OSOYOOS LAKE SEDIMENT CORE PROJECT – FINAL REPORT

Assessment of the changes in trophic state of Osoyoos Lake, British Columbia: A Paleolimnological Assessment

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Final Report to the Okanagan Basin Water Board, submitted on behalf of the University of British Columbia Okanagan

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ABSTRACT

To obtain better historical information on nutrient loading to Osoyoos Lake, sediment cores were collected from the north and south basins of Osoyoos Lake in June 2008. ^{210}Pb dating was used to develop a chronology for the cores, and to estimate rates of sediment accumulation. Changes in algal pigment concentrations and diatom communities, as preserved in the cores, were used to infer changes in algal production and Total Phosphorus (TP) concentrations since European settlement.

The pigment data and diatom-inferred TP levels for Osoyoos Lake generally indicate mesotrophic conditions over the past ~200 years, with highest levels in the north basin between ~ 1950 to 1990, and in the south basin from ~ 1960 to 1990. Post-1990 the diatom-inferred TP values decrease, corresponding to a similar finding in measured phosphorus levels.

In the north basin estimated TP has a strong correlation with PCA axis-2 scores, whereas in the south basin there is a relatively strong correlation with PCA axis-1 scores. This suggests that the changes seen in the diatom assemblages are consistent with the changes seen in the TP estimates, however other factors are also influencing the diatom assemblages. Other factors include climatic variability, which can influence the ice-free period and consequently other limnological variables. Climate and its influence on nutrients, water column stability and the ice-free period is likely one of the forcing factors influencing the abrupt increase of *C. comensis* in both basins.

INTRODUCTION

In 2007 at the Osoyoos Lake Water Science Forum, scientists, researchers, First Nations and political leaders met to discuss the current condition of Osoyoos Lake and its future. Participants identified the need for better historical data as a priority.

To address this need, a proposal for collaborative research was submitted to the Okanagan Basin Water Board, backed by the British Columbia Ministry of Environment, Osoyoos Lake Water Quality Society, Okanagan Nation Alliance, and the University of British Columbia Okanagan. The partners sought to reconstruct historical nutrient concentrations in Osoyoos Lake from palaeoenvironmental data – specifically through pigment and diatom analyses on dated sediment cores collected from the north and south basins. Some palaeoecological research had been conducted at Osoyoos Lake many years earlier, as a part of the Okanagan Basin Study (Anderson, 1973; Pinsent & Stockner, 1974), and as an Okanagan University College student project (Ryder 1994), but recent advances in palaeoecological methods now facilitate a much more detailed assessment of lake nutrient levels and human impacts.

The proposal was favourably received. Grant funding provided by the Okanagan Basin Water Board and British Columbia Ministry of Environment facilitated field work in 2008, and generated sufficient funds for the required ^{210}Pb dating and diatom analyses. This document constitutes the final report of this research partnership to the Okanagan Basin Water Board, and all other individuals and agencies that contributed to the project. The research protocol, outcomes, and conclusions are briefly outlined in the pages which follow.

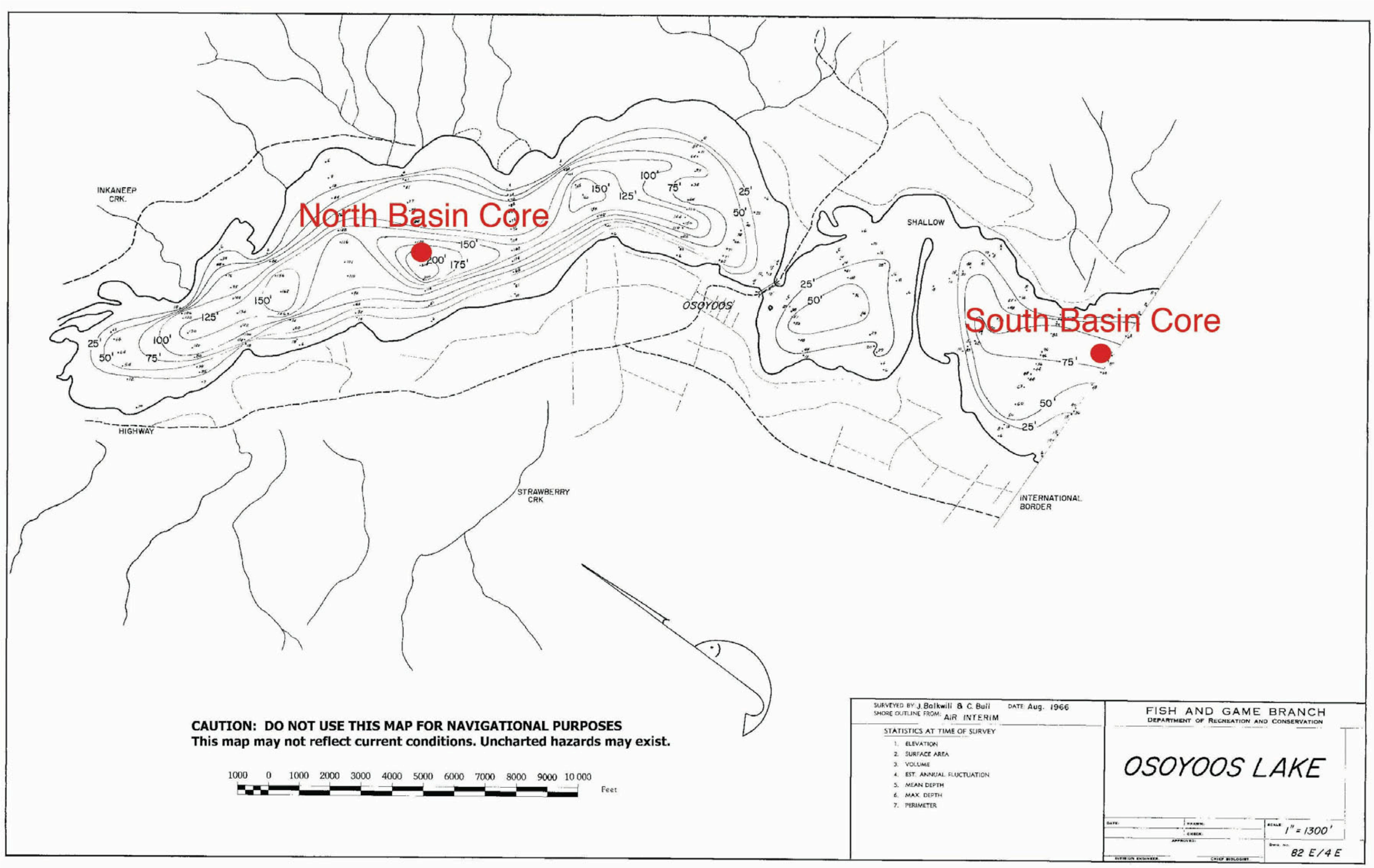

Figure 1. Map indicating approximate location of coring sites in the north and south basins of Osoyoos Lake.

Figure 2. Collection of sediment cores.

Figure 3. Extrusion of sediment cores.

METHODS

Core Sampling Methods

Two sediment cores were retrieved from Osoyoos Lake with a slide hammer corer (internal diameter ~6.35 cm) on June 17th and 18th, 2009 (Fig, 1, 2, 3). The core from the north basin was 90 cm in length and the core from the south basin was 99 cm in length. Samples were sectioned into 0.5-cm intervals, and later shipped to Queen's University via Dr. Irene Gregory Eaves (McGill University). The weight of all samples was determined at McGill University to determine the total wet weight of sediment prior to subsampling for ^{210}Pb, loss-on-ignition, diatom and pigment analyses. Once samples were subsampled for pigment analysis at McGill University, the cores were sent to Queen's University for ^{210}Pb, loss-on-ignition and diatom analyses. Thirty-two intervals were subsampled for diatoms from each of the Osoyoos Lake sediment cores, every 2 cm from 1 to 29 cm, then every 4 cm to 97 cm.

^{210}Pb Dating and Percent Organic Matter

Twenty-one intervals from the north basin core and twenty-two samples from the south basin core were prepared for ^{210}Pb analysis and counted using gamma spectroscopy at PEARL, Queen’s University, with samples more closely spaced in the higher activity region in the top sediments, and at coarser intervals down core. The same intervals for ^{210}Pb analysis were analyzed for percent organic matter.

Samples for the Osoyoos Lake cores were dried in the freeze drier at PEARL (24 hr. cycle) and the dry weight and percent moisture in each sample was determined. Due to the long length of the cores and the previously noted high sedimentation rate in Osoyoos Lake, extra samples (from the standard sixteen) were prepared for ^{210}Pb. Dried sediment was weighed into a plastic tube for gamma spectroscopy and the weight was recorded. The samples were then sealed with epoxy and allowed to sit for two weeks in order for ^{214}Bi to equalize with ^{226}Ra, the parent isotope of ^{210}Pb. Activities of ^{210}Pb, ^{137}Cs and supported ^{210}Pb (via ^{214}Bi) were determined for each sample using gamma dating following the procedures and similar equipment outlined in Schelske et al. (1994). Unsupported ^{210}Pb activities were used to estimate the chronology of the cores using the constant rate of supply (CRS) model (Appleby and Oldfield 1978) using the computer program developed by Binford (1990). Unsupported ^{210}Pb was calculated by subtracting supported ^{210}Pb.

Percent organic matter was determined using standard loss-on-ignition (LOI) methods (Dean, 1974). Briefly, a known quantity of dried sediment (recorded to four decimal places) was heated to 550°C for 2 hours. The difference between the dry weight of the sediment and the weight of sediment remaining after ignition was used to estimate the percent of organic matter in each sediment sample.

Pigment Analyses

A total of 32 sediment intervals from the north basin core were analysed for fossil pigments. The same intervals were also processed for diatom analyses such that direct comparisons could be drawn. Sedimentary pigments were extracted from freeze-dried sediments in acetone under an argon atmosphere at -20°C for 24 hours.

During extraction of the pigments from the sediment matrix, samples were kept in the dark and on ice at all times to avoid pigment deterioration from light, heat, and oxygen (Leavitt and Hodgson 2001). Samples were then centrifuged, the supernatant was decanted and filtered (0.2 µm), and finally placed into sealed glass vials.

Sample extracts were analyzed using a Waters High Performance Liquid Chromatography (HPLC) system equipped with a photo diode array (Waters model 2996) and a multi wavelength fluorescence detector (Waters model 2475) following the solvent protocol outlined in Zapata et al. (2000). The HPLC produces chromatograms in a specific sequence based on the properties of the compounds being analyzed. The resulting retention time and absorbance spectra are then compared to purified reference materials which allowed identification and quantification of the sedimentary pigments.

For all pigments, the area under the curve was used to calculate the quantity present in each sample. Overall, the chromatograms were analysed for a total of 16 phytoplankton pigments. Plots are only presented for the pigments considered most stable (and are thus robust indicators of each algal functional group).

Diatom Analyses

Diatom Preparation and Enumeration

Slides for diatom analysis were prepared using standard techniques (Cumming et al. 1995). Briefly, a small amount of wet sediment was suspended in a 50:50 (molar) mixture of sulphuric and nitric acid in a 20-ml glass vial for 24 hr. prior to being submersed at 70°C in a hot water bath for approximately 5 hr. The remaining sediment material was settled for a period of 24 hr, at which time the acid above the sample was removed. The sample was rinsed with distilled water and allowed to settle once again for 24 hrs. The procedure was repeated approximately 8 times until the sample was acid free (litmus test). The samples were settled onto coverslips in a series of four 100% dilutions, which when dry, were mounted onto glass slides using the high-resolution mounting medium Naphrax®. For each sample, at least 400 diatom valves were enumerated with a Leica DMRB microscope equipped with DIC optics at 1000X magnification (Numerical Aperature of objective = 1.3). Dr. Kathleen Laird identified and enumerated the diatom values. These analyses were based primarily on the references of Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Patrick and Reimer (1966, 1975) and Cumming et al. (1995).

Absolute abundance of diatoms was determined for all samples analysed for diatoms using methods outlined in Battarbee & Keen (1982). Absolute abundances were determined by spiking each of the diatom samples, prior to settling on coverslips, with a known concentration of microspheres. The microspheres were enumerated along with the diatoms and used to calculate estimates of # diatoms per gram dry weight. Total diatom concentration (#/g dry weight x 107) provides a means of assessing whether there were any changes in diatom production during the time period analysed. Accumulation rates were also calculated by dividing the concentration data by the amount of time represented for each of the intervals.

Diatom-based Reconstructions of Total Phosphorus

Inferences of total phosphorus from the diatom assemblages in the core are based on a phosphorus model developed from 268 freshwater lakes from across British Columbia. This dataset includes lakes from several regions within British Columbia. This model is based on estimates of the optima of taxa from weighted averaging regression on untransformed percentage data. The coefficient of determination (r^2) of this model is 0.62, and the bootstrapped r^2 is 0.51 (Moos et al., in press; St. Jacques et al., in press). This model is superior to earlier models developed by Reavie et al. (1995) for several reasons including its better predictive ability and the larger number of samples which provide more analogues for downcore reconstructions.

The total phosphorus inferences were critically assessed to determine if they tracked the main directions of variation in the diatom species assemblages. If the diatom-based phosphorus reconstructions match the main direction of variation in the diatom assemblages in the core, then we can be fairly confident that the diatoms are tracking changes that are related to phosphorus, or correlated variables. If the correlation between the main direction of variation and the diatom-inferred phosphorus values is weak or nonexistent, then other environmental variables (e.g. water column stability, water depth, conductivity, turbulence, etc), or interactions between environmental variables, are likely responsible for the observed changes in diatom assemblages.

Determination of the Main Directions of Variation

The main directions of variation in the diatom assemblages in the Osoyoos Lake cores were determined from the axis scores from a principal components analysis (PCA) ordination using untransformed species abundance data. PCA was chosen to represent the main directions of variation of the diatom assemblages because the gradient length in an initial detrended correspondence analysis was < 1.5 standard deviation units. Correlations between the estimated total phosphorus (TP) and the first two PCA axes were determined.

