Paleo-reconstruction of historic phosphorus loading and diatom community in Mara Lake

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This report was prepared for the Shuswap Watershed Council and presents the results of a paleolimnological study assessing changes in nutrient loading from the Shuswap River and the resultant diatom community in Mara Lake, British Columbia, Canada. This study is one of three which together are intended to provide guidance for evidence-based management actions to reduce nutrient loading to Mara and Shuswap Lakes. The other two studies are:

> Ludwig, M., & Curtis, P. J. (2020). *Phosphorus budget for the Shuswap River*.
>
> Ludwig, M., & Curtis, P. J. (2020). *Phosphorus budget for the Salmon River*.

The major findings of all three studies are synthesized in a summary report:

> Ludwig, M., Hebda, N. J. R., Walker, I. R., & Curtis, P. J. (2020). *Nutrient exports from land-use in Shuswap and Salmon Rivers and paleo-reconstruction of historic phosphorus loading and water quality in Mara Lake: Project summary*.

Raw data are available through the Shuswap Watershed Council.

Project Background

Mara Lake is a 19.5 km^2 freshwater lake in southern interior British Columbia, Canada, that contributes to a robust regional tourism industry and growing property market (Ludwig, 2018; TriStar, 2014). Situated immediately south of the community of Sicamous, the lake and its tributaries receive nutrient inputs from various anthropogenic sources including septic systems, urban stormwater, and agricultural runoff (TriStar, 2014).

Limnological monitoring carried out since the early 1970s shows that water quality in Mara Lake was historically good but has declined in recent decades (Ashley & Hall, 2010; TriStar, 2014). A widespread noxious algal bloom occurred in Mara Lake in May 2010, and elevated spring algae growth was observed for two years thereafter, demonstrating that, despite its large size and rapid flushing rate, Mara Lake is susceptible to water quality degradation (Ashley & Hall, 2010).

Algal growth rates in most freshwater ecosystems are limited by the availability of essential nutrients, primarily phosphorus. Elevated phosphorus inputs can lead to excessive plant and algae growth such as the algal bloom observed in Mara Lake in 2010. Algal blooms can negatively impact aquatic ecosystems by reducing water transparency and thus the depth of the photic zone. Furthermore, as the algal bloom dies off, bacteria decompose the dead organic material and in doing so consume dissolved oxygen, which can lead to oxygen depletion and the development of so-called "dead zones", areas of the lake where oxygen levels are too low to support animal life. Some algae also secrete toxins that are harmful to humans and livestock. Thus, algal blooms resulting from elevated phosphorus levels can be harmful to the health of humans and animals and can significantly degrade the ecological, recreational, and resource values of the lake.

The 2010 Mara Lake algal bloom prompted concern about the health of the lake, and in 2013, Tri-Star Environmental Consulting was contracted by Fraser Basin Council to estimate loadings from nutrient sources to Mara Lake so that management decisions could address the most significant contributors (TriStar, 2014). This study determined that the increased algal growth was driven by high levels of phosphorus entering Mara Lake via its primary tributary, the Shuswap River (TriStar, 2014), which was found to contribute 94.2% of the lake's total phosphorus loading (TriStar, 2014). The study inferred that most of the phosphorus entering the lake was from agricultural stormwater runoff (TriStar, 2014).

Subsequent research undertaken at the University of British Columbia Okanagan by graduate student Meagan Ludwig focused on calculating total phosphorus flux from different land uses within the watershed (Ludwig, 2018). Using three different hydrological modelling techniques, Ludwig (2018) estimated that anthropogenic land uses (urban and agriculture) contribute between 7 to 66 times more phosphorus than undisturbed forest, affirming the conclusions of the TriStar (2014) report.

These studies demonstrate that the current pace and scale of agricultural activities in the Mara Lake watershed threaten its water quality and recreational attractiveness. Nutrient management and remediation measures must be undertaken to reduce anthropogenic phosphorus loading and eutrophication risk if the lake's substantial amenity value is to be preserved. However, due to the relatively short water quality monitoring record for Mara Lake, there exist no baseline data for nutrient concentrations predating land use changes and development in the watershed. Such a baseline is crucial for assessing long-term impacts of land use change and setting realistic nutrient management targets.

Paleolimnology provides proven techniques for reconstructing long-term lake and watershed histories. This study employs a multi-proxy paleolimnological approach to provide an objective, credible inference on the expression of anthropogenic nutrient loading change in Mara Lake. Sediment phosphorus was measured spectroscopically after digestion, and the fossil remains of siliceous algae (primarily diatoms) were analyzed to determine whether there have been changes in the algal community consistent with changes in transparency or nutrient loading. Inferred changes from pre-land-use-change background conditions (pre-20th-century) were compared to contemporary indicators and to estimates of anthropogenic phosphorus loading from mass balance approaches (Ludwig, 2018), as summarized in a separate synthesis report (Ludwig et al., 2020). We evaluate changes in the indicators through time to arrive at a parsimonious interpretation of change in the watershed and lake system. Please note that some of the data and figures presented herein differ slightly from those presented in Ludwig et al. (2020) due to minor refinements of the depth-age model and diatom-based total phosphorus (TP) inference model since the submission of that report.

