Paleolimnological analyses of cultural eutrophication patterns in British Columbia lakes

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Abstract: Diatom-based paleolimnological approaches were used to determine the effects of cultural impacts on eutrophication histories in four lakes from central British Columbia. Stratigraphic analysis of fossil diatoms in ^{210}Pb-dated cores, and inferences of past total phosphorus concentrations using diatom-based models, were used to reconstruct the nutrient histories of Takysie, Tchesinkut, Francois and Tyhee lakes. Diatom microfossils indicate that these lakes are probably naturally productive, but some nutrient enrichment has likely occurred in response to human development (post-A.D. 1850), particularly in Tyhee Lake. However, in Tchesinkut and Francois lakes, some reduction in total phosphorus may have occurred in recent decades. Takysie, Tchesinkut and Francois lakes have been dominated by planktonic diatoms indicative of high productivity (e.g. *Stephanodiscus, Asterionella, Fragilaria crotonensis, Aulacoseira*). Tyhee Lake has been dominated by benthic *Fragilaria* species, but *Stephanodiscus minutulus* has increased in recent decades. These data were pooled with previously published paleolimnological data from British Columbia to summarize cultural eutrophication patterns in this region. Out of eleven BC lakes considered, ten were productive before human intervention, but seven eutrophied further from human activities. One lake exhibited no obvious post-1850 change in diatom assemblage, suggesting little human impact on water quality. In three of the lakes, recent improvements in water quality may have occurred in response to recent mitigation efforts.

Key words: eutrophication, paleolimnology, British Columbia, diatoms, lakes, mining

Introduction

Lake trophic status is closely related to the availability of limiting nutrients, such as phosphorus and nitrogen (Wetzel 1983). While eutrophication can occur naturally, lakes that are situated in areas of human settlement are often subjected to "cultural eutrophication". This is characterized by an accelerated build-up of organic matter, nutrients and sediments in lake basins, resulting from human activities. Cultural increases in drainage basin nutrients can occur directly from point sources, such as sewage and industrial inputs, or from diffuse sources, such as urban runoff, agricultural fertilizers, pastures, and erosion from road construction and deforestation.

Since the arrival of European settlers in British Columbia, cultural eutrophication has been a particular concern, especially in recent decades. Several attempts at rehabilitation have been proposed (e.g. Rysavy and Sharpe 1995) and applied (e.g. Henderson-Sellers and Markland 1987) in efforts to return lakes to their pre-impact water quality conditions. There is concern, however, that mitigation efforts may be being applied to naturally eutrophic lakes, for which attempts at restoration to oligotrophic conditions is unrealistic. Indeed, although many BC lakes have severe cultural eutrophication problems (e.g. Walker et al. 1993), many lakes considered to have "poor" water quality may be naturally eutrophic (Reavie et al. 1995a). In such cases, more realistic mitigation targets should be set.

Paleolimnological studies offer a solution to the problem of inadequate historical data on lakes (Smol 1992). Paleolimnologists use the physical, chemical and biological information preserved in lake sedimentary profiles to elucidate past events that have occurred within their catchments. The study of algal remains (especially diatoms) has allowed reliable reconstructions of historical trophic status in BC (Walker et al. 1993, Reavie et al. 1995a,b, Hall and Smol 1992), as well as many other regions (reviewed in Hall and Smol 1999). Of the many biomarkers available to paleolimnologists, diatoms are the most widely used group of indicators for eutrophication research (Dixit et al. 1992). Diatom valves are particularly useful in paleolimnological studies because their siliceous cell walls are resistant to dissolution and breakage; diatom taxonomy is well defined, and the size, shape, and sculpturing of their valves are taxon-specific, making them easily identifiable using microscopic techniques; many species have well-defined environmental optima and tolerances; they are present in almost all aquatic environments; and fossil assemblages in lakes are often abundant and diverse (Dixit et al. 1992). Stomatocysts, the siliceous resting stages of the chrysophyte algae, are also well preserved in sediments, and they may also be used as indicators of nutrient trends. In general, stomatocyst numbers are reduced in high-nutrient conditions in temperate lakes, so the ratio of stomatocysts to diatom valves can be used to track nutrient shifts (Smol 1985).

Recently, Reavie et al. (1995a) used diatoms in a paleolimnological assessment of six inland BC lakes to determine that three of the lakes had become eutrophic due to human disturbance, whereas the other lakes contained naturally high concentrations of nutrients. The current paper presents a similar assessment of 4 additional dimictic lakes from BC. A recent environmental assessment (BC Environment, unpub. data) of Takysie, Tchesinkut, Francois and Tyhee lakes (north-central BC) was instigated due to concern by local residents over water quality. Additionally, Francois Lake has been impacted by mining activities, so geochemical analyses from that system are also presented. While several lake management policies have been considered, the natural (i.e. pre-disturbance) conditions of these lakes were still unknown. We document the diatom assemblages preserved in the recent sediments of ^{210}Pb-dated lake sediment cores, and, using a recently-developed diatom transfer function (Reavie et al. 1995b), infer past changes in lake trophic status. Primary objectives were to determine the impacts of various human activities in the lake catchments on past limnological quality. Additionally, previous paleolimnological applications to eutrophication in BC were compiled to summarize trends for the region.

Study Region

The four study lakes (Fig. 1) are in close proximity to each other, in the Caribou Aspen - Lodgepole Pine biogeoclimatic zone (Beil et al. 1976). This area is mainly a farming, ranching and logging community, and recreational use increases during the summer months. Much of the area contains undeveloped wilderness. European settlement of the region began in 1807 with the establishment of a trading post. However, no notable development occurred in the catchments of our study lakes until the early 1900s.

Takysie Lake

Takysie Lake (53°52' N, 125°49' W) is a small (5.14 km^2), shallow, slightly alkaline, mesotrophic to eutrophic lake (Table 1) located in the Lakes Forest District of BC. Human settlement in the lake's catchment began in 1910, but most development has occurred since ca. 1930, primarily at the west end of the lake. Small logging operations were undertaken in the catchment during the early 1960s, but more intensive logging occurred between 1979 and 1986. In total, approximately 28% of the catchment has been logged. A small fire burned near the southern shore in 1993. Extensive macrophyte growth and algal blooms have been reported, which are often symptoms of eutrophic lake conditions. Takysie Lake currently has about 10 residences and 12 agricultural lots in its catchment. Potential sources of water quality degradation in Takysie Lake include leaking or failing septic systems, runoff from animal waste, fertilizers and residential (between 16 and 20 residents) and resort/campground use in the west end of the lake. Other issues of concern are shoreline and streambank erosion from grazing animals, sedimentation from forestry roads, and reduction of flushing rate due to a beaver dam in Takysie Creek, upstream of the lake.

Tchesinkut Lake

Tchesinkut Lake (54°06' N, 125°41' W) is located north of Takysie Lake, in the Lakes Forest District. It is a large (33.83 km^2), deep (Z_{max} = 149 m), alkaline lake with relatively low concentrations of nutrients in the water column (Table 1). First recorded human settlement on the lake occurred in 1908, when homesteaders cleared small areas of the catchment. In 1922, a forest fire burned to the shoreline of the lake, but the magnitude of the burn is unknown. Selective logging activities around Tchesinkut Lake occurred between ca. 1930 and 1960, and local sawmills were prominent between 1946 and 1952. In 1970, clear-cut logging began around the lake, and in 1989 a large aspen/cottonwood area on the north shore was cleared for wildlife enhancement purposes. Despite numerous land-clearing activities, only about 15% of the catchment has been logged. Human settlement patterns are believed to have corresponded to logging activities, with most development occurring since ca. 1930. Human development in the catchment consists primarily of cottages, houses (approximately 350 residents, 121 dwellings), industries and agriculture, with the west end of the lake supporting the greatest amount of development. Although no cultural activities have been specifically linked to water quality degradation, possible sources are similar to those noted for Takysie Lake. Inlets and outlets of the lake have also been partially blocked by beaver dams, likely resulting in modifications to flushing rate.

Francois Lake

Francois Lake (53°58' N, 126°23' W) is located between Takysie and Tchesinkut lakes (Fig. 1). To date, this lake is the largest [by surface area (258 km^2) and watershed area (3600 km^2); Table 1] BC lake system to be the subject of a paleolimnological analysis of eutrophication. Due to its great length (~110 km), Francois Lake extends into three forest districts (Morice, Vanderhoof and Lakes Forest Districts). Francois is also deep (Z_{max} = 244 m) and slightly alkaline, and recent measurements indicate that the lake is nutrient-poor (Table 1). The first recorded settlement of this area occurred in 1904, followed by an influx of settlers during the 1920s. By 1930, about 50 homes were present in the catchment. From 1919 to 1952, a herd of about 150 cattle ranged on the north shore, but the herd is currently estimated to be between 2000 and 3000. Several Sawmills were constructed in 1922, but the most extensive logging occurred between 1930 and 1960. Logs were boomed during this time, but this activity was eventually stopped due to damage to fish habitat. In the early 1930s, the first catchment fire was recorded, but between 1920 and 1950 the south slopes were burned annually to enhance grazing. Burning continued after ca. 1950, albeit less frequently, until ~1975. Total clearance by logging and burning activity has resulted in about 40% of the lake's catchment being cleared. A small amount of crop production has occurred in the catchment since human settlement. In 1986, the catchment supported a population of 484 (162 dwellings, approximately 38 occupied lots on the shoreline), and is purported to have increased very little since then.

The Endako Mine, at the east end of the lake, is among the world's primary producers of molybdenum, and may be a potential source of contamination to surface water, ground water and sediments. Mining-related effluents are discharged to Francois Lake from three separate source creeks. The mine was in full production in 1965, but exploration and pit stripping occurred for several years before that time. In latter years, more stringent rules regarding effluent emissions have been implemented, and a BC Waste Management Act discharge permit for the mine has been in place since 1973. Mining, farming, ranching, logging and tourism continue to be the predominant land uses in the watershed. Although no cultural activities have been specifically linked to ecological damage, possible sources of water quality degradation are similar to those noted for the other lakes, with the addition of mining activities.

Tyhee Lake

Tyhee Lake (54°45' N, 127°15' W) is located near the city of Smithers, in the Morice Forest District. It is a relatively small (3.18 km^2), dimictic lake (Table 1). During the most strongly stratified periods, deep waters become anoxic (I. Sharpe, unpub. data). Total phosphorus measurements from May 1995 range from 25 to 56 μg/L, indicating that Tyhee is a mesotrophic to eutrophic system. The littoral zone covers up to 30% of the surface area, and during the icefree season it is densely colonized by aquatic plants (e.g. *Myriophyllum sibiricum*, *Potamogeton* spp., *Lemna* spp., *Spirodela polyrhiza*, *Wolffia columbiana* and *Ceratophyllum demersum*). Approximately half of Tyhee Lake's shoreline consists of emergent vegetation and riparian forest, and the rest comprises primarily residential lawns and beaches. Shoreline uses include boat launches, docks, a provincial park beach, a campground and a seaplane base. Land uses within the catchment include over 100 homes, dairy farming, horse ranching, hobby farming, forage production and logging. Historical information on logging is sparse, but it is estimated that about 30% to 50% of Tyhee Lake's catchment was cleared at some point during the last century. The lake is also subject to a wide variety of aquatic recreational activities. Long-term residents on Tyhee Lake have noticed an increase in frequency and density of algal blooms in recent decades, a change that is believed to be a result of excess nutrient inputs.