Cluster Analysis

Cluster analysis provides a means of grouping those samples that are most similar to each other. The programs, TILIA and TGVIEW 2.02 (Grimm, unpublished), were used to determine similar zones downcore based on the diatom assemblages. The cluster analyses were stratigraphically constrained in order to group the assemblages according to core depth (or core age) using a squared Euclidean similarity coefficient. As with the other analyses, species data were not transformed.

RESULTS

North Basin

^{210}Pb Profile and Organic Matter

The ^{210}Pb activity of the north basin core (Fig. 4a) was low throughout its length, however unsupported ^{210}Pb exhibited a statistically significant exponential decay with the cumulative dry mass in the core. The peak in the ^{137}Cs signal (Fig. 4b) deep in the core at 50 cm confirms the high sedimentation rate in Osoyoos Lake. A distinct peak in ^{137}Cs is a marker for ~1963, since 1963 corresponds to the peak in atmospheric testing of nuclear weapons, and consequently fallout of isotopes such as ^{137}Cs. The peak in ^{137}Cs corresponds reasonably well to the estimated ^{210}Pb date of 1961 at the 43 cm interval.

Analysis of organic matter (OM) from the core indicates highly inorganic sediments with the organic component only comprising ~5 to 12% of the sediments (Fig 4c). Organic matter increases towards the top of the core from ~7 to 12% starting at ~ 15cm (AD 1996). Increases in organic matter can be attributed to several factors including increased in-lake production of organic matter, increased inwash of organic matter, or decreases in the load of inorganic matter to the lake. Potential other causes include diagenetic processes, whereby the more oxygenated top sediments lose organic matter due to decomposition. Which of these processes is the most predominant factor influencing the OM would have to be pursued with further studies.

Pigments

Total phytoplankton production, as indicated by phaeophytin *a* and beta-carotene (i.e. stable pigments that reflect total algal production; Leavitt and Findlay, 1994), as well as functional group-specific indicator pigments all show a general trend of increasing abundance over time (Fig. 5). A small increase is evident in the mid-19th century which may have occurred at or before the time of European settlement and land clearance.

Larger increases are evident beginning about 1900, initially as higher concentrations of lutein (green algae) and alloxanthin (cryptomonad algae). By 1950 concentrations of all algal pigments, including those of cyanobacteria, had increased. Concentrations for all pigments peak in sediments dating to about 1975.

Pigment concentrations subsequently declined, although secondary peaks are evident in near-surface (post 2000) sediments for beta-carotene, echinenone, diatoxanthin and alloxanthin. These secondary peaks coincide with a rapid increase in the pigment preservation index (chorophyll a : pheopigment ratio).

Diatom Assemblage Changes and Analyses

Two-hundred fifty-four taxa were documented in the north basin core from Osoyoos Lake. However, the majority of these taxa are extremely rare. The planktonic component of the assemblage was quite diverse with 16 taxa exceeding ~3-5%. Although the majority of the taxa were benthic only 9 taxa reached abundances of > 4-5% (Fig. 6). For purposes of graphing, those taxa that were less than ~3-4% were grouped into genera and rare centric and benthic taxa.

Cluster analysis suggests two main diatom assemblage zones in the past ~200 years (Fig. 6). Within each of the two major zones there are subzones (e.g., Zone A1 and Zone A2) that are differentiated by cluster analysis.

Proceeding from the past to the present, the period prior to ~1940 (Zone B2) is dominated primarily by meso-eutrophic planktonic taxa *Aulacoseira subarctica* and *Stephanodiscus minutulus*, and the mesotrophic benthic *Staurosirella pinnata*. Oligotrophic planktonic *Cyclotella* (*C. stelligera* and *C. ocellata*) and mesotrophic planktonics *Asterionella formosa* and *Fragilaria crotonensis* are present at lower percentages. Other mesotrophic benthics present include *Staurosira construens* and *Pseudostaurosira brevistriata*. The main changes of the diatom assemblage in Zone B1 (~1940 to 1967) are decreases in the oligotrophic *Cyclotella*, decrease in *Staurosirella pinnata,* small increase in *Stephanodiscus minutulus* and a sharp increase in the mesoeutrophic planktonic *Stephanodiscus parvus.* Zone B1 is the only period in which *Stephanodiscus parvus* reaches more than a few percent.

The abrupt appearance of mesotrophic planktonics *Cyclotella comensis* and *Cyclotella gordonensis* characterizes Zone A. Other changes in the diatom assemblage in Zone A2 (~1967-1991) include an increase in the mesotrophic planktonic *Tabellaria flocculosa* strains and a large increase in the meso-eutrophic planktonic *Aulacoseira subarctica* in the middle of this zone. The main diatom changes in Zone A1 (~1991-2008) are the large decrease in the meso-eutrophic planktonic *Stephanodiscus minutulus* and a small, short-lived increase in the oligotrophic *Cyclotella stelligera* at the beginning of this zone.

Absolute abundances of the diatom taxa (Fig. 7) indicate similar trends to the percent abundance data, indicating that changes in the percent abundances of taxa described above are not due to the confinements of percentage calculations. Zonation was carried out separately for the concentration data. The zones match the percent data, except for a small difference in the placement of the divide between subzones B1 and B2. Total concentrations of diatoms were lowest in Zone B2, increased in Zone B1 and reached peak abundances in Zone A2. Total diatom concentration then declined in Zone A1.

Diatom-inferred total phosphorus (TP) estimates for the past ~200 years indicate mid-summer conditions that vary between ~14 to 23 μgL^{-1} (Fig. 4d). The lowest TP values occurred in Zone B2 and on average were ~16 μgL^{-1}. The highest values of TP occurred in Zone B1, largely driven by the peak in *Stephanodiscus parvus*. Average TP in Zone B1 was ~20 μgL^{-1}, with levels decreasing slightly in Zone A2 to an average of ~19 μgL^{-1}. With the sharp decline in *Stephanodiscus minutulus* in Zone A1, TP levels decreased to levels similar to pre-1930 (average ~17 μgL^{-1}). The lowest values of TP in this zone correspond to the small peak in *Cyclotella stelligera* in the mid- to late 1990s.

The correlation between PCA axis-1 scores (Fig. 4e) and the log TP inferences is very low (r = 0.24), however correlation with PCA axis-2 scores (Fig. 4f) is high (r = 0.71). This indicates that although the changes seen in the diatom assemblages are consistent with the changes seen in the TP estimates, there are other factors which are influencing the assemblages. Most of the dominant taxa (> 5%), which are driving the reconstructions of TP, are well represented in our modern-day calibration set, thus providing evidence that the TP estimates are reliable. One exception to this is the taxon *Cyclotella comensis* which has very low abundances in the calibration set. *Cyclotella comensis* is taxonomically very similar to *Cyclotella gordonensis* (they are often considered together as a group), thus for the TP estimates the optimum for *Cyclotella gordonensis* was used for *Cyclotella comensis*. The value used of 18.6 μgL^{-1} fits with the literature which indicates *Cyclotella comensis* has an optimum of between ~9-18 μgL^{-1}(Werner and Smol 2006).

South Basin

^{210}Pb Profile and Organic Matter

The ^{210}Pb activity of the south basin core (Fig. 8a) was low throughout its length. Unsupported ^{210}Pb however exhibits a significant exponential decay with cumulative dry mass in the core. The peak in the ^{137}Cs signal (Fig. 8b) deep in the core at 43 cm confirms the high sedimentation rate in Osoyoos Lake. The peak in ^{137}Cs matches the estimated ^{210}Pb of 1962 at the same level.

Analysis of organic matter (OM) from the core indicates highly inorganic sediments with the organic component only comprising ~3 to 13% of the sediments (Fig 8c). Similar to the north basin, organic matter increases towards the top of the core from ~8 to 13% starting at ~ 15cm (AD 1996). As in the north basin, further studies would have to be carried out to attempt to differentiate between the various factors that can influence preservation of OM.

Diatom Assemblage Changes and Analyses

Two-hundred and four taxa were documented in the south basin core from Osoyoos Lake. However, the majority of these taxa are extremely rare. The planktonic component of the assemblage was quite diverse with 18 taxa exceeding ~3-5%. Although the majority of the taxa were benthic, only 7 taxa reached abundances of >4-5% (Fig. 9). For purposes of graphing, those taxa that were less than ~3-4% were grouped into genera and rare centric and benthic taxa.

Cluster analysis suggests two diatom assemblage zones in the past ~200 years (Fig. 7). Within the bottom major zone there are subzones that are differentiated by the cluster analysis (e.g., Zone B1 and Zone B2).

Proceeding from the past to the present, the period prior to ~1920 (Zone B2) is dominated primarily by the meso-eutrophic planktonic taxa *Aulacoseira ambigua* and *Fragilaria crotonensis*, the eutrophic planktonic taxon *Aulacoseira granulata*, and the mesotrophic benthic *Staurosirella pinnata*. Other meso-eutrophic planktonics *Aulacoseira subarctica* and *Stephanodiscus minutulus* are present at lower percentages. Other mesotrophic benthics present include *Navicula submuralis*, *Staurosira construens* and *Pseudostaurosira brevistriata*. The main changes of the diatom assemblage in Zone B1 (~1920 to 1982) are large decreases in the eutrophic planktonic taxon *Aulacoseira granulata*, small increases in the meso-eutrophic planktonics *Asterionella formosa* and *Aulacoseira subarctica*, and small increase in the oligotrophic planktonics *Cyclotella ocellata* and *Cyclotella stelligera.* Near the top of Zone B1, there is a large increase in the meso-eutrophic planktonic taxon *Stephanodiscus minutulus.*

As in the north basin, the abrupt appearance of mesotrophic planktonics *Cyclotella comensis* and *Cyclotella gordonensis* characterizes Zone A. In the south basin, the percent abundance of *Cyclotella comensis* reaches ~20%, whereas in the north basin it only reaches ~10%. Other changes in the diatom assemblage in Zone A (~1982-2008) include small increases in mesotrophic planktonics *Diatom tenuis elongatum*, *Tabellaria flocculosa* strains and *Fragilaria capucina.* The meso-eutrophic planktonic *Stephanodiscus minutulus* decreases near the bottom of this zone, at a similar time when a small, short-lived increase in the oligotrophic *Cyclotella stelligera* occurs. After this period there is a very short-lived peak in the eutrophic planktonic taxon *Aulacoseira granulata angustissima*.

Absolute abundances of the diatom taxa (Fig. 10) indicate similar trends to the percent abundance data, indicating that changes in the percent abundances of taxa described above are not due to the confinements of percentage calculations. Zonation matches the percent data zonation, except there is an extra subzone in Zone B. Total concentrations of diatoms were lowest in Zones B3 & B2, increased slightly near the top of Zone B1 and reached peak abundances near the bottom of Zone A. Total diatom concentration then generally declined towards the top of Zone A, but were still higher than in Zone B.

Diatom-inferred total phosphorus (TP) estimates for the past ~200 years indicate mid-summer conditions that vary between ~16 to 26 μgL^{-1} (Fig. 8d). The lowest TP values occurred in Zones A and B1. There is larger variability in these two zones, with the average TP values only slightly higher in Zone B1, ~20 μgL^{-1}, in comparison to an average of ~19 μgL^{-1} in Zone A. The highest values of TP occurred in Zone B2, largely driven by the high abundance of *Aulacoseira granulata*. Average TP in Zone B2 was ~24 μgL^{-1}. The highest values of TP in Zone A occur in the late 1980s, early 1990s and correspond to the peak in *Aulacoseira granulata angustissima* and *Aulacoseira ambigua.* Post ~1992, TP levels decreased to levels similar to those seen in Zone B1 from ~1930 -1960.

The correlation between PCA axis-1 scores (Fig. 8e) and the log TP inferences is fairly strong (r = 0.58); correlation with PCA axis-2 scores (Fig. 8f) is low (r = 0.33). This indicates that although the changes seen in the diatom assemblages are consistent with the changes seen in the TP estimates, there are other factors which are influencing the assemblages. As outlined above, most of the dominant taxa (> 5%), which are driving the reconstructions of TP, are well represented in our modern-day calibration set, thus providing evidence that the TP estimates are reliable, with the exception of *Cyclotella comensis*. As in the north basin the TP optimum for *Cyclotella gordonensis* was used for *C.comensis* (see discussion under north basin section).

DISCUSSION

Pigments

Total phytoplankton production, as indicated by phaeophytin *a* and beta-carotene (i.e. stable pigments that reflect total algal production; Leavitt and Findlay, 1994), as well as functional group-specific indicator pigments all show a general trend of increasing abundance over time (Fig. 5). This pattern is consistent with a history of nutrient additions (from point and non-point sources) in the Osoyoos Lake watershed. For the most part, this pattern is not an artefact of changes in preservation of pigments with sediment depth because the ratio of chl a: total phaeopigments (a common metric for evaluating diagenesis; Guilizzoni and Lami, 2003) is relatively stable over the sediment record. An exception to this observation, however, is the sharp peak between 1999-2008 AD. Based on this peak, we suggest that the higher concentrations of pigments from 1999-2008 AD be interpreted cautiously.

The higher pigment concentrations between 1999-2008 AD may reflect changes in production or perhaps changes in pigment preservation. The increase in diatom-inferred total phosphorus concentrations (DI-TP) at this time provides an indication that nutrient concentrations may have increased. However, this interpretation should be confirmed through comparative analyses of the long-term phytoplankton records from Osoyoos Lake.

A subtle increase in pigments was already evident ~1840 AD (Fig. 5). This event may be related to early land clearance in the region, but it might also pre-date European settlement.

Correlation analyses between the pigment and diatom data showed significant coherence, suggesting that a robust trophic history can be inferred from these records. In particular, we detected a significant correlation between phaeophytin *a* (a metric of total algal production) and diatom-inferred total phosphorus concentrations (DI-TP; Fig. 11). These two independent lines of evidence clearly indicate that nutrient and algal concentrations peaked between 1949 and 1990. We also detected a significant relationship between diatoxanthin (a robust indicator of diatoms; Leavitt and Hodgson, 2001) and diatom concentrations (Fig. 12).

Across the functional group-specific indicator pigments, diatoxanthin showed the largest increase in abundance over time (Fig. 13). These data suggest that changes in algal production over the course of the record have, in large part, been due to changes in diatom production. The most recent peak in diatoxanthin falls within the window where the chl *a*: sum phaeopigment ratio was highest and thus it is unclear whether this represents a real increase in diatom production (as noted above). However, the diatom concentration profile shows a slight increase over this same time window and thus suggests that diatom production increased.