This is the first study of its kind in the Mara Lake watershed. Data and anticipated results from this study are expected to inform best management and remediation measures to manage anthropogenic phosphorus loading and eutrophication risk in Mara Lake.

Methods

Core Collection and Dating

Two sediment cores were collected from Mara Lake. The first was collected in January 2019 using a gravity corer, and the second was collected in November 2019 using a percussion corer. Both were taken from approximately the same spot in the lake. The cores were 23 and 102 cm long, respectively, and were sectioned on-site. The first core was entirely sectioned into contiguous 1-cm intervals, while the second core was selectively subsampled.

Six sediment samples from the first core and three from the second core were sent to Flett Research Ltd for radiometric dating to establish depth-age profiles. Core chronologies were based on measurement of ^{210}Pb and ^{226}Ra radioisotopes using alpha spectrometry. A unified depth-age profile was developed using a linear slope regression model.

Phosphorus Accumulation

Sediment total phosphorus was measured using standard methods (Andersen, 1976). Briefly, wet sediment was subsampled from each core interval, weighed, dried, and re-weighed to calculate bulk density. Samples were then combusted in a furnace at 450°C for 4 h and re-weighed to calculate loss-on-ignition (LOI). Next, 20 mL 1N HCl was added to LOI sediments in lidded plastic vials. Samples were agitated and heated at 200°C for 1 h with lids on, then left to cool and settle at ambient temperature for 24 h. The liquid from the settled sediment solution was then decanted into glass vials for spectrophotometric analysis.

A 0.5 mL subsample of supernate was drawn from each sample and 24.5 mL of ultrapure water was added. Next, 1 g of potassium persulfate was added to each of the dilute supernate subsamples before autoclaving for 1 hr. Samples were then removed from the autoclave and cooled at room temperature for 1 hr before 4 mL of prepared reagent was added to each (reagent composition: 50 mL 5N H_2SO_4, 5 mL potassium antimony tartate solution [~0.0035 g/mL], 15 mL ammonium molybdate solution [~0.04 g/mL], 30 mL ascorbic acid solution [~0.0176 g/mL]). Samples were left to develop colour for 10 minutes before absorbance readings at 885 nm were taken using a spectrophotometer, which was blanked with ultrapure water.

Diatom Analysis

Approximately 5.0 mg of well-homogenized freeze-dried sediment was subsampled from each core interval and suspended in 5.0 ml 30% hydrogen peroxide in a 50 ml polypropylene centrifuge tube for 18 h before being immersed in a heat bath at 80°C for 6 h. The samples were allowed to cool and settle at ambient temperature for 1 h, then rinsed by filling each tube to 50 mL with ultrapure water and centrifuging for 10 m at 1200 rpm, after which the supernatant was aspirated down to 5 ml. This rinse-centrifuge-aspirate cycle was repeated three times for each sample. To neutralize carbonates, 1.0 ml 10% hydrochloric acid was added to each tube and allowed to react for 1 h, then the rinse-centrifuge-aspirate cycle was again repeated three times for each sample. After the final aspiration, samples were diluted to 20.0 mL with ultrapure water. Slides were created by pipetting 700 µL of well-mixed sample solution onto cover slips and allowing it to dry, then mounting the slips onto glass slides with Naphrax permanent mounting medium.

For the first core, every second interval was analyzed for diatoms, starting at 0 cm (i.e., 0-1 cm, 2-3 cm, … 22-23 cm), and for the second core, three selected intervals (25-36 cm, 75-78 cm, and 125-127 cm) were analyzed, totalling fifteen slides. Diatom valves were enumerated at 1000x magnification using a Zeiss AX10 compound microscope equipped with differential interference contrast optics (numerical aperture = 1.3). An INFINITY5-3 camera with accompanying software (Infinity Analyze; Teledyne Lumenera, 2019) was used along with printed and online photographic keys (primarily Diatoms of North America, 2019; Cumming et al., 1995; Krammer & Lange-Bertalot, 1991a,b; 1997) to identify diatom valves to the lowest taxonomic level confidently attainable, typically species. On each slide, random fields of view were selected and all eligible diatom valves within were counted until a minimum of 300 valves per slide was reached, a threshold considered to provide adequate statistical power for most datasets (Battarbee, 2001). Only diatom valves with ≥50% of the valve visible and intact were considered eligible, to avoid double-counting. Siliceous golden-brown algae (Chrysophyceae) scales were also counted, but only identified to class.

Diatom assemblage changes in the Mara Lake sediment cores were evaluated to determine if they indicated variations in phosphorus loading over time, and if they were consistent with the sedimentary phosphorus record and modern water chemistry data. Diatom diversity indices (rarefied taxonomic richness and Shannon's diversity index; Birks, 2010; Chao et al., 2014) were calculated and plotted over time, as were total diatom frustule and chrysophyte scale accumulation. Stratigraphically constrained cluster analysis by means of incremental sum of squares (Grimm, 1987) was carried out on the diatom percentage data using TILIA paleontological software (Version 2.6.1; Grimm, 2019) to objectively delineate diatom assemblage zones. Finally, historical TP concentrations in Mara Lake were reconstructed using diatom-based TP inference models previously developed using weighted-averaging regression on a 251-lake British Columbia calibration dataset (Cumming et al., 2015). Undetermined valves laying in girdle view were excluded from all analyses except total diatom accumulation, while taxa designated "cf." (short for the Latin *confer*, meaning "compare", i.e. *similar to*) were treated as unique taxa in all analyses except the TP reconstruction.

