Report on the results of the paleolimnolgical proxies from the five cores from Babine Lake (British Columbia, Canada)

Title of funded project (NF-2017-I-30 QU): Babine Lake, British Columbia - Sockeye Salmon nursery ecosystem structure, functioning & productive capacity: An integrated fisheries, limnological, and paleolimnological assessment

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Summary

Herein, we provide a summary of this multi-year project, and the progress that we have made over the last year (Table 1).

Table I: State of the analysis to date and progress since last report of the different analyses for the paleolimnological assessment of Babine Lake

Analyses	Progress since last report
Sediment geochronology	Finalized Progress since last report: The age-depth models are complete.
Sedimentary pigments	Finalized Progress since last report: All cores were run on the HPLC .
Diatoms analyses	Finalized Progress since last report: Count for the Pinkut, North Main Basin, Morrison Arm, and North Arm cores are complete.
Cladoceran analyses	Finalized Progress since last report: Count for Pinkut, North Main Basin, Morrison Arm, and North Arm cores are complete.
Loss-On-Ignition	Finalized Progress since last report: All cores were process for LOI analysis.
Isotope Analyses	Analyses are in cue for analysis

All analyses on this project are proceeding well. A total of five sediment cores were collected from Babine Lake in 2017. All cores have been run for radioisotopes from which dating profiles have been developed. Analyses of sedimentary pigments and diatom algal micro-fossils (proxies of lake food web primary production) and cladoceran zooplankton sub-fossils (a proxy of secondary production) are complete. Loss-on-Ignition, an indicator of the organic content in sediments is also complete. Analysis for elemental carbon, nitrogen and carbon and nitrogen isotopes was sent to Dr. Bruce Finney, and are awaiting the results, but these are expected soon (within a few months, but hopefully in April). As outlined Section 6 of the proposal we are well on the way to meeting our schedule: the results of the bioindicator analyses are complete, and are synthesized in this report (Year 2, points 1 and 2); submitting this report (Year 2, point 3); Cécilia Barouillet, is progressing well on her PhD, and is on time to defense by the end of the summer (Year 2, point 4). We are now in the process of waiting for the isotopic data, that is necessary for the interpreting our proxies. We are now in the process of organizing

these results for publication, which will be followed by disseminating our findings (Year 2, points 5-7).

Introduction

Babine Lake is a Sockeye Salmon (*Oncorhyncus nerka*) nursery lake from the Skeena River watershed, located on the Interior Plateau of British Columbia, Canada (Fig. 1). It is the largest salmon spawning lake in British Columbia containing populations of anadromous Sockeye salmon and landlocked Kokanee (*O. nerka*). As Babine Lake produces ~90% of the Skeena River Sockeye Salmon (Beachman et al. 2014), it is also considered as the most economically valued fisheries lake in the Skeena River watershed.

In the early 1960s, results from a survey of *O. nerka* populations in Babine Lake suggested that the *O. nerka* productive capacity was limited by the access to spawning grounds (Johnson 1961). Following this survey, the Babine Lake Development Project (BLDP) was implemented in 1962 in an attempt to maximize the rearing capacity of Babine Lake in the main basin to enhance salmon productivity. The BLDP largely consisted of the establishment of the world's largest artificial spawning channels for Sockeye Salmon at the Fulton and Pinkut rivers. Although the BLDP resulted in an increase of the smolt outputs and adult returns of *O. nerka*, an apparent decline in freshwater survival (inferred from the fry:adult survival ratio) has been recorded since ca. 1991 (Cox-Rogers and Spilted 2012), and recent limnological surveys indicate that the trophic status of Babine Lake varies considerably from year to year, an observation that could have important consequences on the feeding ecology of the juvenile salmon (Selbie et al. *in prep*). Several confounding factors could have compromised the enhancement of the carrying capacity of the system (BLDP) - logging, mining, shoreline development, and climate change - complicating the underlying mechanisms responsible for the recent decline in salmon recruitment.

A thorough understanding of long-term variations in *O. nerka* nursery ecosystem dynamics is required to tease apart the relative influences of the different potential stressors. In the absence of long-term monitoring data, paleolimnological techniques (Smol et al. 1992) have been used to reconstruct salmon population dynamics and past ecological and environmental changes in salmon nursery lakes (Finney et al. 2000; Selbie et al. 2007). For instance, sedimentary cladoceran remains are a useful indicator to track changes in secondary production and fish predation (Sweetman and Finney 2003). Multi-trophic paleolimnological analyses of sedimentary remains of diatom, cladoceran, and isotopes have also been successfully used to track variations in past salmon runs that are influenced by the cumulative impact on their critical freshwater habitats, overfishing, dams, watershed disturbance, and climate variability and change (Finney et al. 2000; Selbie et al. 2007).

For this research project, we employ a multi-proxy paleolimnlogical approach which focuses on the analysis of sedimentary algal pigments (all algal groups), diatoms (an important group of siliceous algae), cladoceran zooplankton, stable isotopes and changes in organic matter composition of sediment to reconstruct changes in trophic conditions and possibly the salmon population dynamics in Babine Lake over the last ~200 years.

Study Site

Babine Lake is a large (49 km^2) Sockeye Salmon (*O. nerka*) nursery lake from the Skeena River watershed, located ~500 km upstream of the Pacific Ocean in the Lake Babine Nation traditional territory on the interior plateau of British Columbia (BC), Canada (Fig. 1). The climate of the region is continental with warm summers and cold winters. The meteorological records of the last 100 years indicate that average annual air temperatures has increased by at least ~1.5 °C (Fig. 2). Babine Lake is dimictic lake with high levels of dissolved organic carbon, and an average euphotic zone of ~7 m (Shortreed and Morton 2000; Shortreed et al. 2001). The hydrological regime of Babine Lake is snowmelt driven. The Babine Lake region is contained within the sub-boreal spruce biogeoclimatic zone, and about 4% of the watershed of is covered by wetlands (Fig. 1). The morphology of Babine Lake is complex and composed of multiple basins, including a long and deep Main Basin (Main Arm, mean depth= 71 m) and three shallower basins (North Arm, Morrison Arm and Hagan Arm, Fig. 1).

In the early 1962, three spawning channels were established on Babine Lake tributaries (two on the Fulton River and one on the Pinkut River) as part of the BLDP, increasing the average escapement from 0.5 to 1.4 million (Wood et al. 1998) and enhancing the nutrient loading from salmon carcasses. According to Wood et al. (1998), the first significant returns of salmon originating from the enhancement facilities occurred in 1975. Today, the spawning period of the Babine Lake salmon population extends from September to October and is characterized by three different overlapping runs (early, middle and late) (Wood et al. 1998): the early run, mostly composed of the natural population, spawn in the main arm; while the middle run, composed of the enhanced populations, spawn in the Fulton and Pinkut rivers; and the late run spawn in the Babine River. The middle run is the most abundant and occurs in July, however, recent analysis showed some annual variability in the timing of migration (Beacham et al. 2014).

Since the 1920s, the Babine Lake watershed has been actively exploited for copper and gold mining, and logging (Fig. 1). More specifically, mining activities became important in the region after 1966, with the construction of the Granisle Mine by Granby Mining and Smelting Ltd, an open-pit copper mine on Sterrett Island in Babine Lake. In 1972 another open-pit mine, the Bell Mine, opened in the watershed of the Hagan Arm. The Granisle Mine closed in 1982, but the Bell mine operation continued until 1992. During mining activities, the city of Granisle was built on the shores of Babine Lake and its population grew to over 2000. The value of past mining production was estimated at $1.13 billion (1986 dollars) by the Ministry of the Environment. Logging activities have also occurred in the catchment of Babine Lake, starting in the 1920s. In the 1980's, the eastern shore of Babine Lake underwent intensive clear-cut logging, and in 1990, logging in the Morrison Arm watershed were expedited in order to help reduce habitat suitable to the pine beetle (Levy et al. 1990). According to Shortreed and Morton (2000), 12.3% of the Babine Lake drainage basin was clear-cut logged, while 1.2% was selectively logged since 1980. Today, ~31% of the watershed is covered by young forest (i.e. forest less than

140 years old), ~33% cover by old forest (i.e. forest greater than 140 years old and greater than 6 meters in height), and ~12% has been recently logged (over the past 20 years).

Methods

Core collection

Five gravity cores were retrieved from depositional basins within Babine Lake in October 2016 and September 2017 (Fig. 1) using a Glew gravity corer (Glew et al. 2001). Three cores were retrieved from the Main Basin, and from the North Arm and Morrison Arm. Among the cores from the Main Basin, the Fulton core from the mid-Main Basin and Pinkut core from the southern Main Basin were retrieved in the vicinity of the outflows of Pinkut Creek and the Fulton River (where the enhanced populations of salmon spawn) to attempt to capture the spatially-resolved nutrient and planktivory signals arising from the Babine Lake Development Project (BLDP), while the cores from Morrison Arm and North Arm are expected to be mainly influenced by the natural spawning populations. The North Main Basin core completed the spatial gradient along Babine Lake. All sediment cores were sectioned at 0.25-cm intervals for the first 20 cm and at 0.5-cm intervals to the bottom of the core. The sectioned samples were transferred into sterile storage bags shortly after collection, and stored at 4 °C. Details on the cores can be found in Table 1.

Sediment chronology

Radioisotopic dating (^{210}Pb, ^{137}Cs, ^{214}Pb, and ^{214}Bs) was performed on all sediment cores at the PEARL dating facility using an Ortec gamma counter, similar to the one described in Schelske et al. (1994). A Constant Rate of Supply (CRS) model was used to estimate the sediment chronology based on the unsupported ^{210}Pb activity in each core. Briefly, the age of the sediments was determined using the radioisotope ^{210}Pb, which has a half-life of approximately 22.3 years, and therefore can be used for the dating of sediments, normally up to ~150 years old. More specifically, we used the "supported" ^{210}Pb and "unsupported" ^{210}Pb found in the sediment. The unsupported ^{210}Pb corresponds to the concentration of ^{210}Pb that comes from the fallout of ^{210}Pb from the atmosphere into lakes which then adsorbed onto small particles that settle to the sediment. The supported ^{210}Pb is derived from the decay of ^{226}Ra that is already part of the sediment matrix and does not originate from atmospheric sources. As the supported ^{210}Pb is found in equilibrium with its short-lived precursor ^{214}Bi in the sediment the measurement of supported ^{210}Pb is done by gamma counts of ^{214}Bi. The difference between total activity of ^{210}Pb and the unsupported ^{210}Pb is used to determine the 'unsupported' ^{210}Pb, which is used to estimate the age of the sediment, using the Constant Rate of Supply (CRS) model (Appleby and Oldfield 1978).

To help assess the accuracy of the CRS model, the peak in the concentration of ^{137}Cs activity was used as an independent dating marker for the ~1962-63 horizon in the sediment core, which marks the peak fallout from atmospheric nuclear testing.

Sediment geochemistry

Loss-on-Ignition

Sample for Loss-on-Ignition (LOI) were prepared at every 0.5 cm for the top 20cm of each core. LOI was completed following the methods outlined in Heiri et al. (2001). Clean crucibles were placed in a muffle furnace at ~105°C for 30 minutes to dry prior to being transferred into a desiccator. The empty crucibles were weighed and ~0.1 g of freeze-dried sediment was added to the crucibles. The samples were heated to 550°C in a muffle furnace for four hours. The crucibles were transferred to a desiccator and allowed to cool prior to weighing The fraction of weight loss between 105°C and 550°C is an estimate of the percent organic matter in the sediments. The crucibles were then returned to the muffle furnace and heated to 950°C for 2 hours, allowed to cool in a desiccator and weighted. The weight loss between 550°C and 950°C is an estimate of the carbonate fraction in the sediments.

Elemental carbon and nitrogen, and stable isotopes

Samples for isotope analysis were prepared every 0.25cm interval for the top 10 cm for all cores to provide a more detailed analysis of the most recent history, at every 0.5cm intervals until 20 cm, and every 1cm to the bottom of the core. Isotope analysis was completed at Idaho State University following the methods outlined in Talbot et al. (2001) and Wolf et al. (2001). A subset of samples were acid (HCl) washed to assess the influence of carbonate on the carbon isotopes. The comparison between acid-washed and raw samples can reveal difference in carbon isotopes. If no significant difference are found the raw samples will be retained for analysis. Homogenized sediment samples were freeze-dried and analyzed for C (%), N (%), $\delta^{13}C_{org}$ and, $\delta^{15}N_{org}$ by continuous flow isotope-ratio mass spectrometry (CF-IRMS). $\delta^{15}N$ has commonly been used as a proxy of salmon population dynamics, and $\delta^{13}C$ and C:N ratio as a proxy of inputs from the catchment relative to autochthonous sources.