Abrupt Appearance of Cyclotella comensis

Recent increases in small *Cyclotella* species (including *C. comensis*/*gordonensis* group) have been noted in many Arctic and temperate lakes around the world (Rühland et al. 2008). These changes were attributed to climatic changes such as increased air temperatures and increased ice-free periods of the lakes. The temporal extent of ice cover can influence many variables within the lake ecosytem, including nutrient levels, lake temperature, water column stability and light availability (e.g., Bigler & Hall 2003). The few seasonal studies of *C. comensis* primarily suggest that it blooms in the late summer, early fall, but can also have small blooms in the spring (Pappas

& Stoermer 1995, Raubitschek et al. 1999, Wolin & Stoermer 2005). *C. comensis* is often found in the deep chlorophyll maximum in the metalimnion where nutrient levels can be higher (Wolin & Stoermer 2005, Rühland et al. 2008).

Some studies have suggested that the recent increases seen in *C. comensis* may be related to increased nitrogen levels. The experiments of Pappas & Stoermer (1995) indicated that increasing nitrogen levels and increasing N:P ratios had a positive influence on the abundance of *C. comensis*. Werner and Smol (2006) found a negative correlation between *C. comensis* and nitrogen, but found a positive correlation with TN:TP levels. This study of ~ 100 Ontario lakes noted that *C. comensis* was more common in polymictic lakes with high summer Si:TP concentrations. Other studies have also suggested that changes in epilimnetic Si:P ratios may influence the abundance of *C. comensis* (e.g., Wolin & Stoermer 2005). The very abrupt appearance of *C. comensis* in both basins suggests its appearance may not be solely related to the decreasing phosphorus levels that started in the 1980s, since measured phosphorus levels did not decrease substantially in the lake until the mid 1990s. Additionally, both diatom-inferred records indicate that levels did not decrease until the 1990s (Fig. 14). Thus this increase in *C. comensis* occurs prior to substantial changes in the inferred TP levels of the lake. As a consequence, this abrupt increase in *C. comensis*, as seen in other records (e.g., Rühland et al. 2008), may be related to climatic factors that can influence nutrient levels, water column stability, and seasonality.

A detailed study of Lake of the Woods - White Fish Bay showed an increase in *Cyclotella* species with a corresponding decrease in *A. subarctica*, suggesting that stratification was likely stronger and occurring for longer (Rühland et al. 2008). A number of studies showed a similar decrease in *Aulacoseira*, which need strong mixing to remain in the water column, whereas the smaller *Cyclotella* can remain in the water column under more stratified conditions. In contrast, the north basin of Osoyoos Lake indicates both an increase in percent abundance and concentration of *A. subarctica* slightly after the abrupt appearance of *C. comensis* (Figs. 6 & 7). In the south basin of Osoyoos Lake, *A. ambigua* generally decreases in percent in Zone A, but has some peaks as high as in Zone B, prior to the large increase in *C. comensis* (Fig. 9). The concentration data (Fig. 10) on the other hand suggests *A. ambigua* increases for the first half of the *C. comensis* zone (Zone A). Similarly, a return to slightly higher percentages of *A. subarctica* occurs in Zone A, and concentration data suggests *A. subarctica* is at its highest in this zone.

The increase in *C. comensis* along with an increase in *Aulacoseira* somewhat contradicts more stratified conditions. However, what it may be indicating is an extended ice-free period since *Aulacoseira* often bloom under the ice and into the early spring, whereas *C. comensis* is more typically a late summer, early autumn bloomer. Regardless of the actual mechanism behind the *C. comensis* increase, it is likely related to changes in climatically influenced variables.

Chronology, Diatom Concentration, Accumulation Rates and TP

The age models from both cores are based on linear interpolation between the dated intervals based on the Binford output, and extrapolation of the samples below the dated level based on the sedimentation rate of samples near the bottom of the dated portion. Both cores show a good correlation with a polynomial fit which follows closely the shape of the sample curve and thus similar to using a linear interpolation between the dated samples (Figs. 15 & 16). Based on these age model data, accumulation data were calculated from the diatom concentration data. In the north basin there is a fairly strong, statistically significant (Fig. 17, $r = 0.64$, $p < 0.01$), correlation between concentration data and accumulation data. The correlation between inferred TP and concentration data is weaker, but still statistically significant (Fig. 18, $r = 0.47$, $p < 0.01$). The correlation between inferred TP and diatom accumulation is very weak and not statistically significant. In general the data suggests that diatom concentration, diatom accumulation and diatom-inferred TP are all higher post-1940, with declines post-1990, except accumulation increases towards the top.

In the south basin there is a very strong, statistically significant (Fig. 19, $r = 0.84$, $p < 0.01$), correlation between concentration data and accumulation data. The correlation between TP and concentration data is weaker, but still statistically significant (Fig. 20, $r = 0.39$, $p < 0.01$). The correlation between TP and diatom accumulation is weak and not statistically significant. In general the data suggests that diatom concentration and diatom accumulation increase post-1940, with highest concentration and accumulation in the 1980s.

Comparison of North and South Basins

There is excellent correspondence in the general diatom changes and estimated TP levels between the analyses of the cores from the two basins. Both show the abrupt appearance of *C. comensis* and *C. gordonensis* and both indicate a decrease in TP post-1990. There is a difference in the timing of the onset of *C. comensis* between the two cores and a difference in the timing of the recent high TP levels. In the north basin the onset of *C. comensis* occurs at ~1970, whereas in the south basin the onset occurs at ~1980. The period of the recent high TP levels are also separated by approximately 10 years, with the north basin around 1950 to 1990, whereas the south basin is around 1960 to 1990. The difference in timing between the two basins is either a real difference between the two basins or difference in the accuracy of the age models. The south basin core has an excellent correspondence between the ^{210}Pb estimate and the peak ^{137}Cs of 1963, whereas in the north basin the peak in ^{137}Cs occurs at 50 cm, whereas the ^{210}Pb estimate of 1963 occurs at 43 cm. This might be due to ^{137}Cs mobility within the core or less certainty in the unsupported ^{210}Pb estimates due to lower total activity.

Comparison with Earlier Studies

Three earlier palaeoecological studies examined sediments from Osoyoos Lake. Anderson's (1973) study was primarily focused on land-use changes in the south Okanagan, as indicated by terrestrial plant pollen preserved in a core taken from the north basin. Anderson indicates the estimated date at the bottom of the 33 cm long core as about 1885, with an average sediment accumulation rate of 0.38 cm/yr.

Pinsent & Stockner (1974) report on analyses of sediment from each of the major Okanagan basin lakes. *Fragilaria crotonensis* and *Melosira italica* were the most common diatom taxa recorded from Osoyoos Lake. Increases in diatom concentrations and organic carbon content were both interpreted as evidence for a long-term trend towards greater nutrient loading.

Ryder (1994) analysed sediments in two cores (33 and 48 cm long) from the south basin of Osoyoos Lake for phosphorus, metals, and midge (chironomid) remains. ^{210}Pb dating indicated high rates of sediment accumulation, with each core spanning approximately 25 years of lake history. Although phosphorus concentrations in the cores were highest in the uppermost sediments, these high concentrations were a likely artefact of upward post-depositional migration of phosphorus in the sediments. In contrast, there was little evidence of change in the midge community, suggesting that oxygen availability had not changed greatly in the interval 1970-1993. Increases in Mo and Ca concentrations were interpreted as possible indicators of increased lake productivity. The calcium increase potentially indicated increased biogenic $CaCO_3$ deposition through algal photosynthesis. Under anoxic conditions Mo deposition may be enhanced in association with sulphides.

In addition to earlier palaeoenvironmental studies, ongoing monitoring efforts offer a basis for comparison. Although direct measures of phosphorus are not available for years prior to the Okanagan Basin Study, Jensen (2007) reports that TP has been declining in Osoyoos Lake, and other Okanagan Basin Lakes, over the past 30 years. This trend is a reflection of better controls on nutrient loading, including especially enhanced P removal at municipal sewage treatment facilities.

Results from the current study are generally based on longer, better-dated sediment cores, allowing a more thorough reconstruction of human impacts on the lake than in the earlier paleoenvironmental studies. Analyses of algal pigments and diatom-inferred TP were not conducted in the earlier studies. These provide better measures of algal production and nutrient concentration; thus, providing a clearer picture of changes in the lake's productivity through time.

Current results from ^{210}Pb dating indicate high rates of sediment deposition, similar to those reported by Ryder (1994). High accumulation rates are not surprising given the region's high topographic relief, sparsely vegetated landscape, easily erodible glacial lake deposits, and extensive human disturbance (including upstream channelization of the Okanagan River).

Results from the pigment analyses and diatom concentration estimates are consistent with earlier studies in suggesting an overall trend towards greater lake productivity since European settlement, with peak productivity c. 1975. Declining pigment concentrations from 1975 - 2000 accurately track the TP trend evident in monitoring data. However, the secondary peaks in some pigments post-2000 may be preservation artefacts – no parallel change is evident in the monitoring data.

The diatom-inferred TP values do not offer the same clear trend. These inferences suggest no clear trend in the north basin, and an overall decline in TP since European settlement in the south basin. The peaks of inferred TP about 1975 and more recent declines are, however, consistent between the two basins, and with TP monitoring data.

SUMMARY

In summary, the diatom-inferred TP levels and pigment data for Osoyoos Lake generally indicate mesotrophic conditions over the past ~200 years, with highest levels in the north basin between ~ 1950 to 1990, and in the south basin from ~ 1960 to 1990 (as well as pre-1920). Post-1990 the diatom-inferred TP values decrease, corresponding to a similar finding in measured phosphorus levels. In the north basin estimated TP has a strong correlation with PCA axis-2 scores, whereas in the south basin there is a relatively strong correlation with PCA axis-1 scores. This suggests that the changes seen in the diatom assemblages are consistent with the changes seen in the TP estimates, however other factors are also influencing the diatom assemblages. Other factors include climatic variability, which can influence the ice-free period and consequently other limnological variables. Climate and its influence on nutrients, water column stability and the ice-free period is likely one of the forcing factors influencing the abrupt increase of *C. comensis* in both basins.

ACKNOWLEDGEMENTS

We would like to thank the Okanagan Basin Water Board, Osoyoos Lake Water Quality Society, Okanagan Nation Alliance, British Columbia Ministry of Environment, and the University of British Columbia Okanagan for their support throughout this project. We are especially appreciative of the grant contributions provided by the Okanagan Basin Water Board and British Columbia Ministry of Environment. Without their financial contributions it would have been impossible to complete our investigations. Funding for the pigment analyses was provided by the Natural Sciences and Engineering Research Council (NSERC) and the Canada Foundation for Innovation (CFI).

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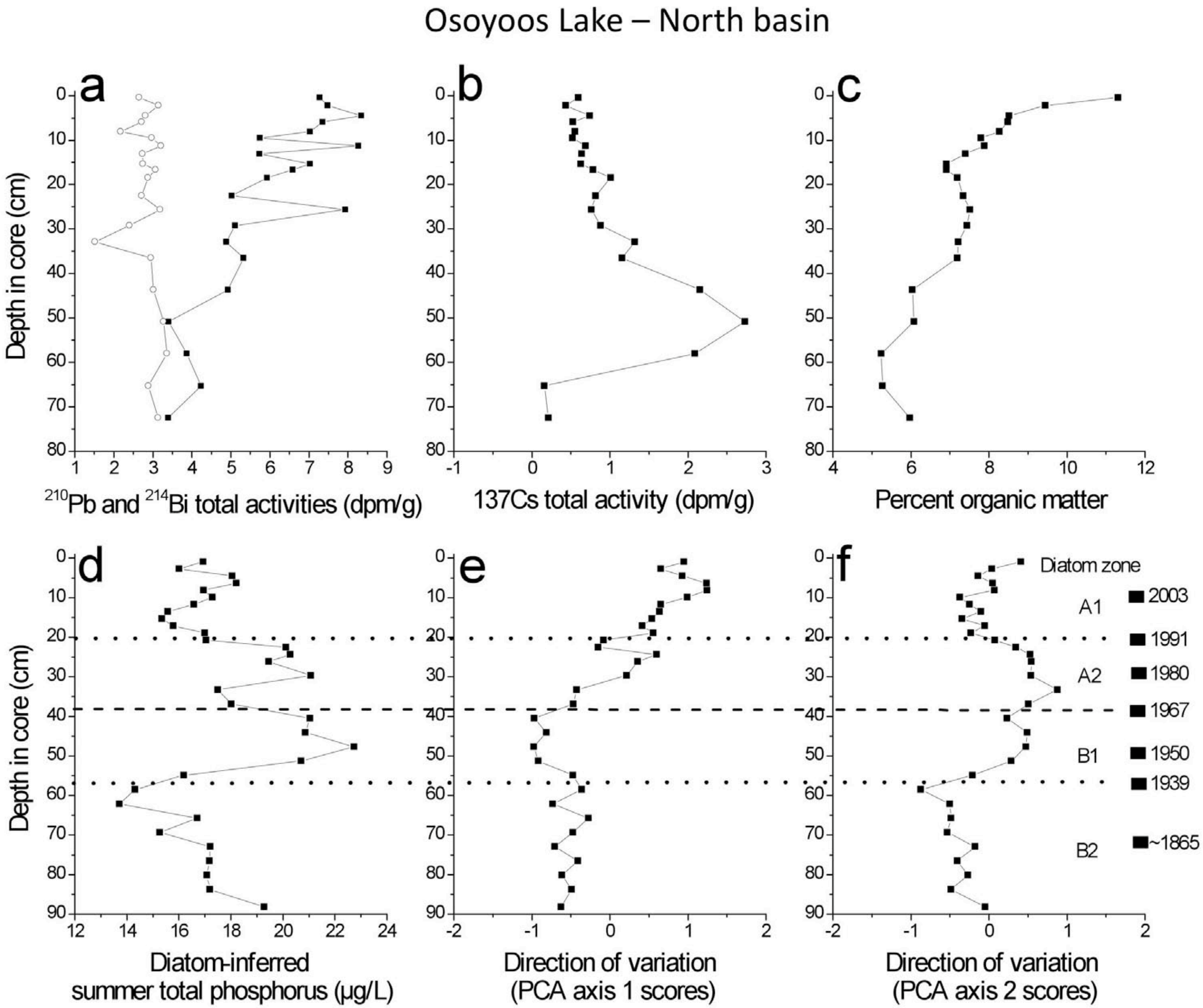

Figure 4. Summary diagram for the north basin of Osoyoos Lake showing: a) total ^{210}Pb activity; b) total ^{137}Cs activity; c) the change in the percent of organic matter in the core; d) diatom-based estimate of late-summer total phosphorus; e) the main direction of variation in the diatom assemblage data - PCA axis 1 scores and f) the main direction of variation in the diatom assemblage data - PCA axis 2 scores.