Results

Core Chronology

The ^{210}Pb activity profile of the first core shows an irregular but approximately exponential decrease as a function of depth. The maximum activity of 8.63 DPM/g observed in the topmost dated section (0-1 cm) is about 1.7 times the lowest activity of 5.11 DPM/g observed in the lowest dated section (17-18 cm). ^{226}Ra was measured at 2.34 DPM/g and 2.32 DPM/g in section 3-4 cm and section 19-20 cm, respectively. The net unsupported ^{210}Pb activity in section 17-18 cm is significantly higher than the nearest neighbouring ^{226}Ra measurement, indicating that background levels of ^{210}Pb were not achieved in this core. Dry bulk density values gradually increase with depth, from 0.033 g/cm^3 at section 0-1 cm to 0.421 g/cm^3 at section 17-18 cm.

In the second core, ^{210}Pb activity is low in all sections, with only the topmost dated section (25-26 cm; 2.41 DPM/g) registering marginally higher than the nearest neighbouring ^{226}Ra measurement (19-20 cm; 2.32 DPM/g). This indicates that background levels of ^{210}Pb were likely achieved, but because the core lacks surface sediments, a complete ^{210}Pb inventory was not obtained and thus a constant rate of supply model could not be applied. Dry bulk density values vary from 0.404 g/cm^3 to 0.510 g/cm^3 and do not appear to increase with depth.

A unified depth-age profile was developed using a linear slope regression model (Figure 1). The regression was performed on the ^{210}Pb activity from the first core only ($R^2 = 0.9478$) due to the uniformly low ^{210}Pb activity in the second core. Sedimentation rates were relatively high with an average rate of about 0.223 g/cm^2/y. Because dated sections below 26 cm exhibit ^{210}Pb activity that is not significantly different from background levels, dates older than about 1950 are rough estimates only.

Phosphorus Accumulation

Phosphorus accumulation in Mara Lake sediments increased by about 20% from 1980 to present day (Figure 2). This is broadly consistent with observations of increasing nutrient levels in Mara Lake over recent decades (TriStar, 2014).

Because phosphorus accumulation depends on loading, and loading depends significantly on discharge, phosphorus accumulation was compared to discharge from the Shuswap River from 1980 to present, using data from the Water Survey of Canada. Discharge did not exhibit a trend over this period, thus contemporary increases in phosphorus accumulation are independent of discharge.

Phosphorus accumulation in the 19th century is only represented by a single sample, which exhibits the second-highest value in the time series (0.294 mg/cm^2/y), surpassed only by a peak of 0.299 mg/cm^2/y in 2008. Discharge data are not available for the 1800s, consequently this high historical value may be attributable to wetter conditions causing more discharge in the Shuswap River.

Diatom Analysis

A total of 327 unique diatom taxa were found in the Mara Lake sediment samples. This figure excludes undetermined valves laying in girdle view because such specimens cannot be unambiguously identified as belonging to unique taxa (except for *Aulacoseira* species). Of these 327 taxa, 283 were identified to genus level or lower, and 194 were identified to species level or lower. In terms of diatom valves, 4550 valves were counted in total, of which 3975 (87%) were unambiguously assigned to a unique taxon, 3891 (86%) were identified to genus level or lower, and 3670 (81%) were identified to species level or lower.

The dominant diatom taxa, defined here as those comprising ≥1% of the total valve count or ≥2% of the valves in any sample, are plotted in Figure 3. A diverse range of planktonic and benthic diatom species are represented in the dominant assemblage, including centric, monoraphid, araphid, biraphid, and nitzschioid morphologies (Figure 4). To ensure data quality, the identities of the dominant diatom taxa were independently verified by an experienced taxonomist (J. Brahney, personal communication, May 2020).

The diatom assemblage shows considerable change over time, especially among centric, planktonic taxa. The most abundant diatom, centric species *Discostella stelligera*, exhibits relatively low values before about 1900, peaks at 24% abundance around 1980, and declines rapidly thereafter to pre-20th-century levels. This is notable because *D. stelligera* has a low TP optimum of 5.3 µg/L (Cumming et al., 2015) and is commonly associated with oligotrophic conditions. *Stephanodiscus minutulus* and *Stephanodiscus parvus*, a pair of centric diatoms with relatively high TP optima (26.5 and 27.5 µg/L, respectively; Cumming et al., 2015) exhibit a roughly opposite response to that of *D. stelligera*, reaching minimum levels around 1960. *Pantocsekiella comensis*, another planktonic centric species, is absent from the record until about 1990, after which it rapidly increases to steadily comprise 5-7% of the assemblage. Other taxa, including a variety of benthic monoraphid, araphid, and biraphid species (e.g., *Achnanthidium minutissimum*, *Staurosirella pinnata*, *Sellaphora saugerresii*) maintain relatively steady levels throughout the profile.

Stratigraphically constrained cluster analysis of the complete diatom dataset reveals that diatom assemblages in sediments older than 1995 are more alike than they are to diatom assemblages in younger sediments (Figure 3).

