Trophic history of Shelburne Pond, Shelburne, Vermont

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1. ABSTRACT

Eutrophication not only causes changes in productivity and water chemistry, but also impacts aesthetic and recreational values of a lake. It is usually the latter reasons that spur attempts to restore bodies of water to their original, pre-settlement conditions. However, some lakes are naturally eutrophic, and it may be impractical to attempt to change their trophic status. Typically, a lake is considered eutrophic when it hosts large blooms of algae, while mesotrophic and oligotrophic lakes support less aquatic plant life overall, and have less of their total biomass attributed to algae. Paleolimnological analyses may be used to determine whether anthropogenic forcing has caused a lake to become eutrophic, and therefore may be a candidate for remediation.

This study utilizes sediments from hypereutrophic Shelburne Pond, in Shelburne, Vermont. The pond supports a thick stand of macrophytes in spring, but by summer a thick scum of blue-green algae covers it. The pond's watershed was occupied by European settlers in 1725 A.D, was heavily grazed by sheep during the 1800s and early 1900s, and has been logged, farmed, and fertilized to the present. Since several anthropogenic activities may have contributed to the eutrophication of Shelburne Pond, it is a good candidate for determining if humans have caused the pond's productivity to increase.

In early 2006 we collected a 3.83 m long piston core and a 79 cm long freeze core from the deepest part of Shelburne Pond. Sediment chronology from ^{210}Pb and ^{14}C dating indicates that approximately 5500 years of the pond's history are recorded in the retrieved sediments. Core samples were analyzed for a large array of indicators of trophic state, including organic matter content, C stable isotopes, C/N, total and available phosphorus concentrations, biogenic silica, diatom composition, and paleopigments.

All paleo-productivity proxies indicate that Shelburne Pond was oligo-mesotrophic before European settlement, and has become increasingly productive since the mid 19th century (~1850). Eutrophication rates intensified after ~1900, and reached peak levels during the past two decades (post-1990). Comparison of the sedimentary record with historical data suggests a causal relationship between deteriorating water quality in the pond and human activities in its watershed. Forest clearing since 1810, a switch to mechanized agriculture around ~1850, and intensive dairy farming during most of the 20th century, all resulted in progressive nutrient enrichment.

Despite these significant recent trends, data extending past the post-settlement record suggest that, although generally lower, Shelburne Pond's productivity levels were at times quite significant during the past few thousand years. The causes of these, apparently natural, fluctuations remain to be investigated.

2. INTRODUCTION

2.1 Statement of the problem

Shelburne Pond, in Shelburne, VT, has been identified by the VT Department of Environmental Conservation (VT DEC) as a nutrient-impaired lake, and therefore a possible candidate for remediation measures. Spring and summer mean phosphorous concentrations, chlorophyll *a* concentration, and Secchi transparency, all classify the lake as hypereutrophic by Vermont DEC guidelines (Table 1). The pond supports a thick stand of macrophytes (primarily *Potamogeton crispus* L.) in spring (DeYoe, 1981; our observations) but by summer a thick scum of blue-green algae covers it. Episodes of oxygen depletion and fish kills are often reported, especially during the past two decades (Borre, 1986; State of VT Agency of Natural Resources, unpublished reports; our observations). These events are likely due to water column oxygen deficiency caused by the aerobic decomposition of the abundant algal and macrophyte biomass during the warm summer months, August in particular.

Archeological evidence suggests that humans have occupied and utilized the Shelburne Pond area for at least 8000 years (Petersen et al., 1985). European settlement of the pond's watershed dates back to 1725 A.D. Recorded history of the settlement indicates that at that time Shelburne Pond was still pristine (Droege, 1981). Since colonial times, land-use of the watershed has seen drastic changes. The forest was cleared starting in 1810, and agriculture soon became the mainstay for many settlers. Dairy farming and sheep pasture were also common land-uses. A shift from agricultural to low-density residential use has occurred during the past few decades.

Table 1: Limnological attributes of Shelburne Pond, including mean long-term concentrations of spring and summer P, Chlorophyll *a*, and Secchi transparency (From VT DEC Water Quality Division web site).

Lake Area (Ha)	Basin Area (Ha)	Max. depth (m)	Mean depth (m)	Volume (m^3)
182.9	1991.9	7.6	3.3	6,132,872
Spring P ug/L (21 y)	**Summer P ug/L (6 y)**	**Secchi disk m (6y)**	**Chlorophyll *a* ug/L (6 y)**	**Trophic state**
93 ± 15	155 ± 43	0.8 ± 0.4	90 ± 27	Hypereutrophic

2.2 Proxy selection

We have used a multidisciplinary, multiproxy approach for the reconstruction of Shelburne Pond's trophic history. The rationale for proxy selection is briefly outlined below.

Sediment organic matter content (%C, %N) and C/N ratios

Organic carbon content is the basic parameter used to determine the abundance of organic matter (OM) in sediments (Meyers and Teranes, 2001). The concentration of organic carbon is dependent on three factors: production, dilution and preservation. Increased autochthonous primary production generally results in enhanced accumulation of OM in the sediment, which is reflected by higher %C and %N values. Analysis of element ratios provides supplementary information on nutrient sources and levels of productivity. For instance, the C/N ratio of bulk organic material reflects the relative contributions of algal and land-derived organic debris to sediments, as algae have an average C/N ratio of 6:1 and terrestrial plants ratios in excess of 20:1 (Meyers and Lallier-Verges, 1999).

Stable Carbon Isotopes

Because carbon isotope chemistry varies with the intensity of primary production (Hollander and McKenzie, 1991; O'Leary et al., 1992), its assessment provides valuable information on trophic condition at the time of sediment deposition. For example, in cores from the Great Lakes and shallow Florida lakes, the sedimentary stable isotope record was used to document gradual then more accelerated eutrophication with progressive land clearing followed by urban growth (Schelske and Hodell 1991, 1995; Hodell and Schelske, 1998; Brenner et al., 1999).

Nutrients (P and Si)

There is no consensus on the interpretation of sedimentary phosphorus (P) profiles. The sedimentation of P is assumed to be a first-order process (directly proportional to water column concentration) and that assumption has been integral to the development of phosphorus budget models (e. g., Vollenweider, 1969; Snodgrass and O'Melia, 1975; Dillon and Rigler, 1975). Further, the magnitude of the proportionality constant is empirically related to areal water load (Kirchner and Dillon, 1975; Ostrofsky, 1978), so the accumulation or concentration of P in the sediments of any lake should reflect water column phosphorus concentration. However, Carignan and Flett (1981) demonstrated the potential for marked post-depositional mobility in incubated sediment cores, and Nürnberg et al. (1986) showed that many lakes release considerable amounts of previously sedimented P to the overlying hypolimnetic water during periods of anoxia. Both studies suggest that any relationship between water column P and sediment P is tenuous at best. Paleolimnologists have, therefore, been cautious about inferring historical trophic changes in lakes from sedimentary P profiles unless other proxies, such as those used in this study, corroborate these inferences.

The biogenic silica (BSi) content of sediments has been used to infer past primary productivity in marine and lacustrine systems (e.g., Johnson et al., 2002). Biogenic silica is derived from the fossil remains of diatoms, sponge spicules, and plant phytoliths; however, diatoms make up the overwhelming source of BSi in most aquatic systems. Hence, the concentration of BSi in the sediments is a measure of diatom productivity. Changes in BSi concentrations are assumed to be related to phosphorus availability (Schelske et al., 1983). In lakes where phytoplankton growth is P limited, an increase in BSi is taken as evidence for P enrichment that led to greater diatom productivity. Further P enrichment often induces silica limitation and the replacement of diatoms by other taxa in the phytoplankton community. When this replacement occurs, BSi in the sediment decreases. Consequently in lakes with a history of increasing P enrichment, BSi in the sediments initially increases, then decreases (Schelske et al., 1983).

Paleopigments

Because different algal groups photosynthesize with unique pigment combinations, the relative abundance of group-specific pigments and their degradation products in sediments provides information about algal community structure at the time of deposition (see review by Leavitt and Hodgson, 2001). Measurement of pigments common to all algae, on the other hand, yields information about total algal biomass. Paleopigments are not ideal indicators at all sites; they are best preserved in dark, cold, anoxic environments. Paleopigments have been widely analyzed in shallow eutrophic lakes however, apparently being preserved by high sediment accumulation rates and severe anoxia (McGowan et al., 2005).

Diatoms

While paleopigments reveal trends in algal dynamics at the division level, microfossils are examined to determine algal dominants. Diatom assemblages are excellent indicators of environmental parameters, including nutrient concentration and algal productivity levels (Stoermer and Smol, 1999). For instance, abundances and distributions of diatom species are often used to infer past water column P concentrations (see review by Battarbee et al., 2001).

3. STUDY DESCRIPTION

3.1 Study objectives

The overall objective of this study is to reconstruct the trophic history of Shelburne Pond through the analysis of its sedimentary record**.** More specifically, the questions we aim to answer are:

1) *What were the pre-European settlement conditions of Shelburne Pond?*
2) *How has the pond responded to documented changes in land-use since settlement?*

To achieve the stated goals, paleolimnological analyses were used to determine whether anthropogenic forcing has caused the lake to become eutrophic, and therefore may be a candidate for remediation. Ultimately, the scope of this study is to aid in the development of a nutrient control plan for Shelburne Pond.

3.2 Study Site and summary of previous work on Shelburne Pond

Shelburne Pond, 10 mi southeast of Burlington, VT, U.S.A. (44°23’N, 73°9.5’W), is the only large undeveloped natural pond remaining in western Vermont (Fig. 1). As part of the H. Laurence Achilles Natural Area, the pond and its surrounding extensive marshes and bogs have been researched and used for teaching purposes for nearly three decades.

The Shelburne Pond watershed is underlain by four dolomite-rich bedrock Formations – the Cutting Dolomite, Clarendon Springs Dolomite, Bascon, and Shelburne Formation (Doll, 1961). Dolomite is a carbonate rock ($CaMg(CO_3)_2$), and thus weathers fairly easily through the process of dissolution. Although the P content of the dolomite bedrock in the Shelburne Pond area remains to be determined, limestone and dolomite deposits often contain P-rich minerals, which may provide a source of bio-available P.

Whereas studies dealing with the paleolimnological record of Shelburne Pond are very scarce (Carr et al., 1977; Borre, 1986), substantially more is known about modern ecosystem variables, such as seasonal algal population dynamics and nutrient cycling (DeYoe, 1980, 1981; Droege et al., 1981; Ferber, 2001; Ferber et al., 2004; Hanson et al., 1998; Lescaze, 1999). Investigations by DeYoe (1981), Lescaze (1999), and Ferber et al. (2004) have revealed seasonal shifts of dominance from diatoms and chlorophytes during winter and spring, to blue-green algae (cyanobacteria) in the summer. This shift in algal succession appears to occur at a more rapid rate than what is observed in most temperate dimictic lakes (DeYoe, 1981). The shallow depth and well-mixed nature of the pond, coupled with relatively high water temperatures and, possibly, nitrogen limitation (Ferber et al., 2004; Lescaze, 1999), might all favor rapid dominance of cyanobacteria communities.

