

**Near Annual-Scale (1925-1985) Diatom Paleoecological Succession in
Crawford Lake, Ontario: a Candidate Site for the Anthropocene Epoch
Global Boundary Stratotype Section and Point (GSSP)**

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Abstract

The newly proposed Anthropocene Epoch, with a time stamp set in the mid-20th century, is based on the recognition that human induced environmental influences are distinct enough to be preserved in the geologic record. New geologic units require establishment of a Global Boundary Stratotype Section and Point (GSSP), with many sites around the world being considered as the GSSP for the Anthropocene Epoch. The excellent record of a Holocene-Anthropocene boundary preserved in Crawford Lake, near Milton, ON, is a leading Anthropocene Epoch GSSP candidate and as such requires extensive multidisciplinary research if it is to be designated as such.

There is considerable evidence to support the unique nature of Crawford Lake as a leading Anthropocene GSSP contender, including it being a protected site, with preserved laminae in the benthic sediments, and evidence indicative of 1950s nuclear testing. Diatoms have been used as bioindicators for freshwater lakes since the early 1900s and can be used to develop a long-term baseline regarding the health of a lake. To help detect any changes before and after the start of the Anthropocene in the early 1950s, diatoms were analyzed at a near-annual resolution from 1925-1985.

Statistical diatom analysis revealed four assemblages and two subassemblages that characterized distinct depositional intervals through the 1925-1985 interval, with the second assemblage being broken up into two sub-assemblages: Assemblage 1 (1925-1942), Assemblage 2a (1943-1951), Assemblage 2b (1952-1959), Assemblage 3 (1960-1971), and Assemblage 4 (1972-1985). Populations shifted from predominantly centric planktic species in Assemblage 1, to an araphid *Fragilaria*-dominant Assemblage 2. A notable increase in specimen numbers was seen from Assemblage 2a to Assemblage 2b, which lines up with the beginning of the “Great Acceleration” that occurred in the late 1940s and early 1950s. A partial recovery of the centric community that included species such as *Cyclotella distinguenda* and *Lindavia bodanica* was seen in Assemblage 3. Assemblage 4 saw another decline in centric planktic species and the establishment of *Fragilaria* spp., representing littoral attached, and benthic taxa. Based on the population increases seen in the late 1940s and early 1950s, as well as the fluctuations seen in the

centric planktic community, this transition is interpreted as being linked to local and regional “Great Acceleration” anthropogenic stressors.

Key words: Crawford Lake, Anthropocene, diatoms, GSSP, climate

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Statement of contributions of collaborators

Dr. Tim Patterson was the primary thesis supervisor for this project, directing this project and providing much needed aid in general, interpretation, and with editing. Paul Hamilton from the Canadian Museum of Nature also acted as a co-supervisor, aiding greatly with diatom identification, interpretation, and editing. Dr. Nawaf Nasser was lab manager for the duration of this project, and provided help and supervision with navigating lab work, R Studio and Adobe Illustrator.

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Chapter 1 – General Overview of the Proposed Anthropocene Epoch

1.1 Introduction

The impact of anthropogenic activity on Earth's environments has been particularly harmful to freshwater ecosystems making the management of these systems increasingly more difficult (Carpenter and Lathrop, 2008; Winslow et al., 2017; Woolway and Merchant, 2019; Woolway et al., 2020). Records from the recent past and ongoing impacts include eutrophication (Carpenter and Lathrop, 2008), changes in nitrogen cycling (Elser et al., 2009), biodiversity loss (Lake et al., 2000), acidification (Stoddard et al., 1999), changes to the length of open water seasons in colder climate areas (Patterson and Swindles, 2015), and carbon cycling dynamics (Alin and Johnson, 2007) are drivers of change.

These environmental effects have become compounded as the human population has experienced exponential growth beginning from 2.5 billion in 1950 to 7.9 billion in 2021. This remarkable population growth has been accompanied by a phenomenon dubbed the “Great Acceleration”, which has been characterized by increases in land development, fertilizer use, food consumption, water use, non-renewable resource extraction, and energy consumption all of which have contributed to significant environmental change. This unprecedented interval of anthropogenic impact on the environment, has resulted in a fundamental shift in the function and composition of global Earth systems (Steffen et al., 2007, 2015; Subramanian, 2019a). Beginning around 1950, the Great Acceleration is also characterized by deposition and preservation of radioactive isotopic signatures produced during post-World War II nuclear weapons testing. These markers have been established as key indicators to define the initiation of the Anthropocene Epoch (Lewis and Maslin, 2015; Steffen et al., 2015; Zalasiewicz et al., 2017b;

Waters et al., 2018a; Head, 2019). The Anthropocene Working Group (AWG) has proposed an early 1950s date for the beginning of the Anthropocene, and candidate Global Boundary Stratotype Section and Point (GSSP) sites are currently under investigation (Waters et al., 2018; Subramanian et al., 2019b). A GSSP is an internationally agreed upon reference point (anchor site) within a stratigraphic section which defines the lower boundary of a formally recognized unit within the geologic time scale, and Crawford Lake is a leading prospective GSSP candidate for the proposal of the Anthropocene.

As such, the International Commission on Stratigraphy (ICS) have outlined eleven requirements for GSSP sites. These include the potential site having “sedimentation in the section containing the boundary must be continuous without any changes in facies”, “the section containing the marker should be unaffected by tectonic and sedimentary movements, and metamorphism”, and “the section containing the marker must be accessible to research and free to access” (International Commission on Stratigraphy, 2022).

Beginning around 1950, the Great Acceleration is marked and compounded by regional and global impacts, including the environmental isotopic signatures produced from post-World War II nuclear weapons testing. Isotope markers have been proposed as potential anchor points representing the beginning of the Anthropocene Epoch (Lewis and Maslin, 2015; Steffen et al., 2015; Zalasiewicz et al., 2017b; Waters et al., 2018a). The Anthropocene Working Group (AWG) has proposed a 1950s starting date and nine candidate GSSP sites are currently under investigation (Waters et al., 2018; Subramanian et al., 2019b, Head and Gibbard, 2015), with Crawford Lake as one of the strongest candidate sites being considered.

Crawford Lake, a small lake near Milton, Ontario, is well known for its well-preserved annually deposited carbonate-rich varves (Ekdahl et al., 2007). Past studies on the chemically stratified Crawford Lake and its varved sediments, have provided paleolimnological evidence of anthropogenic impacts being archived in the lake over the past 800 years (Ekdahl et al., 2007; Gushulak et al., 2021). As well, the lake and the varved sequence within are currently being considered as a potential candidate for the Anthropocene GSSP by the Anthropocene Working Group of the International Commission on Stratigraphy. This lake has also been used to reconstruct centennial-scale changes in vegetation cover and climate, Indigenous peoples' agricultural practices and history, fire history, cultural eutrophication and how European colonization impacted the area (McAndrews and Boyko-Diakonow, 1989; Clark and Royall, 1995; Yu, 1997; Gushulak et al., 2021; Ekdahl et al., 2004, 2007; McCarthy et al., 2018). The goal of this project is to build on past studies done on the diatom populations of Crawford Lake, but at a near-annual resolution. With such a high resolution, the hope is to determine if there is a significant change in the diatom populations around the early 1950s, as it would provide evidence of the presence of the Great Acceleration (a period of increased industrialization starting in the in the late 1940s and early 1950s) in the Crawford Lake record, providing support for the candidacy of this lake as the GSSP for the Anthropocene (Gushulak et al., 2021; Ekdahl et al., 2004, 2007).

The purpose of this study is to determine if the diatom species populations in Crawford Lake responded nearly annually to the Great Acceleration in the 1950s, which will provide valuable additional evidence that the lake meets the criteria needed to represent the Anthropocene Epoch as the GSSP.

1.2 The Anthropocene Epoch – Conceptual Background

The concept behind the Anthropocene Epoch, along with its formalization as a recognized geological unit has also received considerable criticism (Zalasiwicz et al., 2017b). It should be noted that, an essential part of the process of any modifications to the International Chronostratigraphic Chart and Geological Time Scale are consideration of debate and discussion within the geologic community (Zalasiwicz et al., 2017b). That said, the Anthropocene has several novel and distinctive features that separate it from other geologic units, which has only added to the strong debate surrounding its addition as a stratigraphic unit. Although the Anthropocene has several of the prerequisite traits required for recognition as a formally recognized geological epoch, the more important part is how it holds up against arguments made against such recognition. Some of the arguments against the Anthropocene include the definition and truncation of the Holocene, the historical priority of the “Atomic Age”, and the issues surrounding the etymology as well as the origin of the term “Anthropocene” (Zalasiwicz et al., 2017b). The key issues regarding when the Anthropocene began is not related to the duration of particular epochs, but rather whether the geological record shows that the Anthropocene is already distinct, and its distinctive features will persist for millennia.

It should be noted that the site representing the Anthropocene GSSP should have good documentation and preserve physical, biological, and/or chemical records of global environmental change connected to the Great Acceleration during the mid-twentieth century. As well, it should represent a continuous geological sequence as well as providing a high-resolution estimate for the starting date of the epoch. Ideal locations for the Anthropocene GSSP include lakes, as climate and environmental conditions are recorded in their sediments as biogeochemical/geochemical markers or biological subfossils (Gushulak et al., 2021).

Beginning around 1950, the Great Acceleration is marked and compounded by regional and global impacts, including the environmental isotopic signatures produced from post-World War II nuclear weapons testing. Isotope markers have been proposed as potential anchor points representing the beginning of the Anthropocene Epoch (Lewis and Maslin, 2015; Steffen et al., 2015; Zalasiewicz et al., 2017b; Waters et al., 2018a). The Anthropocene Working Group (AWG) has proposed a 1950s starting date and nine candidate GSSP sites are currently under investigation (Waters et al., 2018; Subramanian et al., 2019b, Head and Gibbard, 2015), with Crawford Lake as one of the strongest candidate sites being considered.

Chapter 2

2.1 Background

2.1.1 Study area

Located approximately one kilometre west of the Niagara Escarpment, Crawford Lake is a small (2.5 ha), deep (up to 24 m) and sheltered body of water. Part of the Crawford Lake Conservation Area, which is managed by Conservation Halton, it has been a protected area since 1969 (Conservation Halton, 2021 (b)). The 4.5 m of post-glacial sediments consist of carbonate-rich varves that have been dated to the late Pleistocene via radiocarbon methods and varve counting (Ekdahl et al., 2007; Conservation Halton, 2021(a)).

Crawford Lake is situated within the Silurian Guelph-Anabel dolomitic bedrock. It is hypothesized that Crawford Lake originated towards the end of the last ice age, after the roof of an underground cavern collapsed (Rybak et al., 1987). In agreement with this hypothesis the basin is surrounded by steep dolomite cliffs reaching a maximum height of 6 m above the lake. These cliffs shelter the lake from wind, contributing to the development of meromictic conditions in the lake water column, due to its small surface area and great depth. Lake-bottom temperatures are at a constant 6°C (McAndrews and Turton, 2010), and have a low BOD showing that the monimolimnion throughout the year remains oxygenated (Gushulak et al., 2021).

The regional climate around Crawford Lake is humid cool-temperate continental. The average annual precipitation is ~910 mm, which is spread evenly throughout the year. The mean July temperature is 20.3°C and the mean January temperature is -6°C (Environment Canada, Millgrove Climate Station, 1993; McAndrews and Turton, 2007).

Soils in the area originated from glacial moraines and spillways and are generally thin in the forested area around the lake. On the Crawford Lake property itself, the soils are assigned to the Dumfries type, developed on the poorly drained organic and mineral soils and coarse textured tills of the moraines. The till is stony, calcareous and gray-brown (Rybak et al., 1987).

2.1.2 Crawford Lake Water Column Chemistry

Water chemistry changes with depth in the water column can document physical, biological, and chemical properties within a lake. Crawford Lake is considered meromictic, where it doesn't completely overturn either the fall or spring – in the case of Crawford Lake, this largely due to its significant depth (up to 24 m deep) and relatively small surface (~250 x 150 m) (Yu, 2003; Turton and McAndrews, 2006; Krueger, 2012). The process of meromixis in Crawford Lake allowed for the accumulation of annually laminated sediments over the past ~2000 years (Yu, 2003). The laminations form in couplets, with a dark, organic rich layer being deposited in the fall, and a white, calcite-rich layer deposited in the spring or summer (Dickman, 1979).