Proxy of primary and secondary production

Sedimentary algal pigments analysis

Samples for algal pigments were analyzed at 0.25cm intervals for the top 7cm of the three cores from the main basin, and the top 10 cm for the two cores from the arms, and thereafter at 0.5 cm intervals to 20 cm. Pigment analysis will be completed using High-Pressure Liquid Chromatography (HPLC) at the Fisheries and Oceans Canada Cultus Lake Salmon Research Laboratory. In order to preserve the pigment in the sediment, the sediment bags were kept frozen prior to analysis. Sediment processing for pigment analysis is done under a green light to avoid photo-degradation of the pigments. The samples are kept cool throughout the sample preparation. Approximately 2 g of wet sediment are subsampled into scintillation vials and freeze-dried. The first step of the pigment analysis consisted of pigment extraction from the sediment matrix. Briefly, between 200 and 400 mg of freeze-dried sediment is transferred to a plastic test tube and 4ml of pure acetone was added. The test tubes were capped, and placed in a dark freezer at -20°C for 24 hours. In the second step, the solvent containing the extracted pigments is filtered to

eliminate any effects of the sediment matrix. In this step, the test tubes were vortexed and then centrifuged for 15 minutes at 4°C. The supernatant was decanted into a glass luer-lok syringe with a 0.22 μm filter attached at the tip. The solvent was filtered into 5 mL vials that were then are capped and kept in the freezer at -80°C overnight. In the third step, 500 μL of the pigments-acetone solution is transferred into HPLC autosampler vials, and were run in the HPLC, resulting in a chromatograph for each sample, that was analysed for pigment concentrations, which were then standardized to ng/g organic matter.

Sedimentary diatom micro-fossil analysis

Diatom valves were prepared following standard methods (Batterbee et al. 2001) at 0.25 cm intervals for the top 10 cm and at 0.5 cm intervals from 10 to 15cm. Briefly, ~0.2-0.3 g of wet sediment was sub-sampled and placed into a 20 mL glass vial, to which a 1:1 mixture by molar weight of concentrated nitric (HNO_3) and sulphuric (H_2SO_4) acid was added to aid in the digestion of the organic matter. Samples were then heated in a hot water bath (~70 °C) for 6-7 hours and then were allowed to settle for 24 hours before the acid above the sample was aspirated, and the samples rinsed with deionized water. This procedure was repeated until the sample had the same pH as deionized water (approximately eight rinses). Concentrations of diatoms in each sample were also estimated using the microspheres (Battarbee and Kneen 1982). Briefly, an aliquot of a known concentration of microspheres was added to each of the diatom samples, prior to settling on coverslips. The microspheres were enumerated along with the diatoms and used to calculate estimates of number of diatom valves per gram dry weight of sediment. Diatoms were identified and counted along transects on the prepared slide using a Leica DMRB microscope fitted with a 100x Fluotar objective (numerical aperture of objective = 1.3) using differential interference contrast (DIC) optics, at 1000x magnification. Approximately 400 diatom valves were enumerated per slide. Diatoms were identified to the species level or lower, using the following taxonomic references: Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Cumming et al. (1995), Lange-Bertalot and Melzeltin (1996), Camburn and Charles (2000), Fallu et al. (2000) and the online database of Diatoms of the United States (westerndiatoms.colorado.edu). For the diatom *Discostella stelligera*, a common diatom in the cores, 50 values were measured from each sample, to provide an estimate of the changes in this taxon, which has been suggested to be a measure of changes in limnological conditions.

Sedimentary cladoceran zooplankton analysis

Slides for the analysis of cladoceran sub-fossils were prepared following standard methods (Korhola and Rautio 2001) at every 0.5 cm intervals down to a core depth of 10cm. Approximately 1 g of wet sediment was treated with 150 mL of 10% KOH to deflocculate the sediment. The sediment-KOH mixture was then sieved through a 34 µm mesh and material on the mesh was backwashed with double deionized water into a 12mL glass vial, and several drops of safranin glycerine solution (dye) and alcohol (preservative) were added to the sample. A 50 µL subsample of the slurry was pipetted onto a slide and allowed to dry. This process was

repeated as necessary to achieve samples of sufficient concentration for enumeration. In order to calculate the concentration of cladoceran sub-fossils, individuals on the entire slide were counted. A minimum count of 70 individuals per sample were enumerated (Kurek et al. 2010). Standard identification keys were used to identify the remains of cladoceran (Szeroczyńska and Sarmaja-Korjonen 2007; Korosi and Smol 2012a; Korosi and Smol 2012b). The length of the mucro, antenna, and carapace of *Bosmina* spp. and the postabdominal claw of *Daphnia* spp. were measured following the method outlined in Korosi et al. (2010), (Fig. 2). The size of *Bosmina* spp. and *Daphnia* spp. may give insight into past food web planktivory (Korosi et al. 2013).

Preliminary data analysis

A constrained cluster analysis (Grimm, 1987) using the diatom and cladoceran assemblages was performed to provide a framework to help characterize different time-constrained zones in the species data, to describe the broad-scale changes in the core over time. For this analysis, a square-root transformation of the species data was used (Edwards and Cavalli-Storza's chord distance).

Results

Sediment chronology

All sediment cores from Babine Lake have been analyzed for total ^{210}Pb, ^{137}Cs, and supported ^{210}Pb (Fig. 3). The total ^{210}Pb activity in all cores followed an first-order exponential decay that accounted for a large amount of variance (r^2 >0.9, Fig. 3). Background (or supported) levels of ^{210}Pb were reached around 10 cm and 9 cm in the Morrison Arm Core and the North Arm core, respectively, and around 6 and 7 cm in the NMB core, the Fulton core, and the Pinkut core. The cesium peak was well-defined in all cores and reached maximum values at 6 cm in cores originating from the arms of Babine Lake (i.e. Morrison Arm and North Arm), and at 4 cm the Main Basin cores (i.e. North Main Basin, Fulton, Pinkut). The background levels of ^{210}Pb reached at deeper depths and the presence of a deeper cesium peaks suggest that the cores originating from the arms of Babine Lake have a higher sedimentation rate compare to the cores from the Main Basin.

Estimates of the peaks in ^{137}Cs were in some cores a few decades too old, based upon the CRS models of the unsupported ^{210}Pb activities. This problem, in part arises due to the relatively low unsupported ^{210}Pb activities in these cores (cores from the northern watershed). Given the clearly defined ^{137}Cs peak, we decided to use the composite model developed by Appleby et al. (2001), which constrains the CRS model to our ^{137}Cs peak. A second-order polynomial was used to interpolate and extrapolate the dates derived from our age-depth model (see orange line on Fig. 3).

Sediment geochemistry

LOI has been completed for all cores. The 3 cores from the main basin and the North Arm core small increases in organic matter since ca. 1800 (Fig. 4). The Morrison Arm core

contained higher percentage of organic matter (2-times higher than the other cores), and displayed an increasing trend from ca. 1600 to 1750 followed by a slow decline until ca. 1975 when the organic matter increased sharply. The carbonate content of all cores from Babine Lake was low (generally <2%) and stable over the length of the cores.

Proxy of primary and secondary production

Sedimentary algal pigment analysis (see Figs. 5-a to e; pages 6 to 10 of the PDF)

The pigments from all cores has been completed. The pigments found in the sediment cores were dominated by diatoms and chrysophytes (fucoxanthin, diatoxanthin, diadinoxanthin), cryptophytes (alloxanthin, diadinoxanthin) and, blue-green algae (zeaxanthin, lutein, and canthaxanthin). The ratio of chlorophyll-a to phaeophytin-a (Chla:Pheoa), an indicator of preservation, remained relatively stable in the North Arm and Morrison indicating that differential degradation of pigments is likely not an issue of concern for interpreting trends in pigment concentrations in the cores from the arm. In the Fulton and North Main Basin cores, the ratio declined around in the 1920s and stabilized, indicating that the pigments may be more degraded at the top of the core starting in the 1920s in comparison to deeper depths. In the Pinkut core, the ratio showed some variation throughout the core but remained on average stable.

The pigments profiles from the all main basin cores (Pinkut, Fulton, and North Main Basin) showed similar trends with relatively low pigment concentrations until 2009 where all cores displayed an abrupt increase in concentration of all pigments (including chlorophyll *a*, a proxy of overall biomass) and the appearance of diadinoxanthin and fucoxanthin. The increase in concentrations was much more pronounced in the Pinkut and the Fulton cores with an increase in Pinkut core 4x higher than in the Fulton core and 6x higher than in the North Main Basin core. Prior to 2009, the pigment concentration showed small fluctuations, with the cores from Pinkut and Fulton basins, showing low concentrations from ca. 1930 to the recent large increases. The Arms cores (Morrison Arm and North Arm) showed different trends when compare to cores from main basin. In fact, the pigment concentrations in the Morrison Arm core were higher and showed an increase ca. 1970 followed by a decline ca. 2000 until it reached stable values in ca. 2009. The pigments concentration in the North Arm remained stable and relative low over time.

Sedimentary diatom analysis

The analysis of the diatom assemblages from all cores have been completed, and is summarized below for the five cores from Babine lake.

Main Basin Cores (Fulton, Pinkut & North Main Basin) –Figs. 6a to c

All of the cores from the main basin are dominated by similar planktonic taxa. The average composition of the Fulton and North Main Basin samples were comprised of ~70% planktonic taxa and for the Pinkut samples ~80% planktonic diatoms. In all cores from the main basin, the taxa that reached highest abundances were the oligotrophic taxon *Discostella stelligera* and the meso-eutrophic taxon *Aulacoseira subarctica*. Other oligotrophic planktonic taxa common in the cores included *Cyclotella ocellata*. A number of mesotrophic planktonic taxa were also common in the cores, including: *Asterionella formosa, Fragilaria crotonensis*,

Fragilaria nanana and *Tabellaria flocculosa*. Other common eutrophic planktonic taxa included *Stephanodiscus oregonicus, Stephanodiscus minutulus* and *Stephanodiscus parvus.* As is often typical, the benthic diatom assemblage was very diverse, with ~140 taxa identified in the Pinkut core, ~150 in the Fulton core and ~290 in the core from the North Main Basin, but benthic taxa only comprised on average ~20-25% of the assemblage in these cores. Common benthic taxa included *Achnanthidium minutissimum* and the chain-forming Fragilariceae (*Staurosirella pinnata, Staurosira construens* and *Pseudostaurosira brevistriata*), which are combined as a group in the stratigraphies (i.e. Benthic Fragilariaceae). There were no distinct changes in the benthic component of the assemblages in any of the cores from the main basin.

Changes in the composition of the planktonic diatom taxa were similar in all main basin cores, which is illustrated through the similar zonation seen in the cores (Figs. 6a-c). The main basin cores can be described as having three major zones of diatom assemblages. While neither core has large changes in the species composition there are a number of changes that can be noted in the planktonic portion of the assemblages. The lowest percent abundance of *D. stelligera* occurred in Zone B2 (i.e. starting in early 1800s and ending in ca. 1850), with highest abundances in Zone C, and generally higher abundances in Zone A in comparison to Zone B. All main basin cores indicated a lower percent abundance of *A. subarctica* and *C. ocellata* in Zone A (ca. 1945-1950), and generally higher abundances of small *Stephanodiscus* (*S. minutulus* and *S. parvus*) and *F. nanana*, and higher abundance of *Tabellaria flocculosa* in zones A & B (post-1800s).

The diatom concentrations in the main basin were on average higher post-1800. Chrysophyte scales were almost absent in all cores prior to 1900s. The North Main Basin core displayed the first increase in chrysophyte concentrations at around 1920, followed by Fulton in 1950, and Pinkut in 1990. While the timing of the initial increase differs between cores, a second sharp increase was noticeable in all core after 1990 (Fig. 7).

Arm Cores (North Arm and Morrison Arm) –Figs. 6e to d

The average composition was ~25% and 60% planktonic taxa for the Morrison Arm and North Arm cores, respectively (Figs 6e,d). The dominant planktonic taxa in those two cores were the oligotrophic *Discostella stelligera* and the meso-eutrophic *Aulacoseira subarctica,* and the planktonic flora was similar in composition to the main basin cores. The benthic assemblages were very diverse with ~195 taxa found in the North Arm core, and ~219 taxa found in the Morrison Arm core. The benthic assemblages were dominant in the Morrison Arm core representing ~75% of the diatom assemblage, and it was abundant in the North Arm core representing ~40% of the diatom assemblage. The most abundant benthic taxa in both cores were the benthic Fragilariceae.

Although the cluster analysis defined only 2 distinct zones in the cores from the arms, which when constrained to dates corresponded with the Zones A and B observed in the main basin cores. In the Morrison Arm core, Zones B2 (from ca. 1732 to ca. 1823) and A2 (from ca. 1937 to 1993) were characterized by lower abundance of *D. stelligera*, and Zone A was

characterized by slightly higher abundance of *Asterionella formosa*. The relative abundances of small *Stephanodiscus* (*S. minutulus* and *S. parvus*) were higher in both cores in Zone A1 (ca. 1993 in the Morrison Arm core, ca. 1950 in the North Arm core), and the relative abundance of benthic Fragilariceae declines from ~40% to 15% in the most recent zone (Zone A1) in the core from Morrison Arm (Fig. 6e).

The diatom concentrations in the arms cores showed high variably throughout the cores (Fig. 7). The Morrison Arm core displayed the higher diatom concentration when compared to the other cores. The chrysophyte concentrations were the highest in the North Arm pre-1900, but increased in all cores over the past decade (Fig. 7). The timing of the initial increase in scaled chrysophyte varied occurring around 1950 in the core from the North Arm, and after 2000 in the Morrison Arm core (Fig. 7).

Generally the cores showed a decline of in the average of *D. stelligera* diameter size starting ca. 1920, with the exception of the North Arm, which occurs a few decades later (Fig. 8). The average diameter of *D. stelligera* continues to decline until ca. 1960s-1970s, thereafter the average diameter stabilizes around 2µm.