Data aimed at characterizing the isotopic and elemental composition of primary producers within Shelburne Pond and other Vermont lakes were collected since the late ‘90s (Levine et al., 1998; Lini et al., 1998; Lini and Levine, unpublished data). High productivity levels in Shelburne Pond are evidenced by large seasonal fluctuations in the isotopic and elemental composition of algae (Fig. 2).

3.3 Field and laboratory techniques

3.3.1 Coring methods

In early 2006 we collected a 3.83 m long piston core and a 79 cm long freeze core from the deepest part of Shelburne Pond (Fig. 1). The long core was retrieved from the ice using a modified Reasoner piston-coring device. We have used the same device successfully in a number of recent studies (Bierman et al., 1997; Brown et al., 2000, 2002; Noren et al., 2002; Parris et al., in press). The long core was sectioned in 1.5 m increments in the field to facilitate transport back to the UVM Limnogeology Laboratory, where the sections were stored in a HotPack walk-in refrigerated chamber awaiting further processing. Each of the core sections was split in half lengthwise and separated using a specially designed stainless steel core cutter. One half was immediately wrapped and sealed in plastic, then placed in cold storage for archive. The other half was photographed and visually logged. Each section was sampled at 1 cm resolution, with each sample placed in a plastic vial, frozen, and finally freeze dried.

In order to retrieve an undisturbed sediment-water interface we used a freeze-finger corer provided by the Geology Dept., Univ. of Massachusetts. We decided against the use of a Glew gravity corer because of the extremely unconsolidated nature of the substrate. The frozen sediment slab was wrapped in foil and transported back to the laboratory on dry ice and subsequently sectioned using a knife. The remainder of the procedure is the same as outlined for the gravity core.

3.3.2 Dating techniques

Lead-210 Dating:

Sediment chronology of the freeze core is based on alpha spectrometric analysis of ^{210}Pb activities and constant rate of supply calculations. Dating was performed at the St. Croix Watershed Research Station, Science Museum of MN, under the direction of Dr. Dan Engstrom.

Radiocarbon Dating:

Three macrofossil samples were isolated from the piston core (cm levels 71, 176, and 378) for ^{14}C age determination. The samples were converted to graphite targets at the University of Pittsburgh Geology Department, and analyzed by accelerator mass spectrometry at the NSF-Arizona AMS Facility, University of Arizona. The CALIB program v. 5.0.1 (Stuiver and Reimer, 1993) and the calibration dataset of Reimer et al. (2004) were used to convert 14-C dates to calendar years.

3.3.3 Elemental analyses: %C, %N, C/N ratios

Elemental analyses were performed on acidified samples (0.1 N HCl) using a CE Instruments NC 2500 elemental analyzer calibrated with certified standards (OAS B2150 and B2152, Elemental Microanalysis Ltd). The carbon to nitrogen ratio (C/N) values were be calculated from the %C and %N data.

3.3.4 Nutrient analyses: Total and bioavailable P, biogenic Si

Total Phosphorus:

In view of the high concentrations of organic material in Shelburne Pond sediments, total phosphorus was measured on combusted samples using the technique outlined by Andersen (1976). Dry sediments (~40-60 mg) were combusted in a muffle furnace at 550°C for 1 hour. The residue was diluted to 100 mL in 1N HCl, and aliquots analyzed for total P colorimetrically using the heteropoly blue method outlined in Strickland and Parsons (1968). Accumulation rates were estimated as the product of concentration and sediment accumulation rates.

Biologically Available Phosphorus:

Biologically Available P was extracted from dried sediment (~40 mg) by shaking for 24 hr with 10 mL 0.1N NaOH + 0.1 N NaCl (Cowan and Lee, 1976). Diluted extracts were read colorimetrically using the Strickland and Parsons (1968) technique.

Biogenic Silica:

Biogenic silica was measured using the method outlined by DeMaster (1981). Dry sediment samples (~40 mg) were extracted for 2, 3, 4, and 5 hours in hot (85°C) 1% sodium carbonate. Silica was measured on these extracts colorimetrically using the procedure outlined by Strickland and Parsons (1968). Silica concentrations were graphed as a function of extraction time and the extrapolated Y-intercept was taken as a measure of biogenic silica. Accumulation rates for biogenic silica were estimated as the product of BSi concentration and sediment accumulation rates determined by 210-Pb analysis.

3.3.5 Carbon stable isotopes

Stable carbon isotopic analyses were performed with a CE Instruments NC 2500 elemental analyzer coupled to a VG SIRA II stable isotope ratio mass spectrometer. The results are reported using the delta (δ) notation in units of per mil relative to the inorganic standard V-PDB. Analytical precision is ±0.05‰ (based on replicate standards). Sampling resolution was the same as used for elemental analyses.

3.3.6 Fossil pigments

Sedimentary pigments were extracted, filtered and dried under N_2 gas following the procedures of Leavitt et al. (1989). Lipid-soluble (polar) pigments were extracted from the bulk sediments by soaking powdered sediments in a mixture of degassed acetone:methanol:water (80:15:5, by volume) for 24 h in the dark and under an inert N_2 atmosphere at 0° C. Pigment concentrations of the filtered and dried extracts were then determined in each sediment interval using a Hewlett Packard 1050 high performance liquid chromatography (HPLC) system calibrated with authentic standards from the U.S. Environmental Protection Agency, using procedures detailed in Leavitt and Hodgson (2001). Pigment concentrations are expressed as nmoles pigment g^{-1} organic matter (the latter obtained from elemental analysis), an index that is linearly related to algal biomass in the water column (Leavitt and Findlay, 1994).

3.3.7 Diatom analysis and diatom-inferred lake water P reconstruction

Diatom assemblages were analyzed only in the freeze core. Sediments for diatom analysis were digested with H_2O_2 (30%) and CH_3COOH (95%) peroxide to remove organic material, and a standard solution of microspheres (Battarbee and Kneen, 1982) added to allow quantitative estimates of frustules concentration. The cleaned frustules were mounted on slides with Permount. A minimum of 400 valves were identified and tallied for each sample to determine the composition of the diatom community. Diatom composition was determined every 4 cm from the top to the bottom of the core for a total of 21samples. Historical water column total P was calculated using weighted averaging calibration and the data set for the northeastern United States developed by Dixit et al. (1999). Only four taxa (see result section), representing between 85 and 91% of the diatoms counted in each sample, were used with the Dixit et al. (1999) training set. Inclusion of additional taxa in the reconstruction did not significantly change the inferred P values.

4. RESULTS AND DISCUSSION

4.1 Core lithologies and chronologies

Both the freeze core and the longer piston core were composed of homogeneous, dark brown organic gyttja. No distinct changes in color and/or grain size where observed beside the occasional occurrence of plant macrofossil debris. The freeze core, 79 cm in length, displayed a well-preserved water-sediment interface and encompassed the past two centuries of sedimentation (Figs. 3).

Total ^{210}Pb activity declines from surface values around 10.3 pCi/g to a near constant background (supported ^{210}Pb) of 0.5 pCi/g below 72 cm. The down-core decrease is monotonic, though clearly non- exponential (non-linear on a semi-log plot; Fig. 3). The break between sediments containing unsupported ^{210}Pb (72 cm and above) from older sediments with only supported (background) ^{210}Pb is sharp; supported values are well defined by the two bottom-most intervals with similar low activities. Dates calculated according to the constant rate of supply (c.r.s.) model have an uncertainty (based on counting precision -- a minimum error) of less than ± 5 years for the last century. Precision degrades markedly for the two oldest dates (pre-1840). The inventory of unsupported ^{210}Pb in the core (34.9 pCi cm^{-2}) is equivalent to a ^{210}Pb flux of 1.12 pCi cm^{-2} yr^{-1}. This value is about twice that of the mean atmospheric flux of ^{210}Pb for the region (ca. 0.5 pCi cm^{-2} yr^{-1}), indicating that the core-site might over-represents by about 2x sedimentation rates to the lake as a whole.

Sediment accumulation rates are relatively uniform in the early part of the record (pre-1900), but then increase steadily during the 20th century. Maximum accumulation rates occur during the most recent decade and are almost an order of magnitude greater than those of the 19th century. The large increase in sediment flux is typical of lakes with substantial land-use changes in their catchments, although a 10x increase is on the high end of what typically seen in small lakes in agricultural or urbanized landscapes. However, the peak accumulation rates of the last decade (0.11 g cm^{-2} yr^{-1}) are close to average for many urban lakes.

The three macrofossils selected for AMS radiocarbon dating yielded ages ranging from 2035 to 4800 ^{14}C years (Fig. 5). The calibrated dates (Appendix A) indicate that approximately 5500 years of the pond's history are recorded in the 383 cm long piston core. However, comparison with the freeze core record suggest that the piston core dates might have been affected by the so-called "lake reservoir effect", typical of hard-water lakes such as Shelburne Pond. The "lake reservoir effect" is caused by the introduction of old, ^{14}C-depleted carbon from bedrock, sediments, or groundwater. The input of old carbon lowers the $^{14}C/^{12}C$ ratio in the dissolved CO_2 used by algae and other aquatic, non-emergent plants in a lake, and leads to an over-estimate of actual age (Björck and Wohlfarth, 2001). The reported ages might thus be several hundred years older than expected, and further analysis is required to refine pre-settlement chronology.

By comparing the %C, C/N, $\delta^{13}C$, and paleo-pigment records in both the freeze and piston cores, we were able to determine that approximately 48 cm of the top sediment column are missing in the piston core. This is the result of the extremely unconsolidated nature of the most recent sediments in the pond.

4.2 Organic matter and C/N records

Overall OM content in the Shelburne Pond sediments is high, which is not surprising considering its trophic status. In the freeze core (ca. 1800 to 2006), %C and %N values increase from 20 to 26, and 2 to 2.8, respectively. During the same time period, C/N ratios decline from 10.4 to around 9 (Fig. 4). Looking at the records in more detail, we observe that %C, %N, and C/N values vary little in the pre-1900 interval, whereas from ~1900 to 1990 the %C, and %N values steadily increase while C/N values decrease. The most dramatic changes occurred since the early 1990s.

In the piston core, the OM proxies display marked fluctuations, but both %C and %N values are, for the most part, comparable to what observed in the more recent freeze core sediments (Fig. 5). A marked shift towards low C/N values is recorded between cm levels 175 and 300, where values as low as 8.4 are found. These are the lowest values recorded in the whole sedimentary column we retrieved at Shelburne Pond. An increase in C/N values occurs between cm levels 75 and 20, just preceding the two century long decline documented in the freeze core. Due to the lack of accurate chronology for the piston core, we can only speculate on the cause of this increase. If due to increased input of vascular land plant material from the watershed, it might have been related to deforestation practices by early settlers.