Rarefied diatom taxonomic richness shows a generally positive trend over time (Figure 5), increasing from an average of 76±4 taxa per sample prior to 1995 (n=7) to 84±3 taxa per sample thereafter (n=8), a statistically significant increase (Welch's t-test; p=0.005). Note that actual taxonomic richness is undoubtedly higher than the values reported here, due to sample size effects (Battarbee, 2001).

Rarefied diatom taxonomic diversity, as measured by Shannon's diversity index (*H*; Figure 6), is generally stable before 1995, after which it increases rapidly and significantly (Welch's t-test; $p<0.001$), reaching its maximum value in the present day.

Diatom accumulation is a measure of the total number of diatom frustules accumulating per unit sediment surface area per year (Figure 7) and serves as a general proxy for diatom productivity. Values are highest before the 20th century but decline steadily over time, reaching a minimum around 1960. Diatom accumulation increases between 1960 and 1980 and remains relatively steady thereafter, with only minor fluctuations. Modern values are about half of those seen before 1900.

Chrysophyte scale accumulation similarly serves as a general indicator of golden-brown algae productivity (Figure 8). Historical values are low relative to those in recent decades. The minimum value occurs around 1960, after which it increases, peaking around 1990. Chrysophyte scale accumulation subsequently declines through the 1990s, but this trend reverses around 2000 and values increase rapidly thereafter, reaching a maximum in the present day.

Previously-developed diatom-based TP inference models trained on a 251-lake British Columbia calibration dataset were successfully used to reconstruct historical TP levels in Mara Lake. Several model variants were explored, and a version based on simple weighted averaging with inverse deshrinking and no tolerance downweighting was ultimately selected because of its reasonable performance in a previous study in Osoyoos Lake (bootstrapped $R^2 = 0.53$; Cumming et al., 2015) and its plausible output when applied to the Mara Lake dataset. The reconstruction incorporates all taxa shared between the Mara Lake and calibration datasets, ranging from 46-62% (mean = 53%) of the valve count, depending on the sample.

Inferred historical TP values range from about 7 µg/L (oligotrophic) to 15 µg/L (mesotrophic), with values in the past two decades varying from about 10-12 µg/L (mean = 11 µg/L; Figure 9). Inferred TP levels are at their highest prior to the 20th century but decline steadily over time, reaching a minimum around 1960-1980, before increasing rapidly through the 1980s and 1990s, achieving current-day values by about 2000.

Discussion

The present study provides the first multiproxy paleoenvironmental assessment of Mara Lake in the Shuswap region of interior British Columbia. Siliceous algal fossils and sediment phosphorus were analyzed and interpreted with the aid of previously-developed species-environment transfer functions to provide a credible inference of historical phosphorus loading in Mara Lake.

The Mara Lake sediment record preserves a diverse assemblage of over 300 diatom taxa that exhibits considerable compositional change over the past two centuries, especially from about 1980 onward. Cluster analysis reveals a marked shift in the identities and relative proportions of diatom taxa in Mara Lake throughout the 1990s, concurrent with a significant increase in diatom taxonomic diversity. Changes in the relative abundance of key indicator species across this horizon (e.g., *Discostella stelligera, Stephanodiscus parvus, S. minutulus*) suggest increasing phosphorus concentrations in Mara Lake since the mid-20th century and a shift from oligotrophic to oligo-mesotrophic conditions. The diatom community data furthermore suggest that before the mid-20th century, TP levels in Mara Lake may have been comparable to modern values. These changes are especially pronounced among planktonic species, presumably because planktonic species are better indicators of lake-water TP (Cumming et al., 2015). Many benthic species show little change throughout the record.

Output from diatom-based TP inference models is consistent with the changes seen in key indicator species. Diatom-inferred TP is relatively high prior to the mid-20th century, reaches a minimum around 1960-1980, and then increases again from 1980 to present. Modern inferred TP values align well with measured values of about 11 µg/L (Jensen, 2010).

It should be noted that diatoms respond to a variety of environmental variables beyond phosphorus availability (e.g., pH, water transparency, temperature), and these secondary factors are likely partially responsible for the changes observed over time in the Mara Lake diatom record. For example, *Pantocsekiella comensis* appears abruptly in the diatom record in the 1990s, and while this species is known to respond to phosphorus availability (Cumming et al., 2015), it is also known to be highly sensitive to climate-related changes, such as length of ice-free season and stratification (Rühland et al., 2008). However, despite the probable influence of secondary environmental variables on the Mara Lake diatom assemblage, previous studies have demonstrated that the TP inference model employed here is robust and possesses acceptable predictive ability, providing confidence in the conclusions of the current study.

Analysis of sediment phosphorus accumulation by means of spectrophotometry yields a profile that is in good agreement with the diatom-inferred TP reconstruction. Both proxies indicate that phosphorus loading in Mara Lake was relatively high before the 20th century, was relatively low at the onset of major land-use change in the mid-20th century, and subsequently increased throughout the 1980s and 1990s to the oligo-mesotrophic levels seen at present day, which are comparable to those seen prior to 1900.

