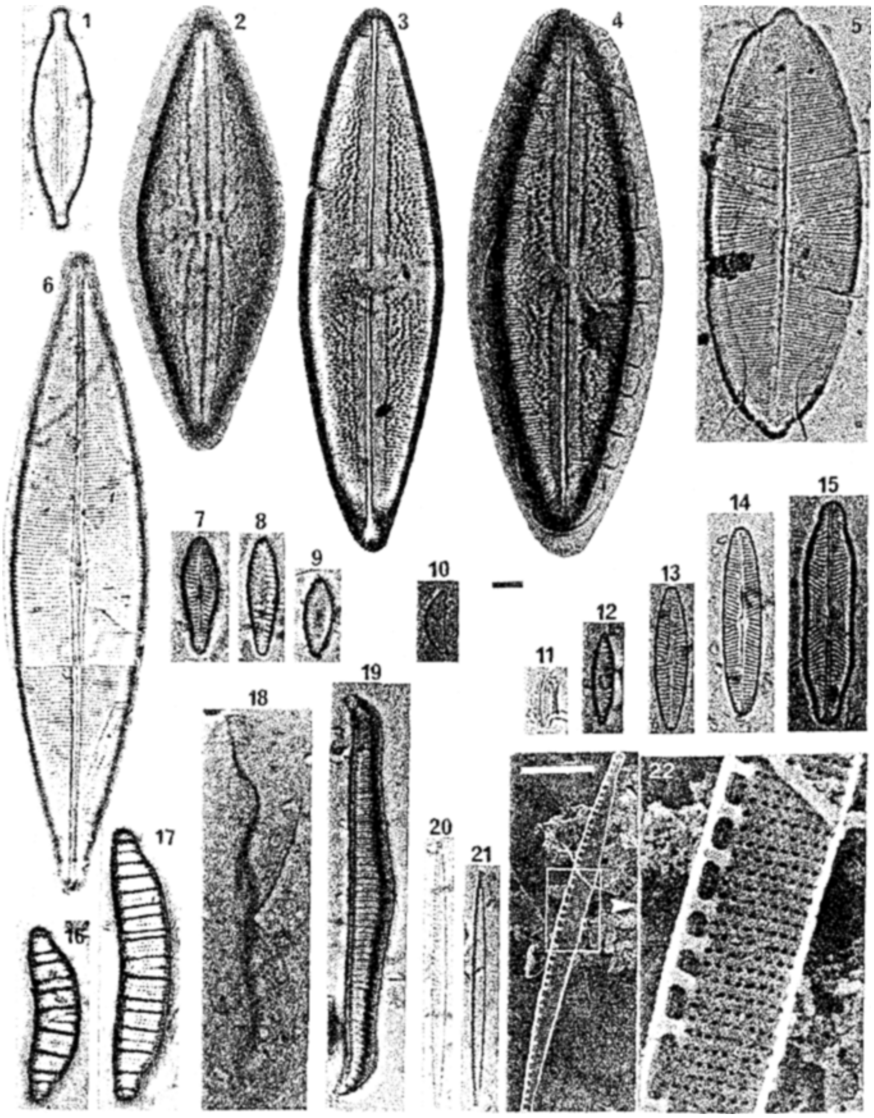

Plate IV. Figs 1–4, *Anomoeoneis sphaerophora* f. *costata* (Kützing) Schmid (LM). Forms shown in Figs 3 and 4 resemble *A. sphaerophora* var. *platensis* Frenguelli. Fig. 5, *Navicula* sp. (LM). Fig. 6, *Navicula cuspidata* Kützing (LM). Fig. 7, *Gomphonema clavatum* Ehrenberg (LM). Fig. 8, *Gomphonema* sp. (LM). Fig. 9, *Gomphonema parvulum* Kützing (LM). Fig. 10, *Amphora veneta* Kützing (LM). Fig. 11, *Nitzschia* sp. (LM). Fig. 12, *Nitzschia* cf. *amphibia* Grunow (LM). Fig. 13, *Navicula* cf. *oppugnata* Hustedt (LM). Fig. 14, *Navicula digitoradiata* (Gregory) Ralfs (LM). Fig. 15, *Pinnularia interrupta* W. Smith (LM). Figs 16 and 17, *Epithemia adnata* (Kützing) Brébisson (LM). Fig. 18, *Entomoneis alata* (Ehrenberg) Ehrenberg (LM). Fig. 19, *Rhopalodia gibba* var. *gibba* (Ehrenberg) O. Müller (LM). Figs 20–22, *Nitzschia incognita* Legler and Krasske. [20, 21] valve views (LM). [22] valve view (SEM). (all scale bars = 5 µm).