In the freeze core, the trend of increasing OM content and decreasing C/N ratios from the oldest to the most recent sediments is consistent with enhanced burial of predominantly algal-derived organic matter. This trend is most striking in the post-1990 interval. Nevertheless, the data from the piston core suggest that productivity levels in Shelburne Pond were quite variable, and periodically high, already during the pre-settlement period.

4.3 Carbon stable isotopes

The freeze core exhibits a sharp positive shift in organic matter $\delta^{13}C$ values starting around 66 cm (~1860). $\delta^{13}C$ values keep increasing until the 1950's and 60', after which they stabilize between -27.0 and -27.5‰ (Fig. 4). By comparison, the isotopic record in the piston core is quite noisy, and for the most part the $\delta^{13}C$ values are more negative (-29 to -29.5‰). Only in the top 25-30 cm, which overlap with the bottom of the freeze core, did we observe a marked shift towards less negative values (Fig. 5).

The interpretation of the $\delta^{13}C$ record in the piston core is complicated by the observed frequent fluctuations. However, the shift towards less negative values documented at the top of the piston core, and persisting through the freeze core, most likely indicates progressive eutrophication of the pond leading to increased burial of algal-derived OM. Recent studies aimed at characterizing the isotopic and elemental composition of primary producers within Shelburne Pond, have shown that algae are significantly enriched in ^{13}C ($\delta^{13}C$ values ranging from -27‰ in winter to -17‰ in summer) compared to macrophytes, wetland vegetation, and land plants found in the watershed (Levine et al., 1998; Lini et al., 1998; Lini and Levine, unpublished data).

4.4 Total P, available P and biogenic silica (BSi)

Phosphorus and biogenic silica concentrations were analyzed only in the freeze core (Fig. 6). Both total and bio-available P concentrations show an increase up-core. In the oldest sediments total P concentrations appear stable around 750 μgP/g sediment dryweight. Starting approximately at the beginning of the 19th century P concentrations in the sediments increase at a rapid and constant rate from 750 to about 1000 µgP/g around 59 cm (~1905). Concentrations continued to increase, but at a slower rate to about 1250 µgP/g at about 23 cm (~1984) when accumulation rates accelerate once again to the present. Available-P concentrations mirror changes in total P concentrations. Available-P is a relatively constant fraction (range 11-18%; std error = 0.3%) of TP at all depths in the core. Phosphorus accumulation rates (ugP/cm^2/yr) show only a slight increase between ~1800 and the end of the 19th century, then a large and steady rate of increase to the present (Fig. 6).

The biogenic silica concentrations displays a trend similar to that shown by P, with a steady increase up-core from 70 cm (~1820). However, to estimate historical diatom productivity, biogenic silica accumulation rates are more revealing. Figure 7 shows BSi accumulation (mg BSi/cm^2/yr). There is a slight increase in accumulation from the bottom of the core to ca. 1900. Since then, accumulation rates have increased at a relatively constant rate. The patterns of P and BSi accumulation are remarkably similar.

Post-depositional mobility of P can often confound any relationship between water column P and sediment P. In the analysis of the sediments of the Bay of Quinte, Schelske et al. (1985) showed a remarkable congruence between accumulation rates of biogenic silica (a measure of diatom productivity) and total phosphorus, suggesting that any post-depositional mobility of P is minimal. A similar pattern is found in the Shelburne Pond sediments - there has been a consistent and parallel (correlation coefficient = 0.992) increase in the accumulation rates of both total P and BSi since ca. 1800. Further, this increase is consistent with trends in other proxies (phaeophytin 〈, ® carotene, echinone, myxoxanthophyll, C/N, etc.) suggesting a dramatic increase in the trophic status of Shelburne Pond since the beginning of the 20th century.

4.5 Diatoms

Four species of diatoms from three genera were dominant throughout the 79 cm long freeze core – *Aulacoseira ambigua*, *Fragilaria construens, Fragilaria pinnata* and *Stephanodiscus nigarae*. For each sample analyzed, all other diatoms represented 15.5% or less of the total diatom composition. The most common taxa are listed in Appendix E, which also lists relative abundances of the four dominant taxa.

Fossil diatom community composition exhibits a significant change from the oldest sediments to the present (Fig. 8). Abundances of *A. ambigua* and *S. nigarae* increased markedly since ca. 1900 (from 40.5% to 71.0%, and 0.6% to 17.7%, respectively). Both *A. ambigua* and *S. nigarae* are centric planktonic diatoms and indicators of mesotrophic lake conditions (Dixit et al., 1999). In addition, the total percentage of *F. construens* and *F. pinnata* drastically dropped from 43.5% to 5.5%. *F. construens* and *F. pinnata* are benthic diatoms, and indicators of oligotrophic to mesotrophic conditions (Dixit et al., 1999; Patrick and Reimer, 1966). Since *F. construens* and *F. pinnata* are benthic diatoms, a decrease in percent composition may indicate progressively declining water clarity due to macrophyte overgrowth and shading by phytoplankton blooms, which would favor centric diatoms such as *A. ambigua* and *S. nigarae.* Changes in fossil diatom community composition are thus consistent with a trend of progressive eutrophication since the early 1900s, with the highest rate of change occurring since ca. 1950. Not incidentally, the shift in diatom composition parallels the steadily increasing accumulation rates of both TP and BSi since ca. 1900 (Figs. 6 and 7).

Analysis of diatom-inferred lake water TP, using the four highly dominant taxa and the training data set of Dixit et al. (1999), indicates that TP levels were about 11.5-12.5 μg/L from ~1800 to ~1900. Since the beginning of the 20th century, inferred TP values gradually increased to a maximum of 14.2 μg/L (Fig. 9). According to VT DEC guidelines, the observed trends would indicate a shift from mesotrophic towards eutrophic conditions. However, these results are in stark contrast to the TP levels measured directly from the lake surface by the VT DEC. Reported long-term average P concentrations are 93 μg/L for spring (21 year record) and 155 μg/L for summer (6 year record).

In Shelburne Pond, diatoms and chlorophytes dominate the phytoplankton community only in winter and spring (DeYoe, 1981). Cyanobacteria appear in May, and can reach bloom densities by June (DeYoe, 1981; Ferber at al. 2004; Lescaze 1999). The rapid rise and continued dominance of cyanobacteria during most of the growing season suggest that in Shelburne Pond diatoms are poor indicators for parameters such as nutrient concentration and algal productivity levels. This would explain the gross discrepancy between measured and inferred water TP concentrations. Other studies have also suggested that diatom-TP models tend to underestimate P in highly eutrophic conditions (Hall et al. 1997, Sayer, 2001).

4.6 Fossil Pigments

Paleopigment assemblages were analyzed only in the freeze core (Fig. 10). All pigment groups show an increase up-core, starting around cm 66-67 (~1850). A more rapid increase in pigment concentration is evident in the top 20 cm of the core (post-1990). Total algal abundance, as inferred from pheophytin A and beta-carotene (common to all algal groups) concentrations, shows a clear increase up-core. Concentrations of cyanobacteria-specific pigments (echinone and myxoxanthophyll) display an even more significant increase, which is not surprising given the present dominance of blue-green algae in Shelburne Pond. Alloxanthin (cryptophytes) and fucoxanthin (dinoflagellates and siliceous algae) concentrations also increase up-core, but most dramatically in the top 15-20 cm. Due to the pigment’s labile nature, the fucoxanthin pattern might be an artifact of post-depositional degradation (Leavitt and Carpenter, 1989). In summary, the documented increase in all sedimentary pigments indicates a general increase in productivity, which started in the second half of the 19th century and rapidly accelerated since the early 1990s.

5. SUMMARY AND CONCLUSIONS

Our paleolimnological analysis of Shelburne Pond shows that present limnological conditions are different from the pre-settlement, oligo-mesotrophic state. All paleoproductivity proxies indicate that Shelburne Pond has become increasingly eutrophic, and that eutrophication has accelerated since the early 20th century. More specifically, four periods of limnological development can be distinguished:

Pre-Settlement (prior to 1725):

The data from the piston core indicate that Shelburne Pond was moderately productive before European settlement began. Native Americans had been using the pond for at least eight thousand years, although the intensity of their utilization increased drastically about 2000 years ago, when the "modern" pond with its marshes was formed (Carr et al., 1977; Petersen et al., 1985). Poor age chronology in the piston core does not allow us to conclusively determine if the variations observed in the %C, %N, C/N, and δ^{13}C records towards the top of the core are related to activities of Native Americans or early settlers.

Cores collected by Carr et al. (1977) in the lake's southern wetland area, suggest that significant peatland/wetland development did not initiate until ~ 2000 yBP. Prior to that, the areas now occupied by wetlands were accumulating a mix of sedge and algae gyttya. Despite the lack of accurate age control, we speculate that the interval of markedly low C/N documented in the lower portion of our piston core might correlate to that early phase of the lake's evolution. The rapid increase in C/N displayed starting at ~75 cm might be related to the development of wetlands, which became a source of vascular OM (i.e high C/N) for the sediments deposited in the deeper parts of Shelburne Pond.

1725-1900:

In the recorded history of early settlers, Shelburne Pond is described as clear, with little plant life (Droege et al., 1981). Because only the last two centuries (~1800 to present) are represented in the freeze core, it is difficult to assess what impact early settlers might have had on the landscape surrounding Shelburne Pond during the first decades after their arrival. Deforestation only began in earnest around 1810 (Droege et al., 1981).

Geochemical (%C, %N. C/N) trends exhibit relative stability until ~1900, although a marked shift towards less negative OM δ^{13}C begins around ~1860. We interpret this shift as the onset of cultural eutrophication of the pond, leading to increased burial of algal-derived OM. The paleopigment records, all of which show increasing concentrations starting ~1850, corroborate this hypothesis. It is at this point in time that cyanobacteria communities start to become dominant. Intensive agriculture in the watershed began around 1850. Thus, it is very likely that agricultural runoff triggered the onset of eutrophication.

Sediment, P, and BSi accumulation rates remain stable and low until the late 1800s. Fossil diatom assemblages are still dominated by benthic forms, indicating that despite increasing algal productivity water clarity has not yet been critically compromised.

1900-1990:

All the paleoproxies used in this study display an increased rate of change starting at the beginning of the 20th century. %C and %N steadily increase, while C/N values drop. OM $\delta^{13}C$ reach their least negative values in the early 1970s, after which they stabilize. Accumulation rates of sediment, P, and BSi, all rapidly increase. By ~1990, sediment accumulation rates are almost an order of magnitude greater than those of the 19th century. By ~1990, benthic diatom taxa have been almost completely replaced by eutrophic, planktonic species. The drastic decline of benthic taxa is a result of declining water clarity due to macrophyte overgrowth and shading by phytoplankton blooms. The paleopigment data suggests a continued increase in algal productivity, with cyanobacteria becoming increasingly dominant.