The mixolimnion (from 0 to ~10 m depth) is characterized by higher pH concentrations compared to values lower in the water column, a reflection of seasonal photosynthesis. Due to the biological activity of silicious diatoms and other algal taxa, low concentrations of elements such as Si, Ca, Fe, and Mn (<?), and other factors such as DIC (under 5 mM from 0-10 m depth, before increasing to 15 mM at a depth of 20 m) and specific conductance (~500 $\mu\text{S}/\text{cm}$ from a depth of 0-10 m, increasing to ~2000 $\mu\text{m}/\text{cm}$ at a depth of 20 m) are exhibited (Ekdahl et al., 2007). Elevated Cl^- concentrations in surface waters are attributed to a relatively recent increase in anthropogenic influences, while lower Cl^- concentrations deeper in the water column can be attributed to pre-disturbance conditions.

Numerous lakes in both the northeastern United States and in Ontario have experienced acidification (beginning in the 1960s and 1970s) due to the deposition of sulphate and other acidic compounds (Stoddard et al., 1999; Environment Canada, 2010; Meyer-Jacob et al., 2019). However, it is not clear whether Crawford Lake has been unimpacted by this acidification, due to the high alkalinity in its surface waters, as well as the buffering provided its limestone setting (McAndrews and Boyko-Diakonow, 1989; Ekdahl et al., 2007). This is despite the probable dissolution and transport of carbonic acid from the limestone geologic setting. Rather, organic carbon sources would have bonded to acidic compounds deposited in the soils surrounding Crawford Lake during the mid-twentieth century, therefore reducing lake-water DOC concentration by limiting its transport to the lake (Monteith et al., 2007; Hruška et al., 2009; Ekström et al., 2011; Hall et al., 2021). This decrease in DOC concentrations was found to be concurrent with reductions in local nutrient inputs because of reforestation (Keller and Fox, 2019). These changing conditions allowed for phyto-benthic production by providing an extended littoral zone (Vadeboncoeur et al., 2008), resulting in the increase in benthic diatoms around 1950 in Crawford Lake (Ekdahl et al., 2007; Kingsbury et al., 2012; Gushulak and Cumming, 2020). A study done by Hadley in 2012 found that increases in DOC in Algonquin Provincial Park's boreal lakes (in Ontario) corresponded with decreases in *Synura* taxa, a type of chrysophyte – suggesting that Crawford Lake experienced the opposite during mid-twentieth water clearing. Crawford Lake had clear water up until approximately 1980 – after the adoption of strict anti-pollution legislature led to the large declines in deposition in nitrogen oxides and sulfur (NAPS, 2019).

2.1.3 Regional Air Quality Around Crawford Lake

According to 2019 data taken from the National Air Pollution Surveillance (NAPS), program, ozone (O₃) levels ranged from 19—22 ppb in January 2019 to 21—29 ppb in July 2019 from multiple sites in Toronto. Hamilton sites saw values range from 21—24 ppb in January 2019 to 28—34 ppb in July 2019. The same sites in Toronto recorded levels of nitrous oxides (NO_x) ranging from 18.8—46.3 ppb in January 2019 to 8.5—29.9 ppb in July 2019, while the sites in Hamilton had values ranging from 12—19.2 ppb in January 2019 to 9.5—15.2 ppb in July 2019. Nitrous oxide (NO) levels ranged from 4 ppb in January 2019 to 2 ppb in July 2019 in Milton, ON. The Toronto site recorded sulfur dioxide (SO₂) levels ranging from 0.1—0.2 ppb both in January 2019 and July 2019, while the Hamilton sites recorded values ranging from 1.7 ppb in January to 3—5.2 ppb in July 2019. The Milton site recorded values of 1 ppb in January 2019, but no values from July 2019 were recorded. Carbon monoxide (CO) levels ranged from 0.22—0.34 ppm at a handful of sites from Toronto in January 2019 to 0.2—0.32 ppm in July 2019. The site from Hamilton recorded CO values ranging from 0.24 ppm in January 2019 to 0.23 ppm in July 2019 (NAPS, 2019). On a broader scale, Canada's VOC levels during the average ozone season (May-September) was approximately 55 ppb in 2017, while one-hour NO_x concentrations were around 12 ppb and eight-hour ozone concentrations were approximately 58 ppb in the same year (US EPA and Environment and Climate Change, 2019).

Acid deposition had peaked locally in 1970, primarily caused by the emissions of nitrogen oxides and sulphurs from industrial sources. These sources would have been both local to the region as well as arriving upwind from sources in the industrial heartland of the United States. Even though Crawford Lake is considered to be a highly buffered system, with its dolomitic limestone based, acid deposition would have likely impacted soils within the lake's

catchment. This may have resulted in the binding of compounds, such as humic compounds, which may have contributed to the dissolved organic carbon (DOC) of local lake systems (Monteith et al., 2007; Hruška et al., 2009).

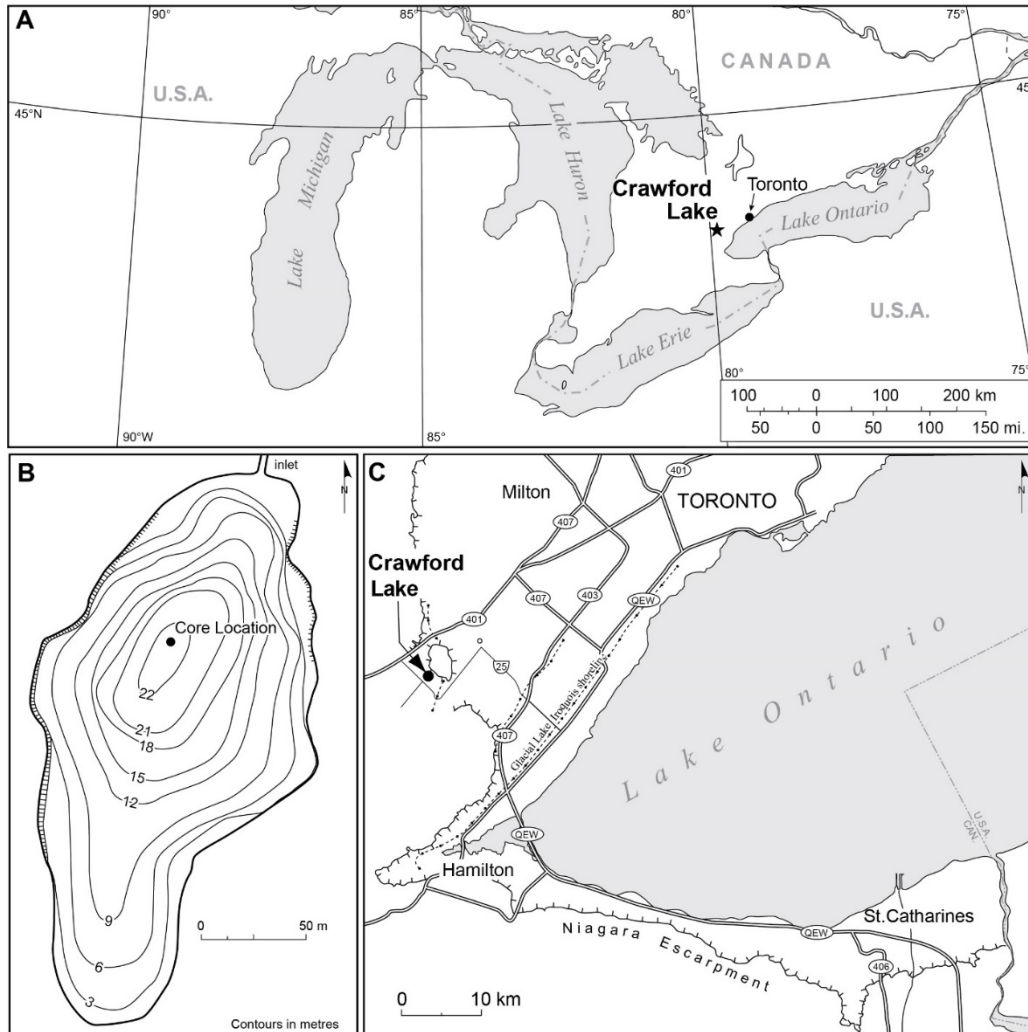


Figure 1: Location map of Crawford Lake. A. The relative location to Canada's largest city, Toronto. B. Lake bathymetry. C. location relative to the Niagara escarpment

2.1.4 Cultural history based on paleolimnological analysis

The cultural history of Crawford Lake has been divided into four depositional periods based on pollen, diatom, and geochemical data. These periods are pre-Iroquoian (pre-1268AD), Iroquoian (1268-1486AD), post-Iroquoian (1487-1866), and Canadian (1867-present) (Ekdahl et

al., 2007). Previous studies have shown two distinct periods of cultural eutrophication, the Iroquoian Period, and the Canadian Period.

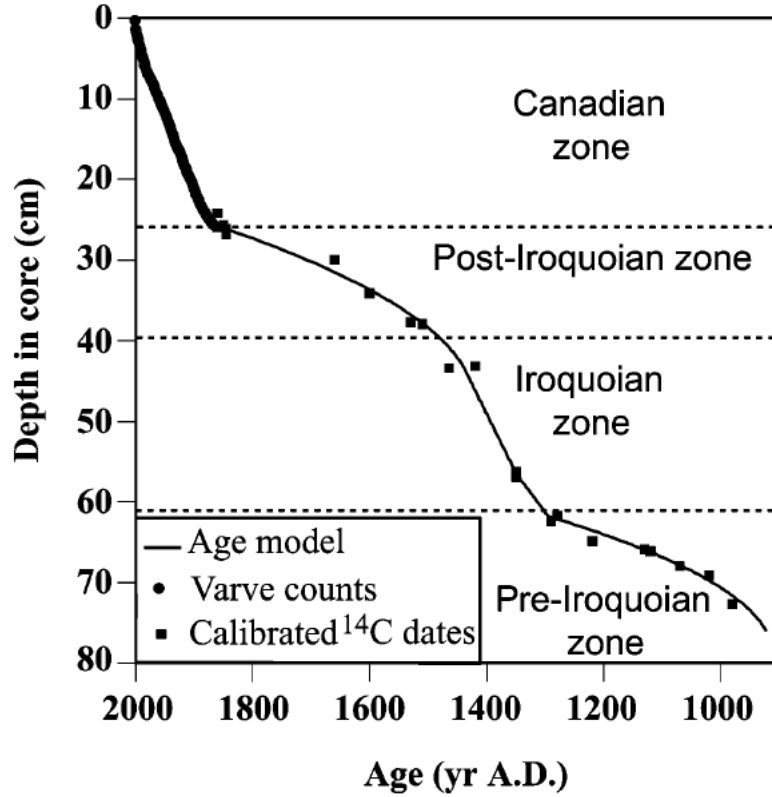


Figure 2: Calibrated accelerator mass spectrometry (AMS) ¹⁴C ages, varve counts, and age model plotted vs. depth. Four equations, fit to ¹⁴C date trends, made up the age model. $A = 1.3436d^2 - 211.35d + 9225.1$ was the equation used for the pre-Iroquoian zone. A is the depositional age and d is depth (cm). Age is based on linear sedimentation rates for the Iroquoian zone. Source: Ekdahl et al., 2004.

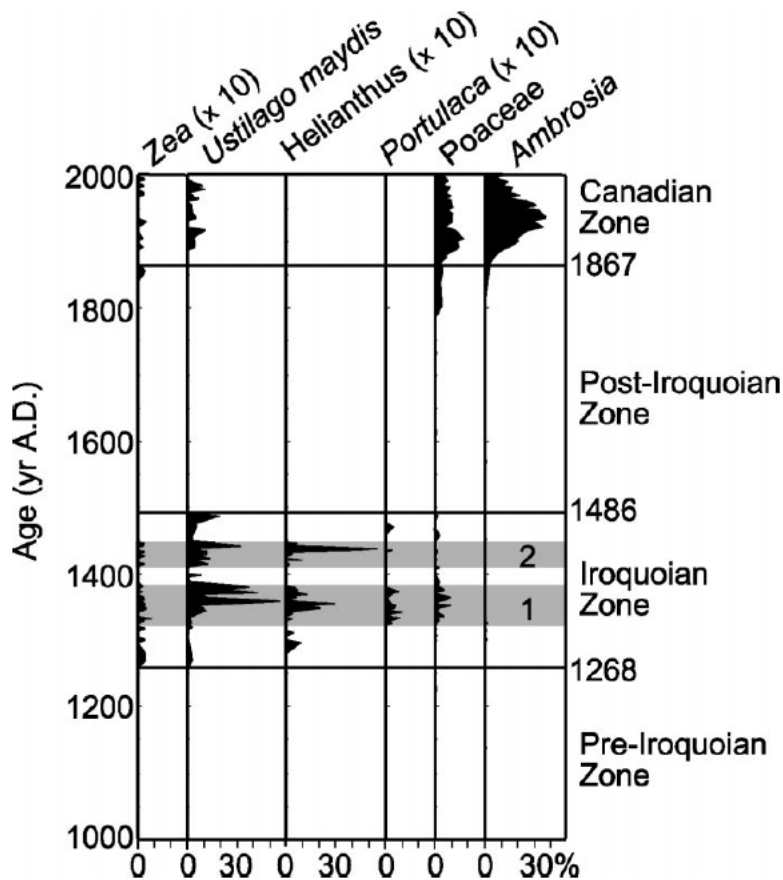


Figure 3: Crawford Lake pollen taxa stratigraphy by Ekdahl et al., 2004; recorded from 1000 A.D. to 2001 A. D. Shows *Helianthus* and *Zea cultigens*, *Ustilago* fungal spores, and *Ambrosia*, *Portulaca*, and *Poaceae*, the latter three are disturbance-related plants. The shaded parts illustrate the two periods of Iroquois settlement nearest the lake, based on pollen evidence. Units are percentages of total counted pollen grains. Source: Ekdahl et al., 2004.