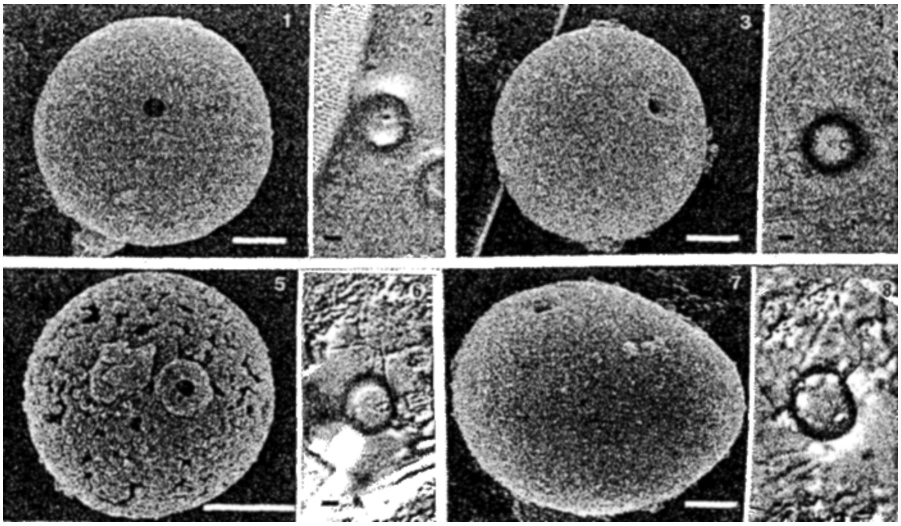

Plate V. Fig. 1, stomatocyst 9 (SEM). Fig. 2, stomatocyst 9 (LM). Fig. 3, stomatocyst 46 (SEM). Fig. 4, stomatocyst 46 (LM). Fig. 5, stomatocyst cf. 125 (SEM). Fig. 6, stomatocyst cf. 125 (LM). Fig. 7, stomatocyst cf. 122 (SEM). Fig. 8, stomatocyst cf. 122 (LM). (all scale bars = 2 µm).

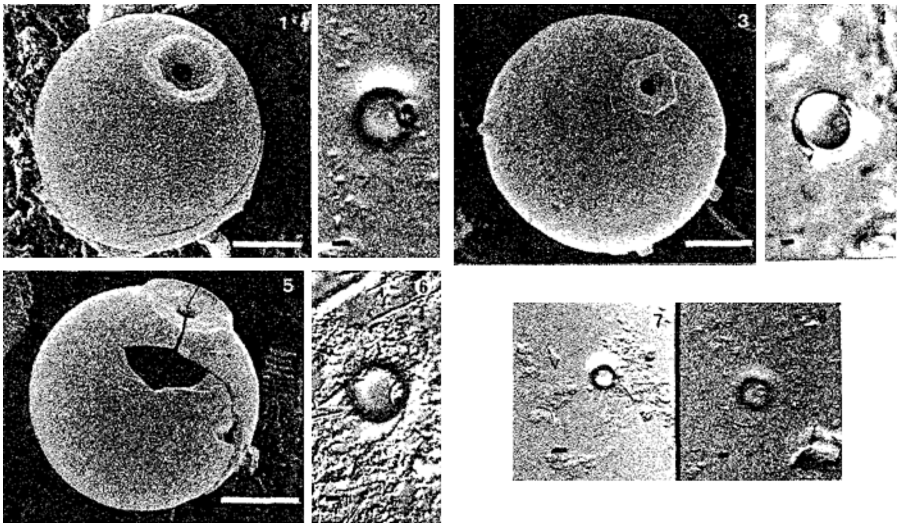

Plate VI. Fig. 1, stomatocyst 146 (SEM). Fig. 2, stomatocyst 146 (LM). Fig. 3, stomatocyst 115 (SEM). Fig. 4, stomatocyst 115 (LM). Fig. 5, stomatocyst 147 (SEM). Fig. 6, stomatocyst 147 (LM). Fig. 7, unidentified stomatocyst 5 (LM). Fig. 8, unidentified stomatocyst 6 (LM). (all scale bars = 2 µm).