Materials and Methods

Six sediment cores were collected for this study (Fig. 1): one core from Takysie Lake, two cores (east and west) from Tchesinkut Lake, two cores from Francois Lake (east and west), and one core from the deepest part of Tyhee Lake. Cores of varying lengths (Takysie = 32 cm, Tchesinkut west = 39 cm, Tchesinkut east = 43 cm, Francois west = 40 cm, Francois east = 30 cm, Tyhee = 51 cm) were collected from deep basins of each lake using a Glew (1989) gravity corer equipped with a 6.35-cm inside diameter core tube. Each core was sectioned into 1-cm slices using a close-interval extruder (Glew 1988) and stored in Whirlpak® bags prior to subsampling. At PEARL, subsamples of sediment were taken for water, organic and mineral content analyses, ^{210}Pb-dating, and diatom preparation.

Dating and Geochemical Analyses

For ^{210}Pb dating analyses, sediment subsamples (approximately 30 g of wet material) of selected intervals were dated by Mycore Ltd. using the constant rate of supply (CRS) model and other methods described by Cornett et al. (1984), Appleby and Oldfield (1978) and Binford (1990). Procedures used were identical to those described by Reavie et al. (1995a). ^{210}Pb dating is limited to ~150 years before present, so extrapolations beyond this period were made based on calculated sediment accumulation rates. Binford's (1990) computer program was used to calculate the dates.

Sediment water, organic and mineral matter contents were determined by weight loss during 1 hour drying at 100 °C, 1 hour ignition at 550 °C, and residual weight after 1 hour ashing at 1000 °C, respectively (Dean 1974).

Sediment geochemical analyses for Francois Lake were performed according to methods documented in the Pacific Environmental Science Centre (1997) manual. Samples were dried at 60°C, sieved with a 150 μm mesh, finely ground and digested with nitric acid (HNO_3) and hydrochloric acid (HCl) in a microwave oven. Samples were cooled, settled and decanted. Analysis for each sample was then performed via inductively coupled argon plasma atomic emission spectrometry (ICP-AES) (simultaneous multi-element analysis), graphite furnace atomic absorption spectrometry (GF-AAS) (low level analysis) and cold vapour atomic fluorescence spectrometry (CV-AFS) (mercury analysis) (PESC 1997).

Slide Preparation and Microscopy

For each core, selected intervals were prepared for diatom analysis. Subsamples of wet sediment (0.3 - 1.0 g) were heated for one hour in a mixture of potassium dichromate and sulfuric acid to digest organic matter. Samples were then repeatedly washed in distilled water and allowed to settle until they were free of residual acid. The siliceous remains were settled onto coverslips, and the coverslips were mounted on glass slides using a permanent mounting medium (Naphrax®). For each slide, at least 300 diatom valves were identified and counted along transects under oil immersion at 1000X. Diatom taxonomy was based primarily on Krammer and Lange-Bertalot (1986-1991), Camburn et al. (1984-1986), Patrick and Reimer (1966) and Cumming et al. (1995).

In Tyhee Lake, chrysophyte cysts were sufficiently abundant so that the ratio of cysts to diatom valves could be calculated (Smol 1985).

Inferring Total Lakewater Phosphorus

The diatom transfer function used to reconstruct spring lakewater total phosphorus concentration (TP) was constructed by determining the relationship between water chemistry variables and diatom distributions in the surface sediments of BC calibration lakes (Reavie et al. 1995b). Quantitative TP inferences were performed using the computer program WACALIB version 3.3 (Line et al. 1994). The distribution of TP measurements for the calibration set (Reavie et al. 1995b) was skewed toward the oligotrophic extreme of the spectrum, so calculations were performed using transformed (ln(TP + 1)) data (see Birks 1995 for details). The root mean squared error of model reconstructions, calculated from transformed data, is 0.33, but for brevity we do not present errors for stratigraphic TP reconstructions, which have been back-transformed. The diatom-inferred spring total phosphorus concentration (DI-TP) values generated by WACALIB were subsequently back-transformed. Birks (1995) provides thorough reviews of these methods.

Fit to TP and analog tests

Fossil diatom assemblages that exhibit a close relationship to [TP], or that have close modern analogues with calibration lake-set data, are likely to provide reliable qualitative and quantitative TP inferences. The following fit and analogue methods are described by Birks et al. (1990), and have been applied to fossil data by, for example, Reavie et al. (1995a) and Hall and Smol (1993).

For determination of 'lack-of-fit' to TP, the residual distance of modern samples to the TP axis in a constrained canonical correspondence analysis (CCA; using the computer program

CANOCO version 3.12) of each calibration lake-set provides a measure to assess the 'fit' of fossil samples to TP. Samples with high residual distance from the TP axis exhibit 'poor fit' to TP. When run passively, fossil samples were also positioned about the TP axis by means of transition formulae. Fossil samples with a residual distance greater than the distance of the extreme 10% of the calibration set were considered to have 'poor fit' to TP.

Analogue matching was used to identify fossil diatom assemblages with poor analogy to modern assemblages in the calibration lake sets. Briefly, a dissimilarity index (χ^2) was used to compare every fossil sample with all calibration samples. Using Monte Carlo permutation tests, fossil samples with a minimum squared χ^2 greater than the extreme 5% of the squared χ^2 for the modern samples were considered to have no 'good' modern analogue. These calculations were performed using the computer program ANALOG version 1.6 (Line and Birks unpublished program).

Results and Discussion

Fit to TP and analogue tests

Three lines of evidence suggest that our diatom-inferred TP concentrations should be reliable for our four study lakes. First, the 167 diatom taxa included in the TP inference model (Reavie et al. 1995b) included 89% or more of the diatom sum in each of the fossil samples, indicating a good overlap between modern and fossil samples. Second, sediment diatom samples exhibited a 'good fit' to TP in a constrained CCA of the BC training set, except for the following samples: 31-32 cm, Takysie Lake core; 29-30 cm, Tchesinkut Lake west core. Third, all fossil diatom assemblages had 'good' modern analogues within the calibration lake set.

^{210}Pb chronology

Geochronological analyses indicated fairly consistent sequences of sediment accumulation. Cores from Tyhee, Tchesinkut and Francois lakes showed typical exponential profiles (Fig. 2), as would be expected if accumulation rates remained relatively constant (Binford 1990), hence we are confident that relatively undisturbed sedimentary profiles have been obtained. Replicate cores for Tchesinkut Lake have almost identical depth/time relationships (e.g. ca. 1900 occurs at approximately 12 cm depth in each core), suggesting that accumulation rates have been similar in the east and west cores. Cores for Francois Lake indicate that sediment accumulation may have been slightly higher in the west core.

The Takysie Lake core does not provide a typical ^{210}Pb profile. Above the 30 cm interval, the increase of ^{210}Pb is nearly linear, indicating that the rate of sediment accumulation has likely been increasing in Takysie Lake, resulting in greater dilution of ^{210}Pb near the surface of the core. ^{210}Pb counts were converted to calendar years, and it appears that each core represents more than 150 years of sediment accumulation.

Sediment characteristics

Water content in all six BC cores gradually decreased downcore, reflecting increasing compaction of the lower sediments (data not presented). Organic content, estimated by loss-on-ignition (LOI), and carbonate content, exhibited little or no fluctuation in the core profiles, so interpretations are not made.

Takysie Lake

Qualitative Assessment of Diatoms

A total of 141 diatom taxa was identified in the Takysie Lake core. Fifteen 'common' diatom taxa were identified (Fig. 3; 'common' species were presented in diatom profiles if they occurred at ≥3% in any interval). Sediment deposited before ca. 1900 was dominated by the eutrophic centric taxon *Stephanodiscus parvus*. Several other eutrophic taxa were also present at lower relative abundance (e.g. *S. hantzschii*, *S. minutulus*, *Asterionella formosa* and *Fragilaria crotonensis*, among others). Presuming that anthropogenic impacts on this lake were minor prior to ca. 1900, it is likely that Takysie Lake is somewhat naturally productive. Between ca. 1900 and ca. 1965, *Stephanodiscus* taxa decreased in relative abundance, and were partially replaced by several benthic (e.g. *Fragilaria pinnata*) and tychoplanktonic (e.g. *Tabellaria quadriseptata*) taxa. The beginning of these shifts is coincident with the onset of settlement in the area, and may reflect an expansion of littoral habitat, characterized by an increased abundance of macrophytes (Reavie and Smol 1997, Douglas and Smol 1995). Between ca. 1965 and ca. 1985, *Stephanodiscus* taxa again dominated in relative abundance, but these diatoms then declined, and by 1997 the eutrophic *F. crotonensis* was the largest portion of the assemblages. *Stephanodiscus parvus* and *F. crotonensis* are both considered eutrophic taxa, and multi-species calibration approaches (Reavie et al. 1995b, Wunsam and Schmidt 1995) rank these taxa with similar nutrient (i.e. total phosphorus concentration) optima. Hence, this recent change reflects continued high nutrient conditions, but eutrophication has probably not been severe. Chrysophyte stomatocysts were not sufficiently abundant in Takysie Lake sediments to warrant detailed consideration. The scarcity of chrysophytes, however, is consistent with productive conditions (Smol 1985).

Total Phosphorus Reconstruction

Diatom-inferred spring total phosphorus concentration (DI-TP), using the Reavie et al. (1995b) model, indicates that Takysie was likely a mesotrophic lake prior to the ca. 1950s, as DI-TP fluctuated between 17 and 18.2 µg/L during this time (Fig. 4A). The interval between ca. 1950 and ca. 1993, which was characterized by increased human development and logging in the catchment, is marked by a slightly higher DI-TP, with concentrations fluctuating between 22.8 and 25.1 µg/L. DI-TP for the surface interval suggests continued eutrophication, reaching 27.9 µg/L. This recent inferred eutrophication was influenced by the recent increase in *Fragilaria crotonensis*, which has a TP optimum within the eutrophic range (Reavie et al. 1995b).

In summary, increased anthropogenic nutrients appear to have resulted in some eutrophication. However, prior to human settlement, Takysie Lake was probably already a mesotrophic system. Human influences have had relatively little impact on this system.