Taken together, diatom-based TP inference modelling and sediment phosphorus data indicate that phosphorus levels in Mara Lake today are probably not unprecedented in its history. The phosphorus yield of undisturbed forest in the Shuswap watershed is extremely low (Ludwig, 2018), so the relatively high inferred phosphorus values prior to major land-use changes are somewhat surprising. A possible explanation is that elevated phosphorus inputs may have been driven by higher historical discharge from the Shuswap River. Discharge data do not exist for this time period, so this explanation must remain speculative. It is also likely that erosion in the watershed and riverbed were lower in the past, potentially increasing the phosphorus concentration in sediment by reducing the total sediment load (i.e., dividing the phosphorus load by a smaller amount of sediment). These processes are not mutually exclusive, and both may have been operating.

Another key conclusion of this study is that total phosphorus levels in Mara Lake at the onset of major land-use change in the 20th century were likely lower than today and have increased since the 1980s. This is significant because this time period lies within the lifetime of many residents of the Shuswap region, meaning the "baseline" condition of Mara Lake for these individuals is likely to be its oligotrophic mid-20th century state. Within living memory, residents have witnessed the consequences of steadily increasing phosphorus loading in Mara Lake.

Overall, the paleolimnological inferences of increasing phosphorus loading and increasing abundance of bloom-forming algae in recent decades are consistent with contemporary observations and the mass balance of phosphorus in the Shuswap watershed as land use has changed. The results of the present study are summarized along with estimates of anthropogenic phosphorus loading from mass balance approaches in a separate synthesis report (Ludwig et al., 2020), which contains a variety of actionable management recommendations for reducing phosphorus loading to Shuswap and Mara Lakes.

Acknowledgements

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Figures

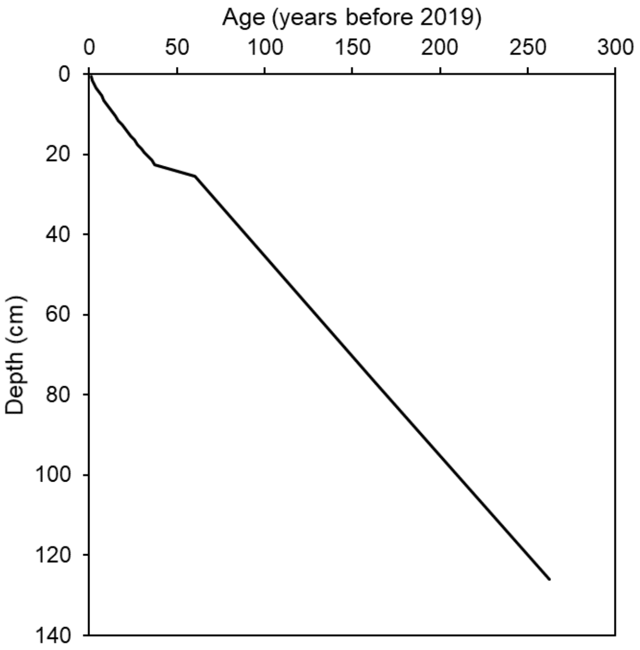

Figure 1. ^{210}*Pb age-depth model for Mara Lake sediments determined using a slope regression model. Dates older than ca. 70 years are rough estimates only.*

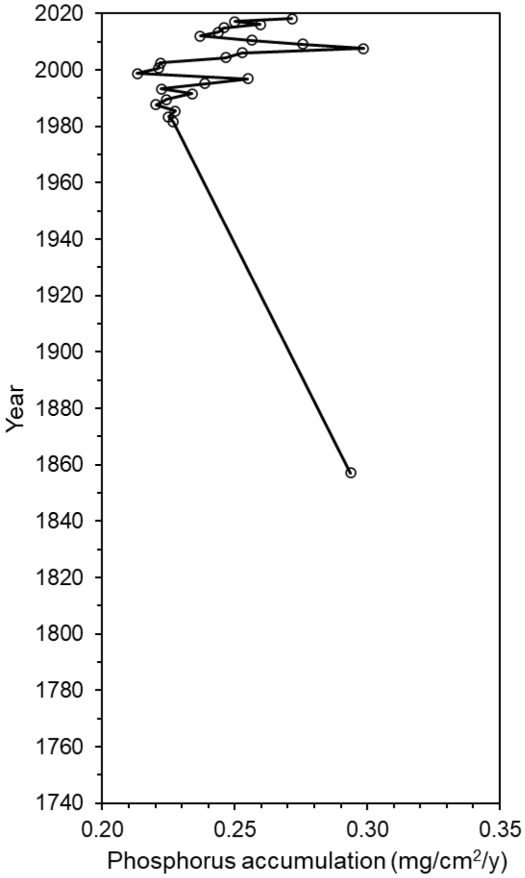

Figure 2. Phosphorus accumulation in the Mara Lake sediments as measured by spectrophotometry. Open circles denote individual samples. Dates older than ca. 1950 are rough estimates only.