2.1.4.1 Pre-Iroquoian Period (pre-1268AD)

The pre-Iroquoian settlement sedimentary record ending in 1268AD is characterized by a homogenous, non-varved sedimentary sequence. The tree pollen assemblage during the pre-Iroquoian Zone to approximately 1300 A.D. suggests *Fagus* and *Acer saccharum* dominating a deciduous forest. The likely source of *Thuja* pollen came from trees growing on the lakeside cliff, and *Pinus* trees were rare. (McAndrews and Turton, 2007).

2.1.4.2 Iroquoian Period (1268—1486 AD)

The appearance of cultigen pollen, well-preserved varved sediments, increasing mass accumulation rates (MAR) of CaCO_3 and organic carbon, a decrease in organic matter C/N

ratios, and an increase in $\delta^{13}\text{C}_{\text{CaCO}_3}$ values marks the beginning of the Iroquoian zone. These values returned to near pre-Iroquoian levels as activities in the watershed diminished, but organic C/N ratios continued to be low. In addition, thinner, but still well-preserved varves continued to occur in this time interval. Located 300 m north of the lake, the Crawford Iroquoian Village is hypothesized to have had approximately 200 to 250 inhabitants. There was an intermittent period of minimal horticultural activity, which has been hypothesized to represent an abandonment of the watershed in the Crawford Lake area. A second horticultural phase (likely resettlement) followed, spanning from 1410—1445 AD (Ekdahl et al., 2004; McAndrews and Turton, 2007). The Iroquoian Zone has *Cucurbita*, *Zea*, and *Helianthus* pollen together with pollen from grass (*Poaceae*) and the weed *Portulaca*.

Human activity in the watershed led to immediate changes in diatom assemblages at Crawford Lake. *Lindavia michiganiana* and *Lindavia bodanica*, both meso-oligotrophic species, were rapidly succeeded by *Stephanodiscus*, a more eutrophic genus, at the start of the Iroquoian period. It is suspected an increase in human sewage contributed to this change. Fossil rotifers increased during the Iroquoian zone – suggesting elevated nutrient concentrations led to higher algal populations (Ekdahl et al., 2004).

Charred seeds of maize (*Zea*), squash (*Cucurbita*), tobacco (*Nicotiana*), sunflower (*Helianthus*) and bean (*Phaseolus*) were recovered during archaeological excavations done of the Iroquoian Zone village. McAndrews and Turton (2007) observed large dung pellets in lake sediments deposited during the Iroquoian period, and by eDNA analysis demonstrated that they originated from Canada geese. They further observed that they contained pollen grains that were ingested while foraging in cultivated fields adjacent to the lake during the Iroquoian period (1268-1486 AD) (McAndrews and Turton, 2007). They hypothesized that after eating, the geese

then congregated on Crawford Lake, where their pollen-laden dung pellets would sink to the bottom and subsequently become part of the sedimentary record. Such pellet deposition must have been very abundant as they are observed in nearly every core collected from Crawford Lake in sediments deposited during the Iroquoian period, with very few such droppings observed above or below this horizon (McAndrews and Turton, 2007; Patterson, 2019 unpublished data). There was succession to *Quercus* pollens followed by *Pinus strobus* pollens in a mixed forest setting during the Iroquoian Zone.

As Iroquoian horticulture and village settlement expanded, there was a higher amount of runoff and increased nutrient loading, and diatom communities were further altered.

Stephanodiscus (including *Stephanodiscus minutus*, *Stephanodiscus hantzschii* and two species that were either unidentified or unknown) was rapidly succeeded by diatom taxa that thrive under high nutrient concentrations. *Synedra* (*Ulnaria*), although poor at competing for silicon (Si) was very successful in competing for phosphorous (P), and thus increased in abundance first.

Populations of *Synedra* would be succeeded by *Fragilaria crotonensis* and *Asterionella formosa*, suggesting that Si was the limiting nutrient for diatoms with increased phosphorous levels.

Following the *A. formosa* peak was a second increase in *Synedra* (*Ulnaria*) species, suggesting

that as Iroquoian agricultural activity decreased, phosphorous returned to being the limiting nutrient (Ekdahl et al., 2004).

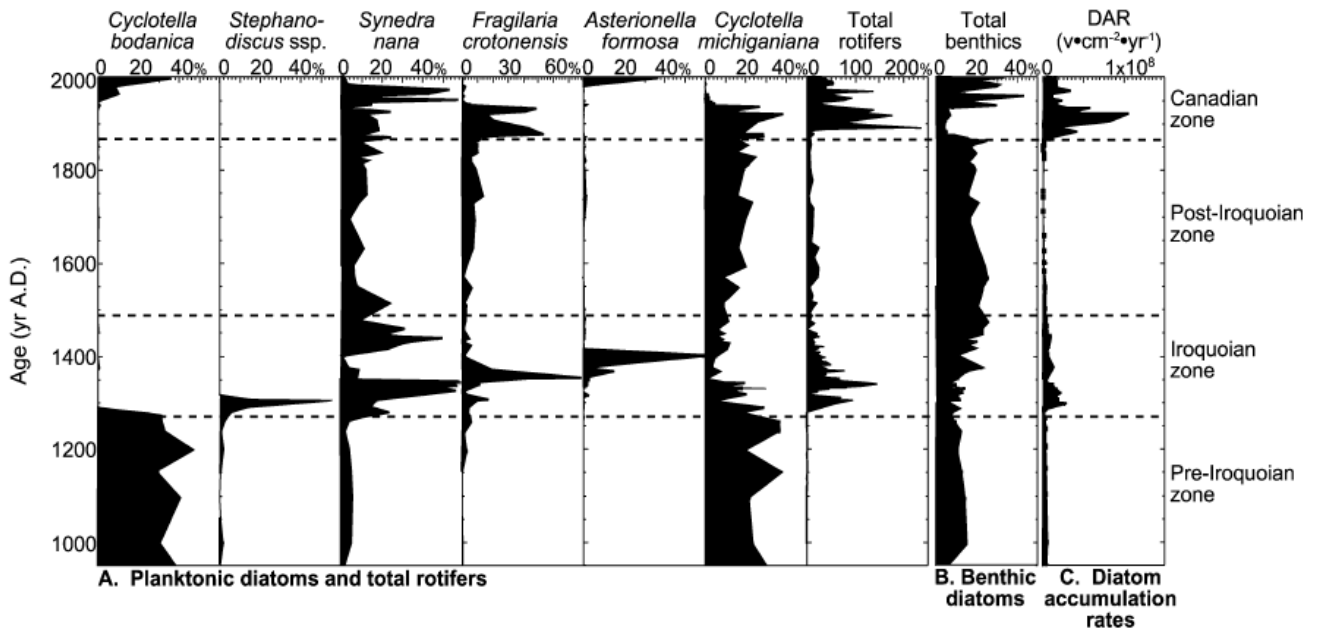


Figure 4: Diatom taxa, total rotifers, and diatom accumulation rates, or DARs. A: Planktonic diatom taxa were expressed as percentages of total diatom valves. A minimum of 500 valves were counted per sample. From left to right, diatom taxa are *Cyclotella bodanica* v. *lemanica*, *Stephanodiscus* species (a sum of a minimum of four species, including *S. minutus*, *S. hantzschii*, and two unknown or unidentified species), *Synedra (Ulnaria) nana*, *Fragilaria crotonensis*, *Asterionella formosa*, and *Cyclotella michiganiana*. Fossil rotifers were expressed as percentages of pollen grains, and include taxa such as *Kellicottia longispina*, *Keratella cochlearis*, *K. quadrata* and *K. heimali* (Edmondson, 1959; Wallace and Snell, 1991). B: Summed benthic species comprising all non-planktonic taxa, primarily *Achnanthydium*, *Cymbella*, *Cymbopleura*, and *Encyonopsis species*. C: Diatom accumulation rates (valves per cm² per year). Zones provided are based on varve counting, diatom taxa, and pollen taxa data. Source: Ekdahl et al., 2004.

2.1.4.3 Post-Iroquoian Period (1486-1866AD)

Based on the disappearance of cultigen pollen taxa, the start of the post-Iroquoian zone began at approximately 1486 A.D. As nutrients inputs and human activity decreased within the watershed, carbon accumulation, sedimentation rates and $\delta^{13}\text{C}$ levels returned to pre-disturbance values. However, continued varve preservation indicates that a meso-eutrophic diatom assemblage persisted through the post-Iroquoian zone (Ekdahl et al., 2004).

Diatom analysis indicated that the lake was not able to recover to pre-disturbance conditions during the period of minimal human activity that characterized the post-Iroquoian interval from 1487-1866 AD (Ekdahl et al. 2007).

2.1.4.4 Canadian Period (1867AD-present)

The Canadian zone is marked by thicker valves, a change to darker brownish-black sediments, and increased accumulation of charcoal, ragweed pollen (*Ambrosia*), and *Poaceae* pollen. This marked the reoccupation of the area in the years between 1822 and 1854, when Canadian farmers moved onto land within two kilometers of the lake (McAndrews and Turton, 2007). Deforestation occurred, and shallow soil on the rocky parts of the lake returned to forest while deeper soils were tilled. A house and barn stood on the site of the village until 1972. Through this interval organic C/N ratios decreased, while CaCO₃ and organic carbon MARs increased. $\delta^{13}\text{C}_{\text{CaCO}_3}$ values underwent insignificant changes. Since the 1970s the site has been protected, particularly in the areas adjacent to the shoreline, as part of the Crawford Lake Conservation Area (Ekdahl et al., 2007).

The historical Canadian Zone has the herbs and weeds including ragweed (*Ambrosia*), *Poaceae*, sheep sorrel (*Rumex acetosella*), and plantain (*Plantago*) along with *Zea* pollen. Macrofossils include leaves from red oak (*Quercus rubra*), trembling aspen (*Populus tremuloides*), *Ulmus* sp., *Populus grandidentata*, *Fagus grandifolia*, *Pinus strobus*, and *Thuja occidentalis* (McAndrews and Turton, 2007).

Pinus peaks were present during the post-Iroquoian Zone but underwent a decline through the Canadian Zone due to historical logging of white pine by European settlers. This led to a succession by the pioneer trees *Ulmus* and *Betula*. However, due to disease causing the eventual death of *Ulmus* trees, *Ulmus* pollen has undergone a decline since 1960. The pre-1810 record shows forest succession as a response to climate change (McAndrews and Turton 2007).

2.2 Methodology

2.2.1 Fieldwork

Freeze cores were collected from Crawford Lake on February 20, 2019, by Dr. Tim Patterson, Andrew Macumber, Riley Steele, and Carling Walsh with personnel from Brock University and Conservation Halton. The weather was overcast and approximately -10°C . The freeze core used for this project (CRA19-2FT-D1) was free-dropped into the lake bottom sediment from ~4 m above the lake bottom at 4:45pm and recovered at 5:20pm, with a bottom time of 35 minutes. The recovered core was 107 cm in length.

Upon recovery, the core was scraped horizontally (to avoid up and down-core contamination) with a putty knife to remove unfrozen material. Afterwards, sections of the frozen sediment were removed from the corer face using metal chisels and a hacksaw and stored in dry ice for transport back to Carleton University. As extended sample storage may be linked to major changes in microbial activity, freezing sediment samples in-situ is an excellent and successful method to not only obtain high-resolution results, but also to preserve samples (Freixa and Romani, 2014). As well, freeze corers were used as they are ideal for extracting cores in water-saturated and unconsolidated sediment; this is because they capture sediment via in-situ freezing (Crann et al., 2015).