Tchesinkut Lake

Qualitative assessment of diatoms

One hundred and forty nine diatom taxa were identified in sediments from Tchesinkut Lake. Despite some variation in species proportions between the west and east cores, the diatom flora profiles of the two cores are similar (Fig. 5). Hence, the west and east cores are discussed together in this section.

The diatom profiles from Tchesinkut Lake reveal rather monotonous histories of relatively stable diatom assemblages (Fig. 5). *Aulacoseira subarctica*, a heavy, mesotrophic (Reavie et al. 1995b) plankter, was the dominant contributor to the diatom assemblages in both cores. Secondarily, the eutrophic *Stephanodiscus minutulus* was also abundant. The basal portions of these cores represent at least 100 years of pre-settlement sedimentation, so it is very likely that Tchesinkut is a naturally productive system. Furthermore, peaks in the relative abundance of some species (e.g. *A. subarctica* in the 28-29 cm interval of the east core, and at 29-30 cm in the west core; *S. minutulus* at 35-36 cm in the west core), prior to extensive human development of the catchment, are of similar magnitude to peaks observed during the 1900s. Hence, most fluctuations in diatom relative abundance may not be attributed to nutrient inputs during the 20th century. Nonetheless, the following exception might represent recent anthropogenic changes in nutrient status. Since ca. 1980, the eutrophic diatom *Asterionella* *formosa* increased in both cores, corresponding to a period of moderate logging and land clearing. *Asterionella formosa* has been a common indicator of anthropogenic disturbances in several paleolimnological investigations (e.g. Engstrom et al. 1985, Brugam 1988, O'Sullivan 1992, Wolin et al. 1991). Chrysophyte stomatocysts were not sufficiently abundant in Tchesinkut Lake sediments to warrant consideration, further reflecting the productive nature of the lake.

Total phosphorus reconstruction

As observed in the diatom profiles, it appears that there have been no notable ecological changes within the time periods covered by the two profiles (Fig. 4B). Fluctuations in DI-TP cover a wide range of TP concentration (27.6-42.2 μg). However, drastic fluctuations in DI-TP occur prior to, and during the period of human development in Tchesinkut Lake's catchment. Inferred TP trends within the last ~15 years indicate a reduction of TP concentration, inferred primarily by the relatively low TP optimum for *Asterionella formosa* compared to the dominating *Aulacoseira* and *Stephanodiscus* species. This occurrence may suggest a slight improvement since the period of maximum land clearing disturbance, however the magnitude of the decrease is no greater than other fluctuations noticed in the DI-TP profile. In light of the entire microfossil history of this lake, it is suggested that further monitoring be undertaken to determine the water quality trajectory. However, as in Takysie Lake, human activities appear to have had relatively little impact on the lake's trophic status.

Francois Lake

Qualitative assessment of diatoms

We identified 159 diatom taxa in the sediment cores from Francois Lake. Little difference is observed between the diatom histories of the east and west cores from Francois Lake (Fig. 6), so they are discussed together in this section. Although stratigraphic resolution is limited due to a relatively low sedimentation rate (e.g. the 20th century is recorded in the uppermost 7 cm of the east core), broad changes in the diatom flora are obvious.

Francois Lake's pre-settlement diatom assemblage is similar to that of nearby Tchesinkut Lake. The dominant taxa prior to ca. 1900 were the mesotrophic *Aulacoseira subarctica*, the planktonic *Cyclotella bodanica* var. *lemanica*, and the benthic taxa *Fragilaria construens* and *F. brevistriata*. These early assemblages suggest a relatively productive system, probably in the mesotrophic range. During the 20th century, the relative abundances of more eutrophic taxa (*Stephanodiscus minutulus*, *C. stelligera* and *F. crotonensis*) have been increasing, displacing *A. subarctica*, suggesting further eutrophication. As observed in other lakes from this region, these shifts correspond to human settlement and deforestation in Francois Lake's catchment. However, although these taxa are indicative of more eutrophic conditions, detailed calibration studies that consider nutrient variables (e.g. Hall and Smol 1992, Christie and Smol 1993, Reavie et al. 1995b) have shown that *A. subarctica* has a consistently high TP optimum when compared to most *Stephanodiscus*, *Cyclotella* and *Fragilaria* species. It is believed that this recent change reflects a slight trophic shift during the 20th century, but more autecological diatom calibration work is required.

Total phosphorus reconstruction

Prior to ca. 1850, diatom-inferred total phosphorus concentrations in Francois Lake fluctuated between 27 and 40 μg/L (Fig. 4C). As in other lakes from this region (Reavie et al. 1995a), it is likely that Francois was a somewhat productive lake, well before human activity in the area. Changes in trophic status apparently began in the early 1900s when, surprisingly, DI-TP began to decrease. The surface intervals showed the lowest DI-TP levels (25.1 μg/L). This recent trend appears to contradict an interpretation based on qualitative analysis of the diatoms. However, because the inference model (Reavie et al. 1995b) is quite strong, and because it applies a multiple-species approach, it is possible that DI-TP is tracking 20th century changes not apparent through qualitative observations of the diatom profiles. In the early 20th century, sockeye salmon migrations to inland BC were devastated by rock slides, dam constructions, overfishing and poor environmental management practices. The reduction in salmon numbers would have reduced an important TP supply to Francois Lake. Also, the inferred TP decline during the last two decades coincides with personnel reductions from 600 to 200 people between 1982 and 1986 at the Endako mining facility, effectively reducing the nutrient loads in effluents to Francois Lake (Endako Environmental Database, unpub. data).

Geochemistry

Geochemical profiles (Fig. 7) for Francois Lake indicate that, prior to 1930, most of the elements maintained relatively steady concentrations. Following Engstrom and Wright (1984) and Engstrom and Hansen (1985), Al, Ca, Fe, K, Mn and Na are considered to be primarily derived from the erosion of silicate minerals within the catchments during this time. Profiles of P, S and

Si show pre-settlement fluctuations. In the east core, P fluctuated unpredictably between 1100 and 7440 μg/g (sediment dry weight), S had a distinct peak during the mid-1700s, and Si peaked in the early 1800s. In the west core, P showed the same erratic trends, and S showed peaks during the mid-1600s, late 1700s and early 1800s. Although we are unable to determine reasons for these pre-settlement events, early fluctuations probably resulted from catchment and/or climatological variations and/or diagenetic factors.

Catchment erosional processes may play a role in the determination of diatom assemblages in this lake. For example, the success of *Aulacoseira* species is often closely associated with erosional supplies of catchment-derived silica, as this genus has high demands for Si (e.g. Kilham et al. 1986). If the consistently high (>600 μg/g of sediment) concentration of sedimentary Si reflects high concentrations of Si in the water column, then high Si concentrations likely contributed to the competitive advantage of *A. subarctica*.

Beginning in the late ~1950s, several metals increased in concentration in the sediments. Because of the low temporal resolution of the top ~6 intervals of each core, pinpointing the peak time of metal inputs is difficult. Inputs of metals appeared at a more recent date in the west core. Because the west site is much farther from the mine than the east core, a delay in metals deposition from mine-related inputs may have occurred. This discrepancy may also be, in part, due to low temporal resolution of our cores, resulting from a low sedimentation rate. Concentrations of the various elements peaked at two distinct times: Ag, As, Ba, Be, Cd, Fe, Pb, Sb and Sn peaked early (late 1950s to 1960s), and invariably decreased in the next adjacent interval; Mn, Mo, Ni, Se and Si all exhibited a more recent peak. Resource exhaustion and enlargement of pits (B. Riordan, Endako Environmental coordinator) may have contributed to temporal changes in metals inputs during the period of mining at Endako. In other words, a shift in a bedrock type may have provided different elements in tailings waste and stockpiled rock, resulting in inputs of different elements in runoff. Some elements (Al, Cr, K, Mg, Na and Ti) exhibited notably lower concentrations during mining activities, possibly because they were diluted by other elements released during mining.

Concentrations of metals are generally higher in the east core, nearer to the Endako Mine. For instance, Fe peaked at 144,400 μg/g dry weight in the east core, but only reached 83,460 μg/g dry weight in the west core. However, between ca. 1940 and ca. 1980, sedimentation rates were lower at the east site (Fig. 2), so these concentrations are not surprising.

Interpretation of geochemical profiles of phosphorus is difficult because of the variety of potential sources of P (e.g. mining, agriculture, detergents, atmospheric deposition, autochthonous material, etc.), and because of diagenetic problems (Engstrom and Wright 1984). Furthermore, P retention in the sediments is strongly controlled by sorption onto iron oxides, which is variably controlled by Fe content and redox conditions. Nonetheless, the recent peak in elemental P is probably due to increased P-binding metals inputs from tailing wastes and stockpiled rock.

Although geochemical conditions have been severely altered in recent decades, metal concentrations since ca. 1980 have returned to pre-mining levels, indicating a reduction in overall loading sources to the lake. This improvement coincides with improvements in mill processing techniques and the implementation of the BC Waste Management Act, which would have reduced contamination in effluents. In particular, for initial treatment, mine effluents have been impounded in wetlands since the late 1970s. However, it is most likely that recent inputs of metals are simply lower since the initial construction of the mine, which dramatically changed the landscape. During first construction, the most intensive pit stripping occurred, metal-rich soils were piled and exposed to leaching, and dams for tailings ponds were constructed from low-grade molybdenum ore. Since this initial surplus of contaminated leachate, metal levels would have gradually declined.

Tyhee Lake

Qualitative Assessment of Diatoms

Sixty-four diatom taxa were identified in the Tyhee Lake core. Only four species (*Fragilaria pinnata*, *F. construens*, *F. brevistriata* and *Stephanodiscus minutulus*) occurred in relative abundances greater than 10%, so a large proportion of the taxa were relatively rare. The diatom profiles (Fig. 8) have well-defined assemblage shifts, so the profiles have been roughly divided into two zones (A and B). Zone A (51-9 cm) represents all intervals earlier than ca. 1950, and zone B (9-0 cm) represents approximately the most recent ~56 years.

Fragilaria construens, *F. pinnata* and *F. brevistriata* are the most common taxa in all intervals below ~1950 (Zone A, Fig. 8). Other *Fragilaria* taxa are also present, but no obvious shifts are noted. The eutrophic indicator *Stephanodiscus minutulus* first appears in significant relative numbers in the late 1700s or early 1800s, and fluctuated in relative abundance until ~1950. The percentage of benthic species fluctuated between 80% and 100% throughout Zone A. This assemblage suggests that Tyhee Lake is naturally eutrophic, primarily due to the early presence of *Stephanodiscus*. While *Fragilaria* taxa tend to be ubiquitously distributed (Patrick and Reimer 1966), they have often been found in slightly eutrophic BC environments (e.g.

Reavie et al. 1995b).