Sheep farming in the area reached its peak in 1900, and approximately 1925 marked the change from sheep to dairy (Droege et al., 1981). Nutrient inputs from diary farms and agricultural fields clearly impacted the nutrient balance of Shelburne Pond, and greatly accelerated the rate of eutrophication.

~1990-present:

This period is marked by the most rapid increase in sediment OM content and decline in C/N values. Sediment, P, and BSi accumulation rates still show increases, but sediment accumulation rates seem to have stabilized during the most recent years.

Perhaps the most dramatic changes are displayed in the paleopigment profiles, which point to a sharp increase in total algal biomass. Colonial cyanobacteria, in particular, experience significant growth during this time period.

It is unclear if recent residential development in the area is responsible for the current hypereutrophic condition of Shelburne Pond. It is possible, although this hypothesis remains to be tested, that the lake-wide fish kills that occurred in 1985 and 1993 (Borre, 1986; State of Vermont Agency of Natural Resources, unpublished reports) provided an additional input of nutrients to the pond. Thousands of fishes were killed during both events, triggered by oxygen depletion due to the collapse of algal blooms. According to articles that appeared in the local newspaper (The Burlington Free Press) the dead fish were not removed by the Fish and Wildlife Department due to cost and lack of manpower.

5. SYNTHESIS

- Sediment accumulation rates in Shelburne Pond have increased almost 10-fold since the late 1800s.
- Sedimentary organic matter content has increased during the past 200 years from 40 to 50%, and C/N values have steadily decreased, indicating increased contribution of algal OM sources to the sediment.
- C isotope values have become significantly less negative since the second half of the 19th century, suggesting increased aquatic productivity.
- Sediment P and BSi concentrations have increased markedly since ca. 1850.
- Diatom assemblages are currently dominated by meso-eutrophic taxa. The abundance of benthic forms has steadily decreased, reflecting declining light penetration and increased nutrient availability.
- Paleopigments support the postulated increase in algal productivity, in particular of cyanobacteria. This trend has accelerated since ca. 1990.
- Data from the piston core suggest that Shelburne Pond’s productivity levels were generally lower, but at times still quite significant, prior to European settlement of the region. The causes of these, apparently natural, fluctuations remain to be investigated.

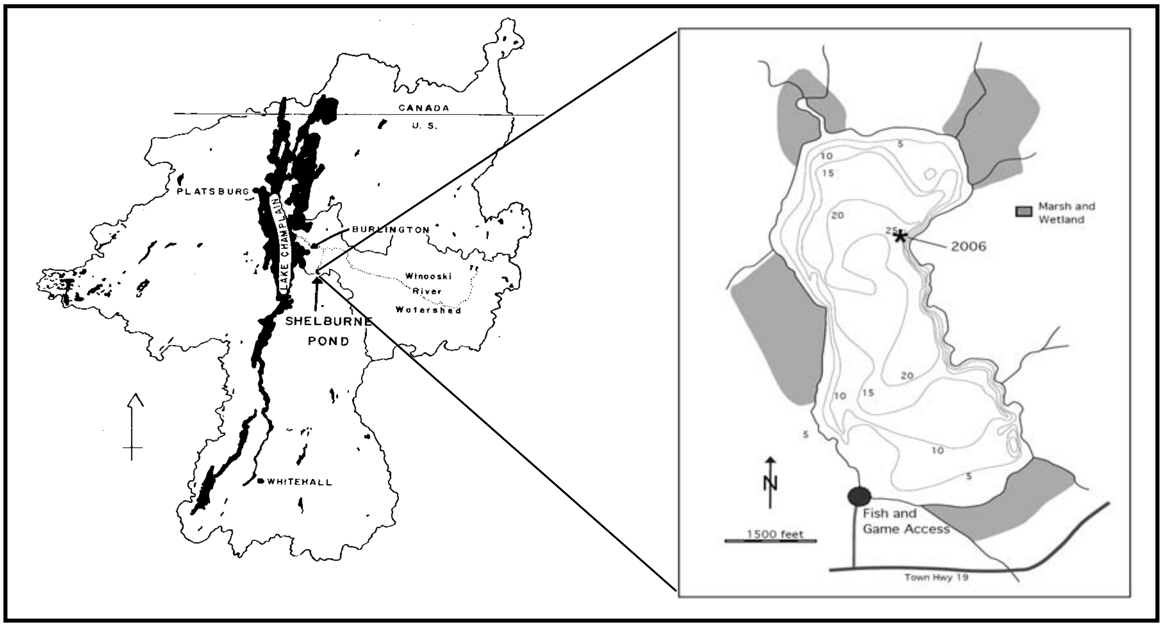

Fig. 1: Location of Shelburne Pond, VT, where a piston core and a freeze-finger core were taken in 2006. * Marks coring location at the deepest point of the pond.

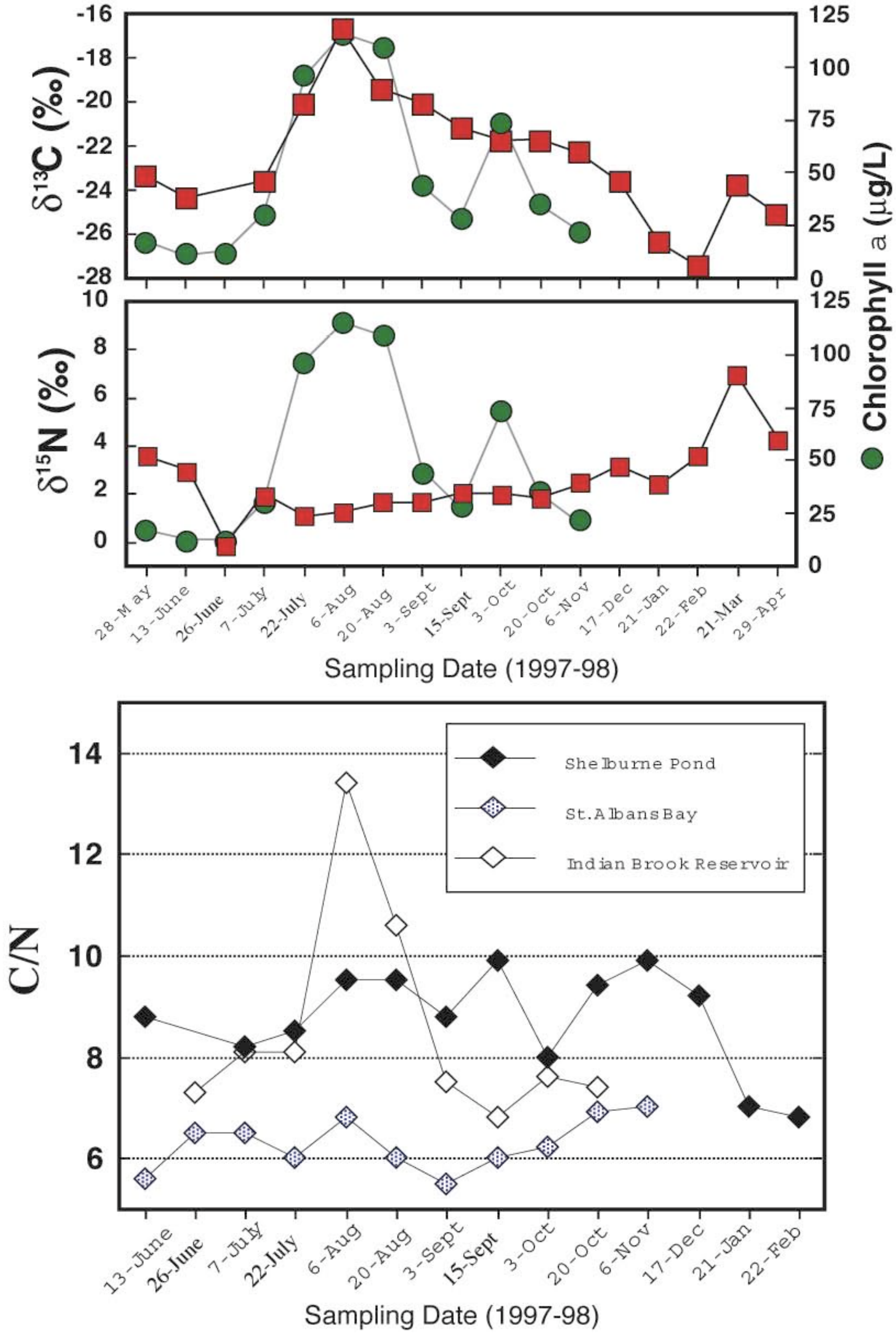

Fig. 2: Top - Seasonal carbon and nitrogen isotopic composition of phytoplankton and chlorophyll *a* concentrations at Shelburne Pond, VT. Changes in isotopic composition are directly related to fluctuations in algal biomass. Bottom - Seasonal seston elemental ratios for Shelburne Pond, St. Albans Bay, and Indian Brook Reservoir. The relatively high C/N ratios at Shelburne Pond are indicative of nitrogen limitation.