2.2.2 Laboratory Work

Core CRA19-2FT-D1 was divided into three sections for ease of transport to Carleton University for further analysis: section 1 (43.5 cm), section 2 (29 cm), and section 3 (36 cm). For the purposes of this project, the time interval being studied was set from 1925-1985 to best encompass the “Atomic Age”, tentatively identified as a key marker of the beginning of the

Anthropocene. Because of this, only sediments from section 1 were used for this project. Due to some material being lost on the right side of the core, the core was vertically cut carefully using a saw. The left side, because it was in better condition, was used to subsample for diatom analysis. To achieve a high, near-annual resolution, the sediment sections (varves) were recovered from the core, using a scalpel. Varves were counted for each subsample, and the varve-year inferred chronology determined by Serack (2020) was used as the chronology for this project.

2.2.3 Diatom Preparation and Analysis Methodology

For diatom processing, the samples were heated in a water bath for 24 hours with hydrochloric acid (HCl) to remove carbonates. After the reactions stopped, the samples were rinsed and centrifuged three times before 10% hydrogen peroxide (H₂O₂) was added to remove organic matter. The samples were left in a warm bath for the 24 hours, and were rinsed and centrifuged another three times. For the last stage, 30% H₂O₂ was added to dissolve any remaining organic matter, and were rinsed and centrifuged three times to remove any remaining hydrogen peroxide. This was all done prior to performing diatom microscopic analysis. Once the rinses were completed, only a slurry containing inorganic particles, chrysophytes, and diatoms remained. To get a subsample of the slurry onto a microscope slide, a pipette was used to mix up the slurry sample and a small amount was moved onto a cover slip and left to dry for approximately 24 hours. Naphrax (an adhesive, refractive index 1.74) was added to the slide while on a hotplate and heated to almost a boiling condition. The coverslip, with the diatom on top, was inverted and placed on the Naphrax and gently flattened on the microscope slide. A minimum of 24 hours was needed to let the Naphrax dry and fix the coverslip to the slide. The protocol used to prepare the samples for diatom analysis was similar to that outlined by Batterbee et al. (2001).

Fifty-five samples were counted using the Olympus BX51 microscope, where a minimum of 400 diatom valves per slide were counted for statistical significance (Patterson and Fishbein, 1989). The magnification used for this project was x1000 with oil immersion. Diatoms were counted by transect, and more than half of the diatom valve was required to accurately identify the species. Counting would typically be stopped when the minimum threshold of 400 diatoms were counted. Diatom identification keys used were Krammer and Lange-Bertalot (1985-1991), as well as Siver and Hamilton (2011). Statistical analyses included constrained cluster analysis (CONISS), on-metric multidimensional scaling (NMDS), and stratigraphic diagrams. Since samples were not spiked, diatom species counts were converted to relative abundance (%). As such, relative abundance was used for statistical analysis.

2.2.4 Statistical Analysis

Most of the statistical analyses were performed in the R environment (version 4.0.4) (R Core Team, 2021), with the exception of the program C2 being used to develop stratigraphic diagrams. Counts from each sample of diatom taxa were converted to relative abundance for ensuing assessment in assemblage structure changes. Unscreened data of the diatom taxa counts were screened using code from the R environment developed by Dr. Andrew Macumber and Dr. Nawaf Nasser. To be considered statistically significant, standard error had to be less than 0.7 of fractional abundance. As well, any species with zero sums were removed. There were 44 diatom taxa originally identified, where 32 taxa were screened and found to be occurring in statistically significant amounts.

Using relative abundance data, diatom assemblages were organized into zones using stratigraphically constrained zones via cluster analysis (CONISS) using Euclidean distance in RStudio. The *rioja* package in R was used to validate the clusters with broken-stick model

assessments (Bennett, 1996; Juggins, 2015). Non-Metric Multidimensional Scaling (NMDS) was done in RStudio with Bray distance to demonstrate the relationships between the different samples and diatom species. Four groups were displayed in the NMDS figure. Stratigraphic diagrams showing the statistically significant diatom taxa were created with the program C2 and edited in Adobe Photoshop.

2.3 Results

In total 44 diatom taxa were identified in the sediments of Crawford Lake deposited between 1925 and 1985. This community was quite diverse and comprised 14 families, 23 genera and 32 species being present in statistically significant numbers. The planktic and tychoplanktic central diatoms included *Cyclotella distinguenda*, *Lindavia antiqua*, and *Lindavia bodanica* (Table 1; Appendix 1). The araphid diatom community was represented by *Asterionella formosa*, *Fragilaria delicatissima*, *Meridion circulaire*, and *Ulnaria delicatissima*. The epiphytic and benthic monoraphid diatoms were composed of *Achnantheidium minutissimum*, *Rosithidium duthiei*, and *Cocconeis placentula*. Finally, for the biraphid diatom community, predominate benthic taxa were *Brachysira microcephala*, *Encyonema lunatum*, and *Gomphonema lateripunctatum*. The dominant species representing between >1% and 58.7% percent relative abundance were *A. minutissimum*, *C. distinguenda*, *F. delicatissima*, *L. bodanica*, and *U. delicatissima*.

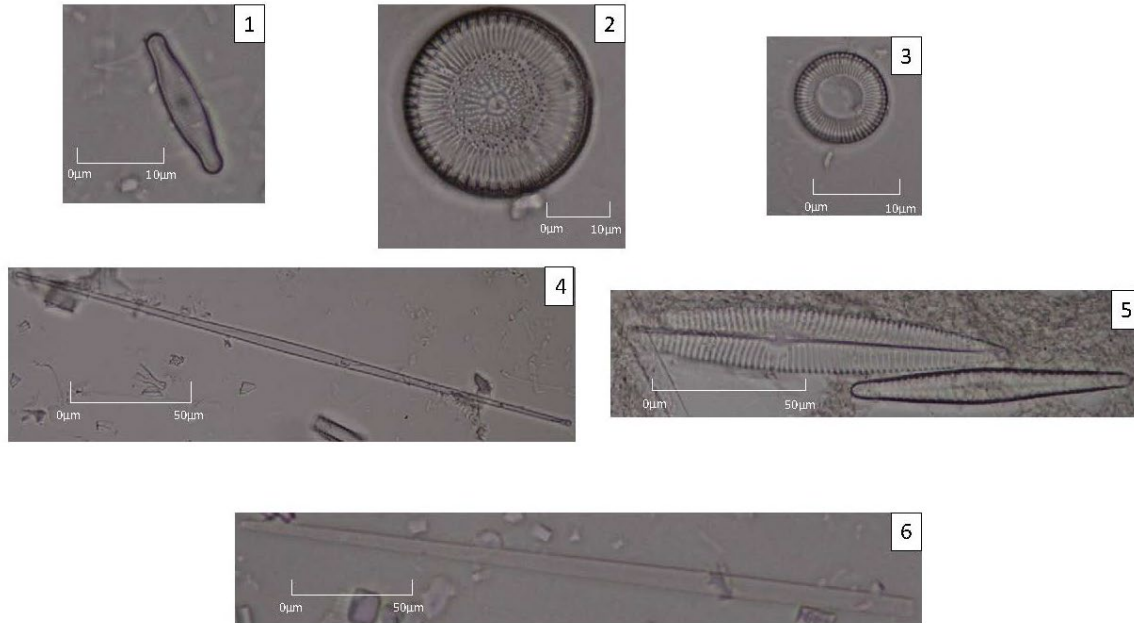


Figure 5: Plates of commonly found diatoms from Crawford Lake, 1925-1985. 1: *Achnanthydium minutissimum*, 2: *Lindavia bodanica*, 3: *Cyclotella distenguenda*, 4: *Ulnaria delicatissima* 5: *Navicula radiosa* (upper diatom) and *Gomphonema lateripunctatum* (lower diatom), 6: *Fragilaria delicatissima*. Photos were taken with a BX51 Olympus microscope (a light microscope) at 1000x with oil immersion and phase contrast.

2.3.1 Temporal Diatom Species Fluctuations

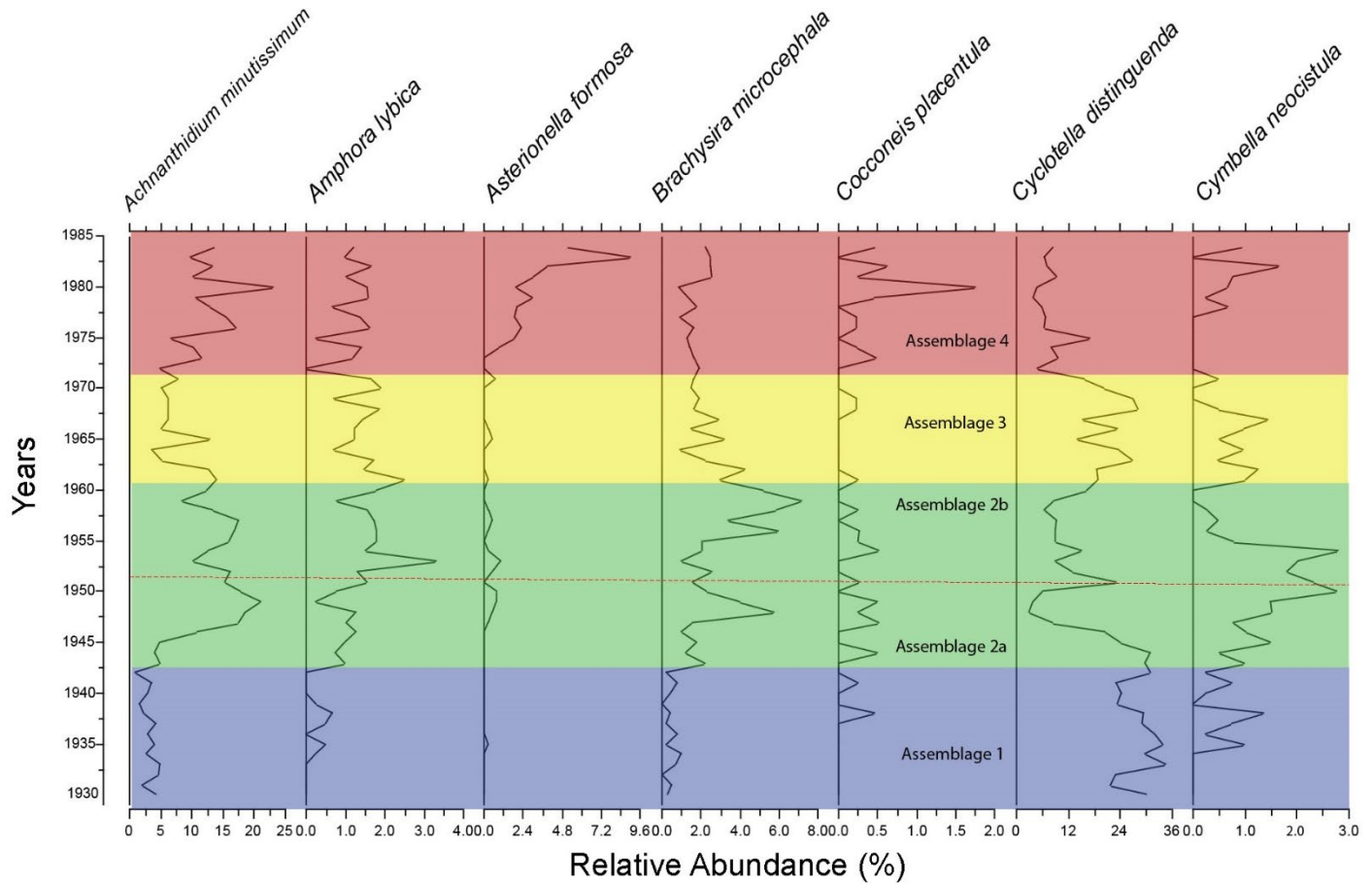


Figure 6: Stratigraphic diagram of the diatom taxa *Achnanthydium minutissimum*, *Amphora lybica*, *Asterionella formosa*, *Brachysira microcephala*, *Cocconeis placentula*, *Cyclotella distinguenda*, and *Cymbella neocistula*. The x-axis shows relative abundance of diatom taxa, while the y-axis shows the chronological year corresponding to each relative abundance value. Assemblage 1 is the blue zone and occurs from 1925-1942. Assemblage 2 is the green zone and occurs from 1943-1959. The red dotted line marks where Assemblage 2 is divided up into Assemblage 2a (1943-1951) and Assemblage 2b (1952-1959). Assemblage 3 is the yellow zone and occurs from 1960-1970. Assemblage 4 is marked as the red zone at the top and occurs from 1971-1985.