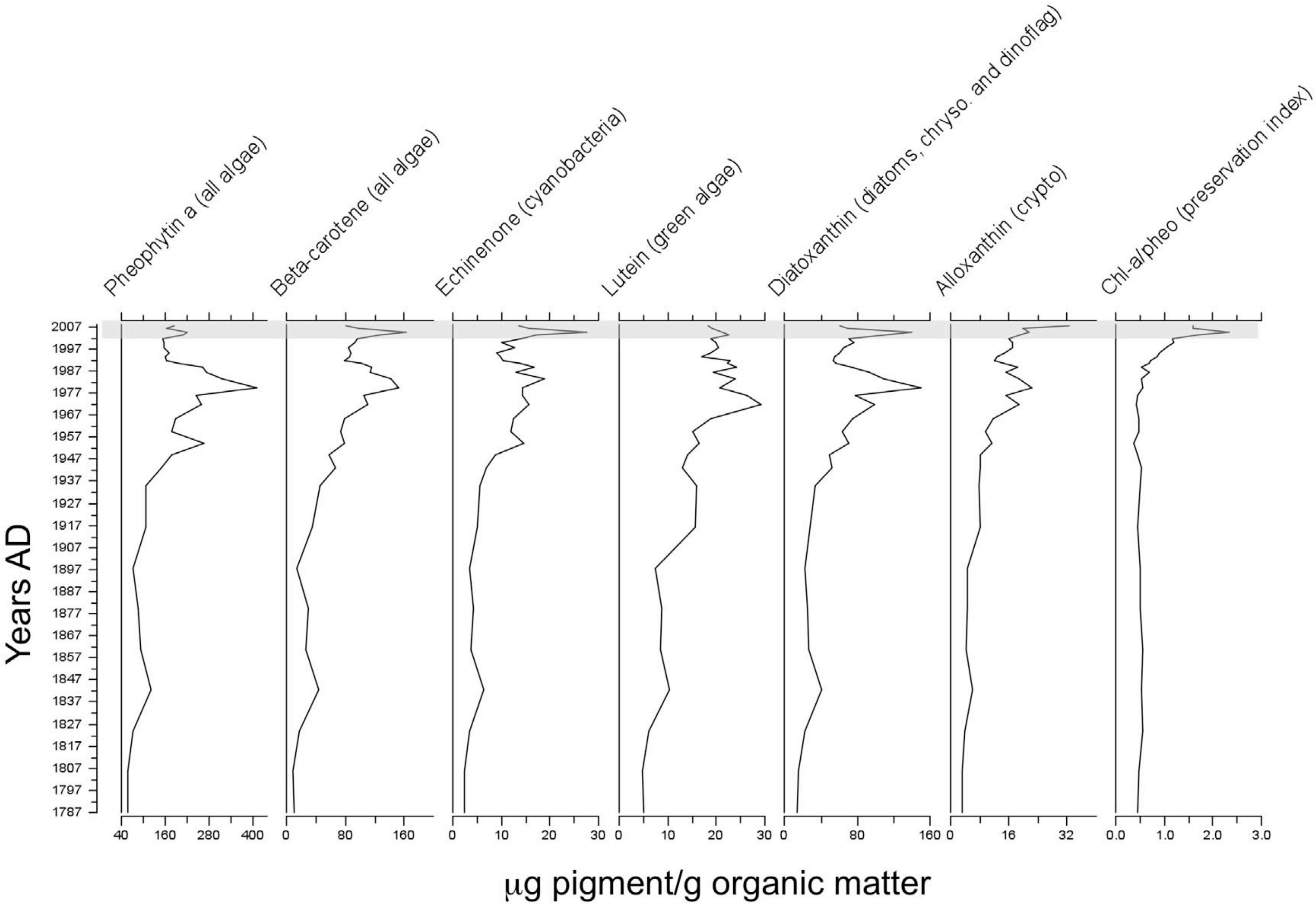

Figure 5. Temporal changes in sedimentary pigments from 1787 – 2008. The zone highlighted in gray indicates where the sediment preservation differs substantially from the rest of the core.

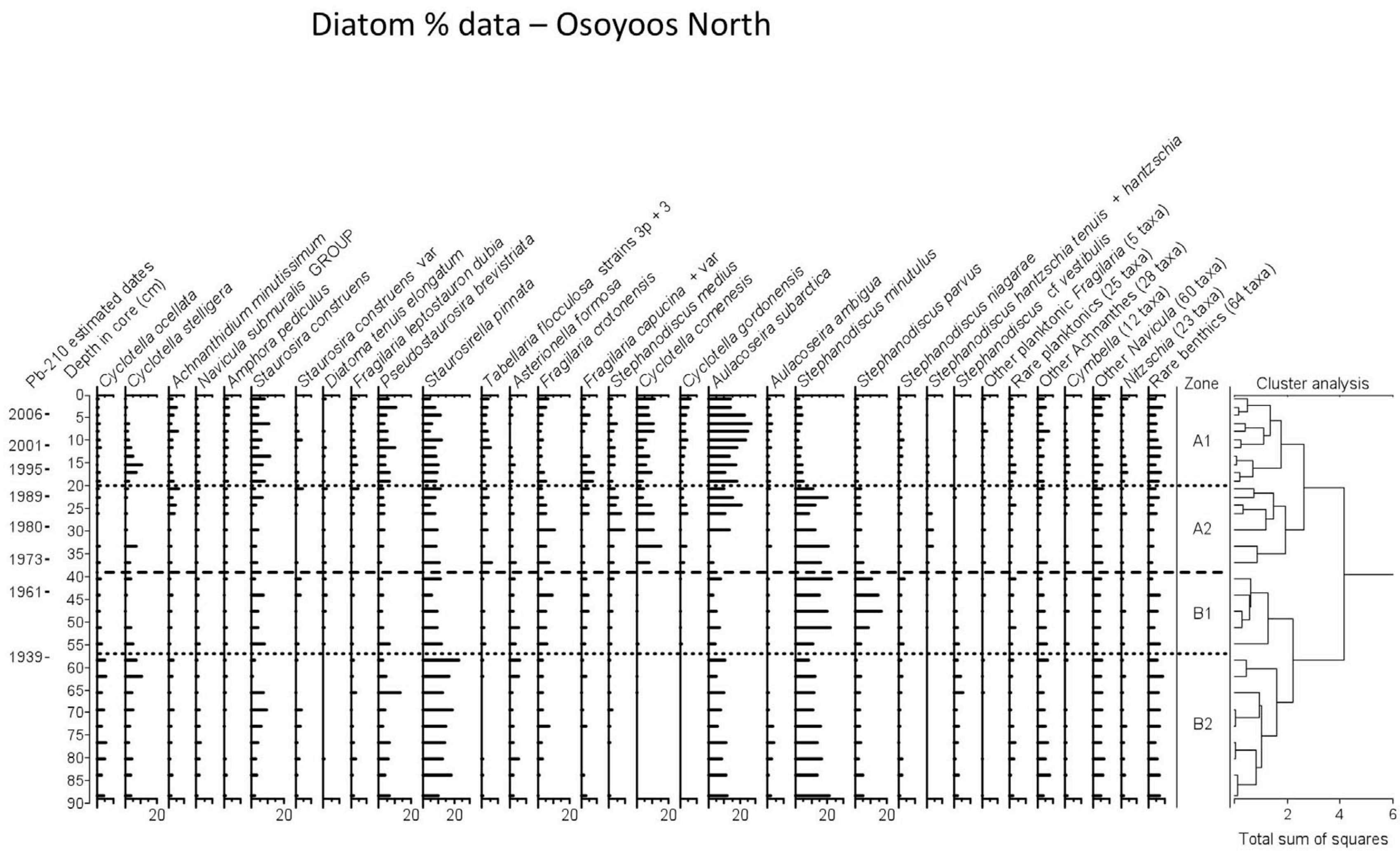

Figure 6. Stratigraphy of the most abundant diatom taxa (>5%) found in the sediment core from the north basin of Osoyoos Lake. The diatom taxa are arranged in order of increasing late-summer total phosphorus (TP) optima.

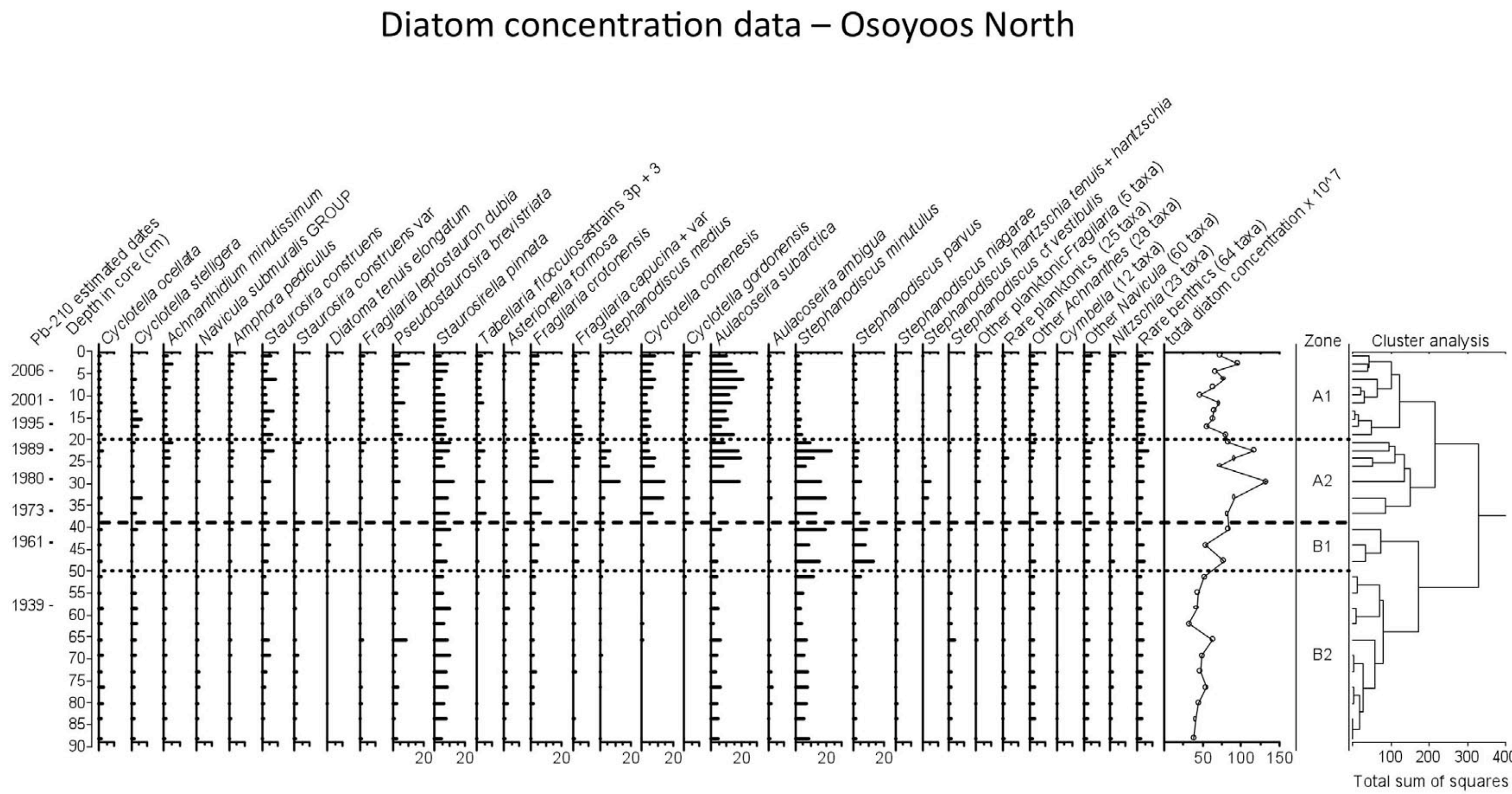

Figure 7. Stratigraphy of the diatom concentration data found in the sediment core from the north basin of Osoyoos Lake. The diatom taxa are arranged in order of increasing late-summer total phosphorus (TP) optima.