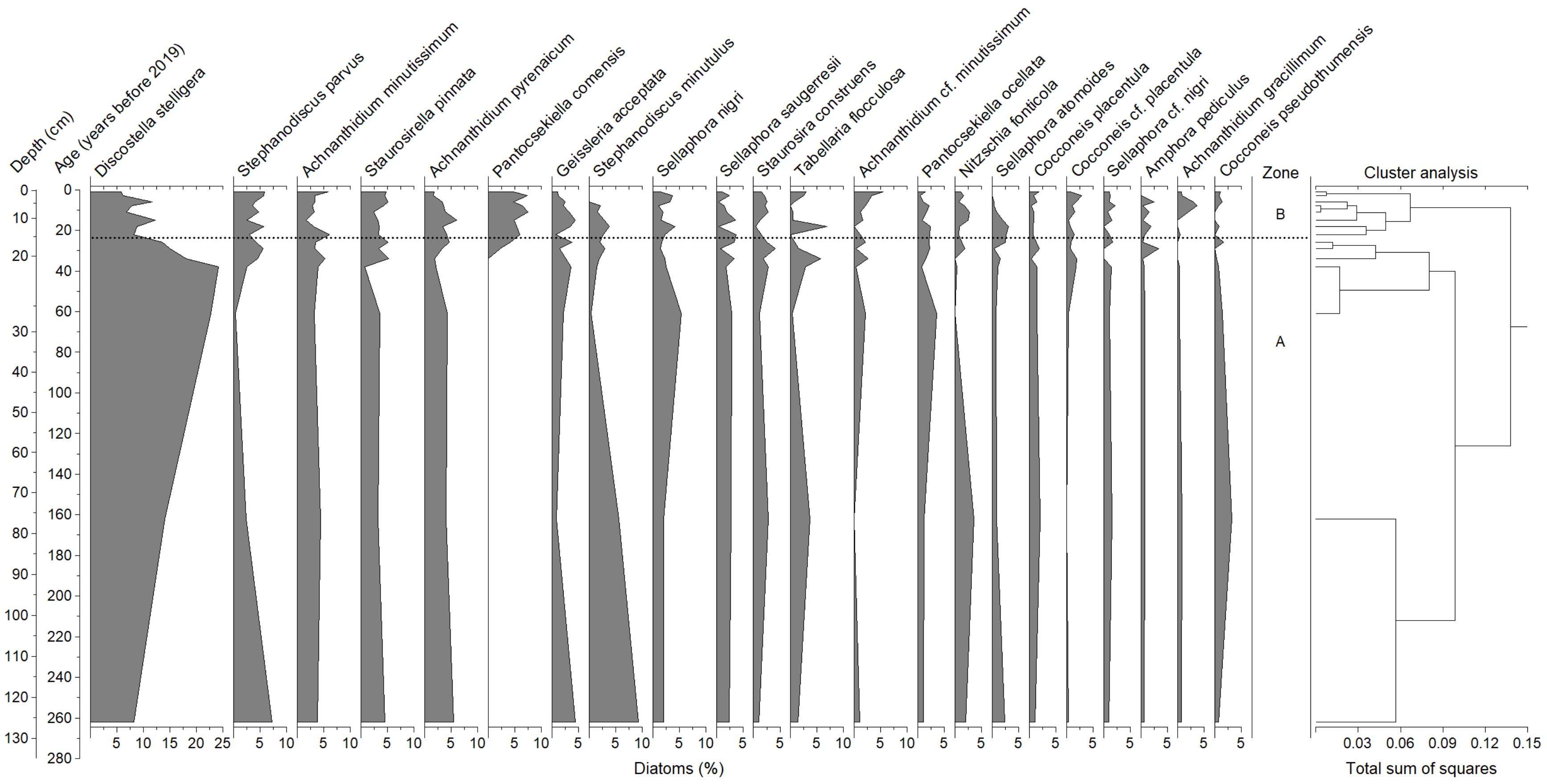

Figure 3. Microfossil percentage data for dominant diatom taxa (defined as those comprising ≥1% of the total valve count or ≥2% in any sample) in the Mara Lake sediment samples. The horizontal dotted line delineates the zones defined by stratigraphically constrained cluster analysis by the method of incremental sum of squares (CONISS). Plotted at right is the dendrogram of dissimilarity generated by the CONISS operation. Ages older than ca. 70 years are rough estimates only.