Since ~1950 (9-0 cm, Zone B), benthic taxa decreased substantially to be replaced in relative abundance by planktonic diatoms. The notable changes are a shift from an assemblage dominated by *Fragilaria* spp., to one dominated by *Stephanodiscus minutulus*. During this period, the planktonic taxa *Cyclotella bodanica* var. *lemanica* and *Fragilaria crotonensis* also increased. Total planktonic diatoms increased from 20% to 51% of the assemblage. These changes are an indication of significant additional eutrophication within the last four decades.

In summary, a qualitative assessment of diatom species changes indicates that Tyhee Lake is naturally productive (mesotrophic), but has eutrophied significantly in response to human impacts in the late 20th century.

The relative numbers of chrysophyte stomatocysts to diatom valves (Smol 1985) decreased from as high as 25% during pre-settlement times, to trace levels (less than 5%) during the last ~90 years (Fig. 8). Chrysophytes tend to thrive in low nutrient conditions, and tend to be uncommon in eutrophic waters of temperate lakes (Sandgren 1988). Smol (1985) used a similar method to interpret past trophic status of Ontario lakes, and noted that a decreased relative abundance of cysts was attributed to small chrysophyte populations during eutrophic periods in the lake's history. The same appears to be true for Tyhee Lake; a relative decrease in chrysophyte numbers due to increased nutrient loading this century.

Total Phosphorus Reconstruction

Of the 64 taxa encountered in the core, 38 were in common with the Reavie et al. (1995b) TP inference model. DI-TP indicates that Tyhee was likely a naturally eutrophic lake, fluctuating between 35 and 43 μg/L prior to European settlement (i.e. before 1850) (Fig. 4D). DI-TP continued to fluctuate until the 1960s, when levels increased to ~46 μg/L. Levels decreased slightly to ~43 μg/L in the 1980s, and increased again to ~49 μg/L in the most recent sediments. The general increase in DI-TP within the last 40 years is a convincing indication of eutrophication caused by nutrient loading, consistent with the qualitative assessment of the diatom species changes. Based on TP measurements from 1985 to 1995, recent lakewater TP concentrations in the surface waters of Tyhee Lake measured as high as ~53 μg/L in the spring (BC Environment, unpublished data), but averaged ~25 μg/L.

General Discussion

The trends in relative abundance of diatoms in BC lakes have provided several insights on the influence of cultural activities on water quality. This study is an extension to previous paleoecological studies of lake nutrient history in BC (Reavie 1997, Reavie et al. 1995a, b, Walker et al. 1993, Hall and Smol 1992).

Prior to European settlement, the four study lakes were relatively productive. Nutrient loading undoubtedly increased since settlement, but the lakes have varied in their responses. In brief, Takysie and Tchesinkut have been little affected, but Tyhee has clearly seen an increase in available nutrient concentrations following intensive human activities in the catchment. Recent land-use practices, such as treatment of agricultural runoff, may have improved water quality to some degree. However, it is more likely that the natural characteristics of these lakes allowed them to withstand long-term human impacts. For example, Tchesinkut is a large (2,079,292 dkm^3) lake system. Due to its volume, it may have been relatively little affected by nutrient inputs thus far. In contrast, Takysie and Tyhee lakes are smaller, shallower systems. Hence, it is not surprising that Tyhee, and Takysie to a smaller degree, showed stronger tendencies towards increased eutrophication. Furthermore, Tyhee Lake has the highest watershed area relative to the lake's size (Table 1), so it is again not surprising that cultural activities have affected Tyhee to a greater degree (Prairie and Kalff 1986). The ratio of human development in the catchment to lake size is similar for these lakes, so it is difficult to assess the relative effects of human development on water quality between lakes.

In the case of Francois Lake, cultural activities have likely caused a change in trophic status. However, as observed in other regions of BC, this lake was somewhat naturally productive before European settlement. Nutrient loading has undoubtedly increased since settlement of this area, but Francois Lake might be seeing a reduction in available nutrient concentrations following reductions in salmon populations. Existing rehabilitation measures, such as water treatment and effluent controls, may also have improved water quality to some degree. Again, due to its large size, Francois Lake may have been able to withstand long-term human impacts, in contrast to the smaller lakes nearby (Tyhee and Takysie lakes). Francois Lake also has unique environmental concerns caused by the presence of the molybdenum mine on the northeast shore. Geochemical analyses illustrated increased metal inputs, particularly during the 1960s, reflecting probable leaching from mining wastes.

Because the Takysie Lake core recorded approximately 200 years of sediment accumulation, it provided an excellent resolution for human-induced changes to the ecosystem. In contrast, the other lake cores incorporated 400 or more years of sediment accumulation, and this slower sediment accumulation rate resulted in a lower resolution for interpretation of recent cultural effects. However, these longer records provide us with an excellent opportunity to observe natural variability (i.e. prior to human impacts) in the fossil data for these systems. In Tchesinkut Lake, for example, some limnological event occurred in the early 1700s, resulting in a peak of eutrophic diatoms (primarily *Aulacoseira subarctica* at 28-29 cm in the west core, and 29-30 cm in the east core). Long-term records such as this illustrate that striking changes can occur from natural events, and that caution must be used when attributing human influence to short-term shifts in water quality. In the case of Tchesinkut Lake, shifts in the relative abundance of *A. subarctica* during the last century are of no greater magnitude than shifts observed between, say, 1600 and 1750.

The analysis of multiple cores has again been useful in documenting the reproducibility of paleolimnological investigations. All four lakes indicate that human influences from approximately the same time period (~1930-1997) are represented in all cores. Multiple cores for Tchesinkut Lake and Francois Lake are similar enough in each system that a single core would probably have been adequate to describe each lake's recent ecological history.

A Summary of Paleolimnological Investigations of Eutrophication in British Columbia

This investigation has provided evidence of natural as well as anthropogenically-induced shifts in nutrient concentrations in BC lakes. Such trends have been observed elsewhere in BC. Here, we present a summary of some of these works, as they relate to the reconstruction of trophic changes since European settlement of the region.

For methodological reasons, it is difficult to compare older (i.e. pre-1990) paleolimnological investigations from BC with recent studies. Nonetheless, earlier studies provided important floristic information on diatom species changes as a result of presumed cultural eutrophication. For example, almost three decades ago, Stockner (1972) described the paleolimnology of Skaha Lake, in the Okanagan Valley. Using what is now considered a crude diatom index (the Araphidineae/Centrales ratio), Stockner (1972) determined that planktonic diatom assemblages had responded to changing nutrient status. More recently, Murphy et al. (1990) inferred, using diatoms and other fossil material from a 13 m sediment core, that Chain

Lake (Northern BC) was eutrophic several thousand years ago, but due to variations in drought conditions, natural fluctuations in trophy occurred. Slight eutrophication occurred following the construction of a dam in 1957, but anthropogenic impacts were relatively minor compared to natural fluctuations.

To date, eleven lakes in BC have been considered in quantitative reconstructions of TP from downcore diatom profiles. For simplification, we provide a tabular summary of works that use similar reconstructive methods (Table 2). These 11 lakes can be roughly grouped into 4 geographical regions: 1) the Skeena region, including Tyhee, Takysie, Francois and Tchesinkut lakes; 2) the Okanagan/Kamloops region, including Williams, Dutch, Pinantan and Wood lakes; 3) the Prince George region, including Tabor and Norman lakes; and 4) the Fort St. John region, including Charlie Lake. Although 11 lakes may be considered a relatively small dataset, to date, no geographical patterns in cultural eutrophication are observed in BC. Rather, cases of both natural and anthropogenic eutrophication appear to be occurring throughout the province.

With the possible exception of Pinantan Lake (Reavie et al. 1995a), these lakes seem to be naturally productive. In seven cases (Williams, Wood, Charlie, Tabor, Dutch, Tyhee, Takysie), human impacts have almost certainly caused deterioration in water quality. These eutrophication events range from relatively minor (Tyhee; increase from 35-43 μg/L to 49 μg/L) to severe (Charlie; increase from 22 μg/L to 62 μg/L). In at least one case (Wood Lake), it appears as though water quality improvement has occurred in recent decades. Pinantan Lake has apparently maintained a consistent, low-nutrient condition since pre-settlement times. Francois and Tchesinkut lakes exhibited past fluctuations in nutrient concentrations, and a possible recent decrease in TP, but, as described previously, model inferences are currently problematic for these lakes.

Conclusion

The managers of lake rehabilitation programs need to carefully consider the diversity of lake histories in BC. While precise reconstruction of past nutrient conditions in North American lakes has not been fully refined, studies such as this illustrate that paleolimnology is a strong tool for defining the presence and extent of cultural impacts, and the potential for rehabilitation. To fully understand the extent and causes of eutrophication in BC, such studies should be extended to other regions of the province. Furthermore, continued lake calibration and autecological analysis of important indicator taxa will refine the current TP inference models. Nonetheless, these analyses have already served to define appropriate goals for mitigation programs. Paleoecological analyses have allowed scientists to determine the natural state of aquatic ecosystems, and to unveil records of subsequent environmental disturbance, when it has occurred.

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Table 1. Summary of morphometric data and recent chemical measurements for Takysie, Tchesinkut, Francois and Tyhee lakes, BC. Chemical measurements were taken from the surface (1 m) water at each coring site (February 1997). Additional total phosphorus data for Takysie Lake were obtained from previous measurements. Total phosphorus levels for Tyhee Lake are summarized from 19 measurements taken during spring turnover periods from 1985 to 1995. Other measurements for Tyhee Lake were taken during spring turnover 1994 and/or 1995. Missing data are indicated by '--'.

Attribute (units)	**Takysie**	**Tchesinkut**	**Francois**	**Tyhee**
Elevation (m)	771.8	760	714.8	549
Surface area (km^2)	5.14	33.83	258	3.18
Watershed area (km^2)	149.2	344.3	3,600	35
Volume (dkm^3)	32,893	2,079,292.3	23,087,948	35,278
Mean depth (m)	6.4	61.5	86.7	11.1
Maximum depth (m)	11.6	149	244	22.2
Perimeter (m)	14,630	47,100	--	9,754
Mean water retention time (years)	--	19	35	5
Total phosphorus (µg/L)	22-130	4-8	6-10	12-53
Total nitrogen (µg/L)	920-1,200	200	250-320	550-610
Conductivity (µS/cm)	150-168	135-136	84-93	364-369
pH	7.1-7.9	7.91-8.08	7.63-7.80	--
Total calcium (mg/L)	16-18	17	9.5-11.0	--
Total magnesium (mg/L)	5.7-6.0	4.4	2.5-2.9	--
colour	35-55	5	9-15	--

Table 2. Summary of paleoecological investigations of eutrophication in BC. Pre-settlement TP estimates were calculated as the average of DI-TP values before ~1850 A.D.