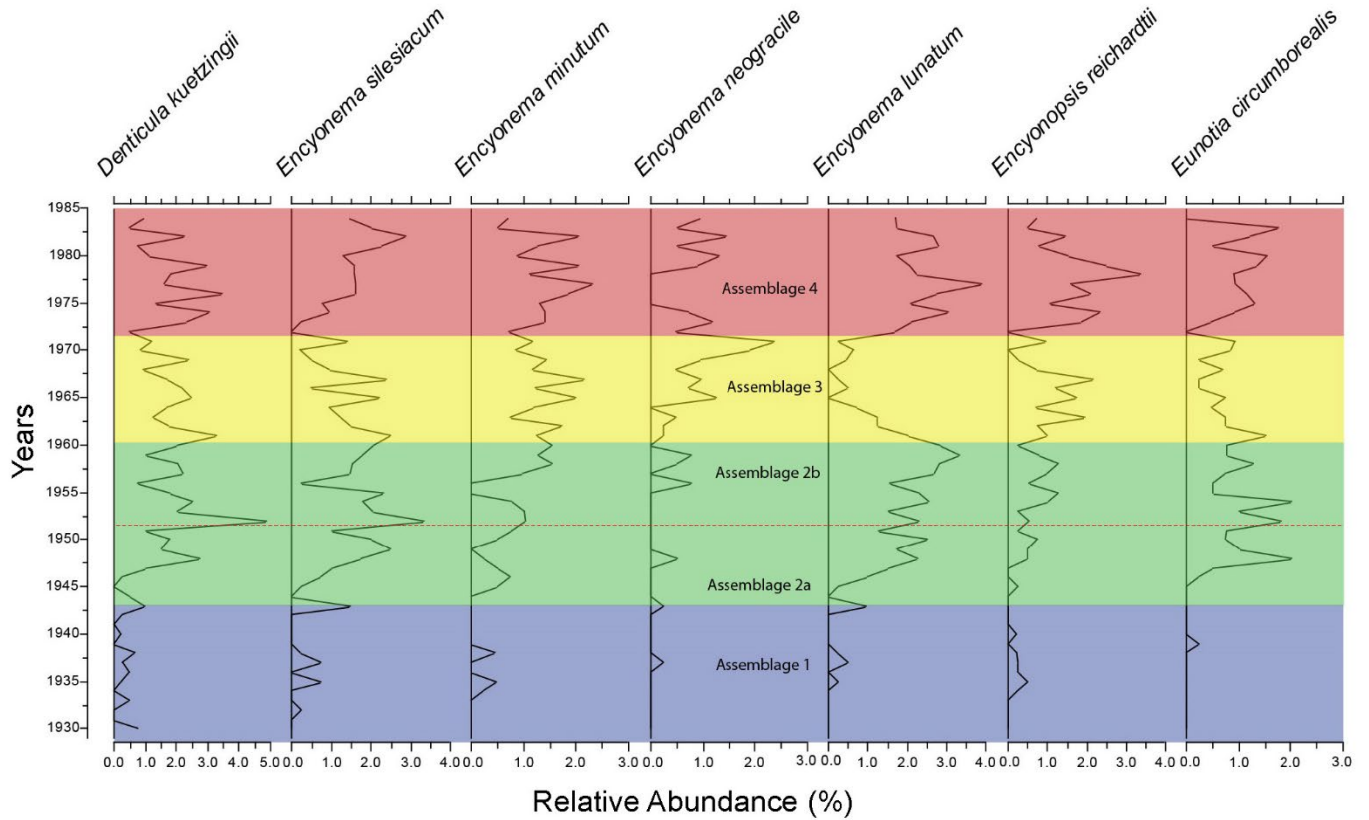


Figure 7: Stratigraphic diagram of the diatom taxa *Denticula kuetzingii*, *Encyonema silesiacum*, *Encyonema minutum*, *Encyonema neogracile*, *Encyonema lunatum*, *Encyonopsis reichardtii*, and *Eunotia circumborealis*. The x-axis shows relative abundance of diatom taxa, while the y-axis shows the chronological year corresponding to each relative abundance value. Assemblage 1 is the blue zone and occurs from 1925-1942. Assemblage 2 is the green zone and occurs from 1943-1959. The red dotted line marks where Assemblage 2 is divided up into Assemblage 2a (1943-1951) and Assemblage 2b (1952-1959). Assemblage 3 is the yellow zone and occurs from 1960-1970. Assemblage 4 is marked as the red zone at the top and occurs from 1971-1985.

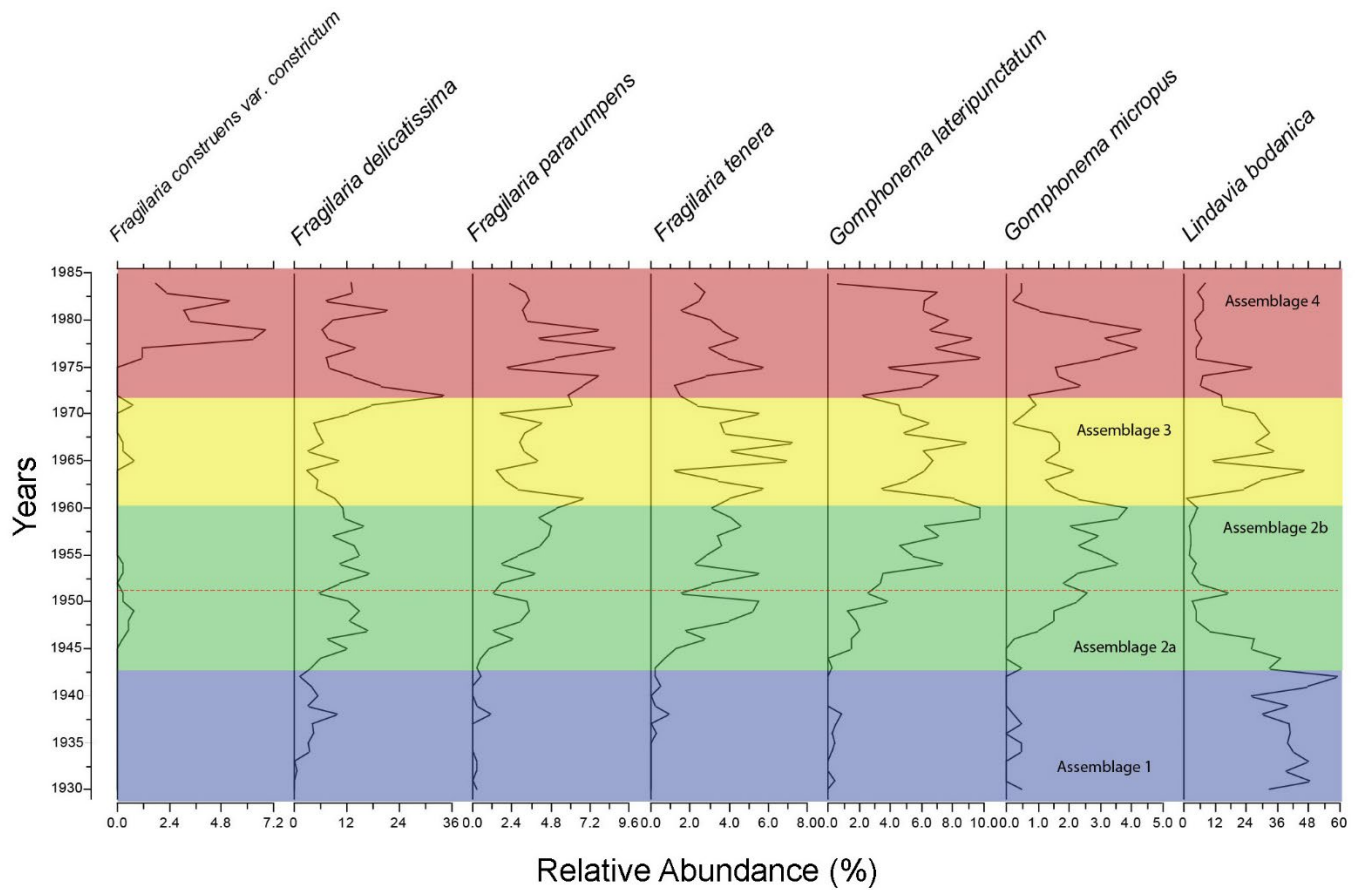


Figure 8: Stratigraphic diagram of the diatom taxa *Fragilaria construens var. constrictum*, *Fragilaria delicatissima*, *Fragilaria pararumpens*, *Fragilaria tenera*, *Gomphonema lateripunctatum*, *Gomphonema micropus*, and *Lindavia bodanica*. The x-axis shows relative abundance of diatom taxa, while the y-axis shows the chronological year corresponding to each relative abundance value. Assemblage 1 is the blue zone and occurs from 1925-1942. Assemblage 2 is the green zone and occurs from 1943-1959. The red dotted line marks where Assemblage 2 is divided up into Assemblage 2a (1943-1951) and Assemblage 2b (1952-1959). Assemblage 3 is the yellow zone and occurs from 1960-1970. Assemblage 4 is marked as the red zone at the top and occurs from 1971-1985.

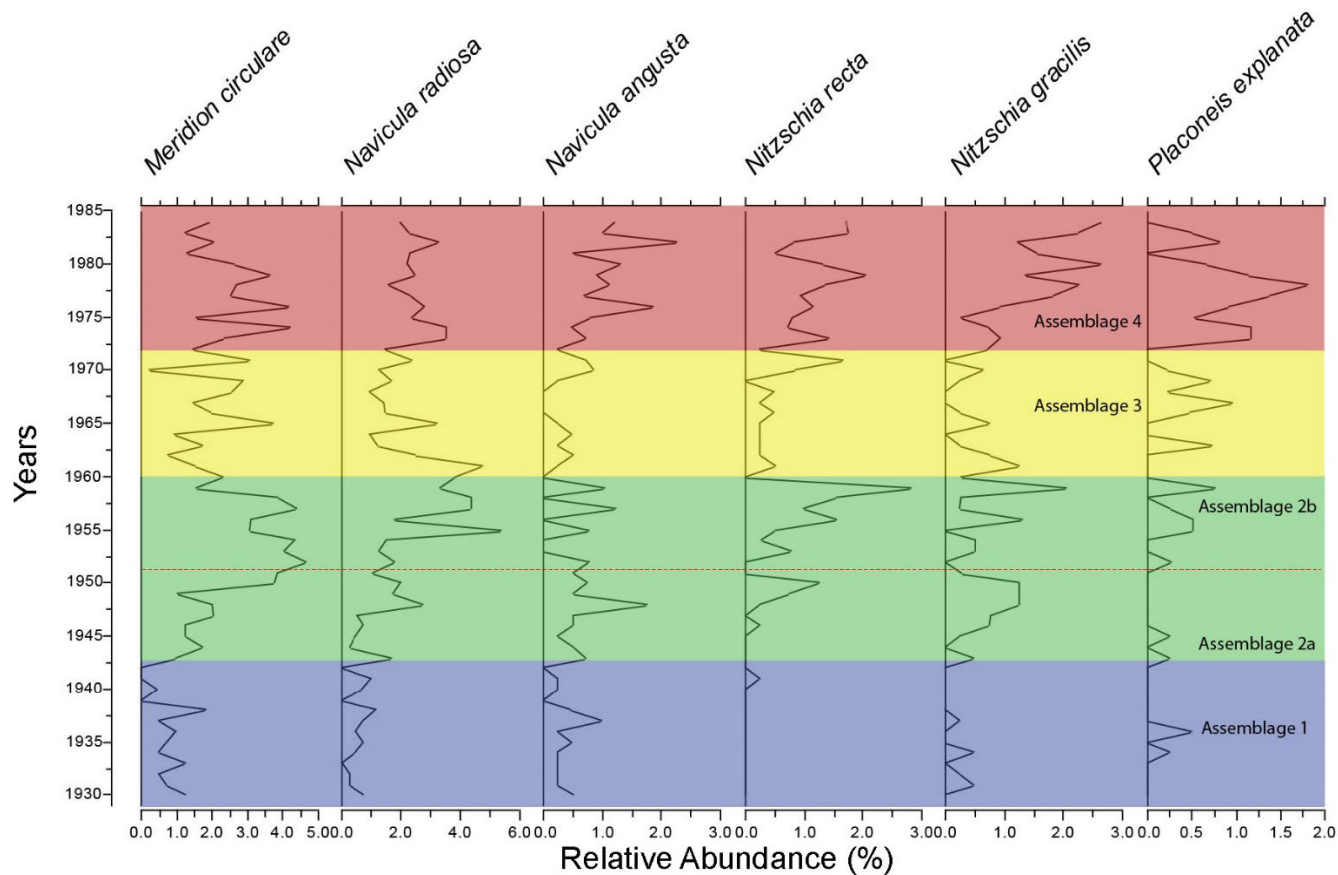


Figure 9: Stratigraphic diagram of the diatom taxa *Meridion circulare*, *Navicula radiosa*, *Navicula angusta*, *Nitzschia recta*, *Nitzschia gracilis*, and *Placoneis explanata*. The x-axis shows relative abundance of diatom taxa, while the y-axis shows the chronological year corresponding to each relative abundance value. Assemblage 1 is the blue zone and occurs from 1925-1942. Assemblage 2 is the green zone and occurs from 1943-1959. The red dotted line marks where Assemblage 2 is divided up into Assemblage 2a (1943-1951) and Assemblage 2b (1952-1959). Assemblage 3 is the yellow zone and occurs from 1960-1970. Assemblage 4 is marked as the red zone at the top and occurs from 1971-1985.