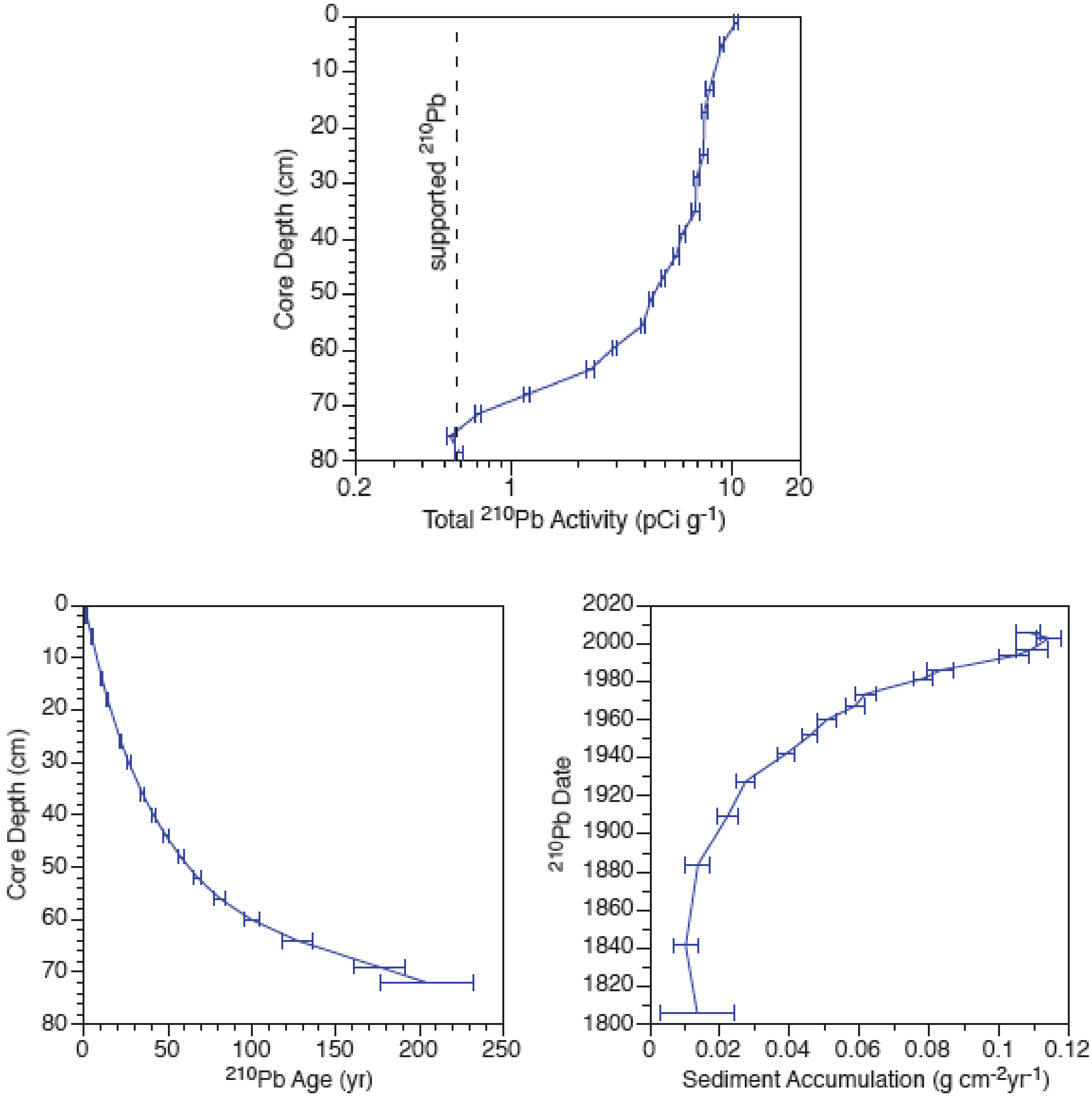

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Fig. 3: Relationship between ^{210}Pb activity, core depth, sediment age, and sediment accumulation rates in the Shelburne Pond freeze-core.

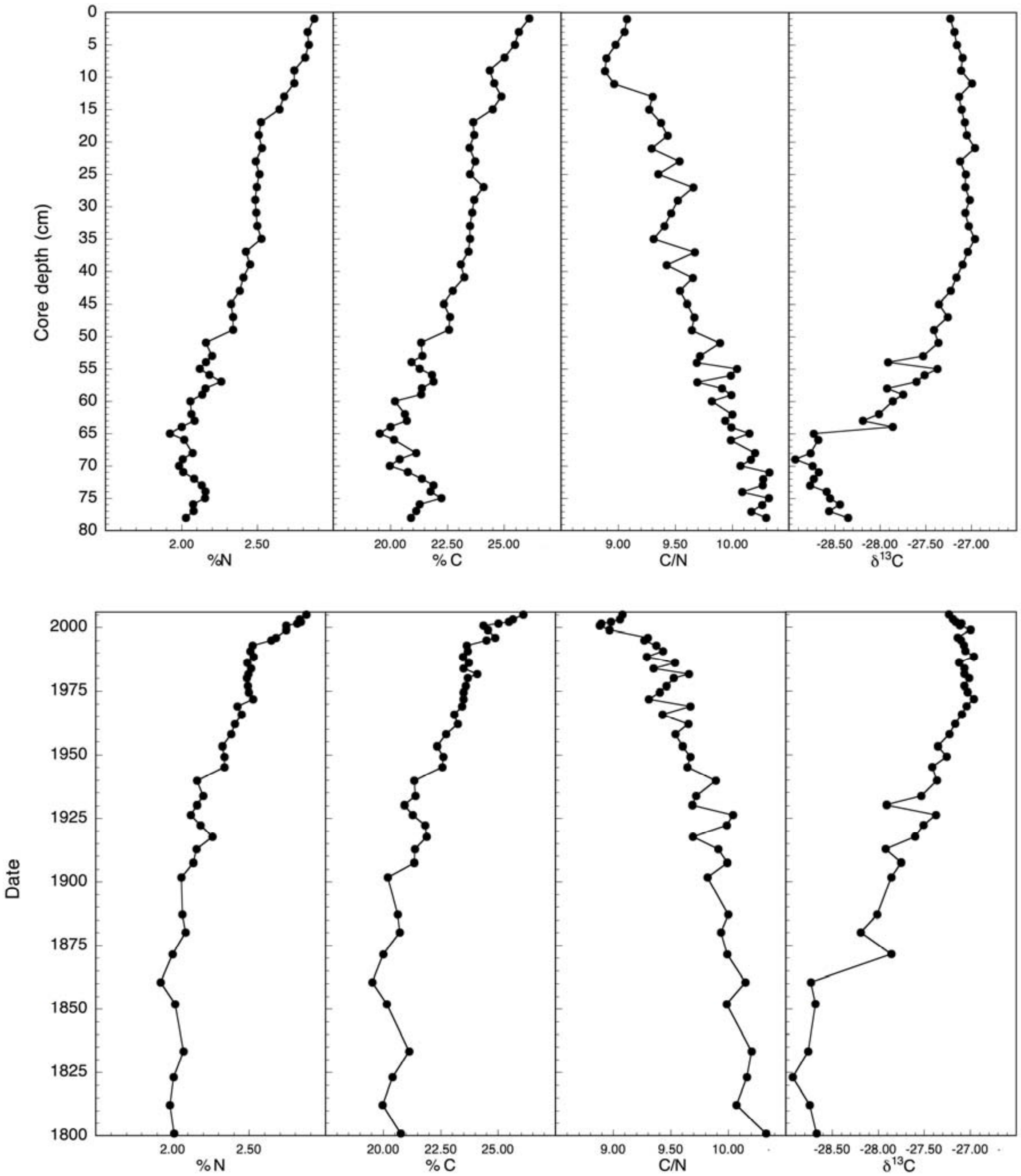

Fig. 4: Elemental (%C, %N, C/N), C isotope records from the Shelburne Pond freeze core (length 79 cm). Ages in bottom plot are based on ^{210}Pb dating.

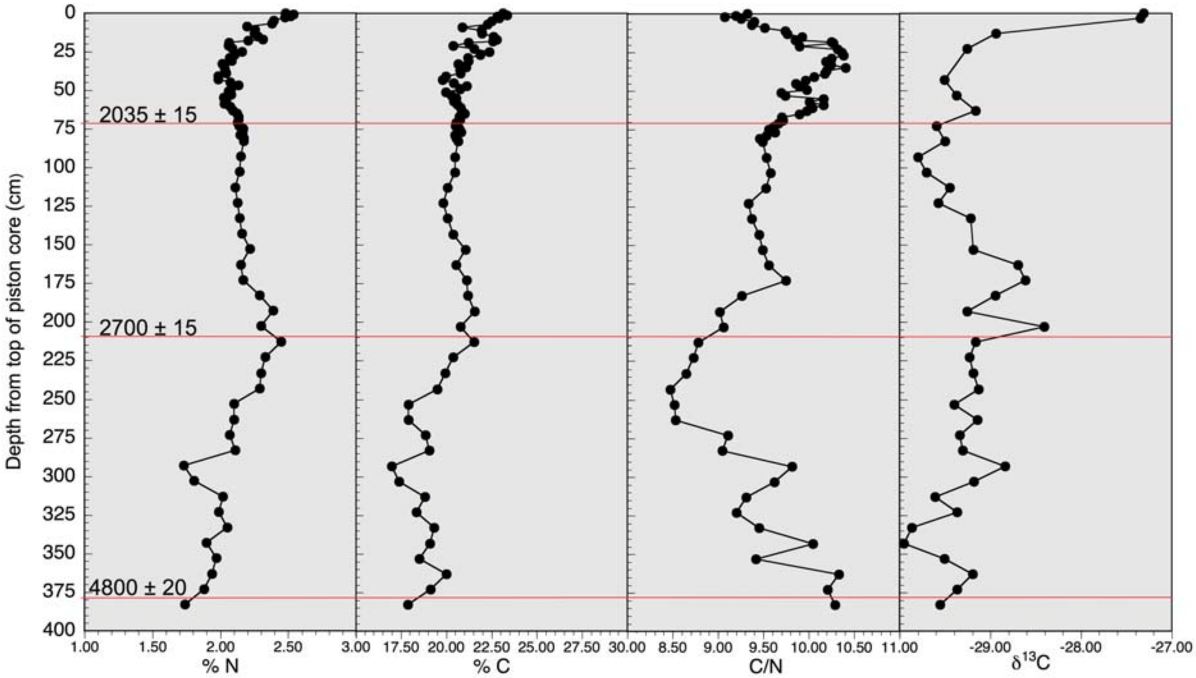

Fig. 5: Elemental (%C, %N, C/N) and C isotope records from the Shelburne Pond piston core (length 383 cm). Approximately 50 cm of the top sediment column are missing. ^{14}C ages are based on AMS ^{14}C dating.