Lake name	Location	pre-settlement TP (range, where applicable)	Peak inferred TP (approx. date, A.D.)	Most recent TP (coring date, A.D.)	Reference
Williams	52°07'N 120°08'W	35-44	61 (1973)	39-45 (1991)	Hall et al. (1997)
Wood	50°10'N 119°38'W	35	58 (1986)	45 (1992)	Walker et al. (1993), Reavie et al. (1995)
Charlie	56°40'N 121°00'W	22	62 (1991)	62 (1991)	Reavie et al. (1995)
Norman	53°47'N 123°22'W	24	25 (1960)	17.3 (1991)	Reavie et al. (1995)
Tabor	53°55'N 122°33'W	35	55 (1980)	49 (1991)	Reavie et al. (1995)
Dutch	51°65'N 120°02'W	13	24.6 (1965)	16.5 (1993)	Reavie et al. (1995)
Pinantan	50°75'N 120°00'W	21	21.4 (1974)	21 (1993)	Reavie et al. (1995)
Tyhee	54°45' N 127°15' W	33-43	49 (1996)	49 (1996)	current paper
Tchesinkut	54°06'N 125°41'W	27.6	42.2 (1970)	35 (1997)	current paper
Takysie	53°52'N 125°49'W	17-18.5	25.1 (1997)	27.9 (1997)	current paper
Francois	53°58'N 126°23'W	27-40	40 (pre-1600)	25.1 (1997)	current paper

Figure captions

Fig. 1. Locations of the study lakes and core sites (indicated by asterisks).

Fig. 2. Plots of ^{210}Pb counts in the six sediment cores, illustrating exponential radioactive decay with depth.

Fig. 3. Profiles of the dominant siliceous microfossils for Takysie Lake. Diatom taxa were combined ecologically to generate the categories "total benthics" and "total planktonics".

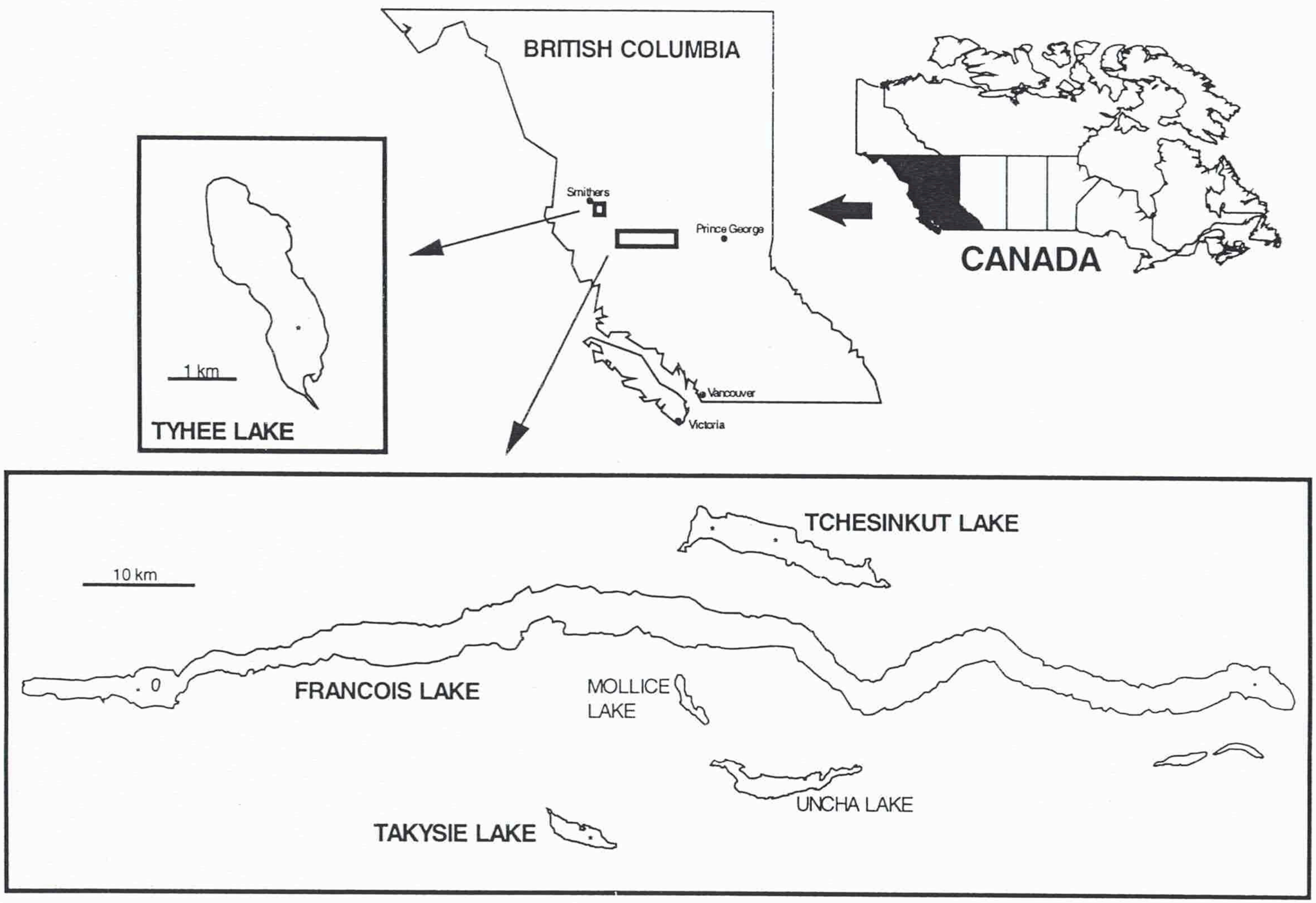
Fig. 4. Profiles of inferred total phosphorus concentrations for Takysie, Tchesinkut, Francois and Tyhee lakes. TP reconstructions were generated using Reavie et al. (1995b)'s model. For lakes with two cores, open circles represent west cores, and small squares represent east cores.

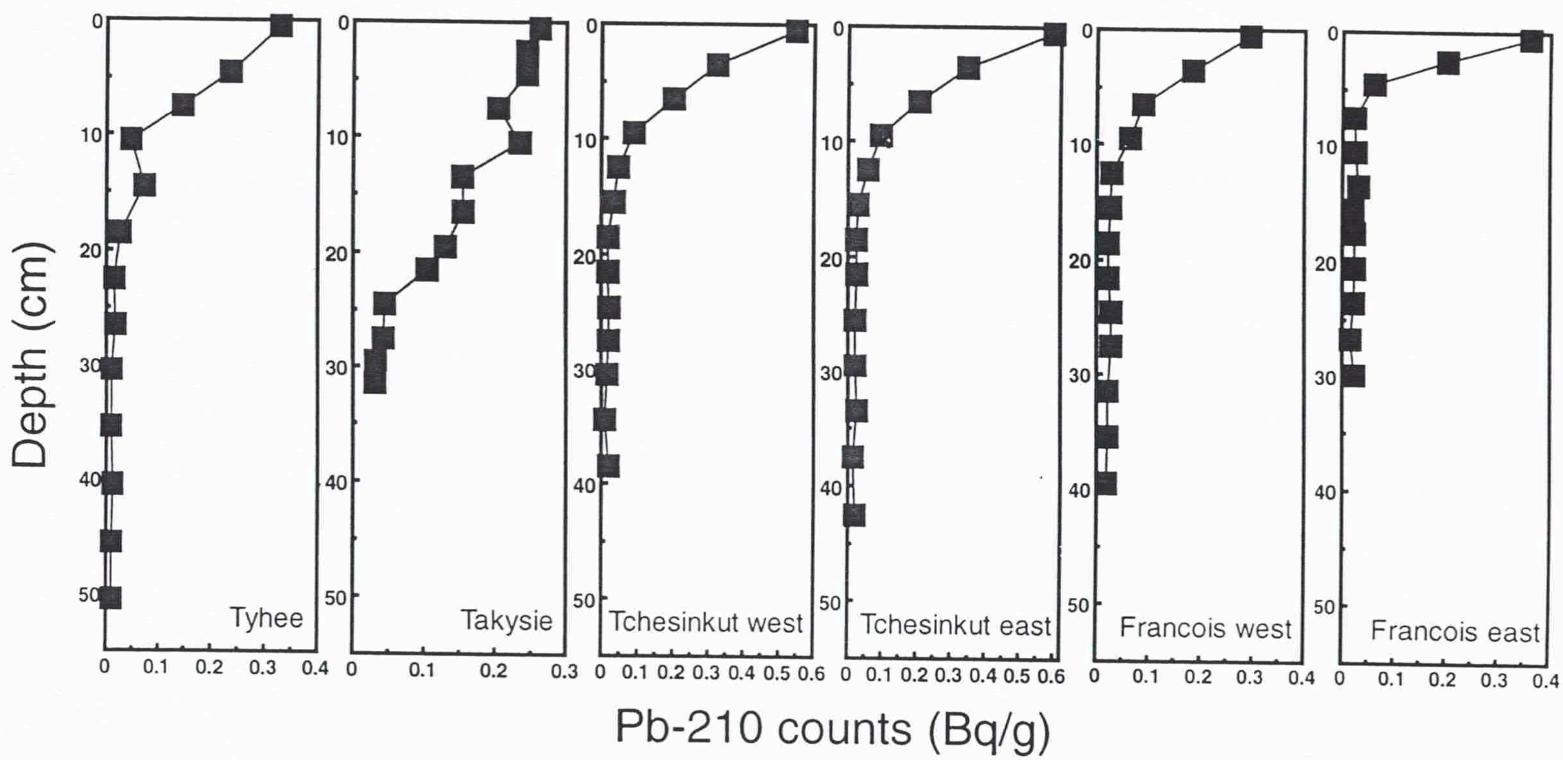
Fig. 5. Profiles of the dominant siliceous microfossils for Tchesinkut Lake west (top) and east (bottom) cores. Diatom taxa were combined ecologically to generate the categories "total benthics" and "total planktonics".