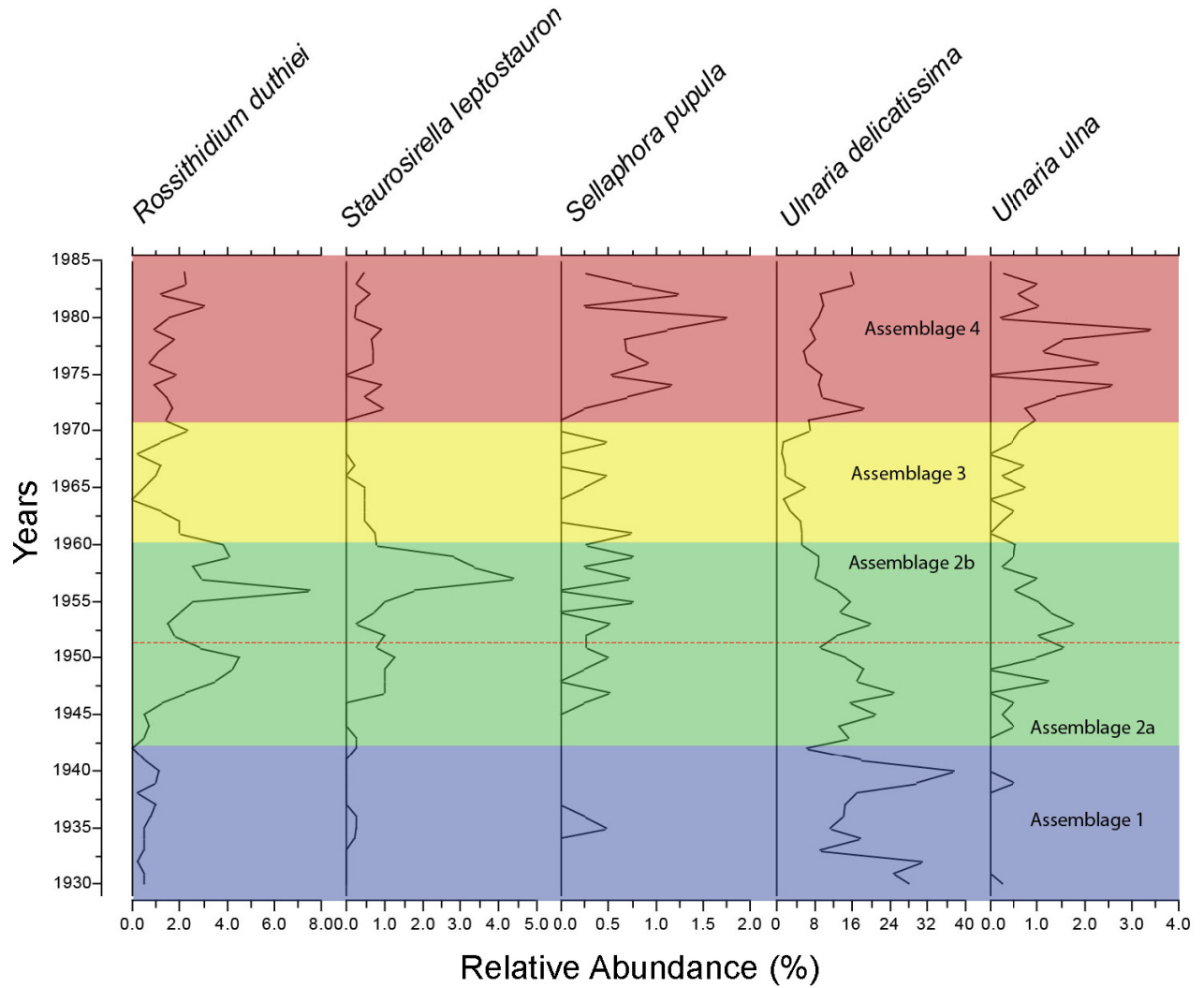


Figure 10: Stratigraphic diagram of the diatom taxa *Rossithidium duthiei*, *Staurosirella leptostauron*, *Sellaphora pupula*, *Ulnaria delicatissima*, and *Ulnaria ulna*. The x-axis shows relative abundance of diatom taxa, while the y-axis shows the chronological year corresponding to each relative abundance value. Assemblage 1 is the blue zone and occurs from 1925-1942. Assemblage 2 is the green zone and occurs from 1943-1959. The red dotted line marks where Assemblage 2 is divided up into Assemblage 2a (1943-1951) and Assemblage 2b (1952-1959). Assemblage 3 is the yellow zone and occurs from 1960-1970. Assemblage 4 is marked as the red zone at the top and occurs from 1971-1985.

2.3.1.1 Assemblage 1 (1925-1942)

The prominent species *Lindavia bodanica* represented 2.9% to 58.7% of the total diatom community structure through the study period (Fig. 8). *Lindavia* spp. were the dominant taxa with a high relative abundance from 1928 to 1943, followed by a dramatic decline to the early 1960s. *Cyclotella distinguenda* (Fig. 6) showed the same trend as *Lindavia* spp. with high relative abundances in the 1920s, 1930s and early 1940s followed by a dramatic decline.

Achnantheidium minutissimum was a prominent taxon and showed the opposite relative abundance changes compared to *Lindavia* spp. and *C. distinguenda* (Fig. 6 and 8). Low abundances of *A. minutissimum* were present during the 1920 to the early 1940s. *Ulnaria delicatissima* was abundant, like *Lindavia* spp. and *C. distinguenda* had high relative abundances during 1925-1940, with subsequent lower abundance from 1940–1970 (Fig. 6, 8, and 10).

Fragilaria spp. had low numbers during the early 1925-1940 period, with increasing numbers through the 1940s and 1950s (Fig. 8). Beginning around 1935, *Cymbella neocistula* had started to appear. Its populations peaked from approximately 1945 to 1960 (up to ~3% relative abundance), after which it then dwindled. Starting in 1929, *Encyonopsis reichardtii* began to appear in the record in low numbers increased after the mid-1940s. *Encyonema minutum* was present in 1929 and disappeared completely from the record from 1934-1940 (Fig. 7).

Encyonema silesiacum populations occurred in low amounts before spiking in 1938 – although it was not present from around 1934 to 1937. *Encyonema neogracile* responded a bit differently compared to *E. minutum* and *E. silesiacum*, appearing intermittently in 1930 and 1933 before more consistently showing up starting around 1940.

2.3.1.2 Assemblage 2 (1943-1959)

Achnantheidium minutissimum experienced a dramatic increase in the mid- to late 1940s and declines in relative abundance from 1950 to mid-1970 period with subsequent increases. *Rossethidium duthiei*, although occurring in lower numbers, followed a similar trend to *A. minutissimum*.

Brachysira microcephala, a less-dominant species (0% to ~8% relative abundance) but still relatively common, underwent a spike in abundance around the mid-1940s (Fig. 6). *Encyonema minutum* populations experienced three more notable collapses, occurring in 1945, 1951, and the early 1970s. However, the population recovered each time, and appeared to increase after each decline (Fig. 7). *Fragilaria* spp. (including *Fragilaria delicatissima*, *Fragilaria pararumpens*, and *Fragilaria tenera*) generally saw increased relative abundances, especially around 1951-1952, with the exception of *Fragilaria construens* var. *constrictum* which saw a decline during that time. As well, *F. construens* var. *constrictum* did not reappear in the record until around 1955 (Fig. 8).

Meanwhile, *Cymbella neocistula*, a species generally occurring in low relative abundances throughout the study period, saw increases in relative abundance beginning in 1945. *C. neocistula* saw a relatively larger increase around 1951-1952, up to ~3% (Fig. 6). *Gomphonema micropus*, another species occurring in low relative abundances, also experienced an increase up to ~3% in 1945, and to ~4% by the early 1950s (Fig. 8). *Navicula angusta* increased to ~2% relative abundance by 1945, but neither declined nor increased in the early 1950s (Fig. 9).

2.3.1.3 Assemblage 3 (1960-1971)

Through the 1960s *Lindavia* spp. again increased but by the 1970s had declined again (Fig. 8). *Brachysira microcephala* began to decrease by ~1965, and went through a population crash in the early 1970s – similar to the relative abundance of several other species around the same time (Fig. 6).

Gomphonema lateripunctatum has low abundances during the early period, with a continuous increase during the 1950s to ~10% relative abundance with stable numbers through the 1960s (Fig. 8). *Cocconeis placentula* began to appear in low amounts around the mid-1940s, but declined from approximately 1963–1967 (Fig. 6). *Encyonema silesiacum* recovered quickly after a population drop in 1952 and was able to largely recover after another population crash in the early 1970s. *Encyonopsis reichardtii* increased a second time around 1962, and like most other diatom taxa, dropped in relative abundance during the early 1970s. However, *E. reichardtii* populations were largely able to recover after a dramatic decline in the early 1970s (Fig. 7).

2.3.1.4 Assemblage 4 (1972-1985)

Lindavia spp. remained at relatively low abundance until the end of the study period in 1985. A recovery of numbers during the 1960s and final decline into the 1980s was also aligned with *Lindavia* spp. (Fig. 8). However, while the *Achnantheidium minutissimum* populations largely recovered after the mid-1970s (Fig. 6), *Rossithidium duthiei* did not. Despite having lower numbers for several decades (1940-1970), *Ulnaria delicatissima* had increasing numbers from 1970-1985 (Fig. 10). *Gomphonema lateripunctatum* taxon underwent a rapid population collapse of the population in the early 1970s with recovery in the late 1970s, followed by declining relative abundance into the 1980s (Fig. 8).

Fragilara spp. had a short peak of growth during the early 1970s followed by a stabilization in relative abundance between 10—15%. *Fragilaria construens* var. *constrictum* saw an increase in relative abundance starting in 1975 to ~7.2% by the late 1970s. Although there was a drop in abundance by 1980, *F. construens* var. *constrictum* still experienced higher relative abundances compared to previous assemblages. *Fragilaria delicatissima* began to increase to approximately 10-12% relative abundance by ~1973-1974, and ranged from ~12-18% for the remainder of the study period. *Fragilaria tenera* began to increase in relative abundance to ~6% after a decline in the early 1970s, but had declined to ~2% by the early 1980s (Fig. 8).

Despite the loss in population in the early 1970s, *Brachysira microcephala* was largely able to recover to values comparable to the pre-1970s steep population declines. *Cocconeis placentula* had another decline in the early 1970s. The *C. placentula* populations had dramatically increased around 1980 but dropped again by 1985 (Fig. 6).

Cymbella neocistula had partially recovered by the early 1970s, then experienced another population crash and did not re-appear in the records until 1978. From the late 1970s until 1985, *Cymbella neocistula* appeared in even lower numbers compared to ~1960–1970 (Fig. 6).

Meridion circulare occurred in relatively low numbers until the mid-1940s, where it significantly increases and stays in relatively consistent high amounts until the early 1970s (Fig. 9). *Navicula radiosa* enjoyed a relatively high abundance from the early 1950s to mid-1960s, after which populations began to decline before crashing in the early 1970s. *N. radiosa* populations recovered partially after this last decline (Fig. 9).