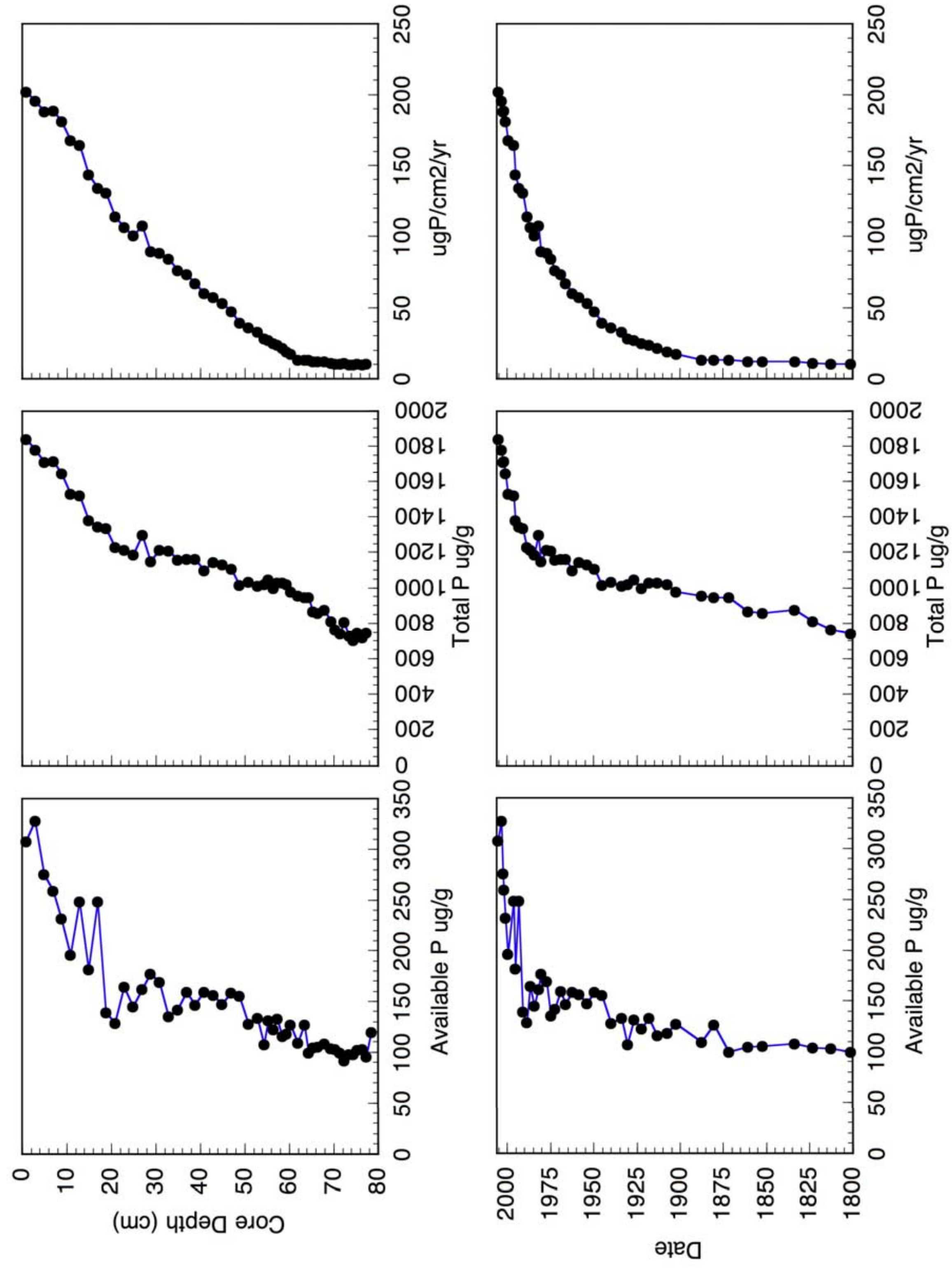

Figure 6: Available and total P concentrations, and total P accumulation rates versus depth (top) and time (bottom).

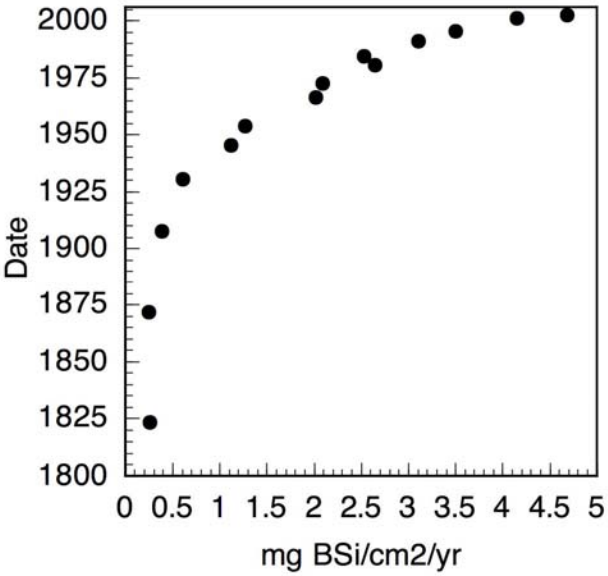

Fig. 7: Accumulation rates of biogenic silica (BSi) versus time.

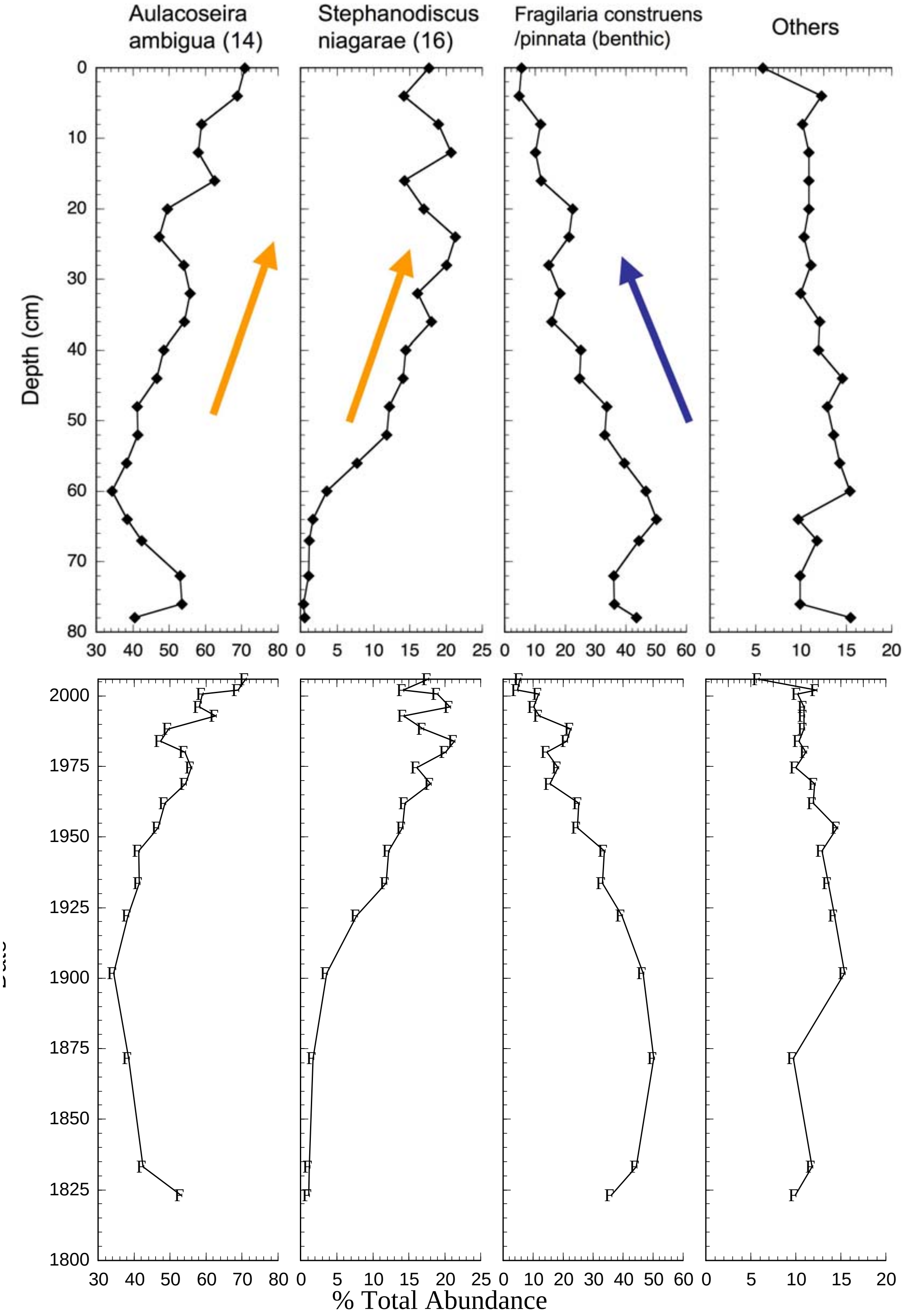

Fig. 8: Fossil diatom stratigraphy for Shelburne Pond, VT. Optimum total P values (µmol L^{-1}) are indicated in parentheses.

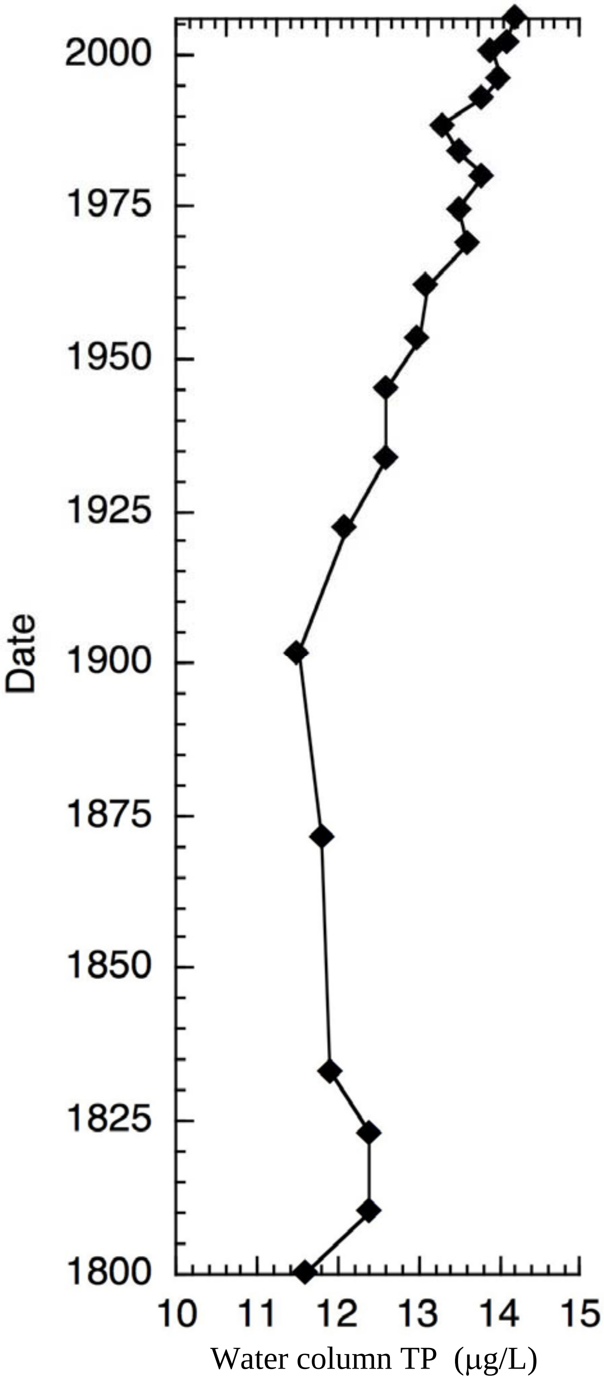

Fig. 9: Diatom-inferred TP for the Shelburne Pond freeze core.