Sedimentary cladoceran zooplankton analysis (Figs. 9a to b)

The analyses of cladoceran zooplankton have been completed for all cores. The cladoceran assemblages in all cores were dominated by the pelagic cladocera, *Bosmina* spp. and *Daphnia* spp. The identifiable headshield remains of *Bomina* spp. were attributable to *Bosmina longispina*; however, the identification of most of the remains to the species level was difficult, due to the presence of other perforations on the headshields that complicate species-level determinations. *Daphnia longispina* complex (planktonic) and littoral *Alona* spp. (mainly dominated by *Alona affinis* Leydig 1860) and *Chydorus* spp. (dominated by *Chydorus brevilabris* Frey 1980 and *Chydorus gibbus* Sars 1891) also were dominant in the cores. The sedimentary assemblage exhibited a diverse composition of littoral-benthic taxa including *Pleuroxus* spp., *Camptocercus* sp., *Eurycerus* sp., and the species *Ophroxus gracilis* Sars 1891, but the overall abundance of benthic taxa were rare (<5%).

All main basin cores and the Morrison Arm core showed an increase in *Daphnia longispina* complex in 1900, which was defined by an important change in the cladoceran assemblages by the CONISS (Fig. 9a). The North Main Basin core displayed a decline in all littoral species in ca. 1960. The arms cores (North Arm and Morrison Arm) also showed a decline in littoral species, however at much earlier time (i.e. ca. 1930).

Changes in the total concentration of cladoceran (#individual. g dry sediment^{-1}) are variable between cores with an increase in ca. 1930 in the main basin cores, and in 1960 in the North Arm core. The Pinkut core also display a second increase in around 2010. The cladoceran concentrations were also much higher in the Morrison Arm core compare to the other cores.

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Table 1 (Page 1/19): Details information about the cores collected from Babine Lake.

Figure 1 (Page 2/19): Map of Babine showing the coring locations and details of the land cover of the Babine Lake watershed to highlight major disturbances (e.g. logging, mining), refer to legend on the map for more details. The 5 insets show a zoom-in of the coring locations to give insight into the different watershed disturbances found around the respective coring locations.

Figure 2 (Page 3/19): Mean annual temperatures recorded at Smithers, BC and Fort Saint James, BC, the closest long-term meteorological stations in proximity to Babine Lake (monthly mean of homogenized daily mean temperature data retrieved from Environmental Canada). A LOESS smoothing (span=0.4) was used as a means of visualizing trends (orange line; the grey shaded area depicts the 95% confidence level interval for predictions from the fitted linear model).

Figure 3 (Page 4/19): Left graphs show the total activities of ^{214}Bi (grey circle), ^{210}Pb (black square) and first order exponential decay of ^{210}Pb (red line) for the Babine Lake cores. Middle graphs show the total activity of ^{137}Cs (purple circle). Right graphs show composite CRS age- (black square), the orange line correspond to the second-order polynomial used to interpolate and extrapolate CRS ages.

Figure 4 (Page 5/19): Results from the Loss-On-Ignition (LOI) analysis with the top graphs corresponding to the changes in % organic matter through time and the bottom graphs corresponding to the changes in % carbonate through time for the 5 cores.

Figures 5a-d (Pages 6-10/19): Change in pigment concentrations (ug/g organic) through time (i.e. Age in Year C.E.) and depth (cm) for the North Main Basin core (5a, page 6), the Fulton core (5b, page 7), the Pinkut core (5c, page 8), the North Arm core (5d, page 9), and the Morrison Arm core (5e, page 10).

Figures 6a-d (Pages 11-15/19): Relative abundance (%) of the dominant diatom species (bar graphs) and diatoms concentrations (#valves/g dry weight x10^8; line graph) along core depth (cm) for the North Main Basin core (6a, page 11), the Fulton core (6b, page 12), the Pinkut core (6c, page 13), the North Arm core (6d, page 14), and the Morrison Arm core (6e, page 15). The vertical lines represent the limits of the zones defined by CONISS.

Figure 7 (Page 16/19): Changes in diatoms concentrations (#valves/g dry weight x10^8) and chrysophytes concentrations (#scales/g dry weight x10^8) through time in all 5 cores from Babine Lake.

Figure 8 (Page 17/19): Changes in *D. stelligera* diameter size along core depth (cm). The top graph represents the propotion of *D. stelligera* with a diameter greater than 5um. The middle graph shows the average diameter based on 50 valves measurements, the error bars represent the standard deviation. Bottom graph shows the relative abundance of *D. stelligera* along depth.

Figure 9a-b (Page 18-19/19): Relative abundance (%) of the dominant cladoceran species or groups (bar graph), ratio of pelagic:littoral (grey area graph), and total concentrations (line graph) through time (Year C.E.) for the main basin cores (figure 9a), and the arms cores (figure 9b). The vertical lines represent the limits of the zones defined by CONISS.

Table 1: Babine Lake cores descriptions and locations.

Core name as shown in Figure 1	Coordinates	Water depth at coring location (m)	Core length (cm)
Pinkut Core	54° 27.332 N 125° 29.749 W	141	58
Fulton Core	54 43.170 N 125 57.476 W	132	51.5
North Main Basin	54 58.170 N 126 16.010 W	134	31.6
North Arm	55 58.170 N 126 34.806 W	66.5	54
Morrison Arm	55 05.115 N 126 15.027 W	30.2	61.5

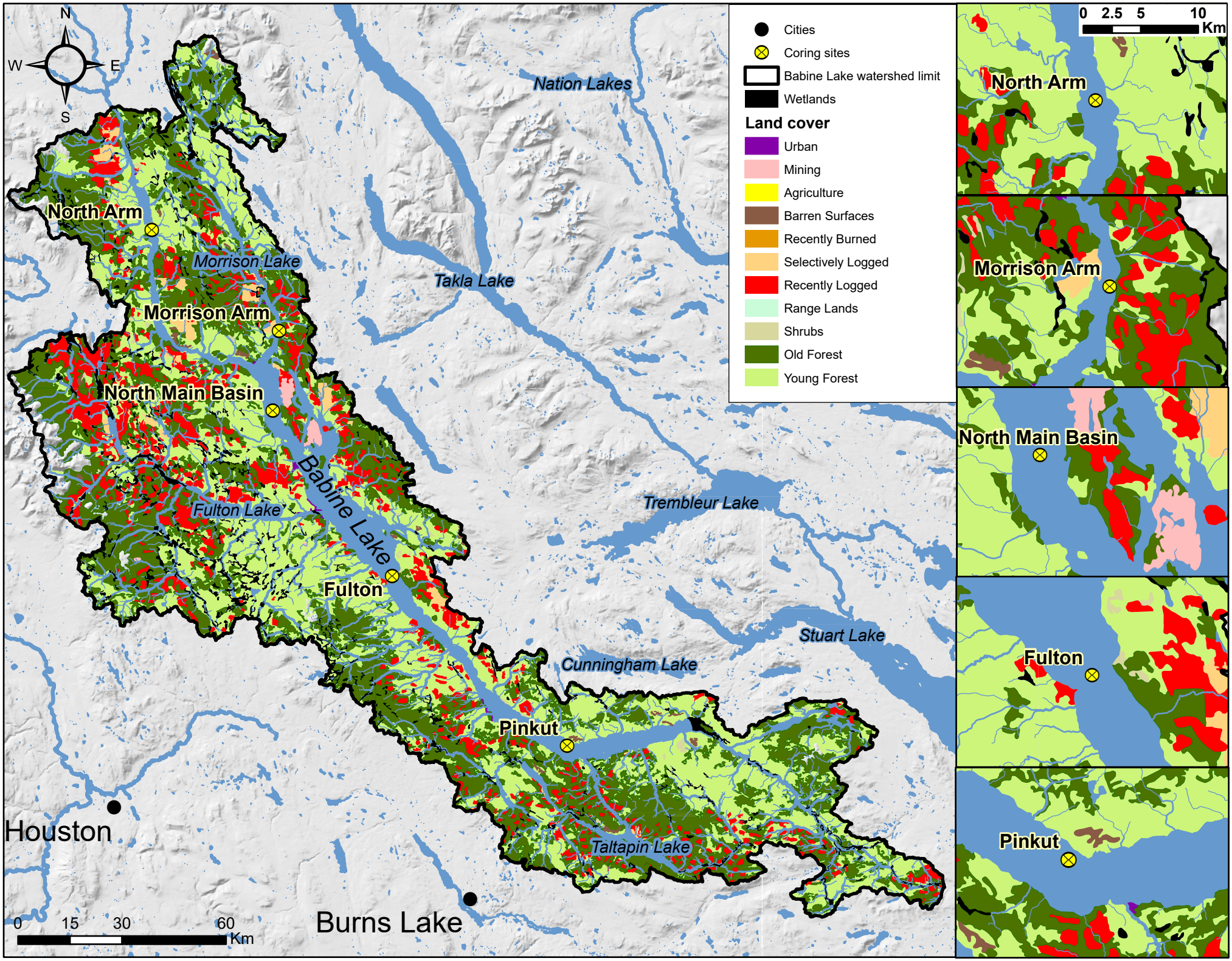

N
W
E
S
Cities
Coring sites
Babine Lake watershed limit
Wetlands
Land cover
Urban
Mining
Agriculture
Barren Surfaces
Recently Burned
Selectively Logged
Recently Logged
Range Lands
Shrubs
Old Forest
Young Forest
Nation Lakes
Takla Lake
Trembleur Lake
Stuart Lake
Cunningham Lake
Taltapin Lake
Babine Lake
North Arm
Morrison Lake
Morrison Arm
North Main Basin
Fulton Lake
Fulton
Pinkut
Houston
Burns Lake
0 15 30 60 Km
0 2.5 5 10 Km
North Arm
Morrison Arm
North Main Basin
Fulton
Pinkut

Figure 2

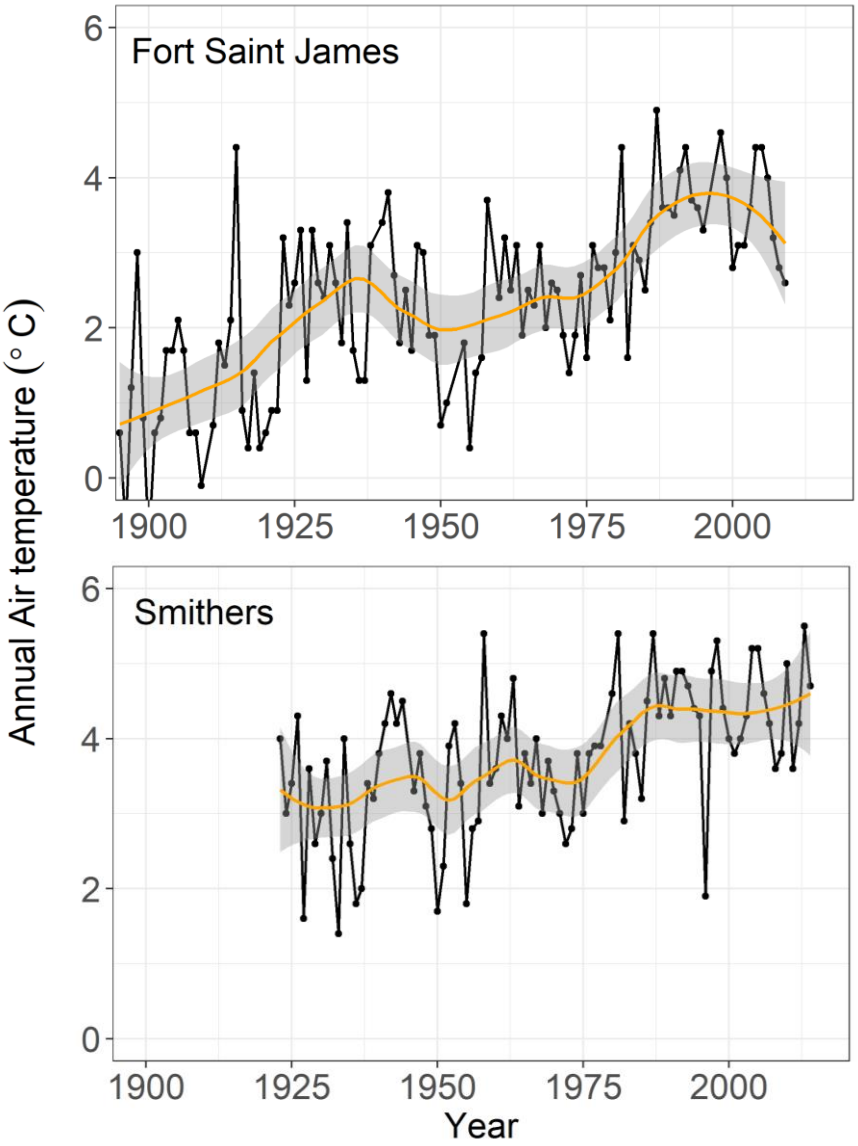

Fort Saint James
Smithers
Annual Air temperature (° C)
Year
0
2
4
6
1900
1925
1950
1975
2000