2.3.2 Diatom Assemblage Chronology

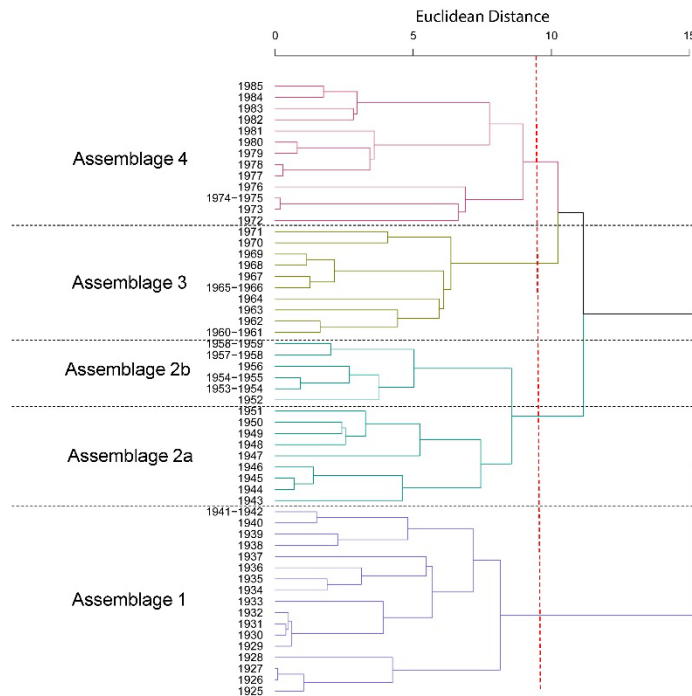


Figure 11: CONISS cluster analysis results showing the relationships of near-annual resolution samples, based on relative abundance of diatom taxa during the study period. Assemblage 1 (blue-purple) occurred from 1925-1942. Assemblage 2 (blue-green) occurred from 1943-1959, and was divided up into Assemblage 2a (1943-1951) and Assemblage 2b (1952-1959) based on increasing relative abundances. Assemblage 3 (yellow) occurred from 1960-1971, and Assemblage 4 (red) occurred from 1972-1985. Although turned 90° for readability, the x-axis are the years sampled while the y-axis is the Euclidean distance between sample years. The red line is the correlation coefficient at a value of approximately 13, and was used to divide up the assemblages. Correlation coefficients are a statistical measure used to represent the strength of the relationship between relative movements of two variables, in this case between the relative abundance of diatom taxa and years from the sample period (1925-1985).

CONISS cluster analysis with Hellinger discrimination and NMDS was used to identify four distinct diatom assemblages that characterized the depositional intervals: 1925-1942, 1943-1959, 1961-1970, and 1971-1985. (Figs. 11 & 12). The period between 1943 and 1959 was further divided into two subassemblages, based on increasing relative abundances of most diatom taxa. Examination of the CONISS results at a finer scale indicated there were short periods of similar community structure (e.g., 1929-1932), but in general fluctuations in community composition were observed (Fig. 3 and 4). Broken-stick model assessments via the *rioja* package in R Studio determined four groups (Bennett, 1996; Juggins, 2015)

The NMDS results showed *C. distinguenda*, *L. bodanica*, *Fragilaria* spp. and *U. delicatissima* creating the early diatom chronology, while the 1943-1959 period (Assemblage 2) was more represented by taxa from many genera including *Achnantheidium*, *Fragilaria*, *Ulnaria*, *Staurosirella*, *Gomphonema*, *Encyonema*, *Nitzschia*, *Cymbella*, and *Navicula* (Fig. 4). The most recent group were positioned was Assemblage 2a (1943-1951) and part way between assemblages 1 and 2 (Fig. 4).

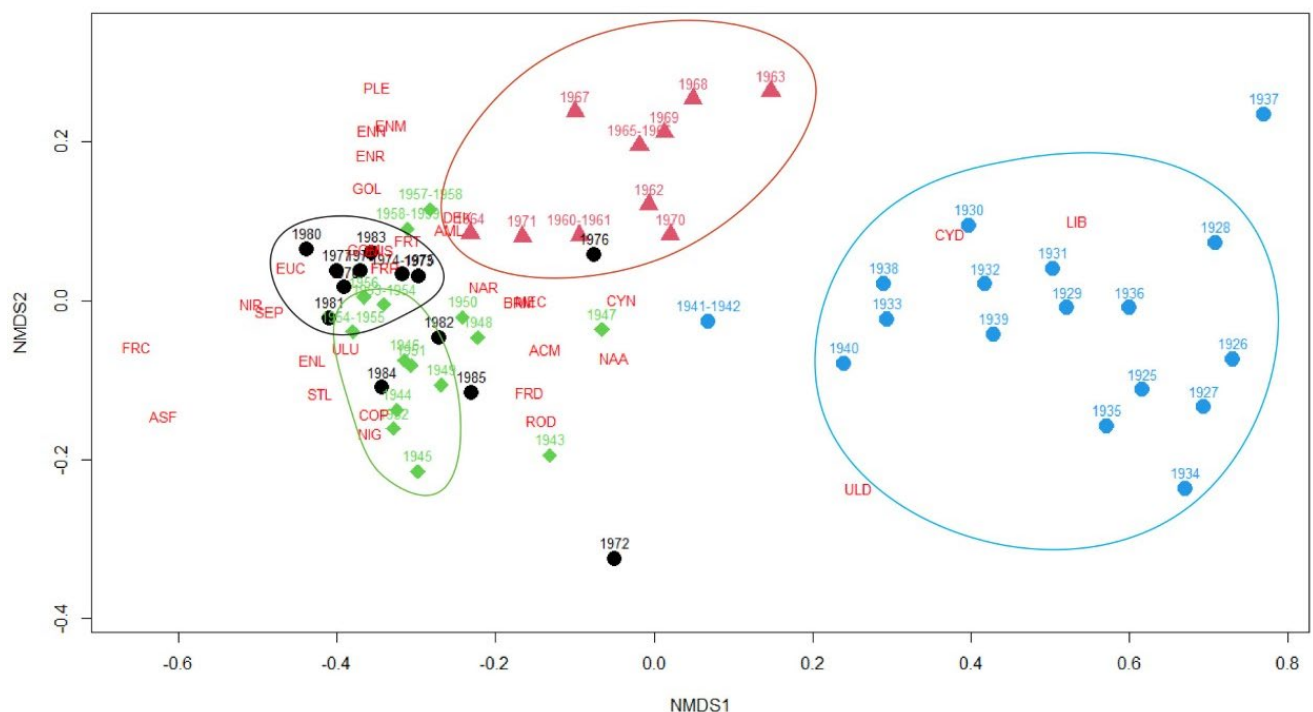


Figure 12: NMDS plot showing the relationship between annually resolved samples and diatom taxa. Assemblage 1 (in blue) occurred from 1925-1942 and was associated with *Cyclotella distinguenda* (CYD), *Lindavia bodanica* (LIB), and *Ulnaria delicatissima* (ULD). Assemblage 2 (in green) occurred from 1943-1959 and was associated with *Fragilaria* species including *Fragilaria delicatissima* (FRD), *Fragilaria construens* var. *constrictum* (FRC), and *Fragilaria pararumpens* (FRP). Assemblage 3 (in red) occurred from 1960-1971, and taxa such as *Achnantheidium minutissimum* (ACM) and *Gomphonema lateripunctatum* (GOL). Assemblage 4 (in black) was associated with *Eunotia circumborealis* (EUC), *Sellaphora pupula* (SEP), and *Cocconeis placentula* (COP). Abbreviations used for diatom taxa in this figure can be found in Appendix C.

2.4 Discussion

2.4.1 Diatom Assemblage Succession (1925—1985)

Through the 20th century, Crawford Lake has been characterized by significant changes in diatom composition, in part supporting the hypothesis that anthropogenic activities in the

Golden Horseshoe, within in the industrial heartland of Canada, as well as climate variability were the primary drivers of these floral changes. The most notable ecological shifts were dramatic changes in the planktic community that dominated from the base of the examined record in 1925 to 1942 (Assemblage 1). A *Fragilaria* dominant assemblage of planktic taxa, along with benthic and epiphytic taxa replaced the centric prominent planktic community from the early 1943-1959 (Assemblage 2a and 2b). Through the period from 1960–early 1970s there was a recovery of the centric community (Assemblage 3). After the 1970s the centric planktic community declined (Assemblage 4) with the establishment *Fragilaria* spp. and littoral attached and benthic taxa, most specifically *A. minutissimum* and *G. lateripunctatum* (Assemblage 3). The significant reduction of the centric planktic community, followed by a recovery and then further reduction, can be linked to the “Great Acceleration” of anthropogenic stressors (Gushulak et al., 2021).

All the key species (*A. minutissimum*, *Cyclotella distenguenda*, *Fragilaria delicatissima*, *Lindavia bodanica*, etc.) are circumneutral to weakly alkaline loving. In terms of nutrient requirements, *C. distenguenda* is considered mesotrophic and the *Fragilaria* spp. identified range from mesotrophic to eutrophic. *A. minutissimum* thrives in disturbed water conditions, and its increases generally lined up with increased human activity in the area. The change in diatom taxa from primarily planktic to primarily benthic may have happened due to both nutrient and sediment loading. In general, planktic species populations decline as sediment loading increases.

Other potential anthropogenic stressors of note are local agriculture and deforestation beginning in the early nineteenth century, but these stressors produced insignificant diatom assemblage changes. This likely results from the absence of a pre-disturbance period in the core used (Gushulak et al., 2021). During the Great Acceleration, regional industry and urbanization

would have further affected lake conditions (Steffen et al., 2015; Gushulak et al., 2021). In addition, a compilation of spheroidal carbonaceous particles (SCP) data from a nearby freeze core collected at the same time of this study shows interesting parallels (Simon Turner, University College London, unpublished data, personal communication). The SCP data supports that a record of the Great Acceleration exists in Crawford Lake. As well, increases in SCPs lined up with population fluctuations in the mid- to late-1920s, the 1940s and the late 1960s. It also showed low occurrence in the late 19th Century, a rapid peak in the early 1950s then an intermittent decline and a lower level of concentrations, by the 1980s and later (Simon Turner, University College London, unpublished data). As well, the SCP data appears to line up with changes to *Fragilaria* spp. populations and decline in planktic species.

2.4.2 Regional Climate Variability (1925-1985)

The regional climate during the interval when Assemblage 1 prevailed in the lake (1925-1942) was characterized by warmer climatic conditions for the region. Thirteen of the 20 years between 1920 and 1940 had higher than average annual temperature for the Toronto-Hamilton Region (Environment Canada, 2021). Similarly, the mean annual temperature increased by ~1 °C between 1970 and 2010 based on climate records from Hamilton and Toronto, Ontario (Watchorn et al. 2008; Environment Canada 2021). This observation is inline with the ecological preferences of the planktic conditions characterizing Crawford Lake during the 1920-1940 (Assemblage 1) and the 1970-1980 (Assemblage 4) intervals. Both Assemblage 1 and Assemblage 3b are characterized by higher relative numbers of taxa such as *Cyclotella distinguenda*, *Lindavia bodanica*, and *Ulnaria delicatissima*. There were no uninterrupted increases in temperature during this time. For example, during the plankton recovery (Assemblage 3a) the interval between 1960 and 1970 had 10 of 10 years being characterized by

lower-than-average mean annual temperatures (Environment Canada, 2021). As a proxy for regional climate, temperature during the Great Acceleration does not appear to be a primary factor in the development of planktic communities in Crawford Lake – likewise warmer and cooler conditions on average for the region were high and low for the littoral (Assemblage 2a, Assemblage 2b, and Assemblage 3) periods of growth (Watchorn et al. 2008; Environment Canada 2021).

The shift from Assemblage 1 (1925-1942) to Assemblage 2a (1943-1959) saw the diatom species populations change from largely open water planktic species (*C. distinguenda*, *L. bodanica*, etc.) to the introduction of several more littoral planktic *Fragilaria* spp. and other species such as *Meridion circulare* and *Gomphonema lateripunctatum*. Assemblage 3 (1960-1971) saw a partial shift back to the populations seen in Assemblage 1, but with additional benthic species such as *Amphora libyca* and *Denticula kuetzingii*. The first part of Assemblage 4 (1972-1976) saw the introduction of several *Fragilaria* spp., and *Staurosirella leptostauron* experienced slightly higher than average populations during this time, except for 1976, while the later portion of Assemblage 4 occurred from 1977-1985. In this later section of Assemblage 4, *Asterionella formosa*, a well-documented eutrophic species, was noted to start appearing in significant amounts, and species such as *Nitzschia recta*, *Eunotia circumborealis*, and *Sellaphora pupula* were also associated with this assemblage, indicating littoral disturbances were present. This is mirrored in studies such as Gushulak et al. (2021), who also noted significant changes to scaled crysophyte and diatom assemblages marked the late twentieth century.

While Crawford Lake is considered a highly buffered system, having a basement of dolomitic limestone, the soils within the catchment of Crawford Lake may have been impacted by acidification – which in turn could have contributed to changes in water clarity at Crawford

Lake. Acidification may have affected the catchment through the binding of compounds, including humic compounds, which typically contributes to the dissolved organic carbon (DOC) of nearby lake systems (Monteith et al., 2007; Hruška et al., 2009). As there was a local peak in acid deposition in 1970, largely due to significant emissions of nitrogen oxides and sulphur. These emissions would have been from industrial sources, both travelling upwind from the industrial heartland of the United States and locally in Ontario (National Air Pollution Surveillance Program, 2020). The peak in acidic deposition in 1970 may have contributed to the significant drop in abundance of multiple diatom taxa in the early 1970s.