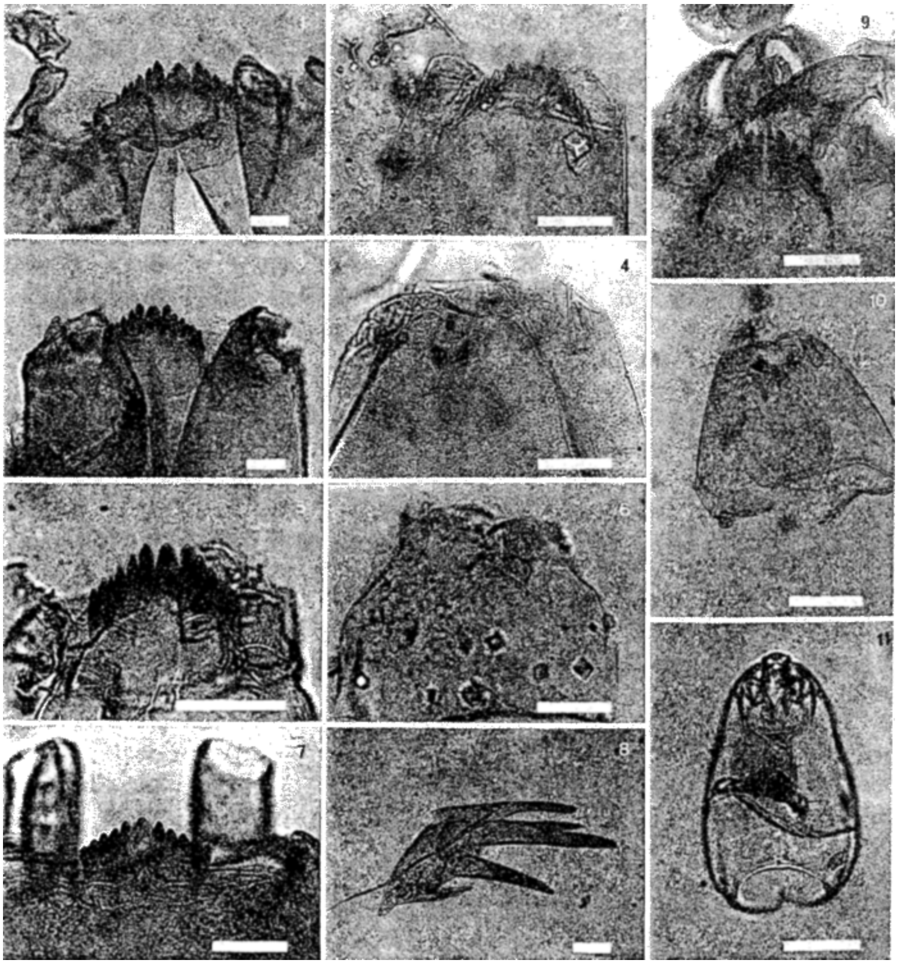

Plate VII. Fig. 1, *Chironomus* 225x. Fig. 2, *Psectrocladius* 445x. Fig. 3, *Glyptotendipes* 225x. Fig. 4, Tribe Pentaneurini 445x. Fig. 5, *Einfeldia* 655x. Fig. 6, *Tanypus* 445x. Fig. 7, Subtribe Tanytarsini 445x. Fig. 8, *Chaoborus americanus* 225x. Fig. 9, *Cricotopus ornatus*-type 445x. Fig. 10, *Procladius* 445x. Fig. 11, *Dasyhelea*? (Ceratopogonidae) 445x. (all scale bars = 50 µm).