Figure 3

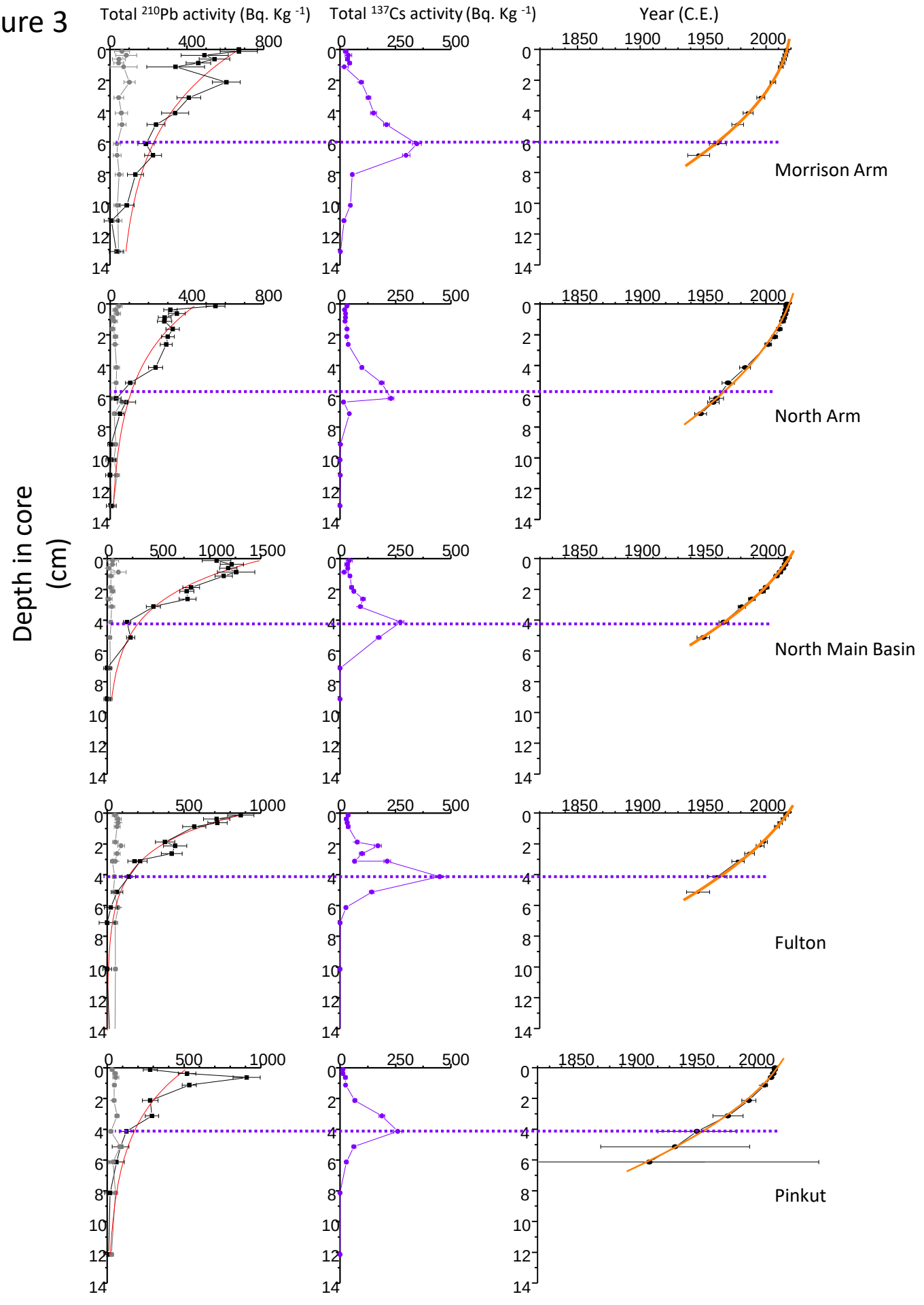
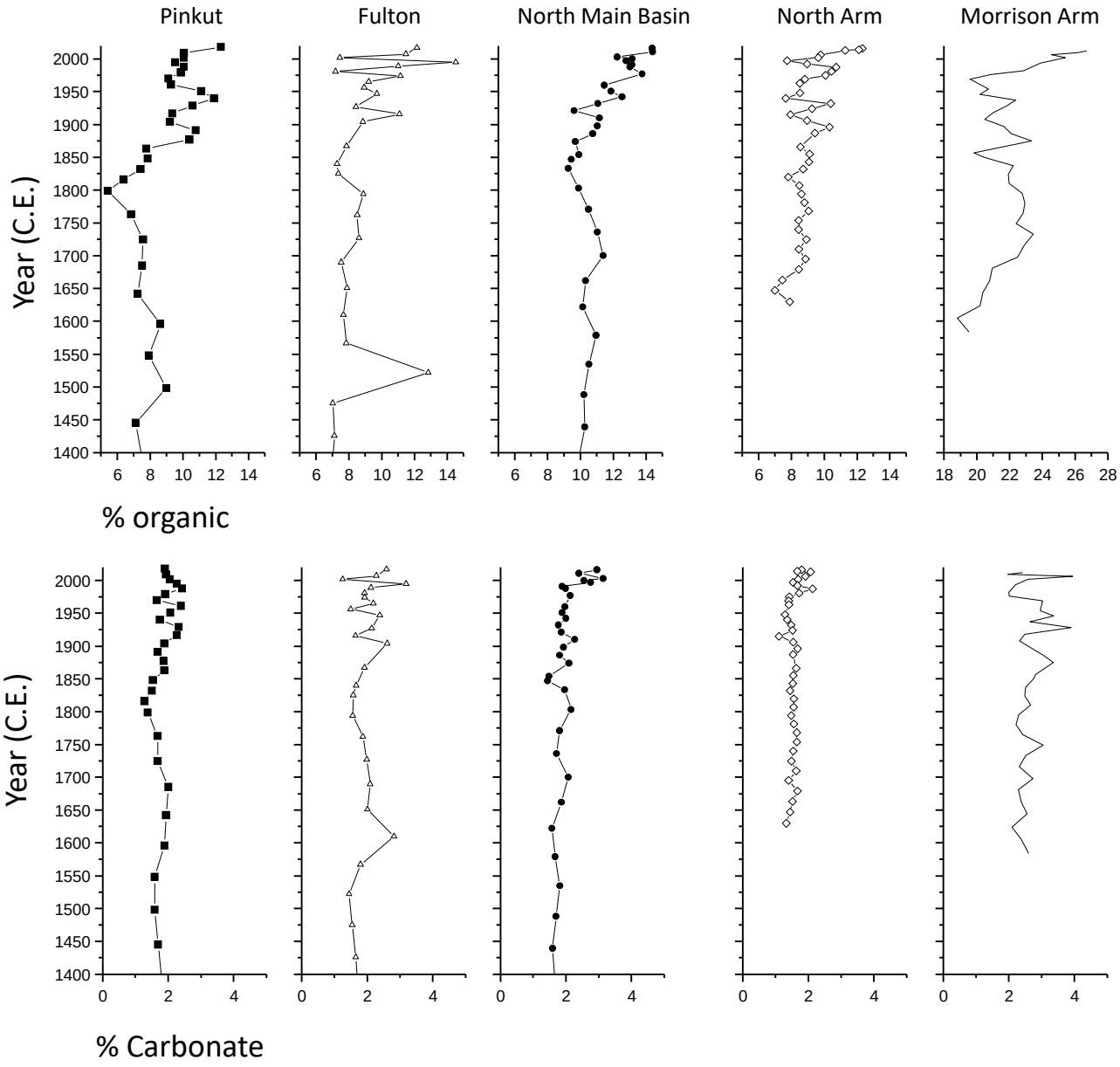
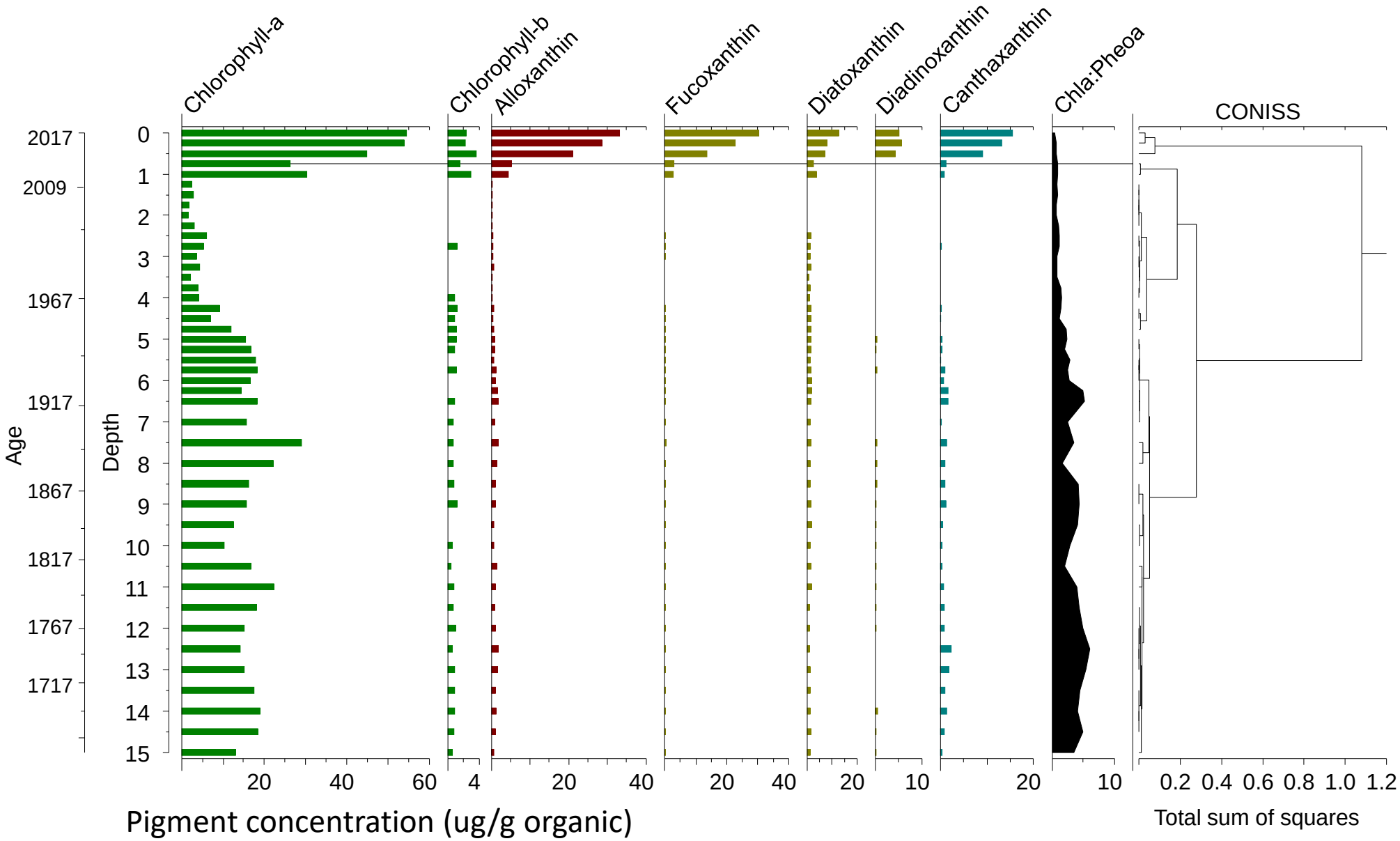

Total 210Pb activity (Bq. Kg -1)
Total 137Cs activity (Bq. Kg -1)
Year (C.E.)
Depth in core (cm)
Morrison Arm
North Arm
North Main Basin
Fulton
Pinkut

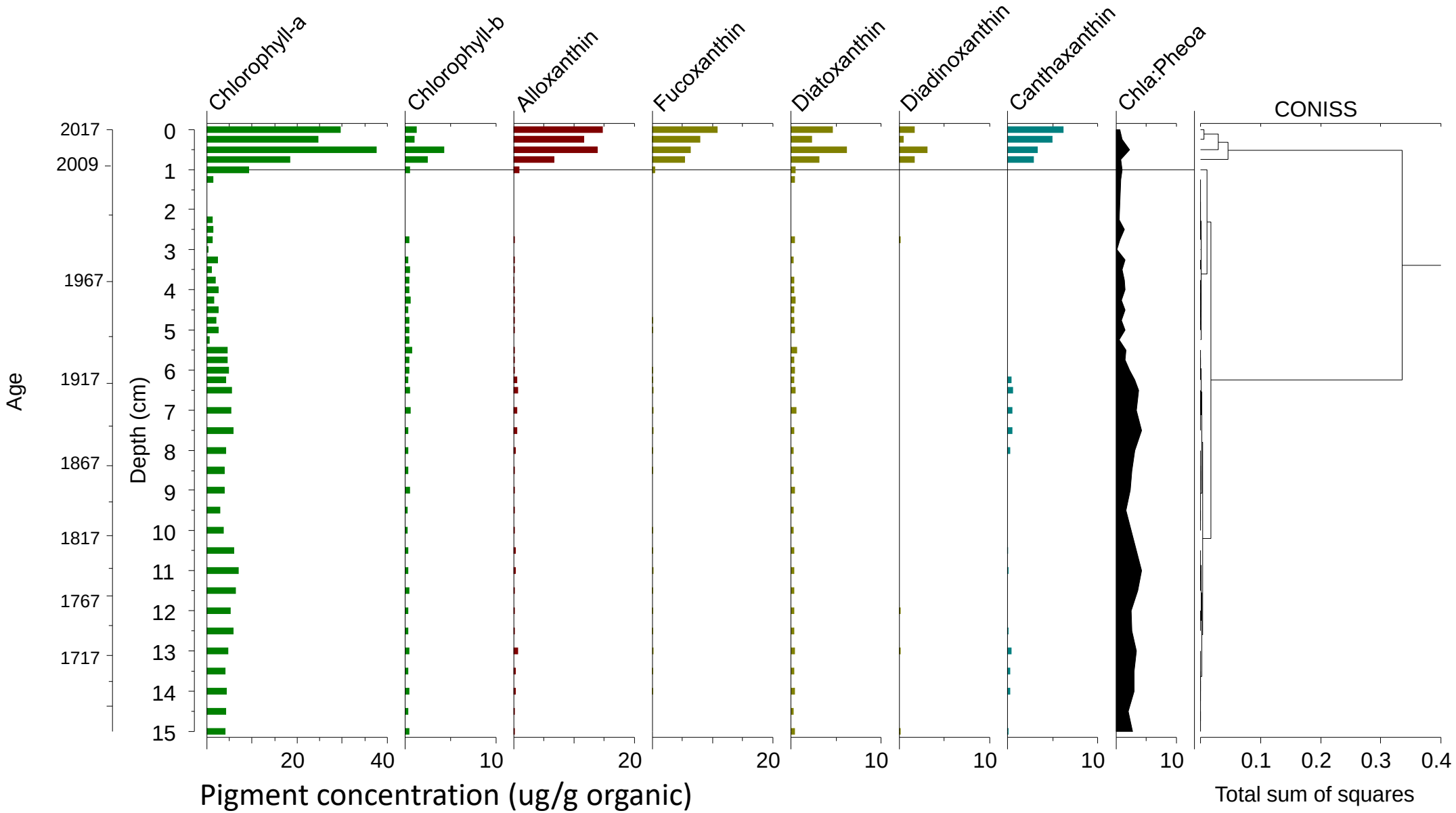
Figure 4


Pinkut
Fulton
North Main Basin
North Arm
Morrison Arm
Year (C.E.)
% organic
% Carbonate