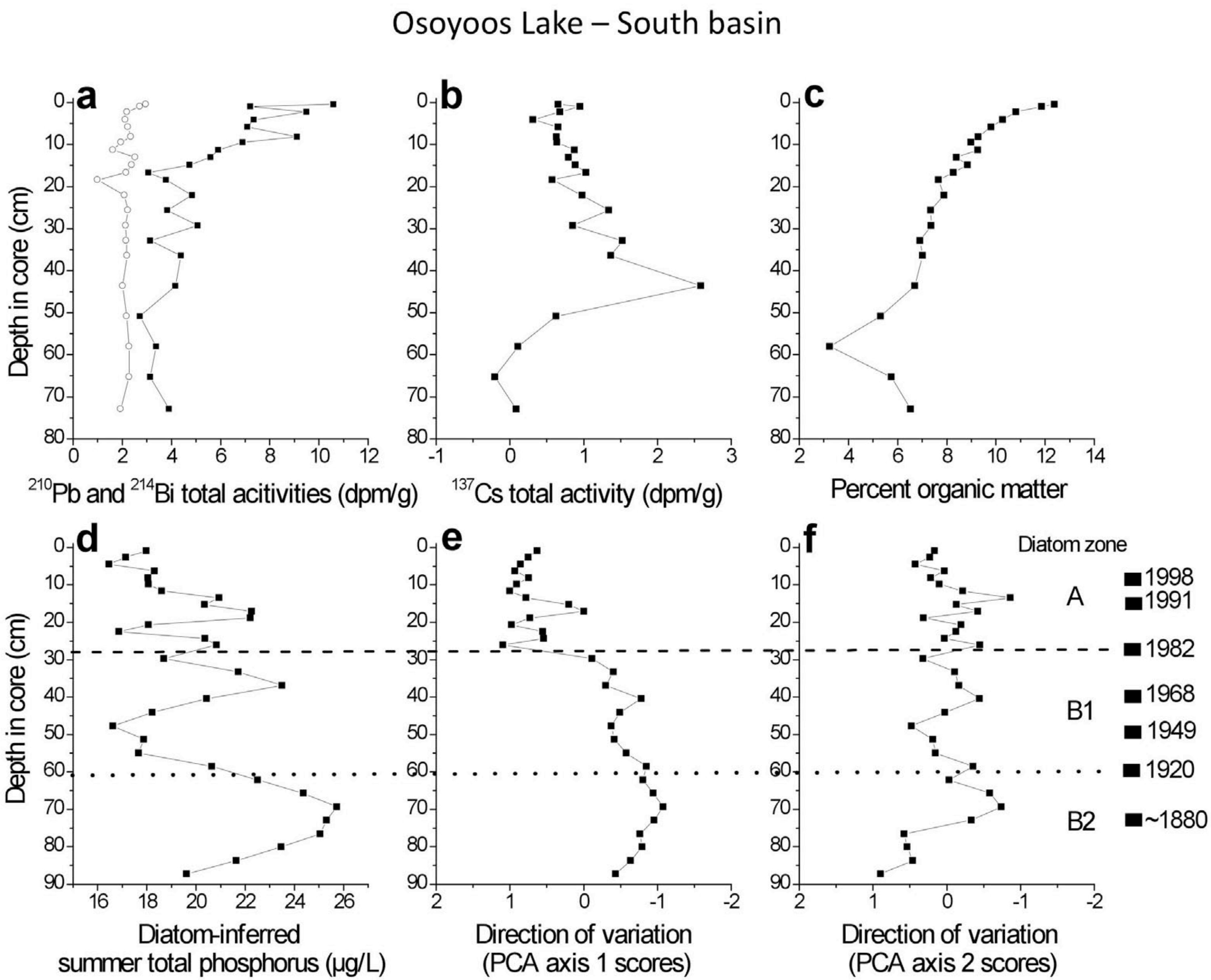

Figure 8. Summary diagram for the south basin of Osoyoos Lake showing: a) total ^{210}Pb activity; b) total ^{137}Cs activity; c) the change in the percent of organic matter in the core; d) diatom-based estimate of late-summer total phosphorus; e) the main direction of variation in the diatom assemblage data - PCA axis 1 scores and f) the main direction of variation in the diatom assemblage data - PCA axis 2 scores.

Diatom % data – Osoyoos South

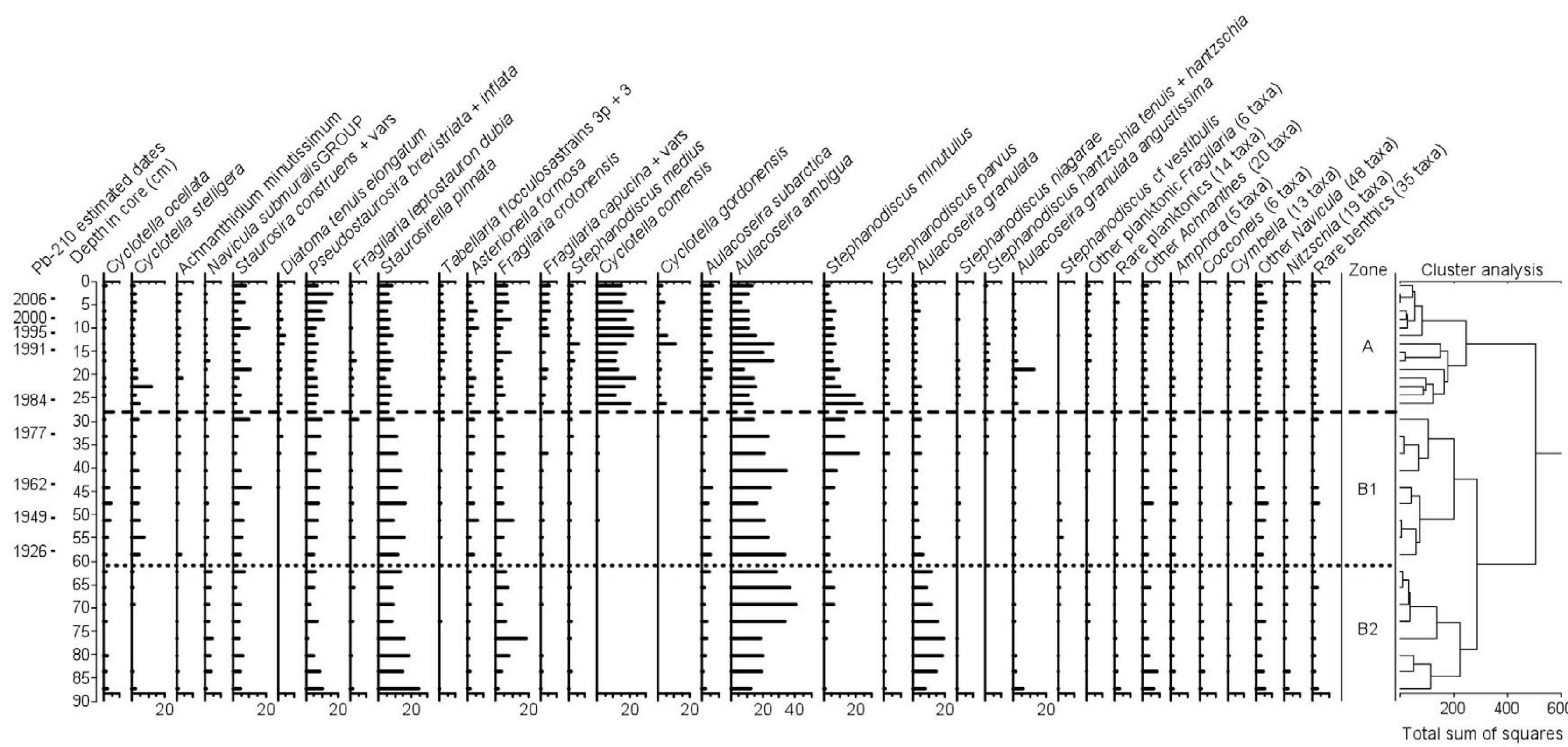

Figure 9. Stratigraphy of the most abundant diatom taxa (>5%) found in the sediment core from the south basin of Osoyoos Lake. The diatom taxa are arranged in order of increasing late-summer total phosphorus (TP) optima.

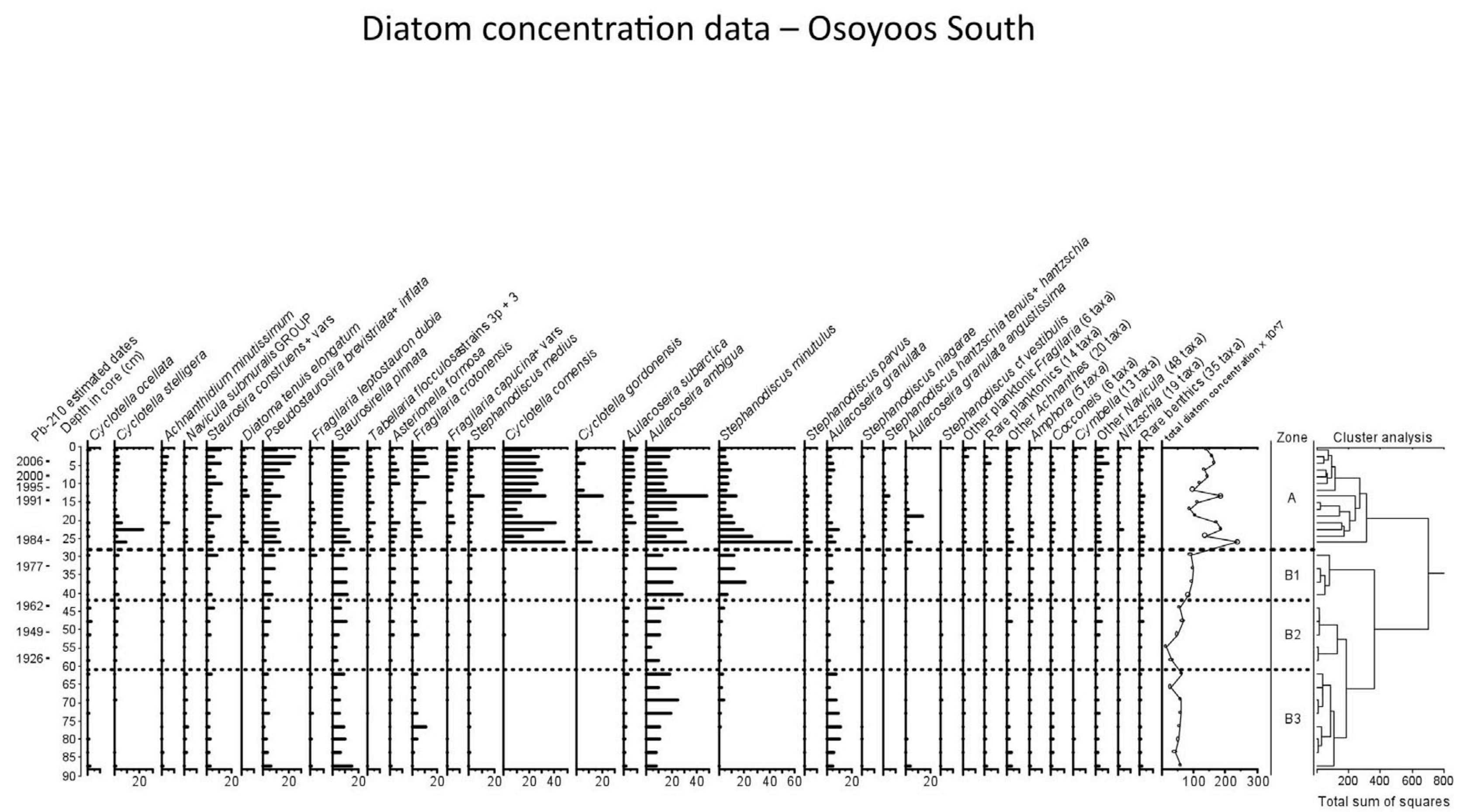

Figure 10. Stratigraphy of the diatom concentration data found in the sediment core from the south basin of Osoyoos Lake. The diatom taxa are arranged in order of increasing late-summer total phosphorus (TP) optima.

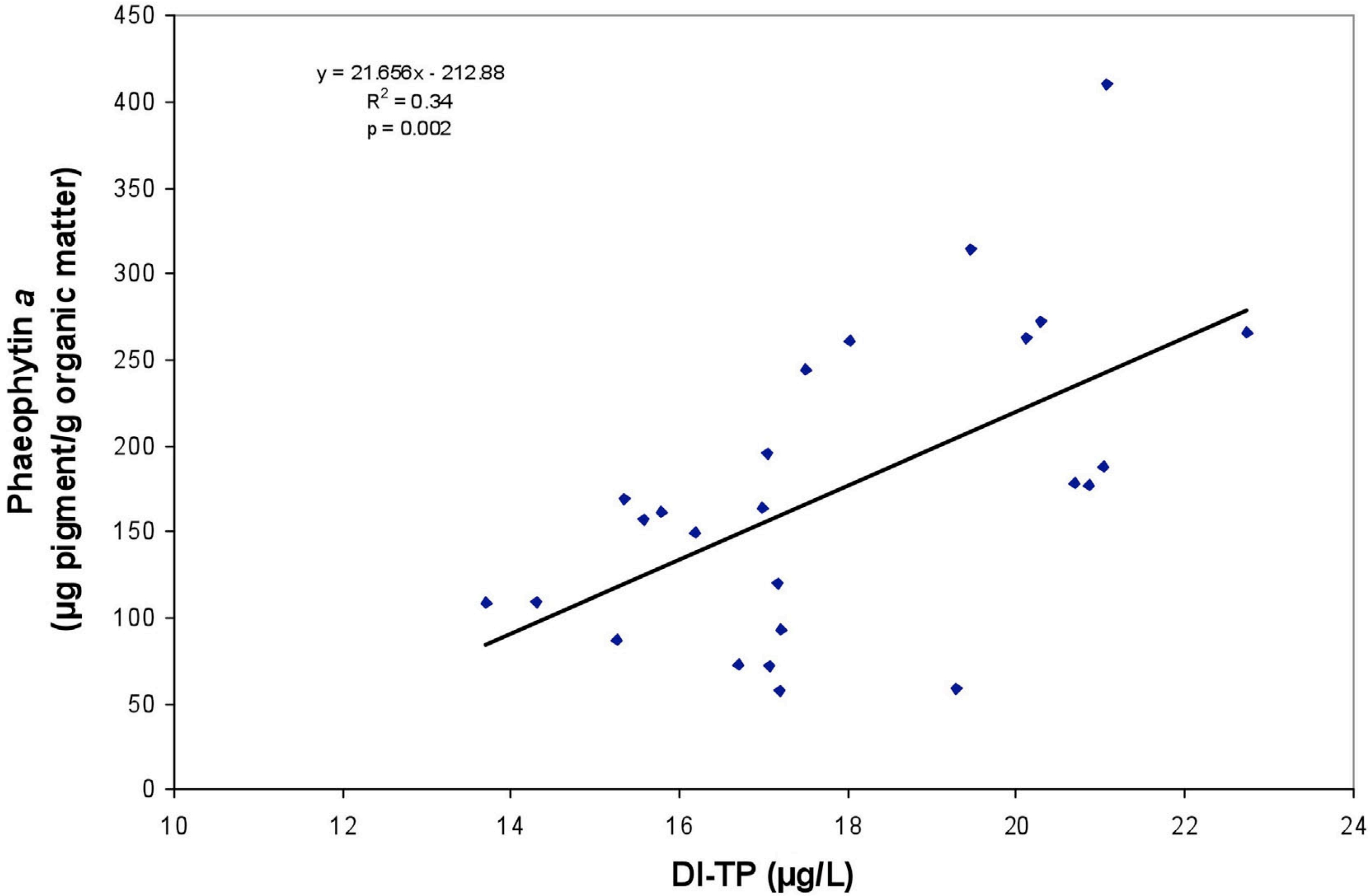

Figure 11. A bi-plot showing the correlation between an indicator of total algal production (phaeophytin *a*) and diatom-inferred total phosphorus concentration (DI-TP). Only data between 1787 and 1998 were used for this analysis (so as not to include the intervals of differing pigment preservation).