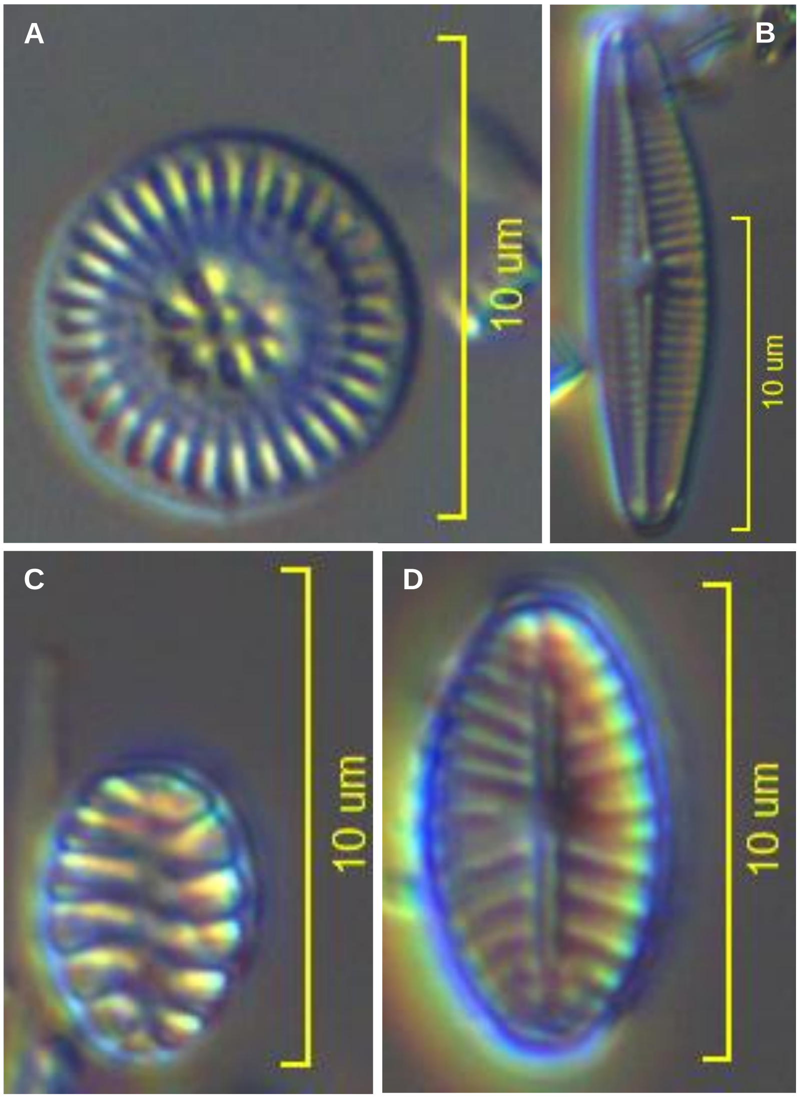

Figure 4. Light micrographs of selected fossil diatom valves from the Mara Lake sediment samples. Images taken at 1000x magnification using differential interference contrast optics (numerical aperture = 1.3). A) Discostella stelligera B) Achnanthidium minutissimum C) Staurosirella pinnata D) Geissleria acceptata

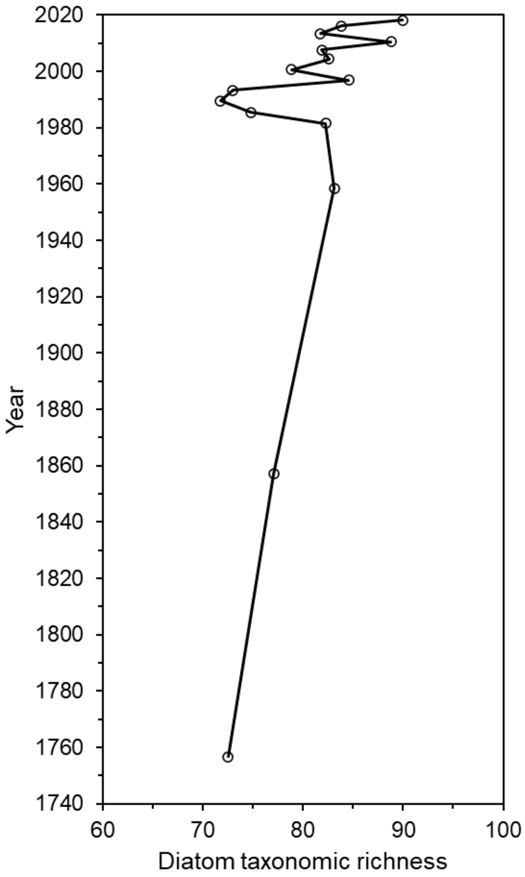

Figure 5. Rarefied taxonomic richness for the Mara Lake diatom microfossil assemblage. Open circles denote individual samples. Dates older than ca. 1950 are rough estimates only.

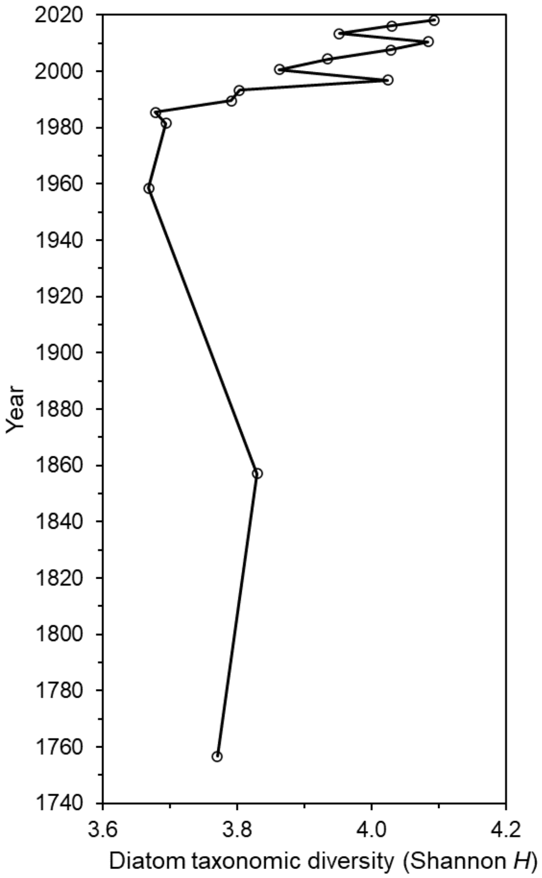

Figure 6. Rarefied taxonomic diversity (Shannon's diversity index, H) for the Mara Lake diatom microfossil assemblage. Open circles denote individual samples. Dates older than ca. 1950 are rough estimates only.