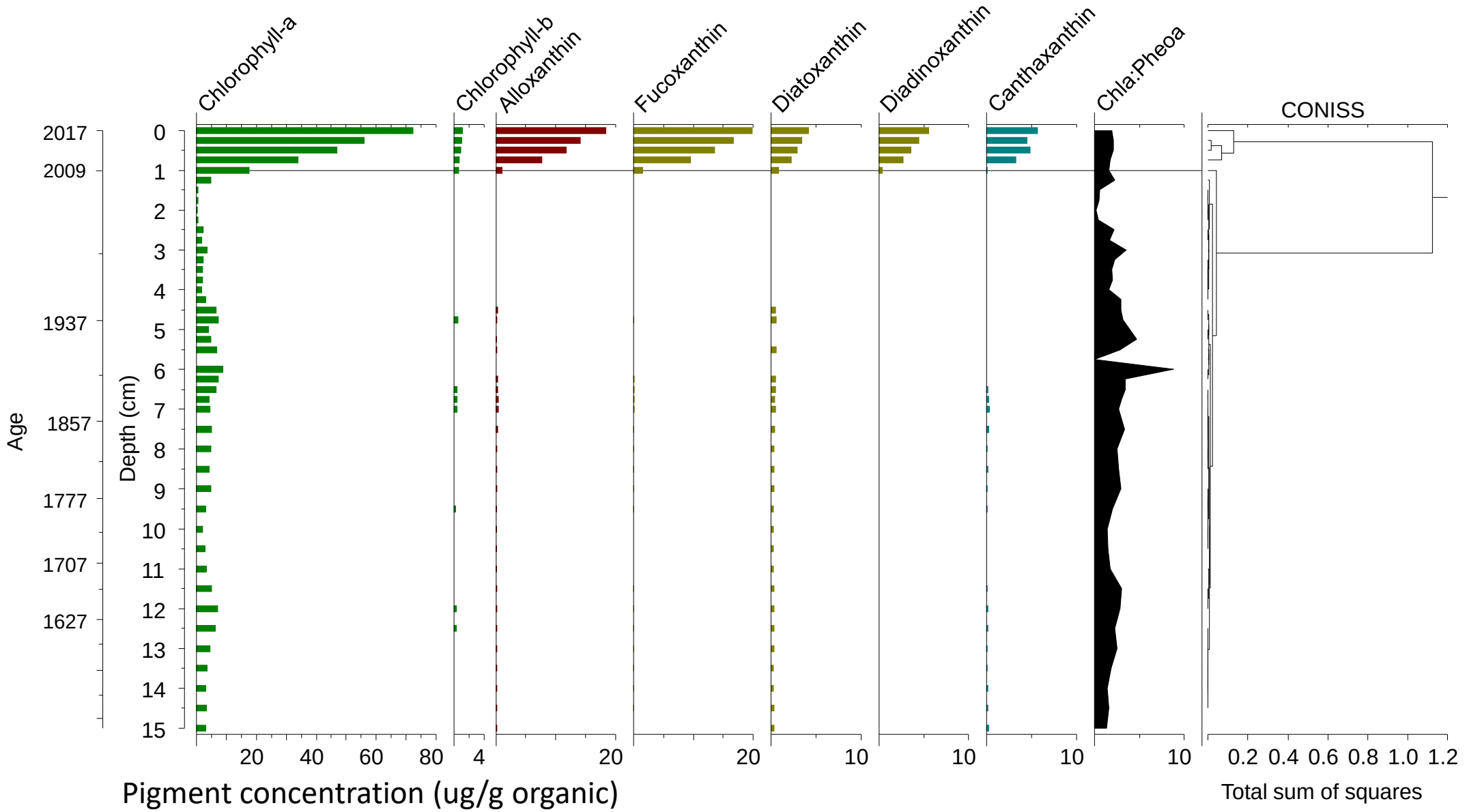
North Main Basin core



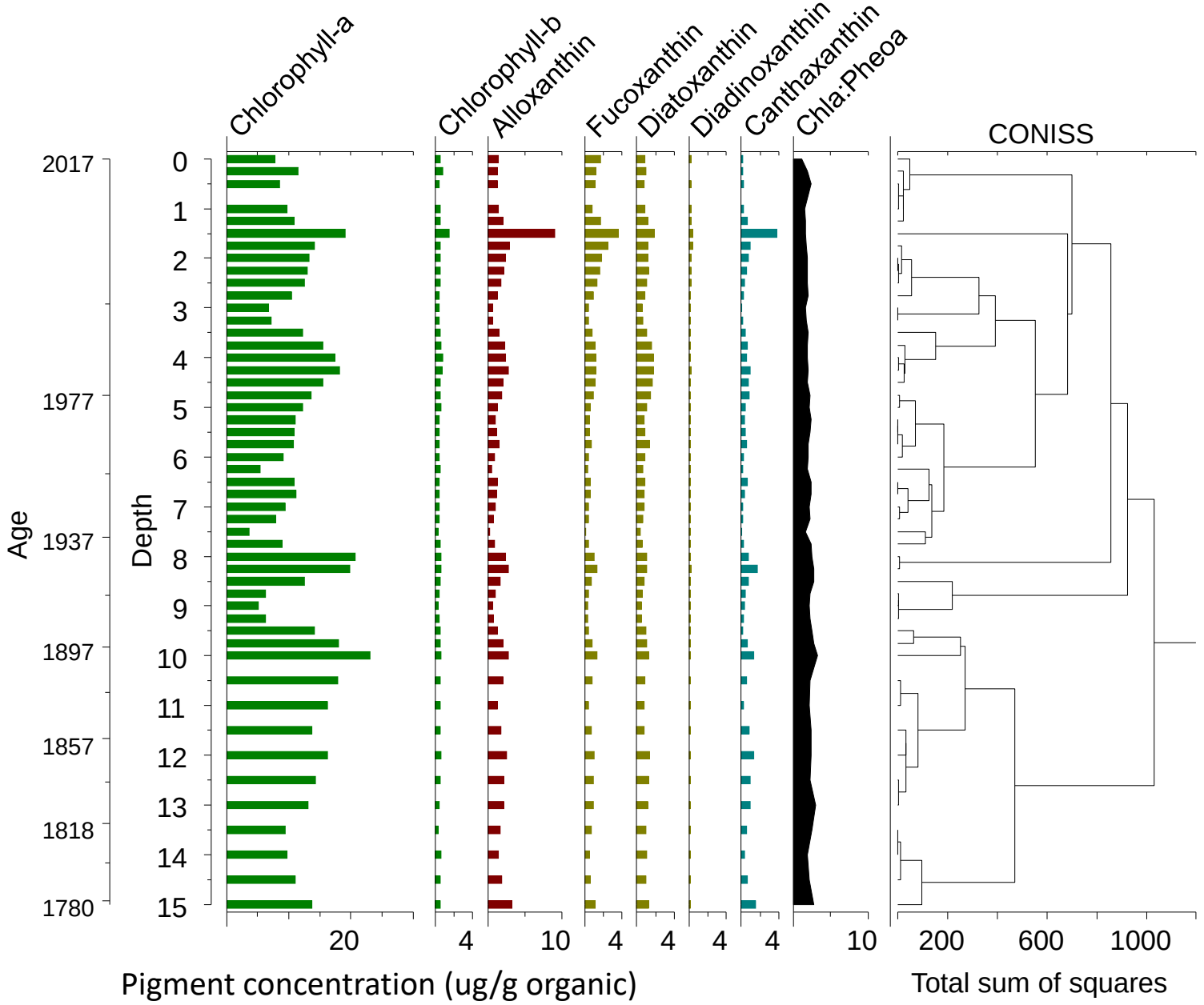
Fulton core


Chlorophyll-a
Chlorophyll-b
Alloxanthin
Fucoxanthin
Diatoxanthin
Diadinoxanthin
Canthaxanthin
Chla:Pheoa
CONISS
Age
2017
2009
1967
1917
1867
1817
1767
1717
Depth (cm)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
20
40
10
20
20
10
10
10
10
0.1
0.2
0.3
0.4
Pigment concentration (ug/g organic)
Total sum of squares

Pinkut core


Chlorophyll-a
Chlorophyll-b
Alloxanthin
Fucoxanthin
Diatoxanthin
Diadinoxanthin
Canthaxanthin
Chla:Pheoa
CONISS
Age
Depth (cm)
2017
2009
1937
1857
1777
1707
1627
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
20
40
60
80
4
20
20
10
10
10
10
0.2
0.4
0.6
0.8
1.0
1.2
Pigment concentration (ug/g organic)
Total sum of squares