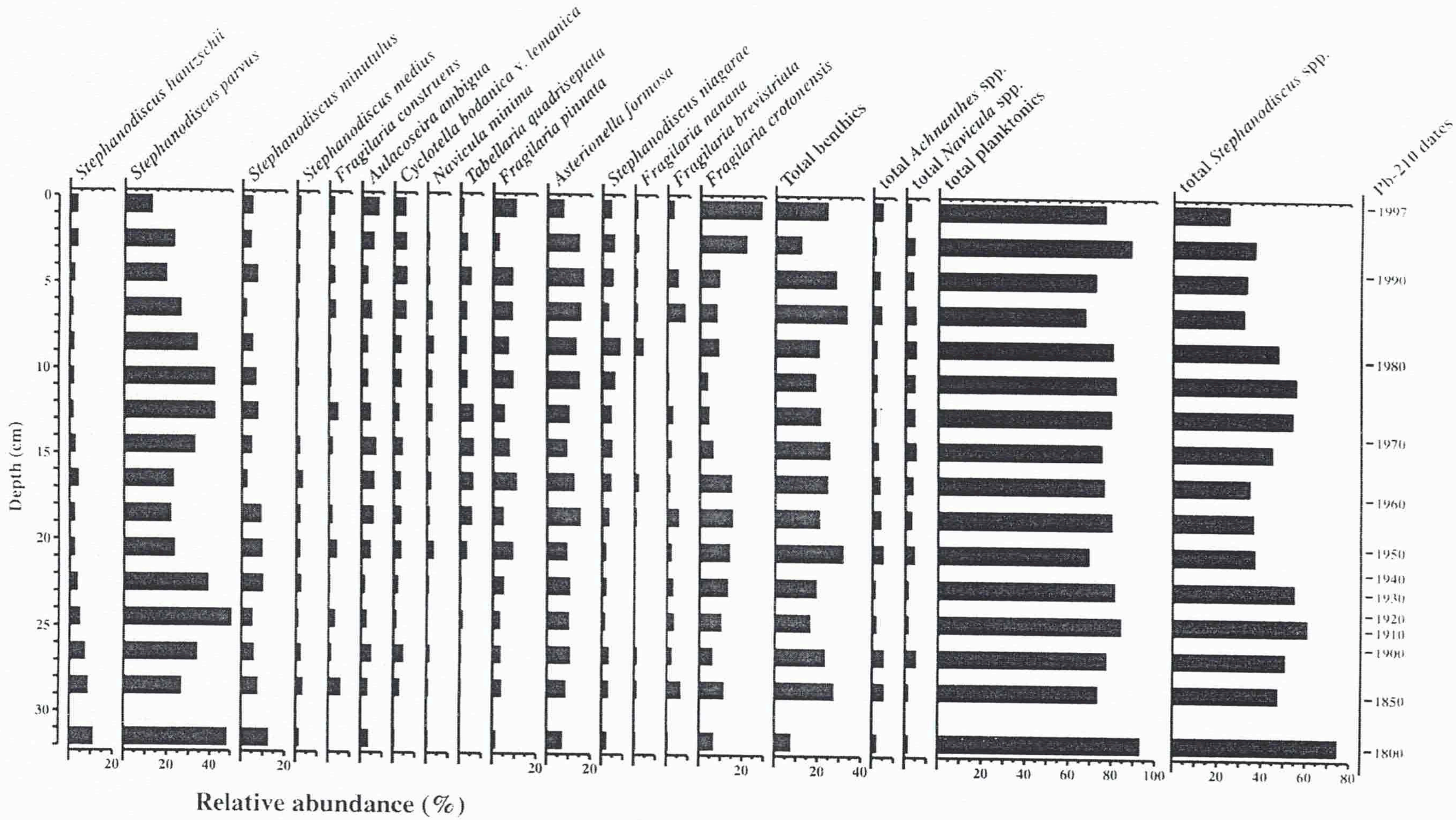
Fig. 6. Profiles of the dominant siliceous microfossils for Francois Lake west (top) and east (bottom) cores. Diatom taxa were combined ecologically to generate the categories "total benthics" and "total planktonics".

Fig. 7. Geochemical profiles for the Francois Lake west (top) and east (bottom) core. The number in parentheses following each element indicates the unit width of x-axis tics in mg per g of dry sediment.

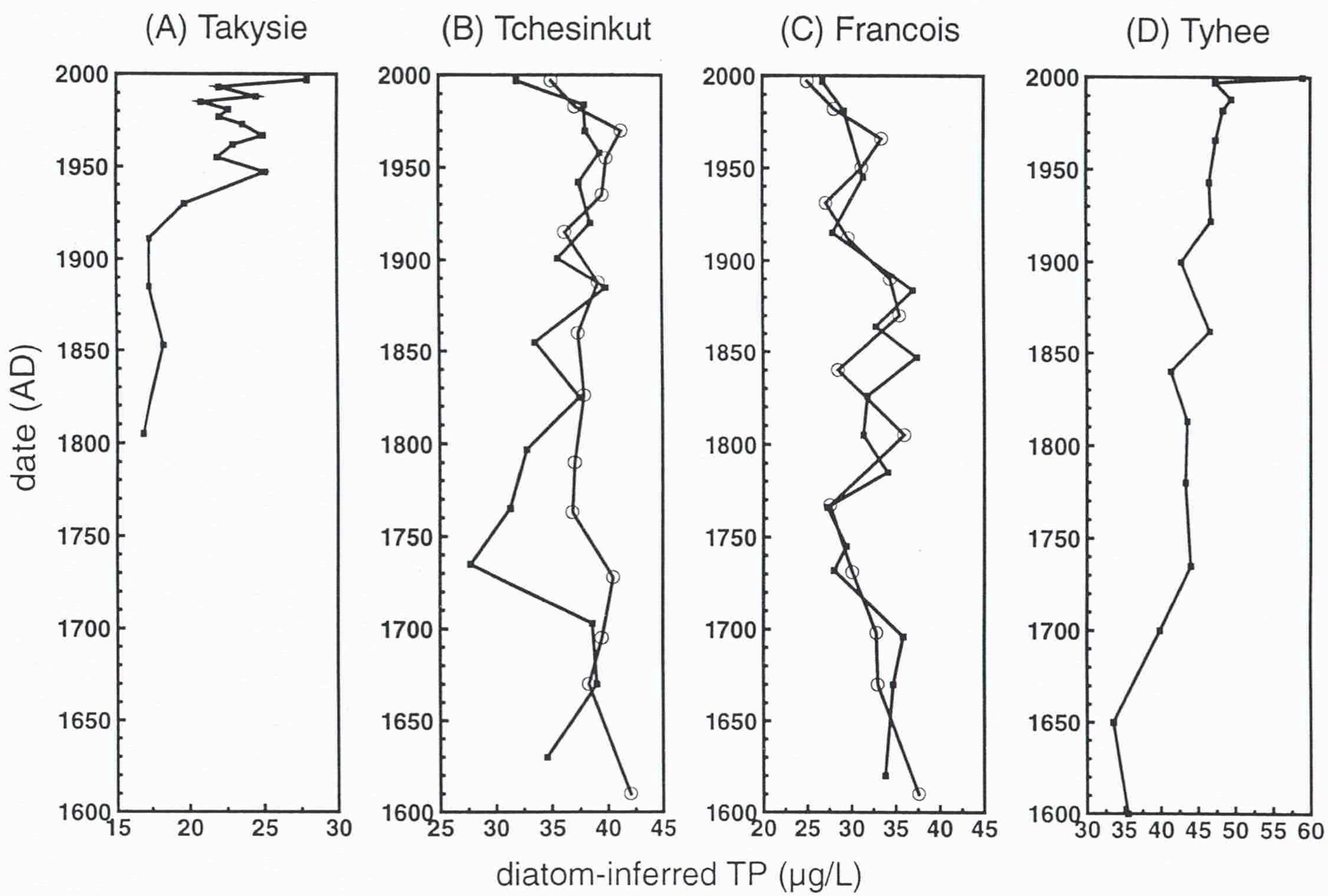
Fig. 8. Profiles of the dominant siliceous microfossils for Tyhee Lake. Diatom taxa were combined ecologically to generate the categories "total benthics" and "total planktonics". Diatom zones (A, B) are based on similarities in assemblages.


CANADA
BRITISH COLUMBIA
Smithers
Prince George
Vancouver
Victoria
1 km
TYHEE LAKE
10 km
TCHESINKUT LAKE
FRANCOIS LAKE
MOLLICE
LAKE
UNCHA LAKE
TAKYSIE LAKE


Depth (cm)
Tyhee
Takysie
Tchesinkut west
Tchesinkut east
Francois west
Francois east
Pb-210 counts (Bq/g)