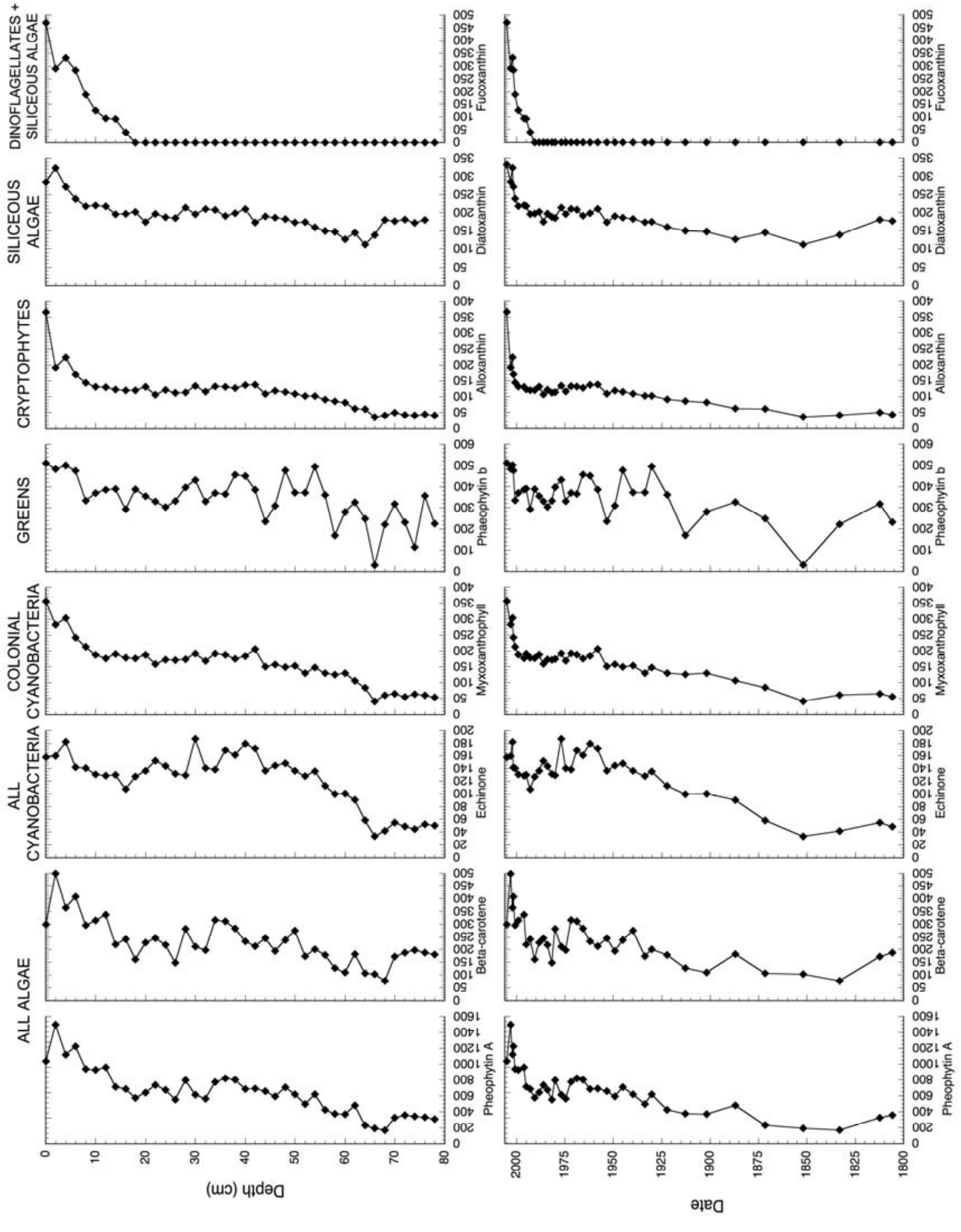

Fig. 10: Depth and age profiles of paleo-pigments representing different algal groups.

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APPENDIX A: 210-Pb and 14-C data for Shelburne Pond

Top of Interval (cm)	Base of Interval (cm)	Age: Base of Int. (yr)	Error of Age (±s.d.)	Date A.D.	Sediment Accum. (g/cm2 yr)	Error of Sed. Accum. (±s.d.)
0	2	1.67	0.65	2005.0	0.1082	0.00369
4	6	4.62	0.67	2002.1	0.1143	0.00354
12	14	10.68	0.65	1996.0	0.1092	0.00465
16	18	14.01	0.68	1992.7	0.1044	0.00432
24	26	21.95	0.76	1984.8	0.0833	0.00374
28	30	26.61	0.83	1980.1	0.0781	0.00274
34	36	34.91	0.99	1971.8	0.0616	0.00296
38	40	41.39	1.12	1965.3	0.0586	0.00279
42	44	48.82	1.35	1957.9	0.0506	0.00273
46	48	57.30	1.67	1949.4	0.0458	0.00237
50	52	67.50	2.20	1939.2	0.0389	0.00259
55	56	81.19	3.26	1925.5	0.0273	0.00269
59	60	99.83	4.59	1906.9	0.0222	0.00301
63	64	127.11	9.24	1879.6	0.0137	0.00352
67	69	176.01	15.14	1830.7	0.0102	0.00356
71	72	204.39	27.57	1802.3	0.0135	0.01071

Supported Pb-210: 0.5556 ± 0.0305 pCi/g

Number of Supported Samples: 2

Cum. Unsup. Pb-210: 34.8596 pCi/cm2

Unsup. Pb-210 Flux: 1.1168 pCi/cm2 yr

Lake	**D14C**	**±**	**Age**	**±**	**Calibrated Age (2σ)**
536-VT-Shel.-SPP5	-450.0	1.1	4800	20	5477:5539 BP
537-VT-Shel.-SPP176	-285.4	1.2	2700	15	2761:2844 BP
538-VT-Shel.-SPP312	-224.0	1.2	2035	15	1931:2010 BP

The CALIB program v. 5.0.1 (Stuiver and Reimer, 1993) and the calibration dataset of Reimer et al. (2004) were used to convert 14-C dates to calibrated years BP.

APPENDIX B: %C, %N, C/N AND CARBON ISOTOPE DATA, FREEZE CORE

core ID	depth interval	Depth cm	%Nitrogen	%Carbon	C/N	$\delta^{13}C$
SP	0-2	1	2.87	26.10	9.08	-27.23
SP	2-4	3	2.83	25.64	9.06	-27.19
SP	4-6	5	2.84	25.47	8.98	-27.16
SP	6-8	7	2.81	25.02	8.90	-27.09
SP	8-10	9	2.74	24.37	8.88	-27.11
SP	10-12	11	2.74	24.57	8.97	-26.99
SP	12-14	13	2.68	24.89	9.30	-27.13
SP	14-16	15	2.64	24.50	9.27	-27.10
SP	16-18	17	2.52	23.63	9.37	-27.07
SP	18-20	19	2.51	23.67	9.43	-27.05
SP	20-22	21	2.53	23.48	9.29	-26.96
SP	22-24	23	2.49	23.72	9.54	-27.12
SP	24-26	25	2.51	23.49	9.35	-27.06
SP	26-28	27	2.49	24.10	9.66	-27.06
SP	28-30	29	2.49	23.68	9.53	-27.01
SP	30-32	31	2.49	23.59	9.47	-27.06
SP	32-34	33	2.50	23.51	9.41	-27.03
SP	34-36	35	2.52	23.50	9.31	-26.96
SP	36-38	37	2.42	23.43	9.67	-27.04
SP	38-40	39	2.45	23.11	9.43	-27.09
SP	40-42	41	2.41	23.25	9.65	-27.16
SP	42-44	43	2.38	22.73	9.54	-27.22
SP	44-46	45	2.33	22.35	9.60	-27.35
SP	46-48	47	2.34	22.61	9.67	-27.26
SP	48-50	49	2.34	22.58	9.65	-27.41
SP	50-52	51	2.16	21.36	9.89	-27.36
SP	52-54	53	2.20	21.40	9.72	-27.53
SP	54-55	54	2.16	20.92	9.69	-27.91
SP	55-56	55	2.12	21.28	10.04	-27.37
SP	56-57	56	2.19	21.82	9.99	-27.51
SP	57-58	57	2.26	21.91	9.70	-27.60
SP	58-59	58	2.16	21.39	9.91	-27.92
SP	59-60	59	2.14	21.35	9.99	-27.75
SP	60-61	60	2.06	20.21	9.82	-27.86
SP	61-63	62	2.06	20.65	10.00	-28.01
SP	63-64	63	2.09	20.72	9.94	-28.19
SP	64-65	64	2.00	20.00	9.99	-27.86
SP	65-66	65	1.92	19.54	10.15	-28.73
SP	66-67	66	2.02	20.15	9.99	-28.68
SP	67-69	68	2.07	21.14	10.20	-28.76
SP	69-70	69	2.01	20.42	10.16	-28.93
SP	70-71	70	1.98	19.99	10.07	-28.74
SP	71-72	71	2.01	20.77	10.33	-28.67
SP	72-73	72	2.08	21.39	10.27	-28.73

core ID	depth interval	Depth cm	%Nitrogen	%Carbon	C/N	δ^{13}C
SP	73-74	73	2.13	21.90	10.27	-28.77
SP	74-75	74	2.16	21.77	10.09	-28.59
SP	75-76	75	2.15	22.24	10.32	-28.55
SP	76-77	76	2.07	21.30	10.26	-28.44
SP	77-78	77	2.08	21.15	10.17	-28.56
SP	78-79	78	2.03	20.90	10.30	-28.35

APPENDIX C: SEDIMENT P AND BSi DATA, FREEZE CORE

core ID	depth interval	Depth cm	Tot P ug/g	Av P ug/g	mg Si/g
SP	0-2	1	1839.2	308.1	
SP	2-4	3	1779.3	328.0	
SP	4-6	5	1709.9	275.5	41.6
SP	6-8	7	1716.8	259.8	
SP	8-10	9	1647.2	231.9	37.8
SP	10-12	11	1529.3	196.0	
SP	12-14	13	1523.2	248.9	
SP	14-16	15	1383.9	181.5	34.1
SP	16-18	17	1346.0	248.8	
SP	18-20	19	1334.9	139.6	31.8
SP	20-22	21	1228.1	129.3	
SP	22-24	23	1214.0	164.5	
SP	24-26	25	1189.2	145.3	33.4
SP	26-28	27	1297.6	161.8	
SP	28-30	29	1150.2	177.3	34
SP	30-32	31	1215.0	169.5	
SP	32-34	33	1210.1	135.6	
SP	34-36	35	1160.4	141.8	33.1
SP	36-38	37	1164.8	159.9	
SP	38-40	39	1163.3	147.1	33.1
SP	40-42	41	1101.3	159.4	
SP	42-44	43	1146.4	156.8	
SP	44-46	45	1131.2	147.7	28.1
SP	46-48	47	1109.3	159.3	
SP	48-50	49	1018.4	155.7	28
SP	50-52	51	1036.7	128.2	
SP	52-54	53	1010.5	133.6	
SP	54-55	54	1023.1	107.7	22.2
SP	55-56	55	1049.8	131.5	
SP	56-57	56	999.1	122.8	
SP	57-58	57	1029.5	132.9	
SP	58-59	58	1029.4	116.3	
SP	59-60	59	1023.6	118.7	19.8
SP	60-61	60	978.3	127.3	
SP	61-63	62	954.6	109.4	
SP	63-64	63	945.2	127.0	
SP	64-65	64	947.8	100.2	18.3
SP	65-66	65	867.6	105.0	
SP	66-67	66	861.3	105.3	
SP	67-69	68	877.3	108.5	
SP	69-70	69	813.9	103.7	19.5
SP	70-71	70	768.4	103.1	
SP	71-72	71	743.8	100.2	
SP	72-73	72	807.6	91.9	

core ID	depth interval	Depth cm	Tot P ug/g	Av P ug/g	mg Si/g
SP	73-74	73	728.0	98.1	
SP	74-75	74	706.8	98.3	32.6
SP	75-76	75	749.2	101.9	
SP	76-77	76	721.4	103.4	
SP	77-78	77	747.4	96.0	
SP	78-79	78	na	119.8	38.3