North Arm core



Morrison Arm core

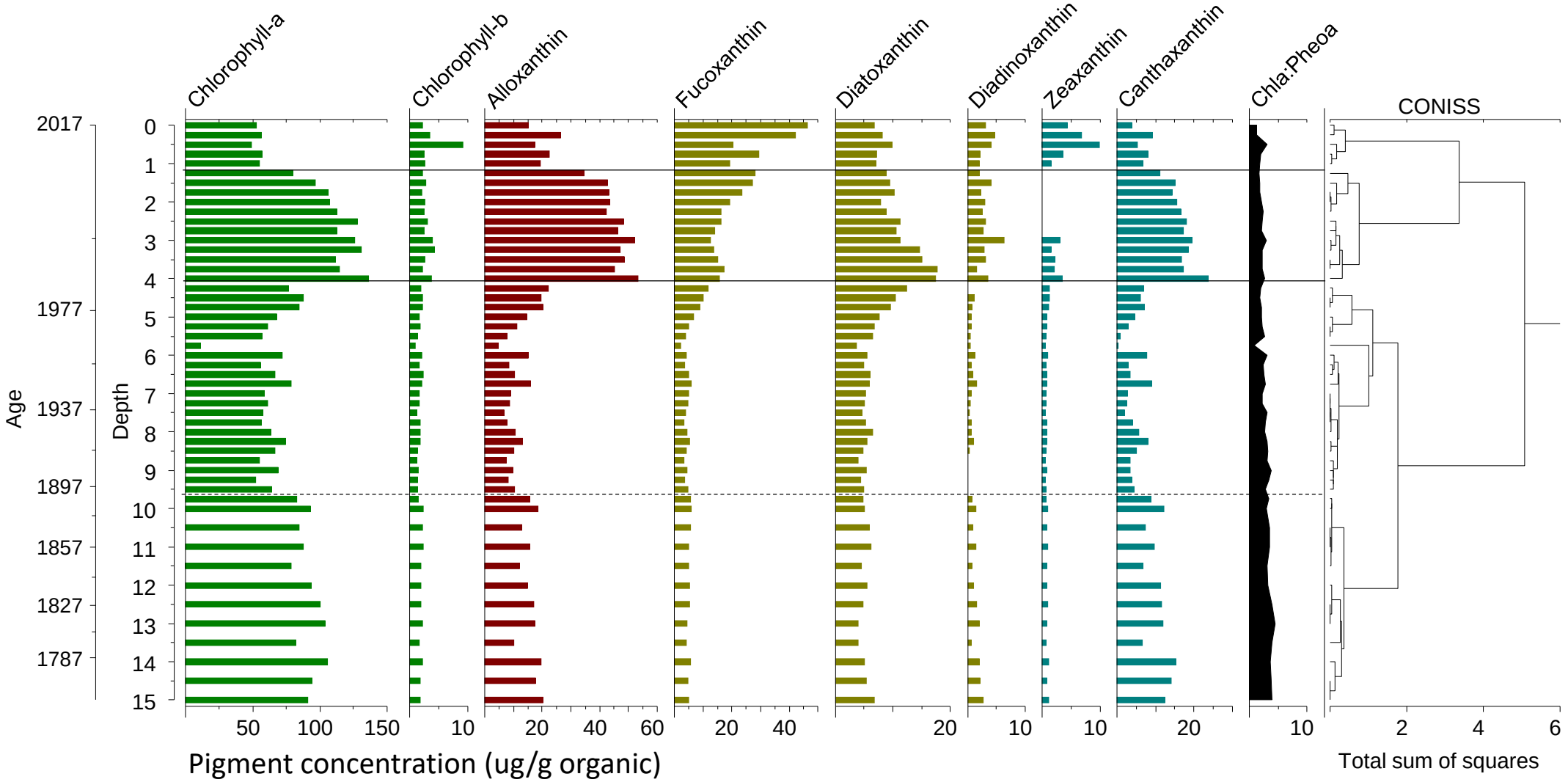


Figure 6a

North Main Basin

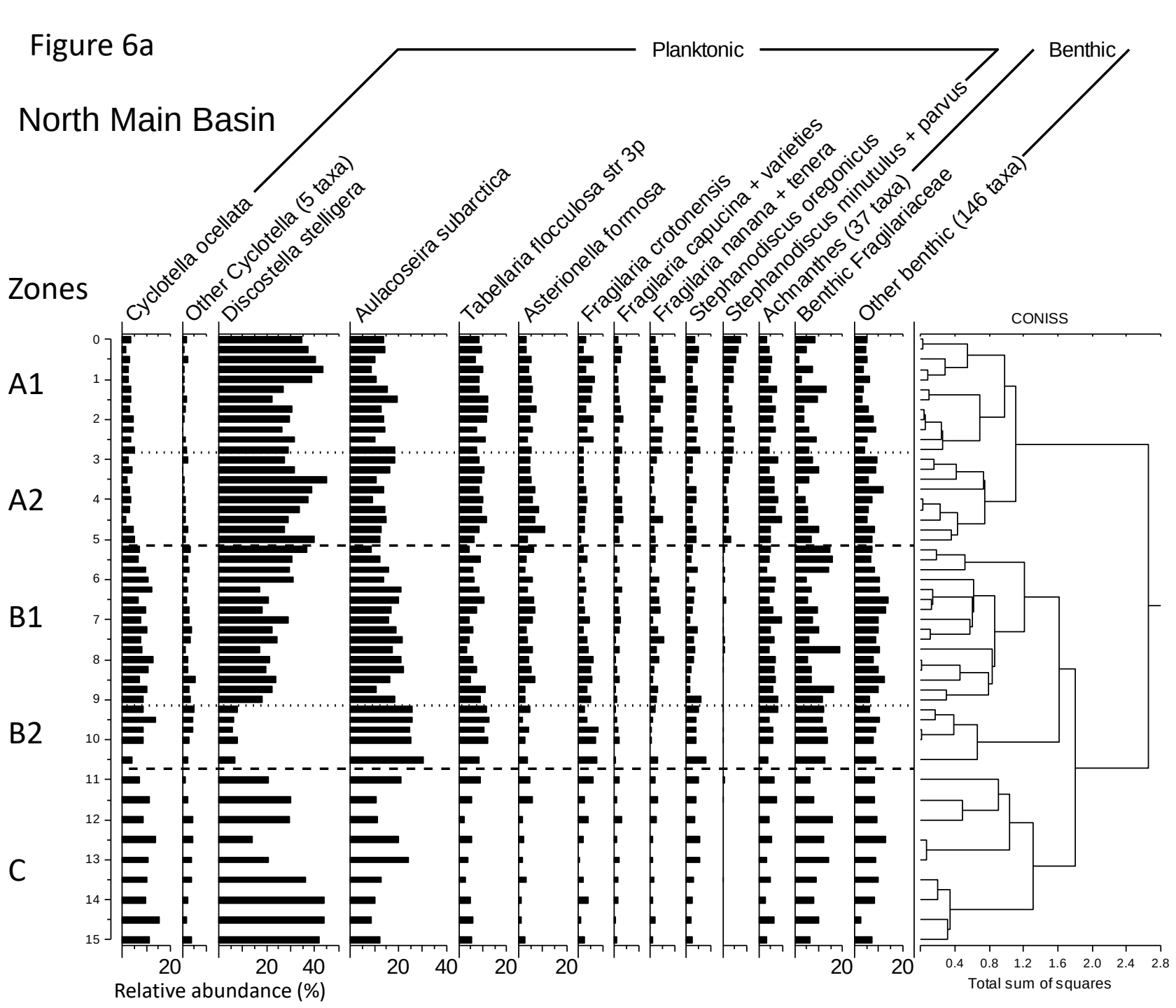


Figure 6b

Fulton

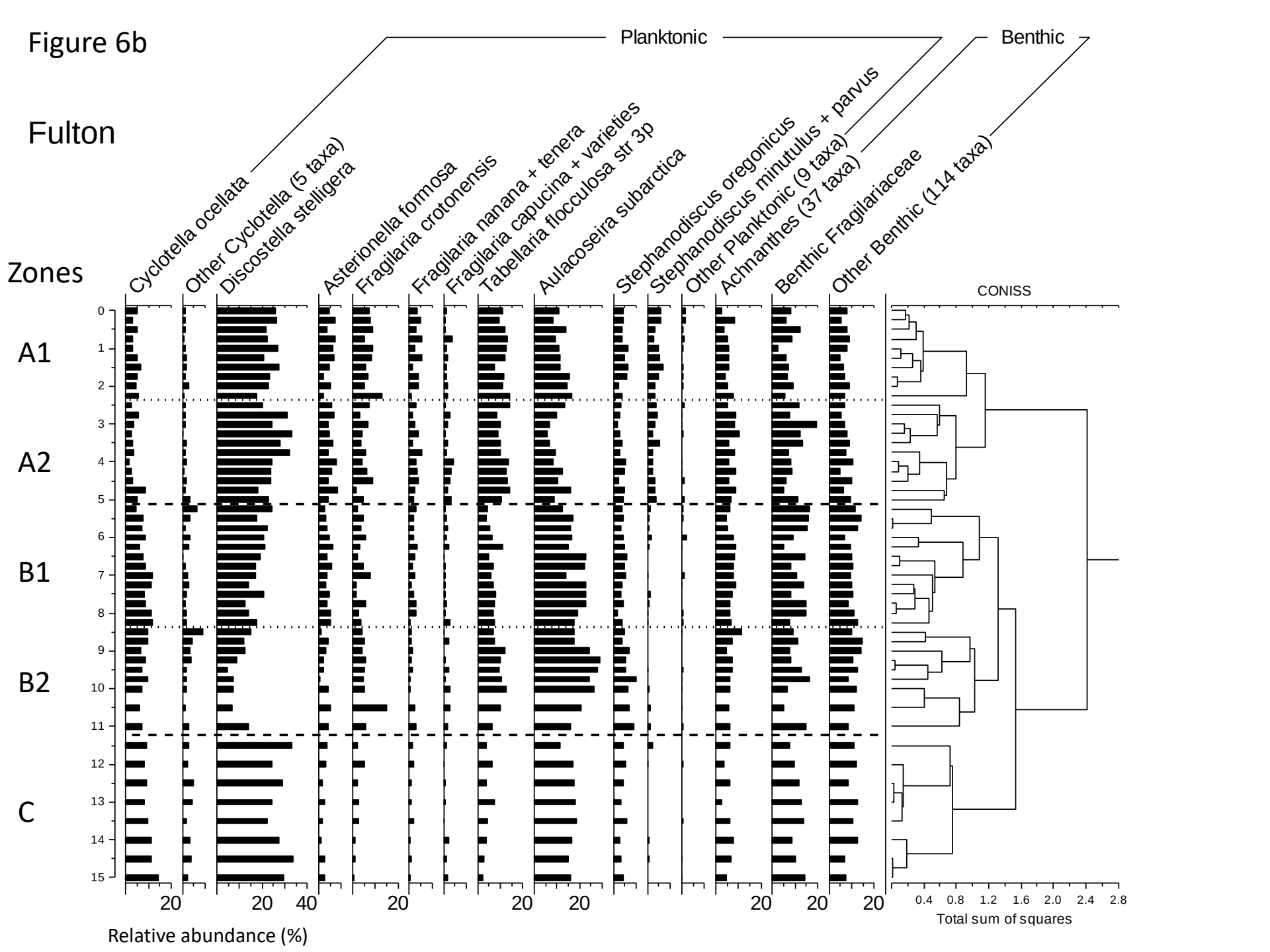


Figure 6c

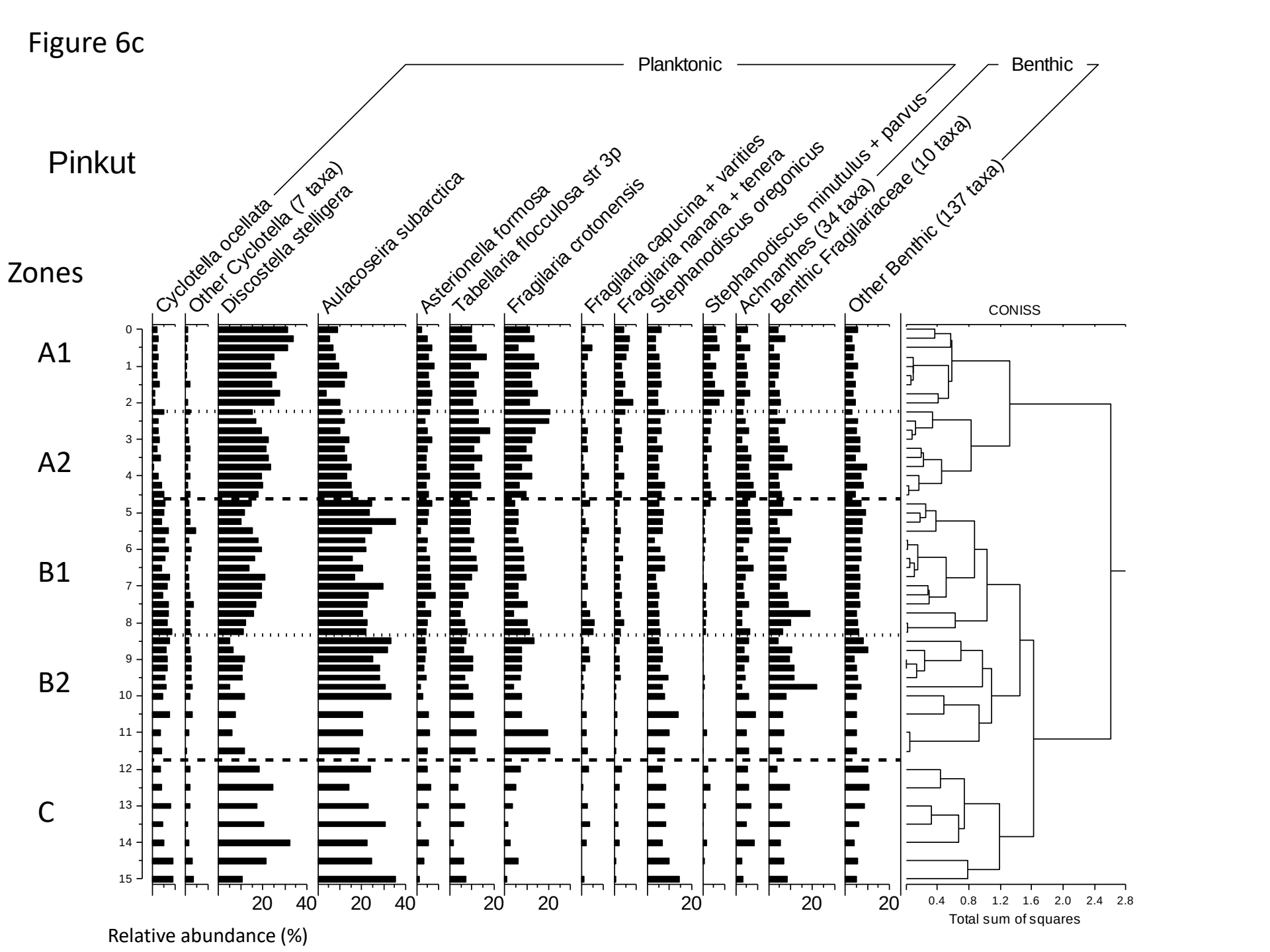

Pinkut
Planktonic
Benthic
Cyclotella ocellata
Other Cyclotella (7 taxa)
Discostella stelligera
Aulacoseira subarctica
Asterionella formosa
Tabellaria flocculosa str 3p
Fragilaria crotonensis
Fragilaria capucina + varities
Fragilaria nanana + tenera
Stephanodiscus oregonicus
Stephanodiscus minutulus + parvus
Achnanthes (34 taxa)
Benthic Fragilariaceae (10 taxa)
Other Benthic (137 taxa)
CONISS
Zones
A1
A2
B1
B2
C
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
20
40
20
40
20
20
20
20
20
0.4
0.8
1.2
1.6
2.0
2.4
2.8
Total sum of squares
Relative abundance (%)