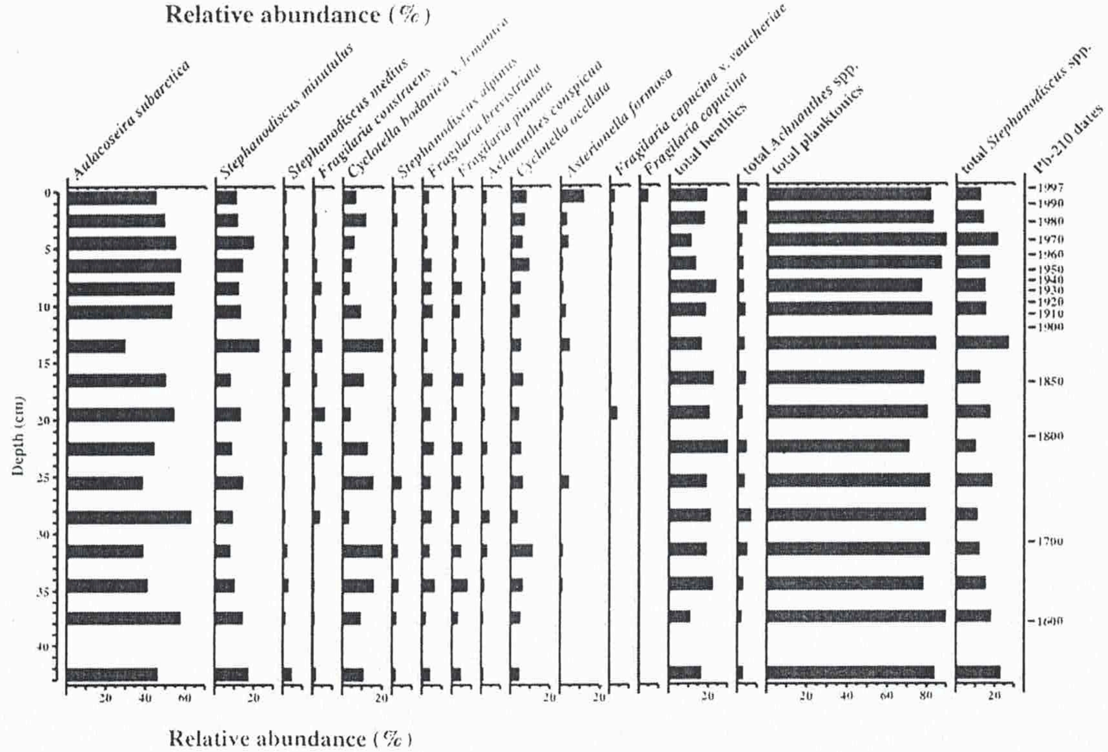


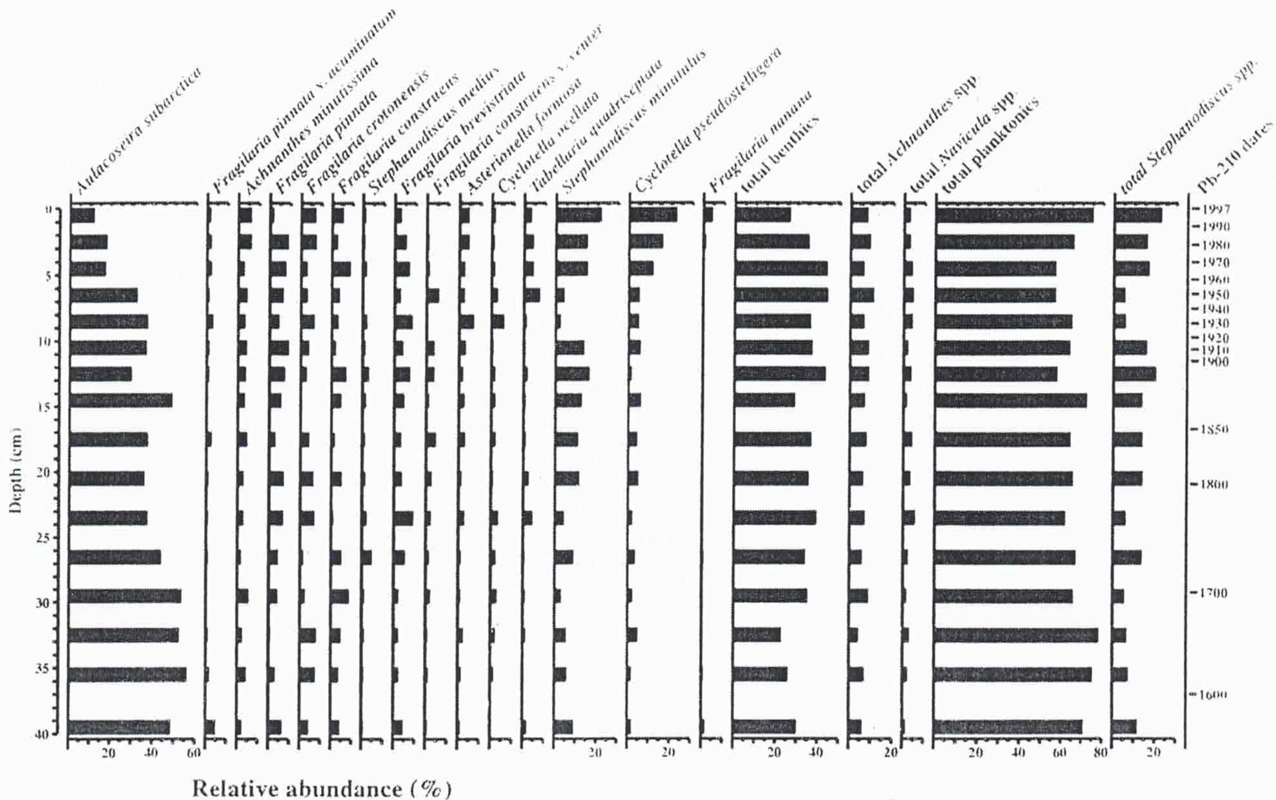
Stephanodiscus hantzschii
Stephanodiscus parvus
Stephanodiscus minutulus
Stephanodiscus medius
Fragilaria construens
Aulacoseira ambigua
Cyclotella bodanica v. lemanica
Navicula minima
Tabellaria quadriseptata
Fragilaria pinnata
Asterionella formosa
Stephanodiscus niagarae
Fragilaria nanana
Fragilaria brevistriata
Fragilaria crotonensis
Total benthics
total Achnanthes spp.
total Navicula spp.
total planktonics
total Stephanodiscus spp.
Pb-210 dates
Depth (cm)
Relative abundance (%)

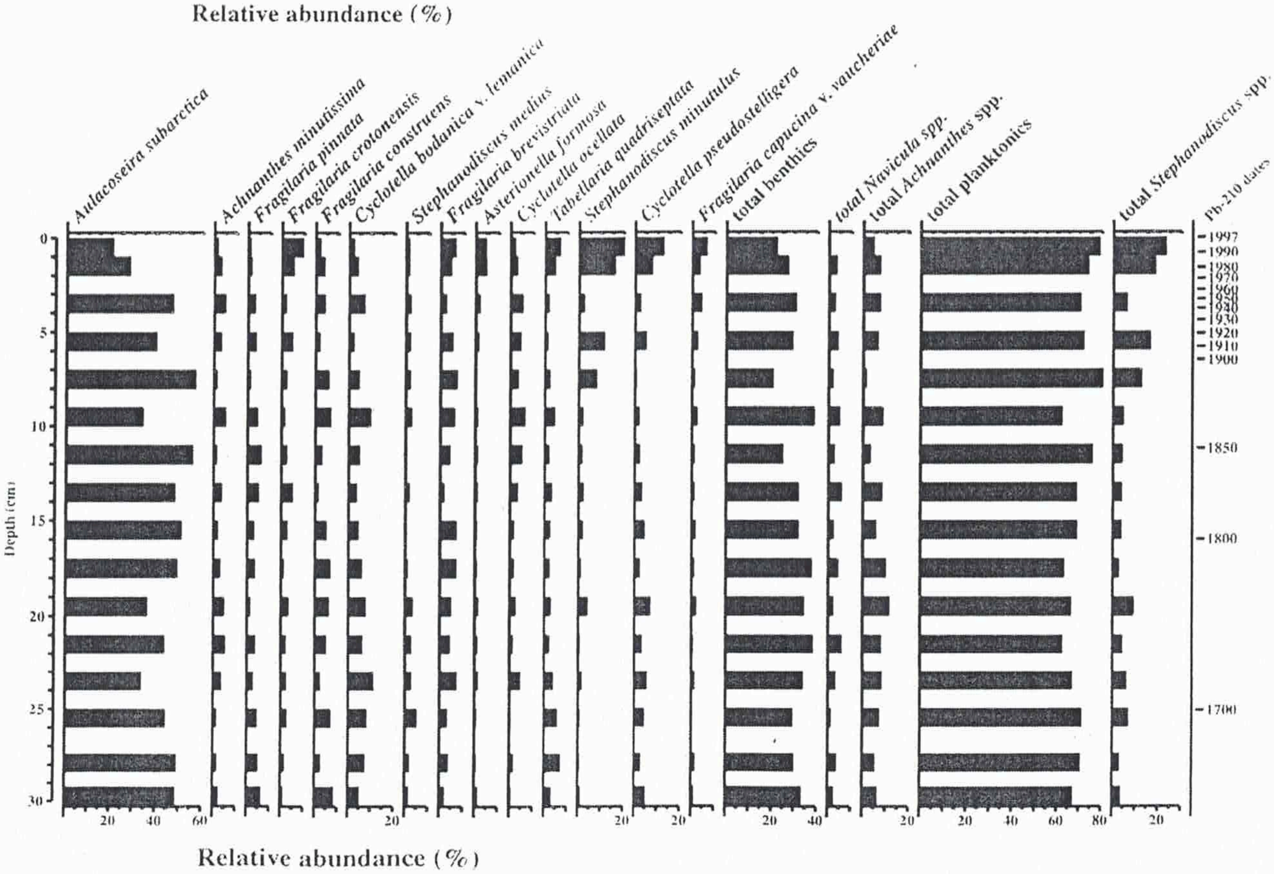


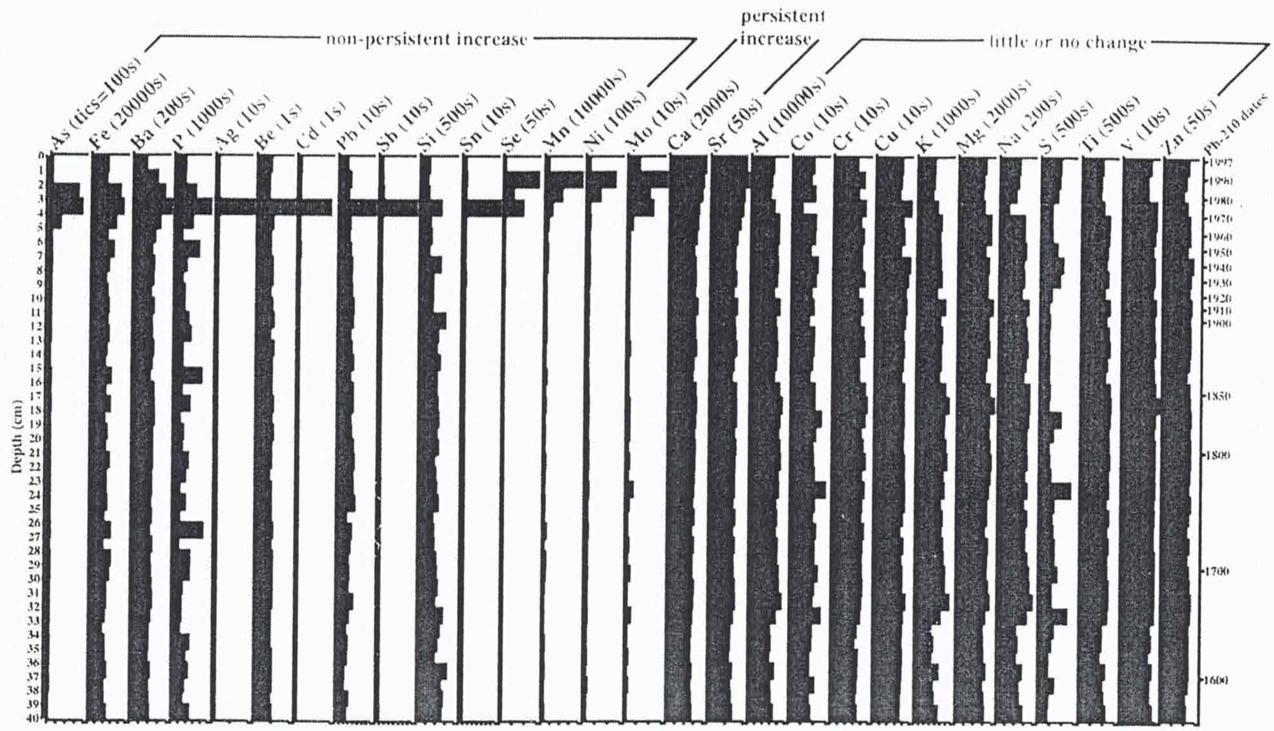
(A) Takysie
(B) Tchesinkut
(C) Francois
(D) Tyhee
date (AD)
2000
1950
1900
1850
1800
1750
1700
1650
1600
15 20 25 30
25 30 35 40 45
20 25 30 35 40 45
30 35 40 45 50 55 60
diatom-inferred TP (µg/L)