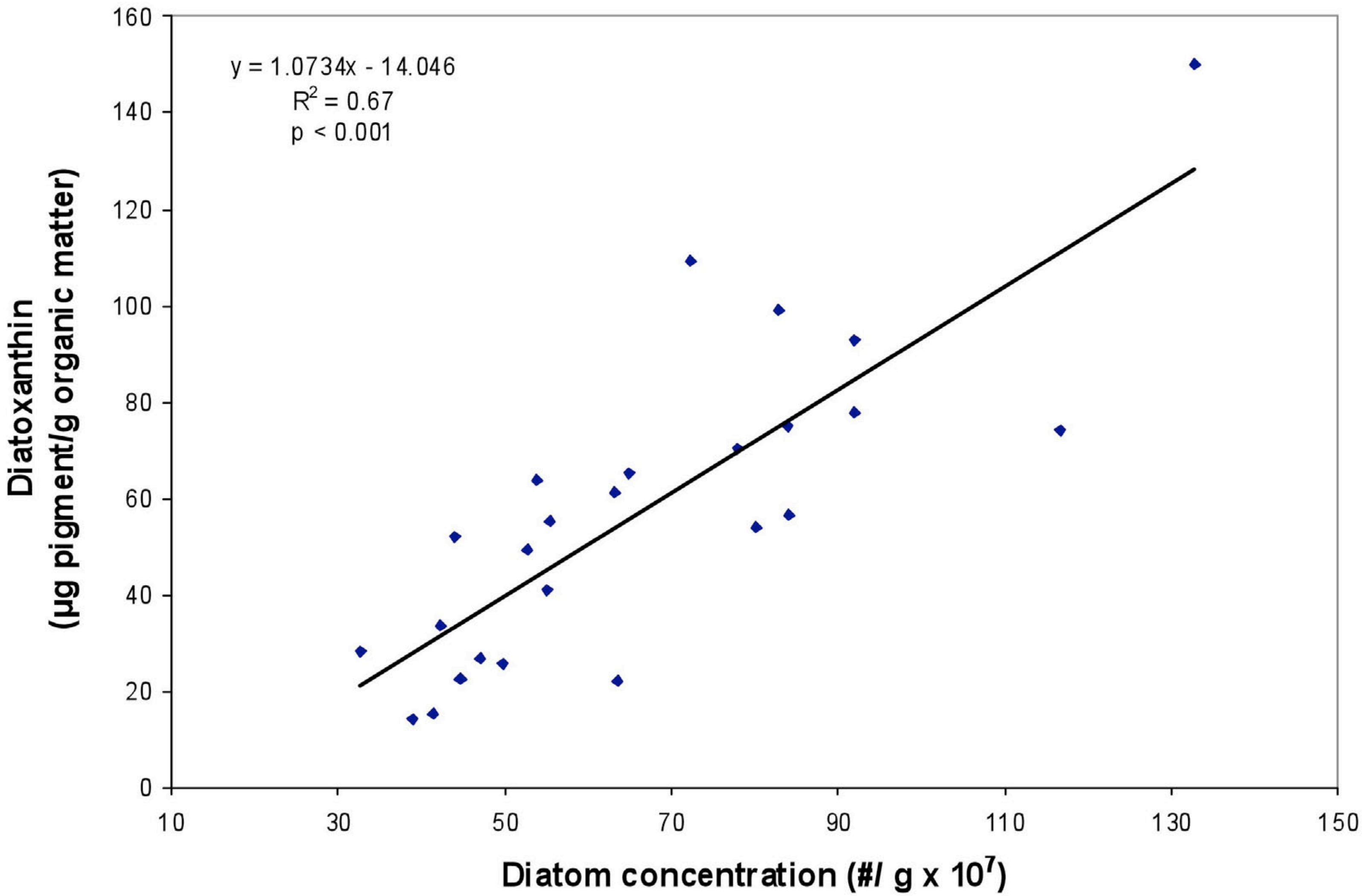

Figure 12. A bi-plot showing the correlation between an indicator of diatom production (diatoxanthin) and diatom valve concentration. Only data between 1787 and 1998 were used for this analysis (so as not to include the intervals of differing pigment preservation).

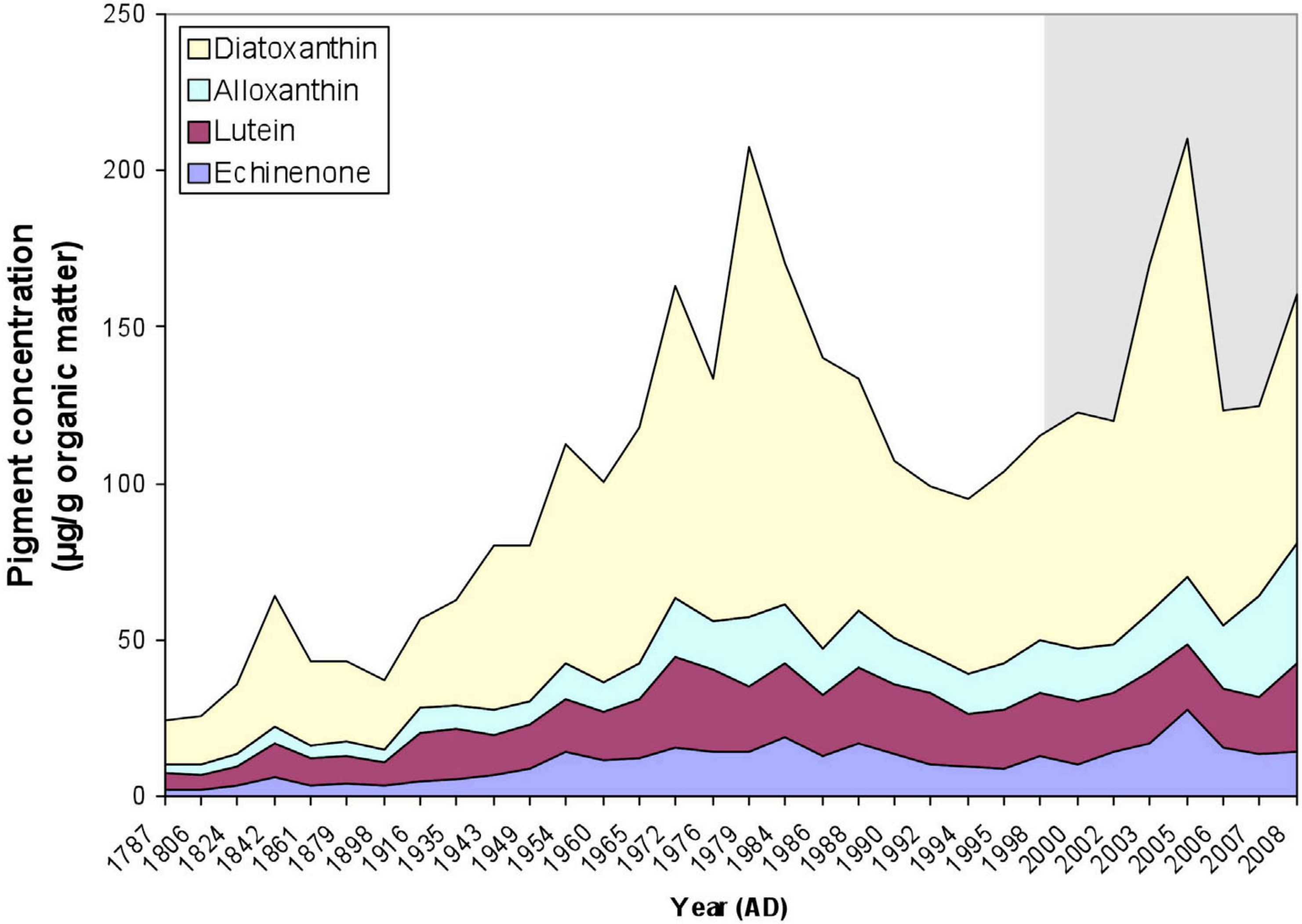

Figure 13. Temporal changes in indicator carotenoid pigments of the major photosynthetic functional groups: diatoxanthin (diatoms, chrysophytes and dinoflagellates), lutein (green algae), alloxanthin (cryptophytes) and echinenone (cyanobacteria). The zone highlighted in gray indicates where the sediment preservation differs substantially from the rest of the core.

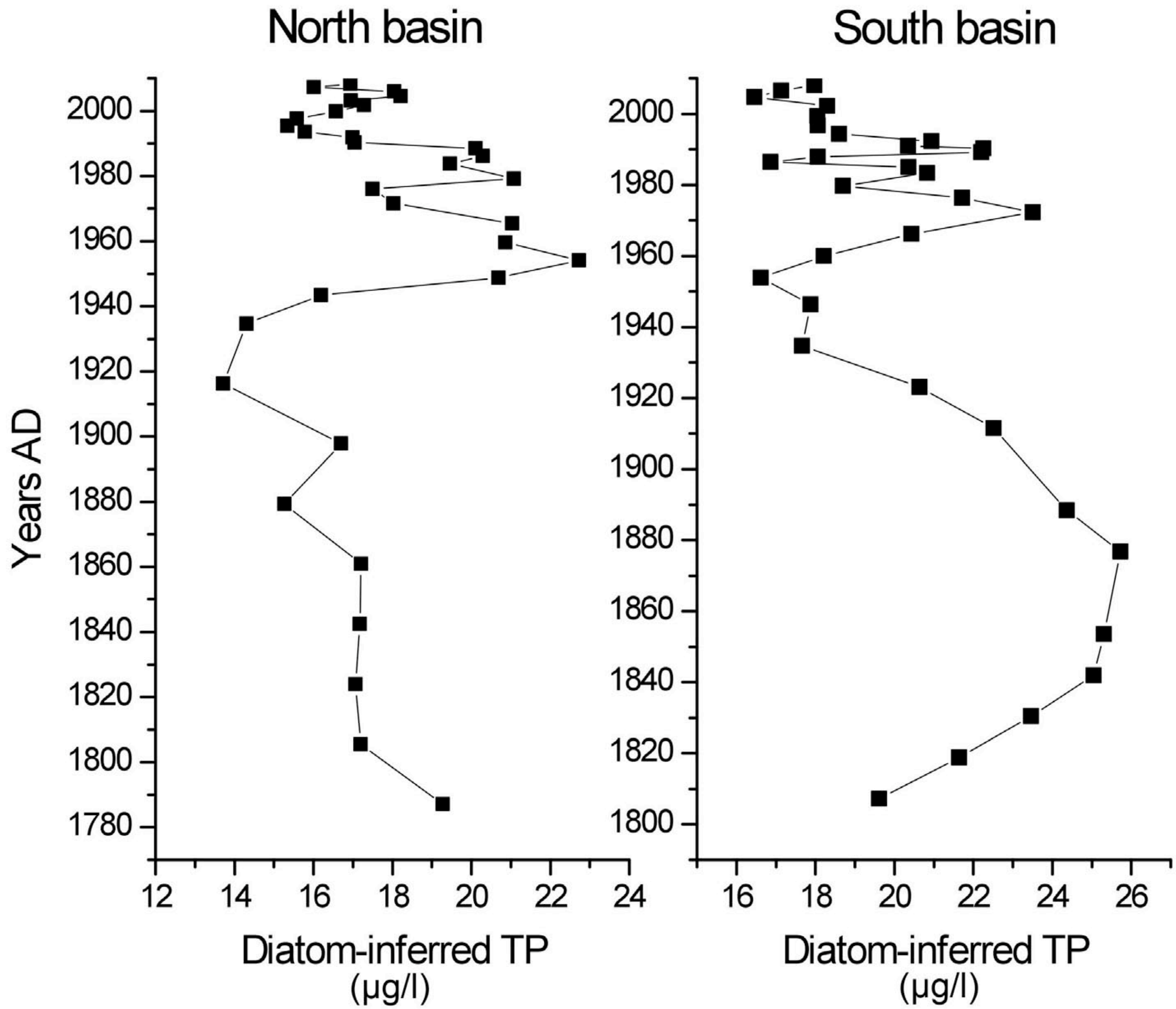

Figure 14. Diatom-inferred total phosphorus for the north and south basins of Osoyoos Lake.