Figure 6d

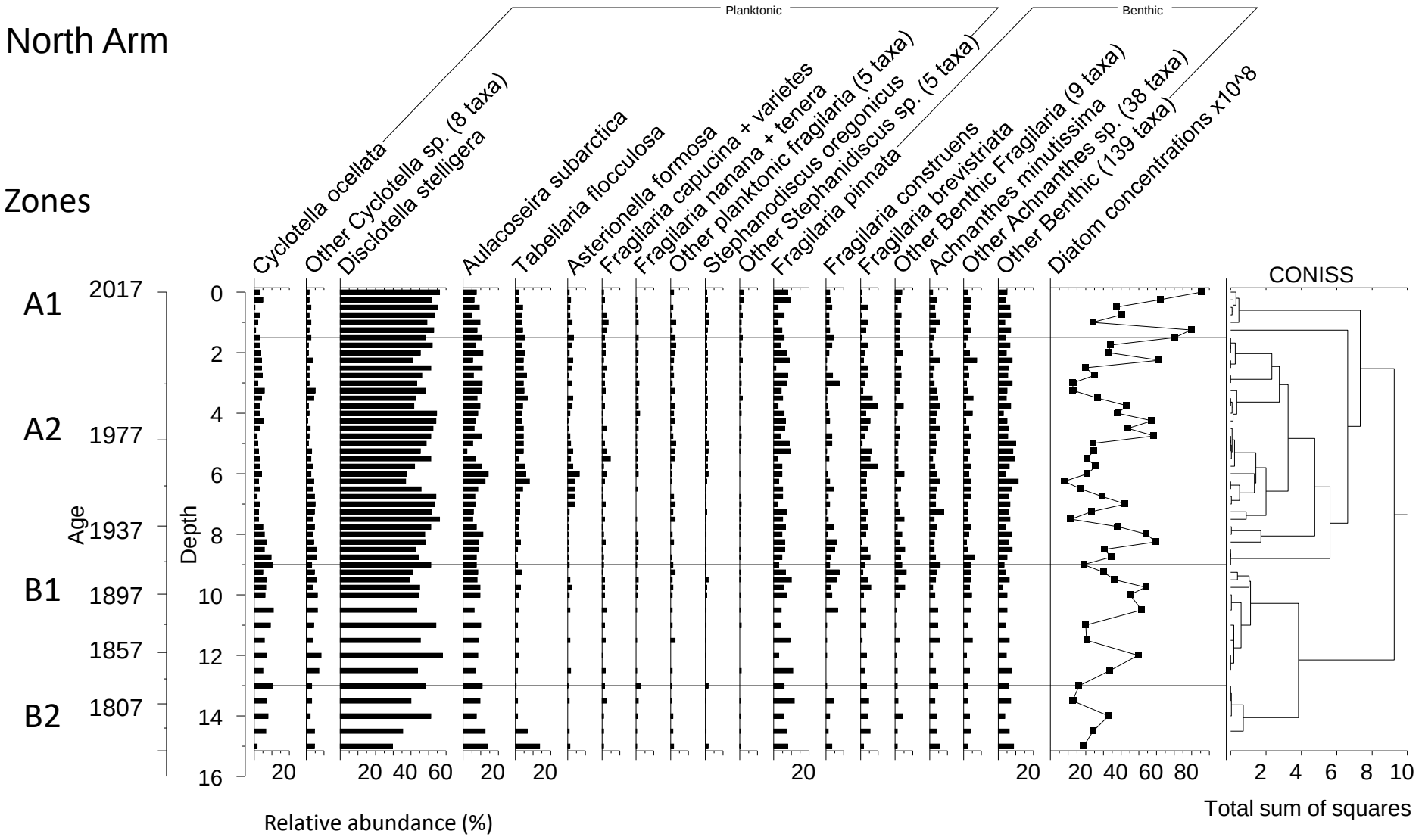

North Arm
Zones
A1
A2
B1
B2
2017
1977
1937
1897
1857
1807
Age
Depth
0
2
4
6
8
10
12
14
16
Planktonic
Benthic
Cyclotella ocellata
Other Cyclotella sp. (8 taxa)
Discotella stelligera
Aulacoseira subarctica
Tabellaria flocculosa
Asterionella formosa
Fragilaria capucina + varietes
Fragilaria nanana + tenera
Other planktonic fragilaria (5 taxa)
Stephanodiscus oregonicus
Other Stephanidiscus sp. (5 taxa)
Fragilaria pinnata
Fragilaria construens
Fragilaria brevistriata
Other Benthic Fragilaria (9 taxa)
Achnanthes minutissima
Other Achnanthes sp. (38 taxa)
Other Benthic (139 taxa)
Diatom concentrations x10^8
CONISS
20
20 40 60
20
20
20
20
20 40 60 80
2 4 6 8 10
Relative abundance (%)
Total sum of squares

Figure 6e

Morrison Arm

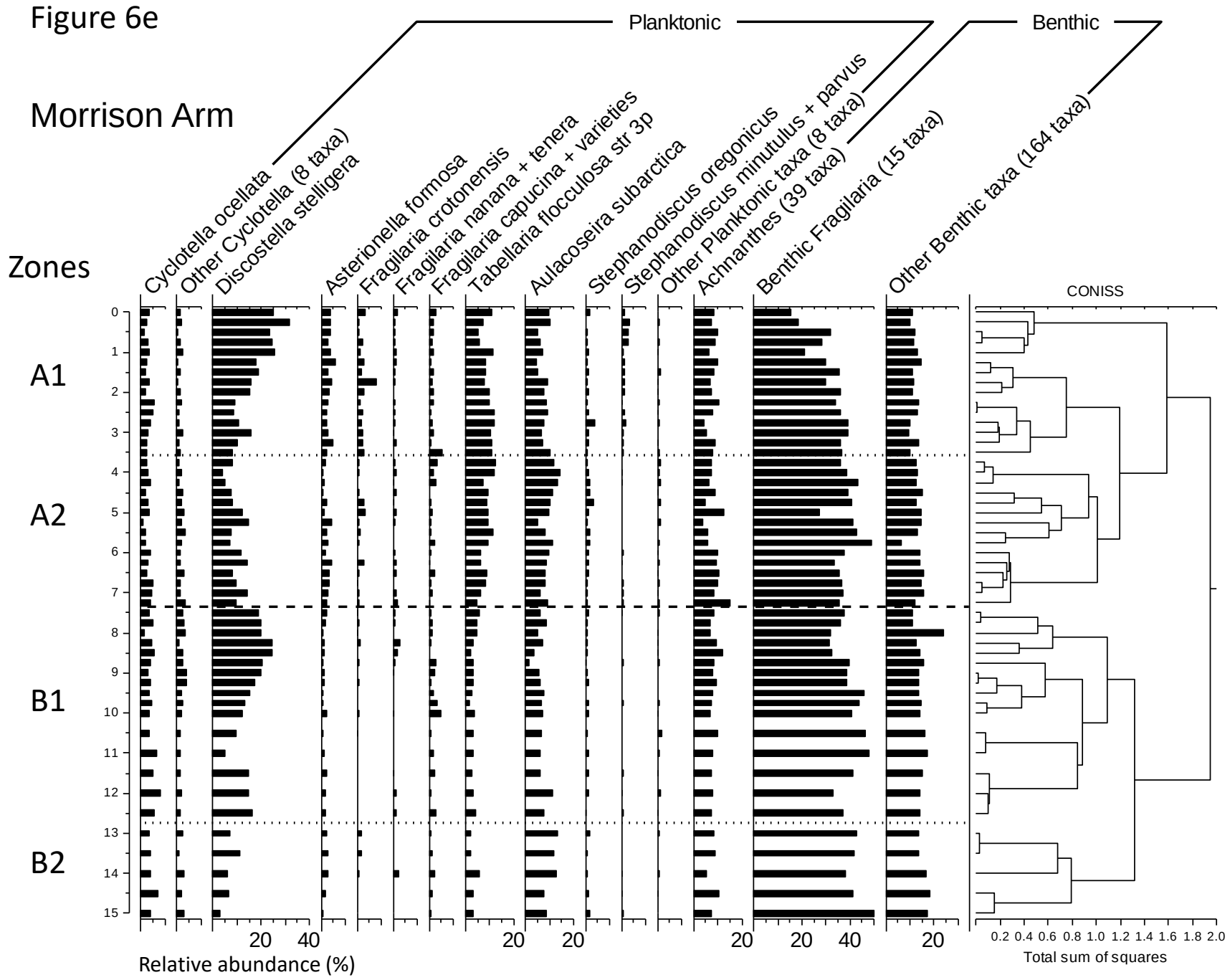


Figure 7

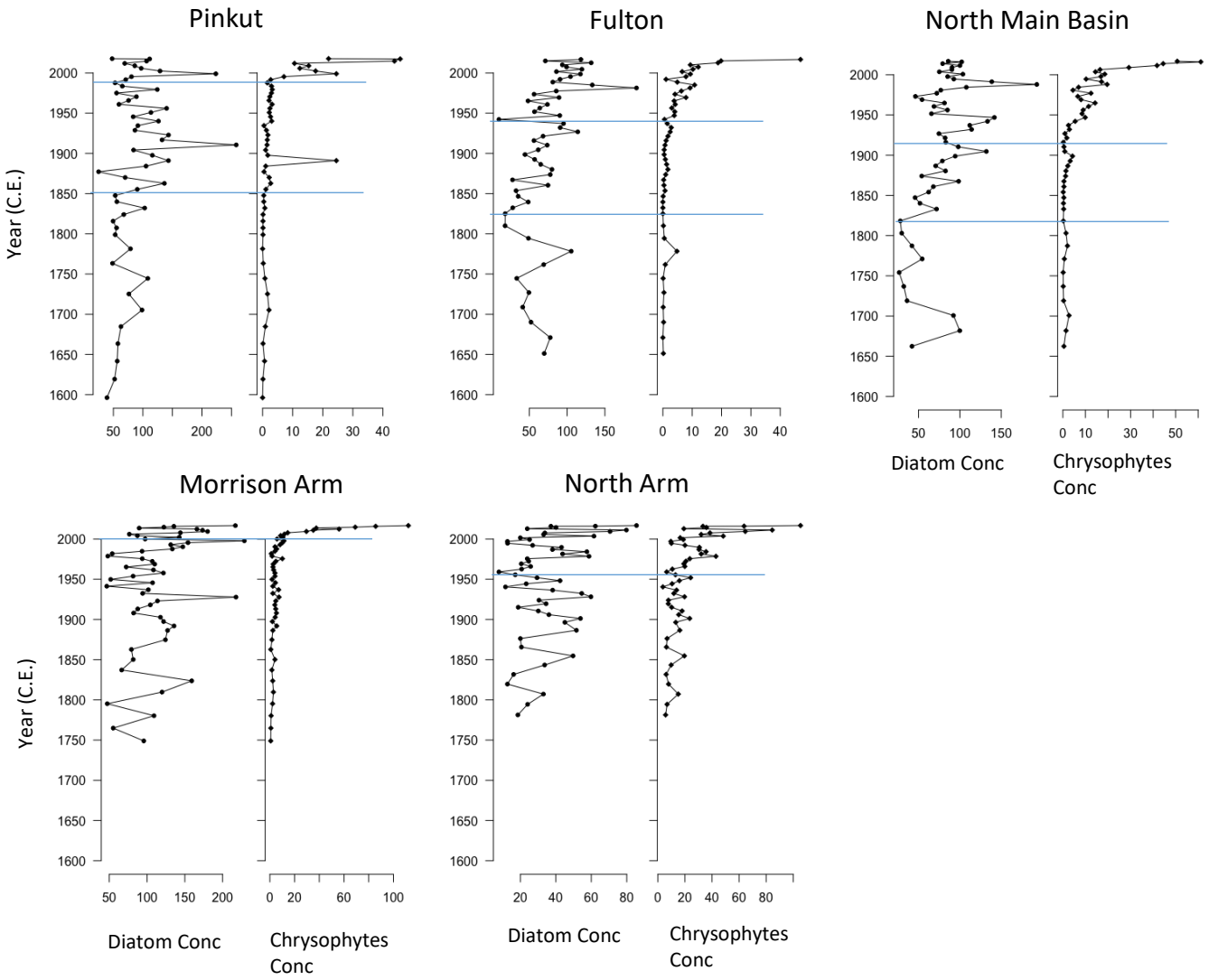

Pinkut
Fulton
North Main Basin
Morrison Arm
North Arm
Year (C.E.)
Diatom Conc
Chrysophytes Conc

Figure 8

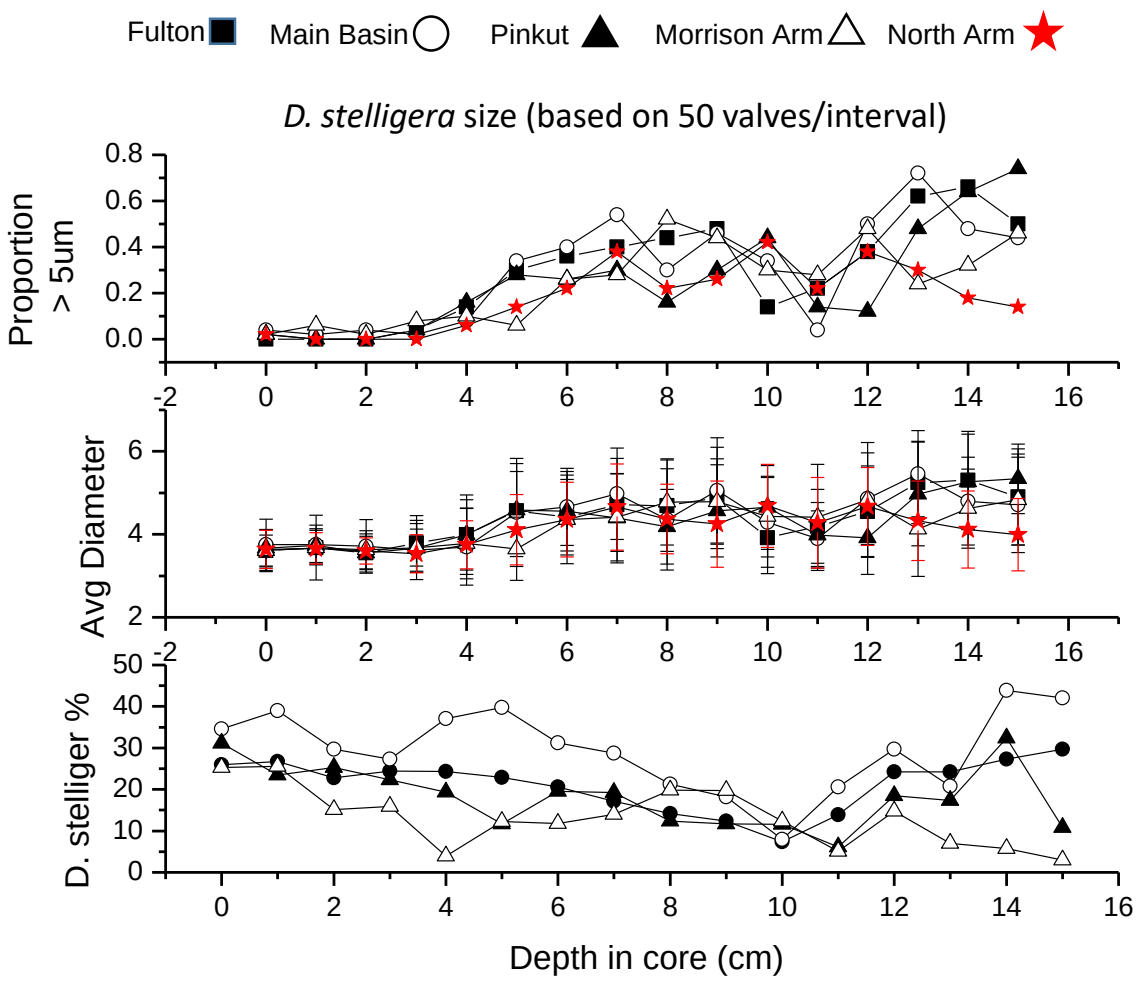

Fulton
Main Basin
Pinkut
Morrison Arm
North Arm
D. stelligera size (based on 50 valves/interval)
Proportion > 5um
Avg Diameter
D. stelliger %
Depth in core (cm)