APPENDIX D: FOSSIL PIGMENT DATA. Concentrations in nmol/g organic matter

Sample / Depth	Depth (cm)	Fuco	Sudan	Myxo	Allo	Diato	Lut_Zea	Cantha
SP 0	0	469	2279	357	367	333	503	201
SP 2	2	291	1818	283	192	285	485	171
SP 4	4	334	1701	304	225	324	491	173
SP 6	6	284	1665	242	170	271	430	153
SP 8	8	188	1845	213	143	239	406	115
SP 10	10	127	1540	188	132	218	389	125
SP 12	12	96	1488	177	131	221	372	123
SP 14	14	94	1876	191	124	218	391	134
SP 16	16	39	1576	179	121	196	386	121
SP 18	18	0	1515	178	121	197	393	121
SP 20	20	0	1396	189	132	203	410	148
SP 22	22	0	1466	160	106	174	359	110
SP 24	24	0	1386	173	122	198	406	111
SP 26	26	0	1479	171	113	188	382	117
SP 28	28	0	1442	174	114	186	378	115
SP 30	30	0	1413	193	134	215	425	129
SP 32	32	0	1383	169	117	197	367	114
SP 34	34	0	1402	193	133	212	426	152
SP 36	36	0	1429	189	131	209	417	129
SP 38	38	0	1462	175	127	192	401	127
SP 40	40	0	1421	185	137	198	441	127
SP 42	42	0	1798	207	139	211	474	138
SP 44	44	0	1438	151	109	173	401	103
SP 46	46	0	1616	158	118	191	417	126
SP 48	48	0	1485	149	115	187	423	124
SP 50	50	0	1383	154	109	183	446	128
SP 52	52	0	1343	130	102	173	421	118
SP 54	54	0	1585	149	103	175	412	125
SP 56	56	0	1509	130	92	160	392	122
SP 58	58	0	1537	126	86	150	368	94
SP 60	60	0	1502	130	82	148	376	106
SP 62	62	0	1380	106	62	128	338	88
SP 64	64	0	1455	84	61	146	359	91
SP 66	66	0	1435	42	36	113	279	55
SP 68	68	0	1360	60	42	139	329	73
SP 70	70	0	1421	66	50	181	424	90
SP 72	72	0	1393	55	42	177	387	65
SP 74	74	0	1387	63	42	182	380	66
SP 76	76	0	1410	61	44	172	370	68
SP 78	78	0	1399	54	42	181	394	67

APPENDIX D, CONT.: FOSSIL PIGMENT DATA. Concentrations in nmol/g organic matter

Sample / Depth	Depth (cm)	Chl_a	Chl_ap	Echine	Phaeo_B	Pheo_A	B-car
SP 0	0	691	349	158	513	1037	301
SP 2	2	569	355	160	485	1502	500
SP 4	4	638	269	182	502	1121	366
SP 6	6	485	315	142	476	1228	409
SP 8	8	335	207	141	336	939	296
SP 10	10	283	193	131	371	925	315
SP 12	12	310	191	129	386	963	339
SP 14	14	269	193	131	391	715	221
SP 16	16	139	159	107	293	690	242
SP 18	18	128	126	128	389	579	163
SP 20	20	126	134	137	356	647	228
SP 22	22	96	96	152	330	741	246
SP 24	24	83	91	144	303	678	220
SP 26	26	105	130	132	333	555	149
SP 28	28	98	127	130	398	801	282
SP 30	30	122	77	188	434	617	213
SP 32	32	91	89	141	330	569	199
SP 34	34	89	136	138	369	780	317
SP 36	36	89	107	169	366	820	312
SP 38	38	78	102	162	457	806	284
SP 40	40	76	72	180	451	690	234
SP 42	42	80	80	172	387	696	214
SP 44	44	37	48	136	236	663	246
SP 46	46	61	69	145	309	597	196
SP 48	48	68	77	149	479	712	239
SP 50	50	64	69	136	373	623	276
SP 52	52	60	75	128	372	498	174
SP 54	54	65	78	136	495	622	203
SP 56	56	50	63	113	362	428	181
SP 58	58	40	49	100	169	380	128
SP 60	60	41	75	100	281	372	111
SP 62	62	36	60	91	326	480	183
SP 64	64	35	47	59	250	233	108
SP 66	66	12	28	34	30	196	103
SP 68	68	26	44	42	223	171	77
SP 70	70	33	55	56	318	327	174
SP 72	72	30	43	49	232	362	188
SP 74	74	14	34	45	117	342	199
SP 76	76	33	55	53	359	334	189
SP 78	78	23	39	50	227	312	182

APPENDIX E: DIATOM DATA (DOMINANT TAXA)

DIATOM COUNTS PER SECTION

Depth (cm)	A. ambig	S. nigarae	Frag. sp.	Sideviews	Total Frag	Others	Total
0	320	80	23	2	25	26	451
4	292	60	18	2	20	52	424
8	282	91	53	4	57	49	479
12	273	97	39	9	48	51	469
16	281	64	37	17	54	49	448
20	277	95	83	42	125	61	558
24	226	102	75	26	101	49	478
28	234	87	34	29	63	48	432
32	246	71	58	22	80	44	441
36	238	79	50	18	68	53	438
40	220	66	79	35	114	54	454
44	242	73	99	29	128	76	519
48	199	59	137	25	162	62	482
52	192	55	117	36	153	63	463
56	183	37	127	62	189	68	477
60	154	16	143	66	209	69	448
64	186	8	122	120	242	47	483
67	205	6	155	59	214	57	482
72	242	5	111	53	164	45	456
76	248	2	112	55	167	46	463
78	206	3	115	106	221	79	509

LEGEND

A. ambig = Aulacoseira ambigua
S. nigarae = Stephanodiscus nigarae
Frag sp. = Fragilaria construens and Fragilaria pinnata
Sideviews = F. construens and pinnata sideviews
Total Fragilaria = Fragilaria construens, F. pinnata and Fragilaria sideviews
Others = all other diatoms
Total = total number of diatoms identified and tallied

APPENDIX E, CONT.: DIATOM DATA (DOMINANT TAXA)

PERCENT COMPOSITION PER SECTION

Depth (cm)	A. ambig	S. nigarae	Frag. sp.	Sideviews	Total Frag	Others
0	71	17.7	5.1	0.4	5.5	5.8
4	68.9	14.2	4.2	0.5	4.7	12.3
8	58.9	19	11.1	0.8	11.9	10.2
12	58.2	20.7	8.3	1.9	10.2	10.9
16	62.7	14.3	8.3	3.8	12.1	10.9
20	49.6	17	14.9	7.5	22.4	10.9
24	47.3	21.3	15.7	5.4	22.1	10.3
28	54.2	20.1	7.9	6.7	14.6	11.1
32	55.8	16.1	13.2	5	18.1	10
36	54.3	18	11.4	4.1	15.5	12.1
40	48.5	14.5	17.4	7.7	25.1	11.9
44	46.6	14.1	19.1	5.6	24.7	14.6
48	41.3	12.2	28.4	5.2	33.6	12.9
52	41.5	11.9	25.3	7.8	33	13.6
56	38.4	7.8	26.6	13	39.6	14.3
60	34.4	3.6	32	14.7	46.7	15.4
64	38.5	1.7	25.3	24.8	50.1	9.7
67	42.5	1.2	32.2	12.2	44.4	11.8
72	53.1	1.1	24.3	11.6	36	9.9
76	53.6	0.4	24.2	11.9	36.1	9.9
78	40.5	0.6	22.6	20.8	43.5	15.5

LEGEND

A. ambig = Aulacoseira ambigua
S. nigarae = Stephanodiscus nigarae
Frag sp. = Fragilaria construens and Fragilaria pinnata
Sideviews = F. construens and pinnata sideviews
Total Fragilaria = Fragilaria construens, F. pinnata and Fragilaria sideviews
Others = all other diatoms
Total = total number of diatoms identified and tallied

APPENDIX E, CONT.: DIATOM DATA (FOR ALL GENERA)

Depth (cm)	A. ambig	S. nigarae	Frag. sp.	Sideviews	Achnan	Anom	Cocconeis	Cyclotella	Cymbella	Diploneis	Epithemia	Eunotia	Gomph	Navicula	Nitzschia	Pinnularia	Stauroneis	Steno	Surirella	Synedra	Tabellaria	Unidentified	Total
0	320	80	23	2	1		4				1	1		3	1	2				7		6	451
4	292	60	18	2			6		1		1	5	2	2						24		11	424
8	282	91	53	4		1	4		2		2	8	2	1	1		1			13	2	12	479
12	273	97	39	9	1		4		2		2	7	3	2	1	1	1			13		14	469
16	281	64	37	17	1		2		4		2	9	1	1		2			1	12		14	448
20	277	95	83	42	2		10		3		3	7	5	1	4	2				7	2	15	558
24	226	102	75	26			3		2		5	10	2	1	6	2						23	478
28	234	87	34	29			3		1		2	6	2	4		1				9		20	432
32	246	71	58	22			4		3	1	1	4	2	1	1	2		1		4	3	17	441
36	238	79	50	18		1	3		3		2	4		3	2	2	2		1	7		23	438
40	220	66	79	35	1		4		3			9	3	2	1	3				9		19	454
44	242	73	99	29	1		6		2		2	8	2	2			1			26		26	519
48	199	59	137	25			7		2		3	10	1	1	2	3	1			5		27	482
52	192	55	117	36		1	3		4		2	5	5		1	7				2		33	463
56	183	37	127	62			7	5		1	2	6	5	2	1	5			1		2	31	477
60	154	16	143	66	1	2	6	2	4		5	5	5	5		2			1		2	29	448
64	186	8	122	120			5				3	8	2			1				1		27	483
67	205	6	155	59	2	2	4		1			5	2		2	1	3				2	34	482
72	242	5	111	53	2		3		2			5	1			1					3	28	456
76	248	2	112	55			3			1	1	5	1		2		1			1	1	30	463
78	206	3	115	106	1		5				1	14				1	1					56	509

Legend

All columns are indicating genera

A. ambig = Aulacoseira ambigua
S. nigarae = Stephanodiscus nigarae
Frag sp. = Fragilaria construens and Fragilaria pinnata
Sideviews = F. construens and pinnata sideviews
Achnan = Achnanthes sp.
Anom = Anomoeoneis sp.
Cocconeis = Cocconeis placentula (epiphitic)
Gomph = Gomphonema parvulum
Steno = Stenopterobia sp.
Synedra = Synedra rumpens
Unidentified = includes sideviews, small pennates, etc.
Total = total number of diatoms identified and tallied