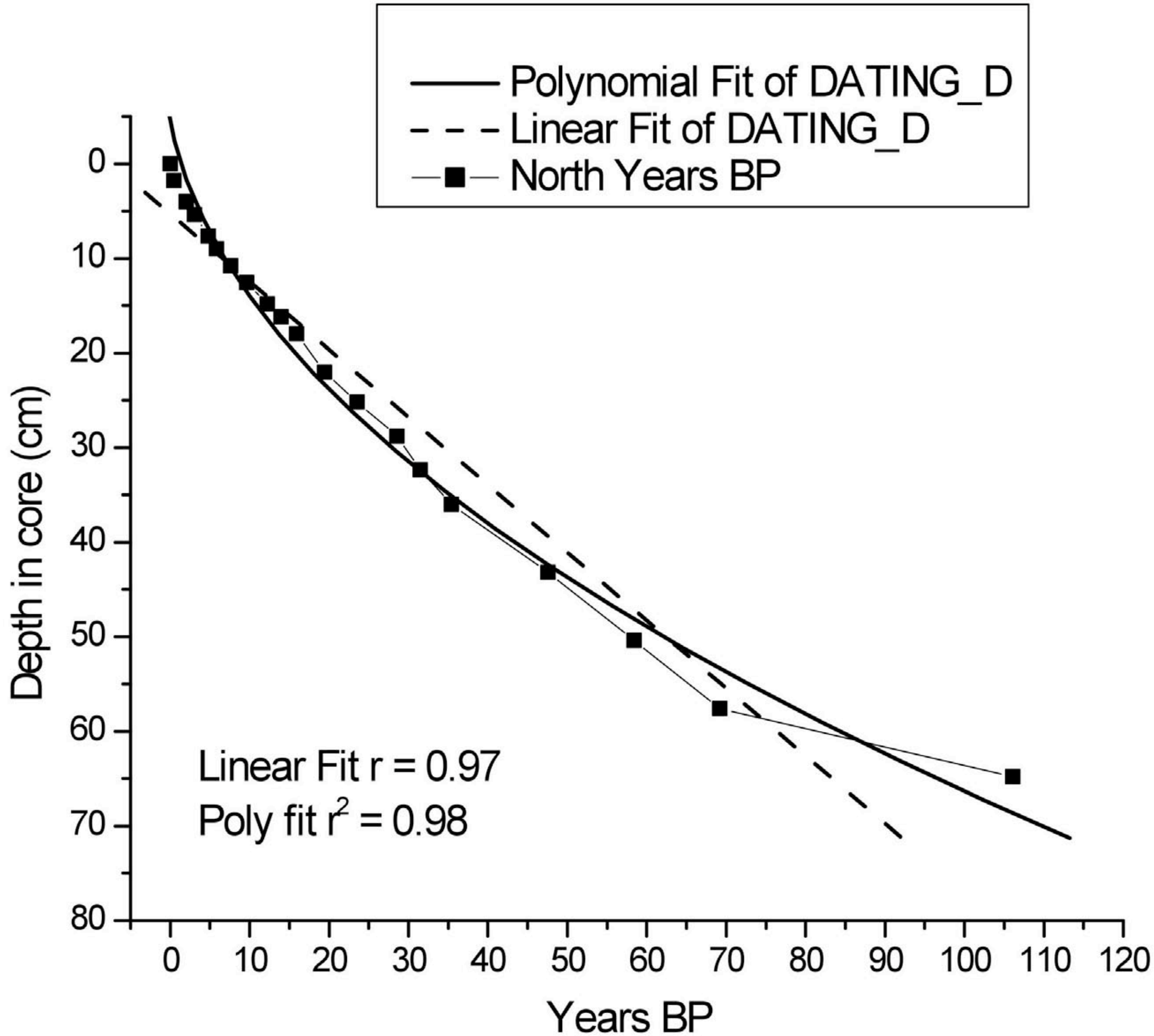

Figure 15. Dating model for the north basin of Osoyoos Lake.

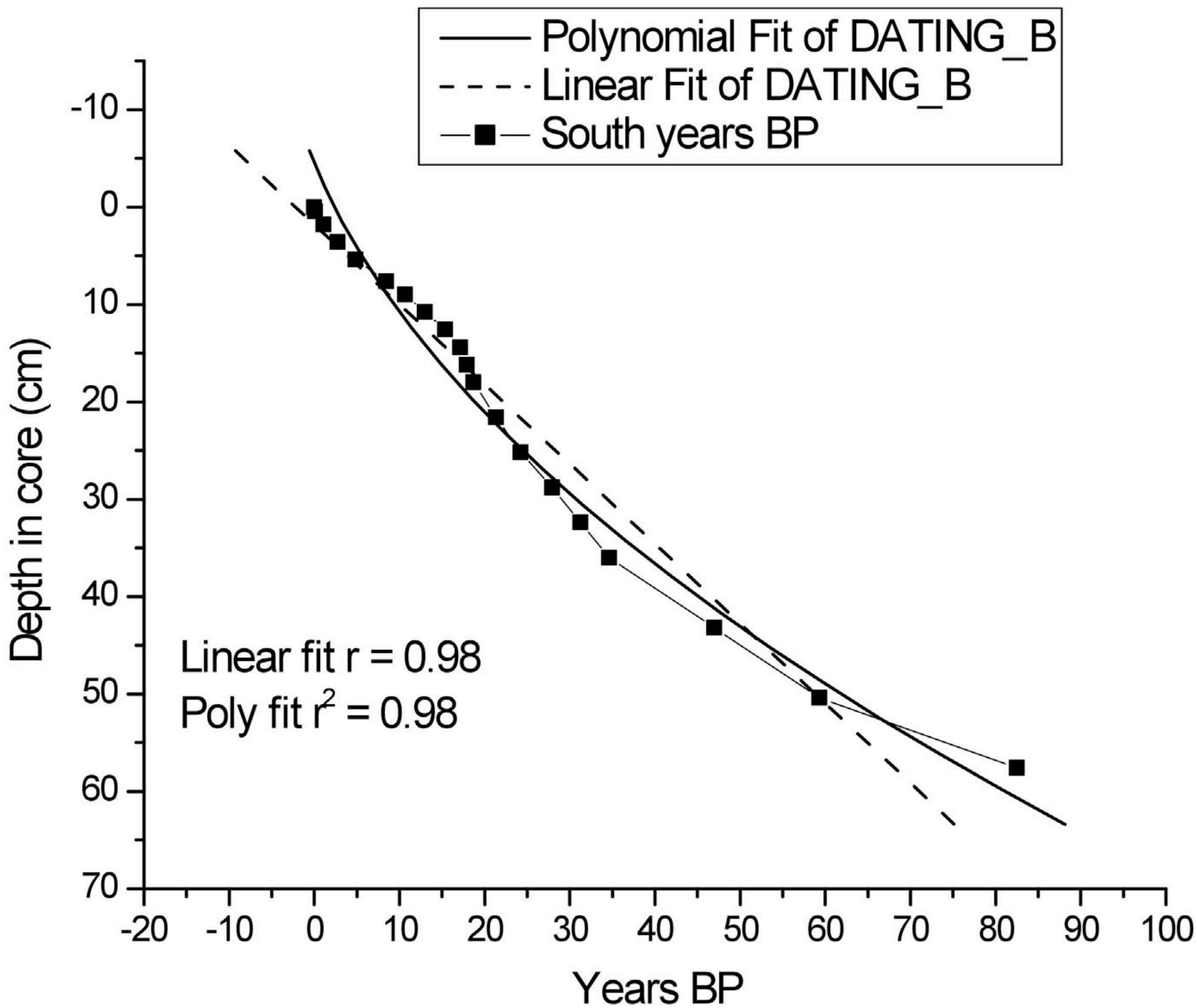

Figure 16. Dating model for the south basin of Osoyoos Lake.

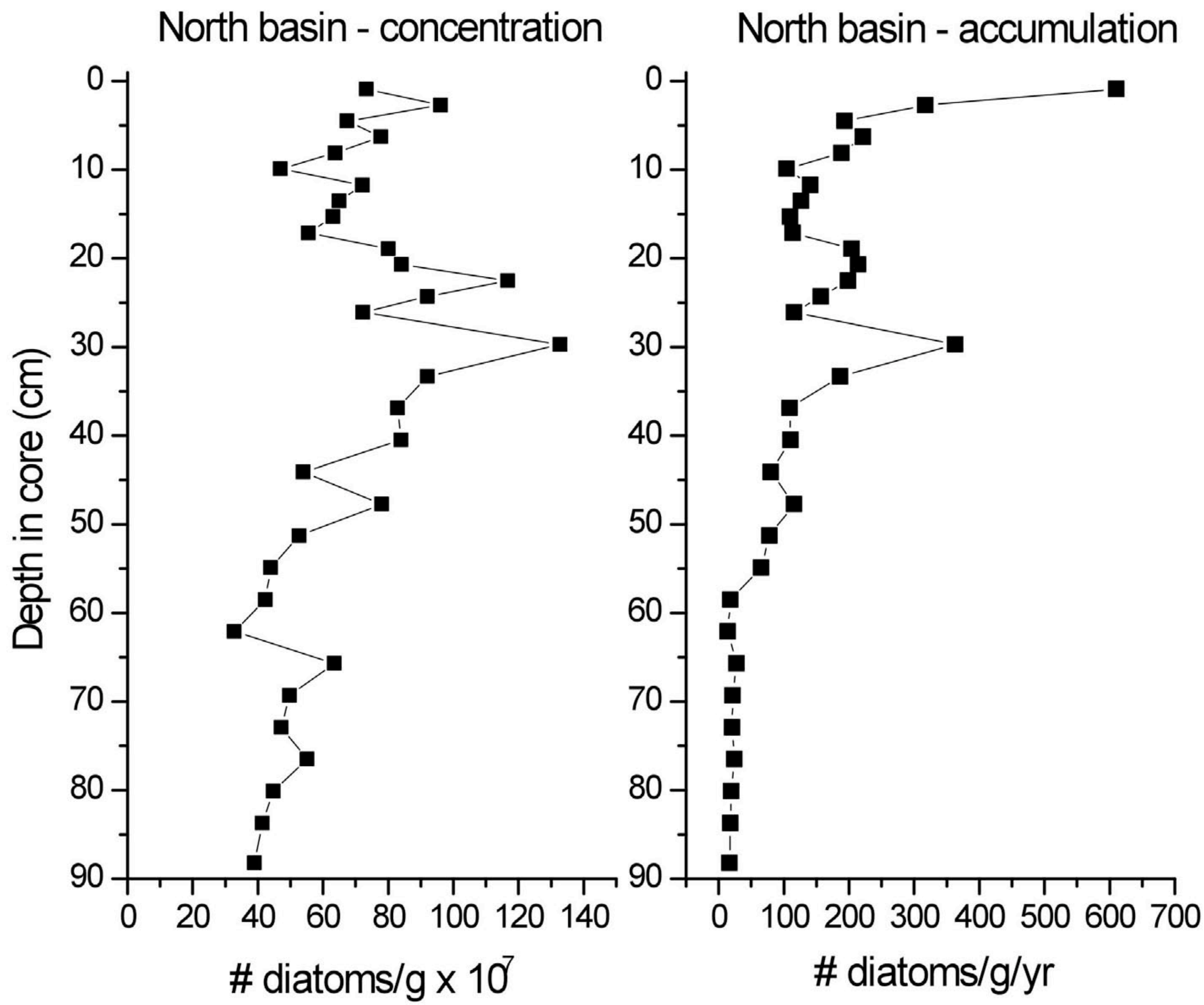

Figure 17. Diatom concentration and accumulation for the north basin of Osoyoos Lake.

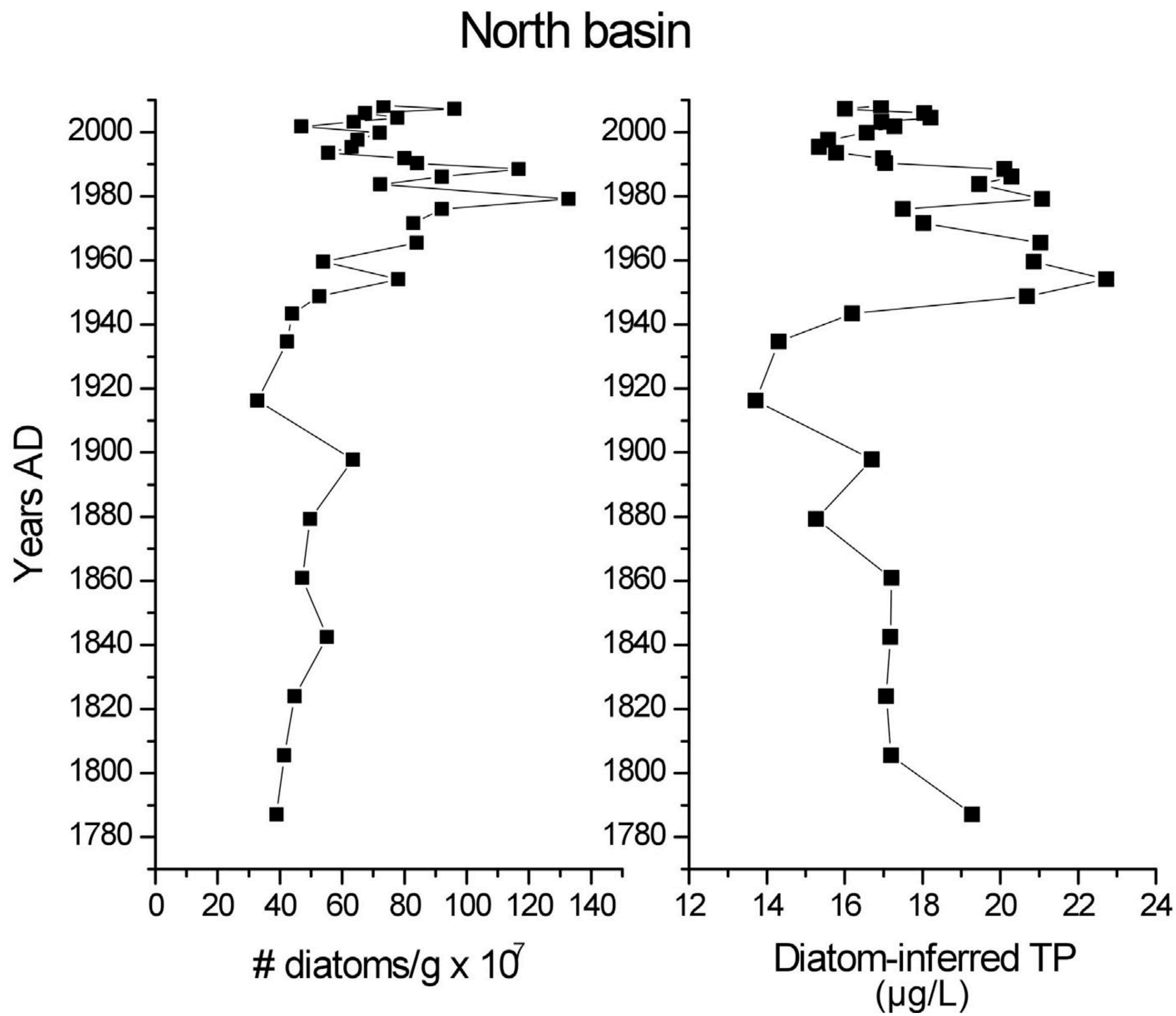

Figure 18. Diatom concentration and inferred total phosphorus for the north basin of Osoyoos Lake.