Figure 9a

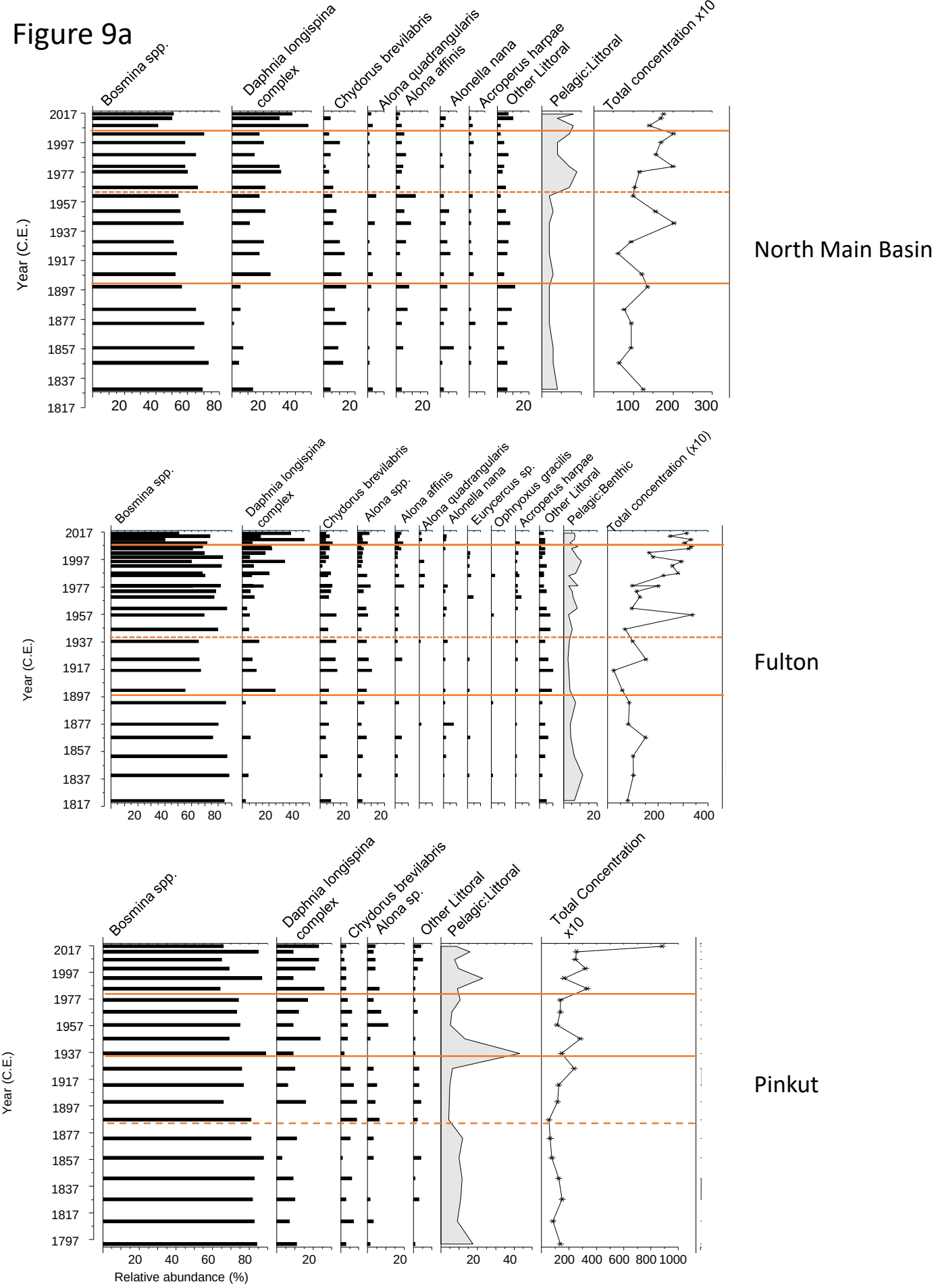
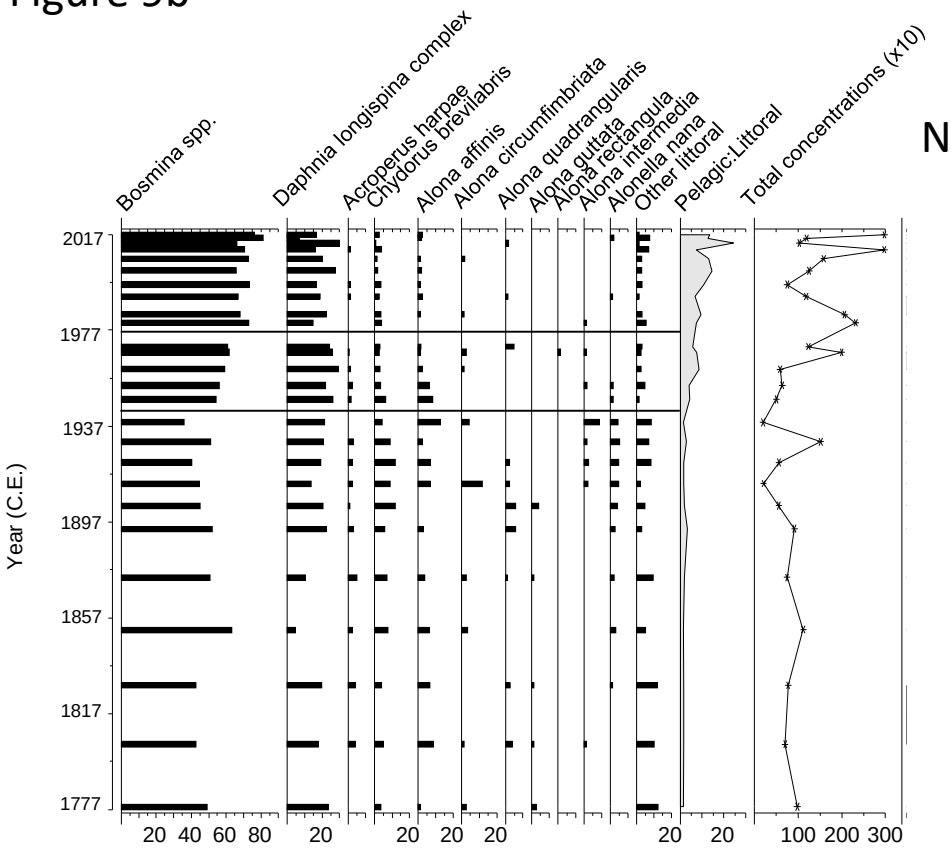
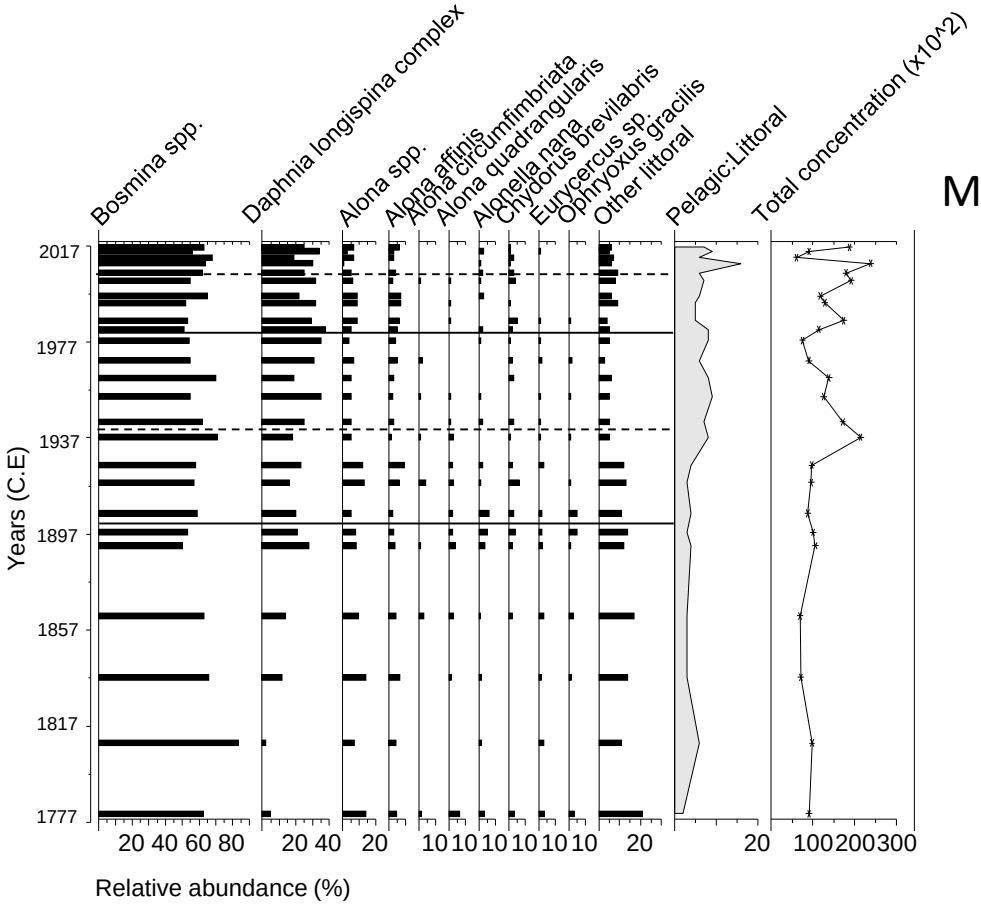

Bosmina spp.
Daphnia longispina complex
Chydorus brevilabris
Alona quadrangularis
Alona affinis
Alonella nana
Acroperus harpae
Other Littoral
Pelagic:Littoral
Total concentration x10
Year (C.E.)
2017
1997
1977
1957
1937
1917
1897
1877
1857
1837
1817
20 40 60 80
20 40
20
20
20
100 200 300
North Main Basin
Bosmina spp.
Daphnia longispina complex
Chydorus brevilabris
Alona spp.
Alona affinis
Alona quadrangularis
Alonella nana
Eurycercus sp.
Ophryoxus gracilis
Acroperus harpae
Other Littoral
Pelagic:Benthic
Total concentration (x10)
Year (C.E.)
2017
1997
1977
1957
1937
1917
1897
1877
1857
1837
1817
20 40 60 80
20 40
20 20
20
200 400
Fulton
Bosmina spp.
Daphnia longispina complex
Chydorus brevilabris
Alona sp.
Other Littoral
Pelagic:Littoral
Total Concentration x10
Year (C.E.)
2017
1997
1977
1957
1937
1917
1897
1877
1857
1837
1817
1797
20 40 60 80
20
20
20 40
200 400 600 800 1000
Relative abundance (%)
Pinkut

Figure 9b


North Arm
Bosmina spp.
Daphnia longispina complex
Acroperus harpae
Chydorus brevilabris
Alona affinis
Alona circumfimbriata
Alona quadrangularis
Alona guttata
Alona rectangula
Alona intermedia
Alonella nana
Other littoral
Pelagic:Littoral
Total concentrations (x10)
Year (C.E.)
2017
1977
1937
1897
1857
1817
1777
20 40 60 80
20
20 20 20
20
20
100 200 300


Morrison Arm
Bosmina spp.
Daphnia longispina complex
Alona spp.
Alona affinis
Alona circumfimbriata
Alona quadrangularis
Alonella nana
Chydorus brevilabris
Eurycercus sp.
Ophryoxus gracilis
Other littoral
Pelagic:Littoral
Total concentration (x10^2)
Years (C.E)
2017
1977
1937
1897
1857
1817
1777
20 40 60 80
20 40
20
10 10 10 10 10 10
20
20
100 200 300
Relative abundance (%)