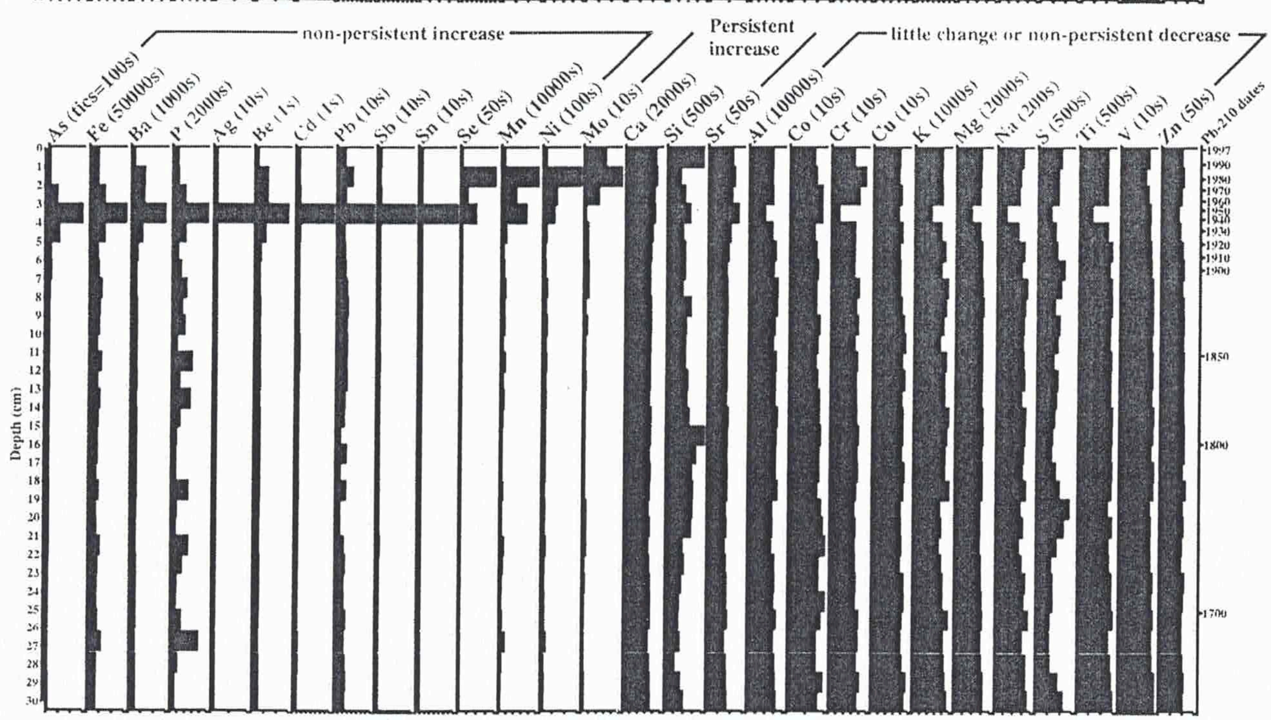

Aulacoseira subarctica
Stephanodiscus minutulus
Fragilaria construens
Cyclotella bodanica v. lemanica
Fragilaria brevistriata
Fragilaria pinnata
Amphora pediculus
Achnanthes conspicua
Cyclotella ocellata
Asterionella formosa
Fragilaria capucina v. vaucheriae
total benthics
total Achnanthes spp.
Total planktonics
total Stephanodiscus spp.
Pb-210 dates
Depth (cm)
Relative abundance (%)

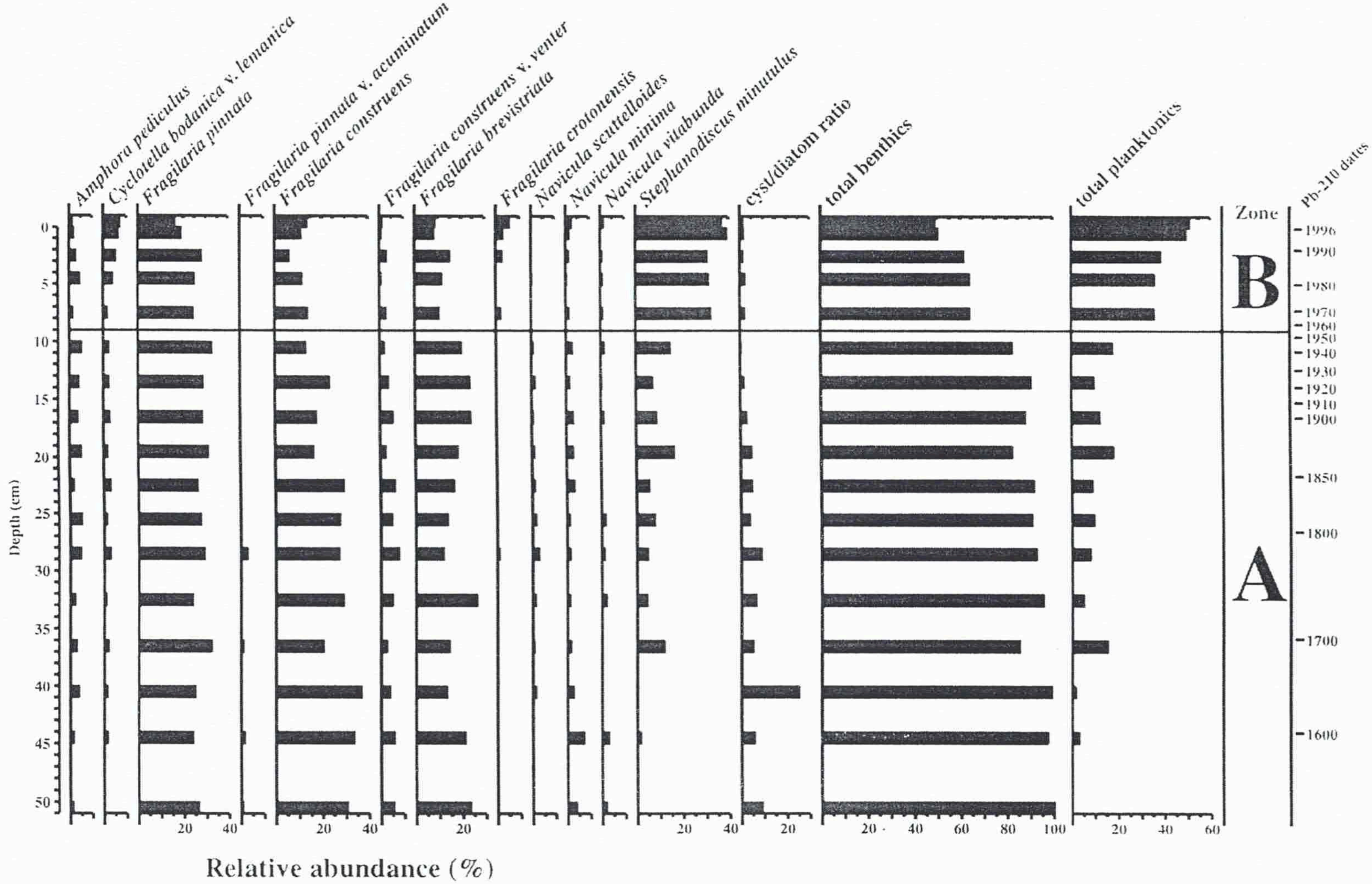

Aulacoseira subarctica
Stephanodiscus minutulus
Stephanodiscus medius
Fragilaria construens
Cyclotella bodanica v. lemanica
Stephanodiscus alpinus
Fragilaria brevistriata
Fragilaria pinnata
Achnanthes conspicua
Cyclotella ocellata
Asterionella formosa
Fragilaria capucina v. vaucheriae
Fragilaria capucina
total benthics
total Achnanthes spp.
total planktonics
total Stephanodiscus spp.
Pb-210 dates
Depth (cm)
Relative abundance (%)


Aulacoseira subarctica
Fragilaria pinnata v. acuminatum
Achnanthes minutissima
Fragilaria pinnata
Fragilaria crotonensis
Fragilaria construens
Stephanodiscus medius
Fragilaria brevistriata
Fragilaria construens v. venter
Asterionella formosa
Cyclotella ocellata
Tabellaria quadriseptata
Stephanodiscus minutulus
Cyclotella pseudostelligera
Fragilaria nanana
total benthics
total Achnanthes spp.
total Navicula spp.
total planktonics
total Stephanodiscus spp.
Pb-210 dates
Depth (cm)
Relative abundance (%)


Aulacoseira subarctica
Achnanthes minutissima
Fragilaria pinnata
Fragilaria crotonensis
Fragilaria construens
Cyclotella bodanica v. lemanica
Stephanodiscus medius
Fragilaria brevistriata
Asterionella formosa
Cyclotella ocellata
Tabellaria quadriseptata
Stephanodiscus minutulus
Cyclotella pseudostelligera
Fragilaria capucina v. vaucheriae
total benthics
total Navicula spp.
total Achnanthes spp.
total planktonics
total Stephanodiscus spp.
Pb-210 dates
Depth (cm)
Relative abundance (%)


non-persistent increase
persistent increase
little or no change
As (tics=100s)
Fe (20000s)
Ba (200s)
P (1000s)
Ag (10s)
Be (1s)
Cd (1s)
Pb (10s)
Sb (10s)
Si (500s)
Sn (10s)
Se (50s)
Mn (10000s)
Ni (100s)
Mo (10s)
Ca (2000s)
Sr (50s)
Al (10000s)
Co (10s)
Cr (10s)
Cu (10s)
K (1000s)
Mg (2000s)
Na (200s)
S (500s)
Ti (500s)
V (10s)
Zn (50s)
Pb-210 dates
Depth (cm)


non-persistent increase
Persistent increase
little change or non-persistent decrease
As (tics=100s)
Fe (50000s)
Ba (1000s)
P (2000s)
Ag (10s)
Be (1s)
Cd (1s)
Pb (10s)
Sb (10s)
Sn (10s)
Se (50s)
Mn (10000s)
Ni (100s)
Mo (10s)
Ca (2000s)
Si (500s)
Sr (50s)
Al (10000s)
Co (10s)
Cr (10s)
Cu (10s)
K (1000s)
Mg (2000s)
Na (200s)
S (500s)
Ti (500s)
V (10s)
Zn (50s)
Pb-210 dates
Depth (cm)



Amphora pediculus
Cyclotella bodanica v. lemanica
Fragilaria pinnata
Fragilaria pinnata v. acuminatum
Fragilaria construens
Fragilaria construens v. venter
Fragilaria brevistriata
Fragilaria crotonensis
Navicula scutelloides
Navicula minima
Navicula vitabunda
Stephanodiscus minutulus
cyst/diatom ratio
total benthics
total planktonics
Zone
Pb-210 dates
B
A
1996
1990
1980
1970
1960
1950
1940
1930
1920
1910
1900
1850
1800
1700
1600
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
20
40
60
80
100
Relative abundance (%)