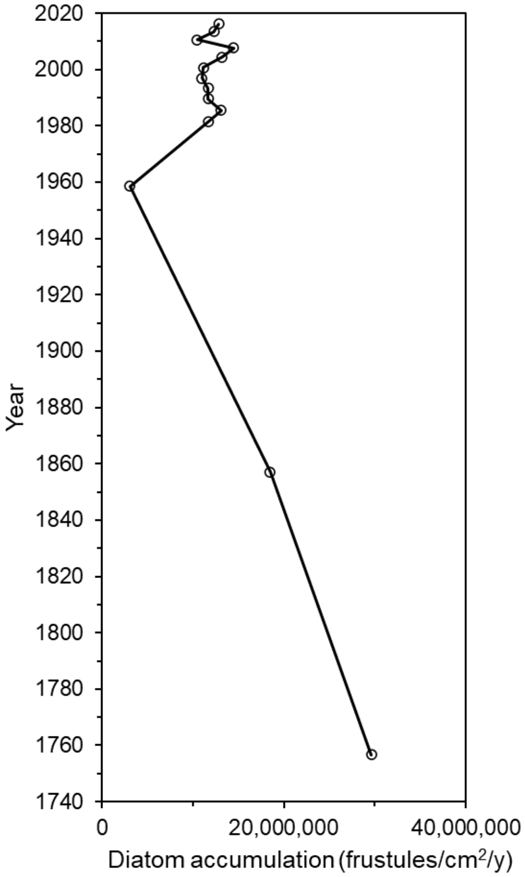

Figure 7. Diatom microfossil accumulation in the Mara Lake sediments. Open circles denote individual samples. Dates older than ca. 1950 are rough estimates only.

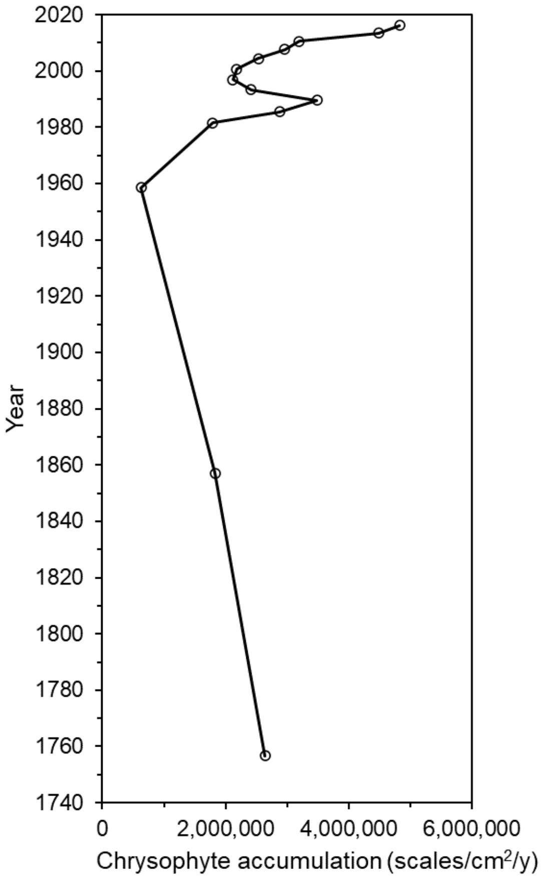

Figure 8. Chrysophyte microfossil accumulation in the Mara Lake sediments. Open circles denote individual samples. Dates older than ca. 1950 are rough estimates only.

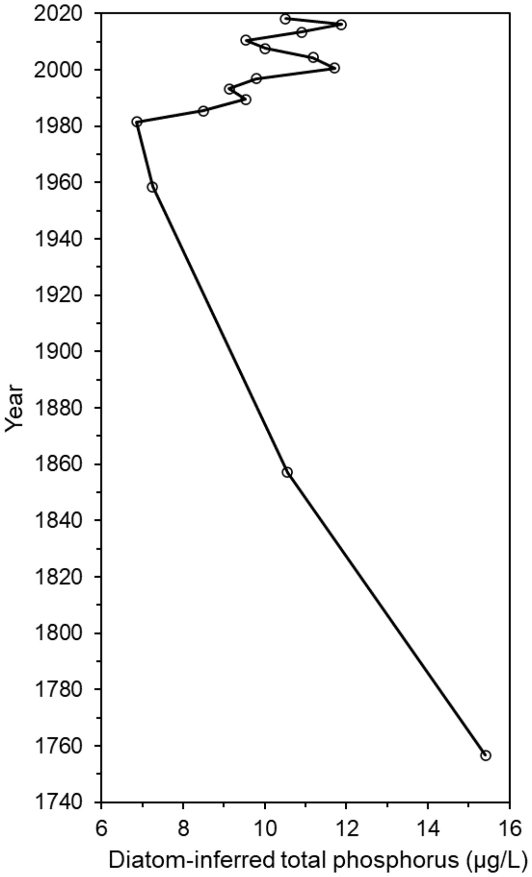

Figure 9. Diatom-inferred total phosphorus reconstruction for Mara Lake. Open circles denote individual samples. Dates older than ca. 1950 are rough estimates only.