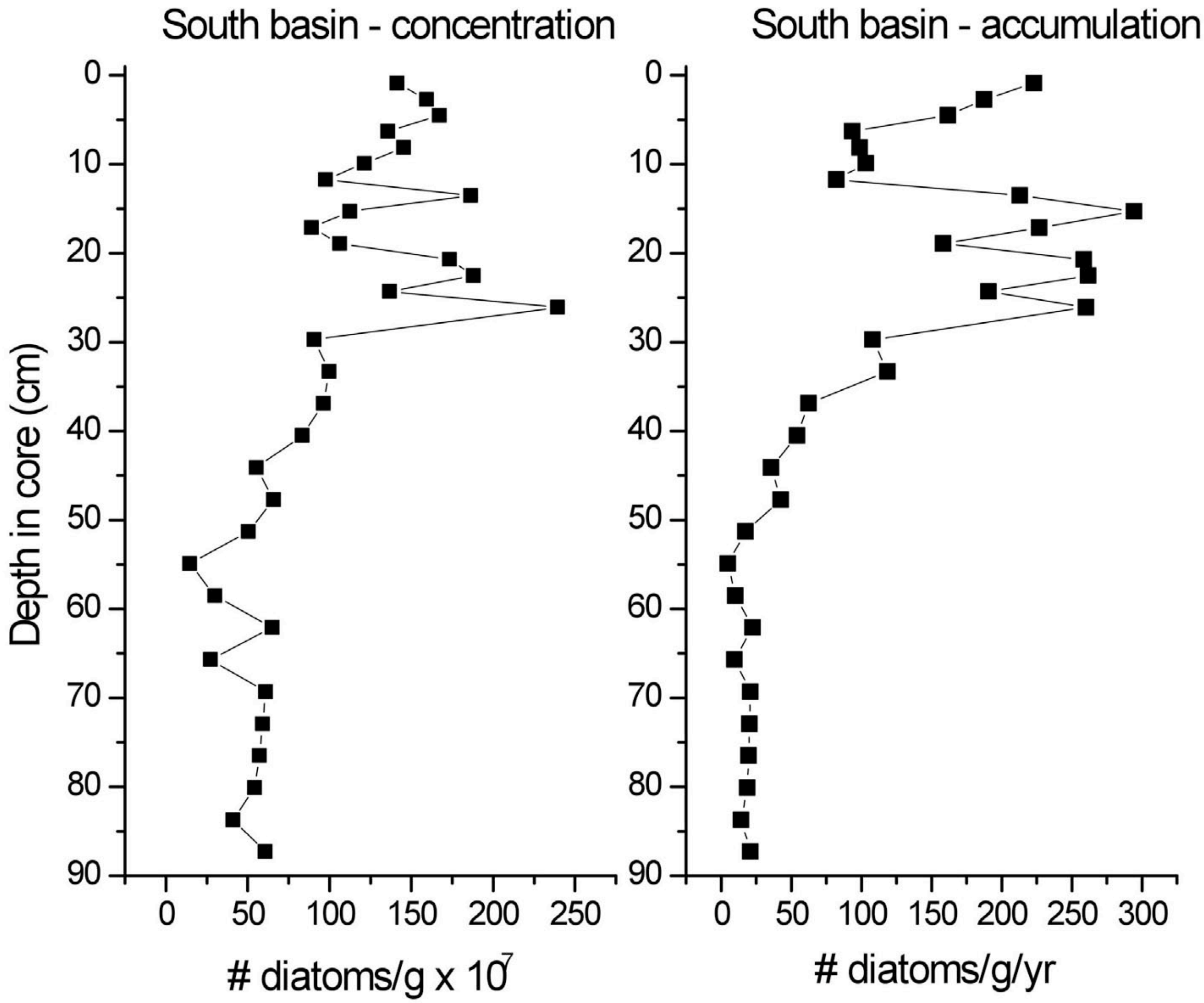

Figure 19. Diatom concentration and accumulation for the south basin of Osoyoos Lake.

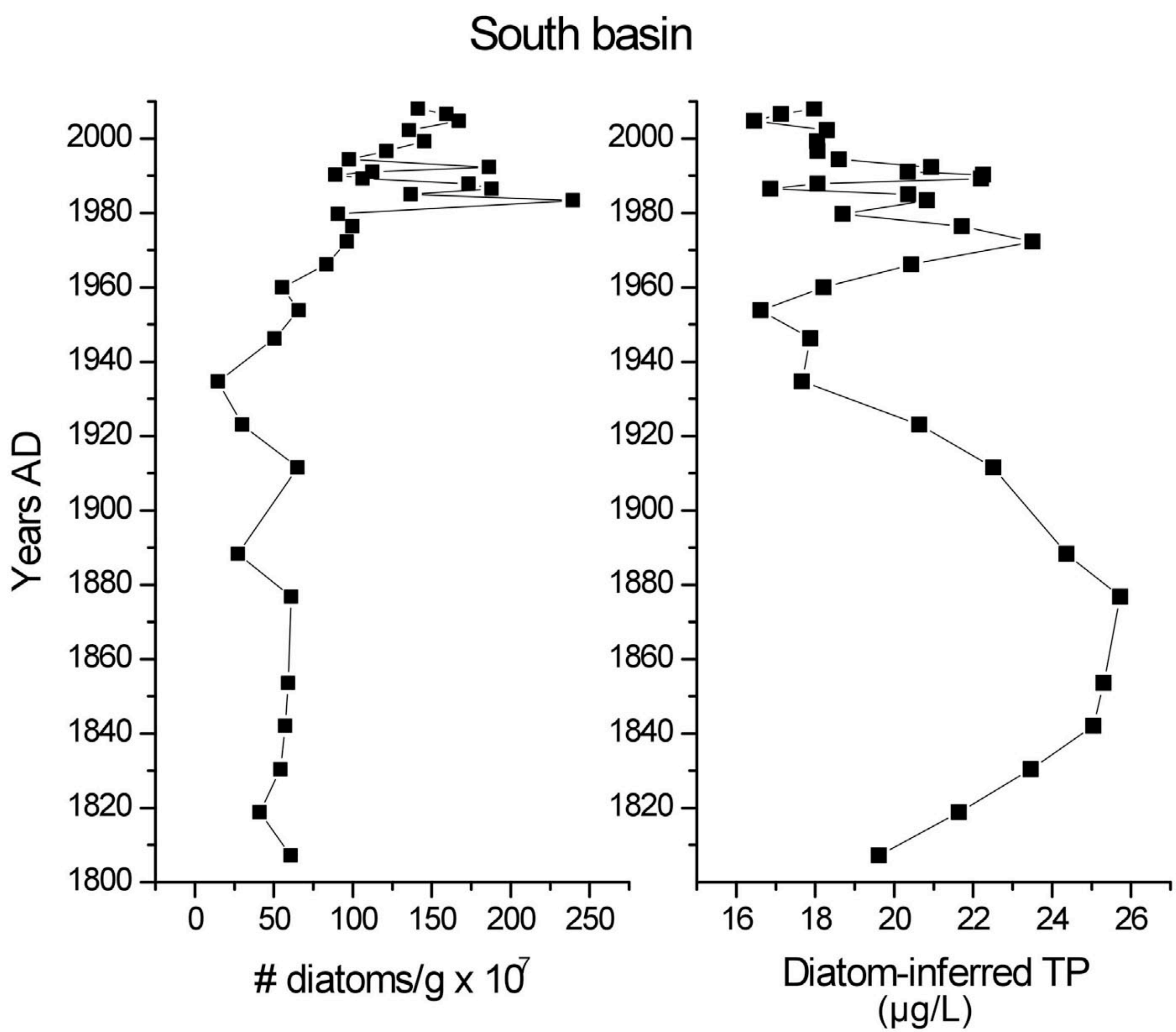

Figure 20. Diatom concentration and inferred total phosphorus for the south basin of Osoyoos Lake.

APPENDIX: MEDIA REPORTS

Media Release | June 10, 2008

OSOYOOS LAKEBED STUDY TO EXAMINE IMPACT OF SETTLEMENT

There's a lot of environmental history at the bottom of Osoyoos Lake. Starting June 16, researchers from UBC Okanagan and the B.C. Ministry of Environment will begin to reconstruct that history by sampling and analyzing sediments from the deepest parts of the lake.

They'll be looking for chemical and biological clues about how human settlement in that part of the South Okanagan has impacted the environment during the past century and a half.

"Lakes are continually accumulating layers of sediment, and preserved in those sediments we have a variety of chemical substances," says paleo-ecologist Ian Walker, Professor of Biology and Earth and Environmental Sciences at UBC Okanagan. "Sediment analysis will indicate the level of nutrient enrichment of the lake before European settlement of the area, and early in that settlement period."

The research is a collaboration between the Okanagan Basin Water Board which provided primary funding, the B.C. Ministry of Environment, Okanagan Nation Alliance, UBC Okanagan, and the Osoyoos Lake Water Quality Society.

"Our intention is to reconstruct historic nutrient concentrations as well as look at the levels of contaminants entering Osoyoos Lake back to the late-1800s," says Michael Sokal, Impact Assessment Biologist with the B.C. Ministry of Environment's Environmental Protection Division in Penticton. "From this information, more accurate and supportable nutrient targets, particularly for phosphorus, may be set for Osoyoos Lake."

The project will involve collecting sediment cores from two locations in Osoyoos Lake, and examining the sediment for the presence of specific toxins and other chemicals -- for example, phosphates, nitrates, the pesticide DDT, PCBs, lead and arsenic -- and algal remains which can indicate, for example, total phosphorus concentrations in the lake during the past.

Walker notes that if the results are similar to recent

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studies of sediments from Wood Lake in the Central Okanagan and Skaha Lake south of Penticton, the upper half-metre of sediments from Osoyoos Lake could reveal evidence of human activities such as fertilizing crops (adding phosphorus and nitrogen), spraying pesticides (historically a contributor of arsenic), and even driving cars with leaded gasoline (causing elevated lead levels).

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news

UBC Okanagan Spring Convocation sees 668 students graduate

UBC degrees were conferred upon 668 graduates during the Spring Convocation ceremonies on Friday, June 6.

"I hope that already, only a few days or weeks after the end of your degree, you are beginning to sense the freedom that a university education provides," UBC President **Stephen Toope** told graduates. "When I talk to our UBC alumni, which I do all the time and all around the world, so many tell me that they realize that university changed the world for them."

In a morning ceremony, 309 graduates from the Barber School of Arts and Sciences received their degrees. Graduates from the faculties of Creative and Critical Studies (96 grads), Education (115 grads), and Health and Social Development (148 grads) received their degrees in an afternoon ceremony.

Read more...

Strong demand for engineering co-op students

"Co-op programs can significantly boost employment opportunities after graduation," says **Erika Annala**, Engineering Co-op Program Coordinator. "The

June 18, 2008

Osoyoos lakebed study to examine impact of human settlement

There's a lot of environmental history at the bottom of Osoyoos Lake. On June 16, researchers from UBC Okanagan and the B.C. Ministry of Environment began reconstructing that history by sampling and analyzing sediments from the deepest parts of the lake.

They're looking for chemical and biological clues about how human settlement in that part of the South Okanagan has impacted the environment during the past century and a half.

"Lakes are continually accumulating layers of sediment, and preserved in those sediments we have a variety of chemical substances," says paleo-ecologist **Ian Walker**, Professor of Biology and Earth and Environmental Sciences. "Sediment analysis will indicate the level of nutrient enrichment of the lake before European settlement of the area, and early in that settlement period."

Read more...

Co-op education program booming

UBC Okanagan is getting a serious boost in profile thanks to a growing number of co-op students working in the community this

Scientists dig deep into history of Osoyoos Lake

By Tracy Clark - Penticton Western News - June 17, 2008

Tracy Clark/Western News

Impact assessment biologist Michael Sokal and Danny St. Hilaire with the Environmental Protection Branch remove the plug on the base of a core sampling tube near Osoyoos Lake.

The sediment at the bottom of Osoyoos Lake has a story to tell.

At least that is what a group of scientists are hoping, as they spent the early part of this week capturing a little of the lake's story in a coring tube Monday and Tuesday morning as part of the Osoyoos Lake bed study.

Researchers from UBC Okanagan and the B.C. Ministry of Environment will use the 80-millimetre samples taken from the deepest portions of lake's north and south basin — which are dated using a technique similar to carbon dating — to reconstruct the history of the lake.

"Lakes are continually accumulating layers of sediment and preserved in those sediments we have a variety of chemical substances,' said Ian Walker, a paleo-ecologist and professor of biology, earth and environmental sciences at UBCO.

The scientists will primarily be looking for biological and chemical information in the sediment — such as phosphates, nitrates, the pesticide DDT, PSBs, lead and arsenic — that will help to determine the impact of human settlement on the lake's environment over the past 150 years.

"Our intention is to reconstruct historic nutrient concentrations as well as look at the levels of contaminants entering Osoyoos Lake back to the late-1800s," said Michael Sokal, impact assessment biologist with the ministry's environmental protection division in Penticton. Similar studies on other Okanagan lakes, including Skaha Lake and Wood Lake, have shown that human settlement has had a major impact. In these studies, researchers found that activities such as fertilizing crops, spraying pesticides and even driving vehicles near lakes have increased the level of harmful substances in the lake, including lead and arsenic.

The study's researchers expect the picture may be similar for Osoyoos Lake.

While Osoyoos Lake is not a major drinking water source for the community, Sokal said determining historical nutrient levels, past fish populations and human impacts in the lake may be vital for supporting aquatic life and the sustaining ecological health in the lake into the future.

"From this information, more accurate and supportable nutrient targets, particularly for phosphorus, may be set for Osoyoos Lake," explained Sokal.

High nutrient levels, for example, could reduce the oxygen levels at the bottom of the lake where larger fish, like salmon, have historically resided. Knowing the past levels could provide scientists with the information to improve conditions that will assist with the restoration of salmon populations in the lake.

The $16,000 study, which is also being supported by the Okanagan Basin Water Bard and Osoyoos Lake Water Quality Society and Okanagan Nation Alliance, is the result of the Osoyoos Lake Water Science Forum, where a group of scientists, researchers, First Nations and political leaders met last year to discuss the current condition of the lake and its future.

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