Decreases in light penetration (as re-browning) following changes in DOC, and ion/metal depositions, possibly due to changes in regional industrial air contamination are likely reflected in reductions in benthic diatom taxa (Monteith et al., 2007; Meyer-Jacob et al., 2019, 2020). This is potentially also the result of an increased influx of DOC from conservation efforts (including the construction of a boardwalk around the lake and an interpretive centre), disturbances related to long-term reforestation efforts related in the local region being designated as a conservation area after 1969, and runoff associated with archaeological excavation of the nearby Iroquoian settlement. Thus, changes in the diatom assemblage related to increased lake turbidity can be attributed to the transport of additional solids and nutrients into Crawford Lake because of these projects. The slightly acidic pH of the monimolimnion can likely be associated with increases in DOC transport, as following introduction of associated humic acids, this phenomenon would have become limited to below the chemocline. However, Crawford Lake has a low enough BOD that the monimolimnion throughout the year remains oxygenated, even with the increases in nutrients (Gushulak et al., 2021). This is partially due to lower surface water nutrient levels, and changing land-use practices over the past 150 years or so – which impact the more nutrient-rich

chrysophyte and diatom assemblages, as they are no longer supported based on these conditions (Ekdahl et al., 2004, 2007; Cumming et al., 2015; Gushulak et al., 2021).

2.4.3 Taxa interactions with a changing environment

Assemblage 1 (1925—1942) has *C. distinguenda* and *L. bodanica* as two of the dominant diatom species in that assemblage. *C. distinguenda* inhabits waters with a high electrolyte content and is considered a cosmopolitan taxon (Urrea-Clos, 2010). Both *C. distinguenda* and *L. bodanica* are associated with oligotrophic to mesotrophic lakes (Allinger and Reavie, 2013; Hui et al., 1996). Although general climate did not seem to be a factor at Crawford Lake, changing water conditions would have caused the disappearance of these taxa and significant changes to the planktic community. Further, the increase in *A. minutissimum*, a species well documented to thrive in environments of poorer conditions, indicates that water conditions did change.

The broad impacts of the Great Acceleration on Crawford Lake are highlighted by increases in both chrysophyte and diatom populations at approximately 1950 (Gushulak et al., 2021). Although in this study there wasn't a major change in assemblages around the early 1950s, there was still a smaller shift in Assemblage 2a around that time. In general, diatom populations began to increase around the early 1950s and introduced species more tolerant of disturbed conditions. *Meridion circulare* is a taxon often associated with unstable environments (Cantonati et al., 2012). *Encyonopsis* spp., *Gomphonema lateripunctatum*, and *Denticula* spp. are associated with higher conductivities and considered xerotolerant, or able to thrive in ephemeral environments, while *Eunotia* spp. are considered acidophilous mire taxa (Cantonati et al. 2012). In addition, *Gomphonema lateripunctatum* is an indicator species for hydropetric springs in carbonate systems (Cantonati et al. 2012). The increasing relative abundance of *G. lateripunctatum* could be indicating changing carbonate conditions due to the influence of

underground springs and water flow. Although beyond the time-scale of this project, processes such as acidification and erosion are potentially still impacting Crawford Lake – perhaps to a lesser extent compared to other lakes in Ontario, but still enough to have an ongoing effect on diatom assemblages and populations. The rise of diatom populations in Assemblage 2a such as *M. circulare*, *N. radiosa*, and *E. silesiacum* in the 1950s may support this theory.

In addition, *A. formosa* was found to first appear in Assemblage 3 and quickly become abundant by around 1980 (Assemblage 4), something that is reflected in similar studies on Crawford Lake (Enache et al., 2011; Hadley et al., 2013; Sivarajah et al., 2016; Gushulak et al., 2021). Such increases can be attributed to declines in nutrient levels in recent years, including nitrogen. This suggests that increasing temperatures or changes to internal lake thermal stratification patterns may be linked to increased *A. formosa* populations in more recent sediment records (Enache et al., 2011; Hadley et al., 2013; Sivarajah et al., 2016; Gushulak et al., 2021). However, based on the limited effects of temperature alone, internal lake thermal stratification patterns may exert more of an influence on *A. formosa* populations.

It should also be noted that although it is unlikely to be the sole or main cause, pellets of Canadian geese excrement can lead to not only eutrophication, but have meromictic conditions accompany it. Few geese land on the lake in more recent years, and it should be noted hunting is prohibited in this area, as Crawford Lake is in a conservation area (Manny et al., 1994, McAndrews and Turton, 2007).

2.4.4 Summary

In total 32 diatom taxa were found in statistically significant numbers in the sediments of Crawford Lake deposited between 1925 and 1985. A CONISS analysis revealed four identifiable assemblages and two subassemblages. Assemblage 1 (1925-1942) included *Cyclotella*

distinguenda, *Lindavia antiqua*, and *Lindavia bodanica* (Table 1; Appendix 1) indicative of developed planktic productive and community assemblages. Assemblage 2a (1943-1951), through the Great Acceleration, was defined by diatom taxa associated with more disturbed conditions, such as *Meridion circulare* and *Gomphonema lateripunctatum*, while Assemblage 3 (1952-1959) saw a shift back towards Assemblage 1. However, it was also defined by new taxa such as *Denticula keutzingii* and *Amphora libyca*. Assemblage 3 occurred from 1960-1971 and was defined by species *Staurosirella leptostauron* and saw the introduction of several *Fragilaria* species. Assemblage 4 (1972-1985) was associated with species such as *Asterionella formosa*, *Nitzschia recta* and *Eunotia circumborealis*, indicating both planktic and benthic productivity, although not similar to pre-Great Acceleration.

Through the study period of 1940-1980, the dominant species ranging between >1% and 58.7% relative abundance were *A. minutissimum*, *C. distinguenda*, *F. delicatissima*, *L. bodanica*, and *U. delicatissima*. Less dominant, but still common species include *M. circulare*, *C. neocistula*, *D. kuetzingii*, and *E. silesiacum*. Most diatom taxa began to increase in abundance and relative abundance in the early 1950s, through the Great Acceleration and most experienced a decline in population through the 1970s – potentially linked to less development after the 1950s. More recently, there has been an increase in general anthropogenic activity in the area, noted by the spike in *A. formosa*. Notable species that were characterized by different relative abundance trajectories in the 1970s include *E. neogracile* and *F. delicatissima*, both of which underwent a population increase during that time. Diatom populations generally increased in the early 1950s. Along with the four distinct assemblages that the CONISS established, Assemblage 2a ended in 1951 and Assemblage 2b began the following year.

Based on both population counts and statistical analyses, there is evidence to support that the diatom populations responded to the Great Acceleration in the early 1950s, as most diatom species increased in numbers starting in the late 1940s and early 1950s. As well, these numbers remained higher since the Great Acceleration. Even though most diatom populations dropped significantly in the early 1970s, they were still able to recover to numbers similar to those during the earlier period of the Great Acceleration.

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Appendices

Appendix A: Most common diatom species counts from Crawford Lake, from 1925-1985

Table 1: Screened diatom population counts of some of the common benthic species

Achnantheidium minutissimum, *Amphora lybica*, *Cymbella neocistula*, *Navicula radiosa*, and *Staurosirella leptostauron* at Crawford Lake, at a near-annual resolution from 1925-1985

	<i>Achnantheidium minutissimum</i>	<i>Amphora lybica</i>	<i>Cymbella neocistula</i>	<i>Navicula radiosa</i>	<i>Staurosirella leptostauron</i>
1985	57	5	4	8	2
1984	39	4	0	9	1
1983	65	8	8	16	3
1982	40	4	3	9	1
1981	105	7	3	10	1
1980	47	7	1	11	4
1979	57	3	3	7	3
1978	67	6	0	10	3
1977	74	7	0	12	3
1976	25	1	0	9	0
1974-1975	43	6	0	15	4
1973	49	5	0	15	2
1972	20	0	0	6	4
1971	33	7	2	10	0
1970	24	9	0	6	0
1969	26	3	0	7	0
1968	27	8	2	4	0
1967	26	6	6	6	1
1965-1966	21	5	4	6	0
1964	52	5	2	13	2
1963	15	3	4	4	2
1962	21	7	2	5	2
1960-1961	51	6	5	10	2
1958-1959	56	10	4	19	3
1957-1958	48	7	0	15	3
1956	33	3	0	13	11
1954-1955	52	6	1	17	13
1953-1954	72	7	2	18	18
1952	65	7	1	7	7
1951	62	7	3	21	4
1950	50	6	11	6	3
1949	40	13	8	5	1
1948	63	5	7	7	4
1947	59	6	9	4	3
1946	70	3	11	8	5
1945	84	1	6	7	4

1944	74	5	6	11	4
1943	69	4	3	2	4
1941-1942	43	5	4	3	0
1940	20	4	6	2	0
1939	16	3	2	1	0
1938	20	4	4	7	1
1937	4	0	1	0	1
1936	14	0	3	4	0
1935	13	0	1	3	0
1934	6	1	0	0	0
1933	10	3	6	5	0
1932	17	2	3	3	0
1931	12	0	1	2	1
1930	16	2	4	3	1
1929	11	1	0	2	1
1928	20	0	0	0	0
1927	19	0	0	1	0
1926	8	0	0	1	0
1925	17	0	0	3	0

Table 2: Screened diatom population counts of common planktic/tychoplanktic/epipelagic diatom species *Asterionella formosa*, *Lindavia bodanica*, *Cyclotella distinguenda*, *Fragilaria delicatissima*, and *Fragilaria pararumpens* from Crawford Lake, at a near-annual resolution from 1925 to 1985

	<i>Asterionella formosa</i>	<i>Lindavia bodanica</i>	<i>Cyclotella distinguenda</i>	<i>Fragilaria delicatissima</i>	<i>Fragilaria pararumpens</i>
1985	57	5	4	8	2
1984	39	4	0	9	1
1983	65	8	8	16	3
1982	40	4	3	9	1
1981	105	7	3	10	1
1980	47	7	1	11	4
1979	57	3	3	7	3
1978	67	6	0	10	3
1977	74	7	0	12	3
1976	25	1	0	9	0
1974-1975	43	6	0	15	4
1973	49	5	0	15	2
1972	20	0	0	6	4
1971	33	7	2	10	0
1970	24	9	0	6	0
1969	26	3	0	7	0
1968	27	8	2	4	0
1967	26	6	6	6	1
1965-1966	21	5	4	6	0
1964	52	5	2	13	2
1963	15	3	4	4	2
1962	21	7	2	5	2
1960-1961	51	6	5	10	2
1958-1959	56	10	4	19	3
1957-1958	48	7	0	15	3
1956	33	3	0	13	11
1954-1955	52	6	1	17	13
1953-1954	72	7	2	18	18
1952	65	7	1	7	7
1951	62	7	3	21	4
1950	50	6	11	6	3
1949	40	13	8	5	1
1948	63	5	7	7	4
1947	59	6	9	4	3
1946	70	3	11	8	5
1945	84	1	6	7	4
1944	74	5	6	11	4
1943	69	4	3	2	4

1941-1942	43	5	4	3	0
1940	20	4	6	2	0
1939	16	3	2	1	0
1938	20	4	4	7	1
1937	4	0	1	0	1
1936	14	0	3	4	0
1935	13	0	1	3	0
1934	6	1	0	0	0
1933	10	3	6	5	0
1932	17	2	3	3	0
1931	12	0	1	2	1
1930	16	2	4	3	1
1929	11	1	0	2	1
1928	20	0	0	0	0
1927	19	0	0	1	0
1926	8	0	0	1	0
1925	17	0	0	3	0

Appendix B: Raw, unscreened diatom population counts

Table 3: Unscreened diatom population counts of *Achnantheidium minutissimum*, *Amphora*

lybica, *Asterionella formosa*, *Aulacoseira ambigua*, and *Brachysira microcephala* at a near-

annual resolution from 1925-1985 at Crawford Lake

	<i>Achnantheidium minutissimum</i>	<i>Amphora lybica</i>	<i>Asterionella formosa</i>	<i>Aulacoseira ambigua</i>	<i>Brachysira microcephala</i>
1985	44	4	79	0	9
1984	39	9	24	7	16
1983	38	4	11	1	13
1982	37	6	9	1	14
1981	63	4	21	3	16
1980	52	1	36	0	4
1979	57	5	21	1	9
1978	39	4	36	4	10
1977	65	8	19	3	12
1976	40	4	12	2	10
1974-1975	105	7	9	0	4
1973	47	7	13	1	6
1972	57	3	9	2	8
1971	67	6	8	0	4
1970	74	7	10	0	7
1969	25	1	7	1	5
1968	43	6	4	4	6
1967	49	5	0	2	7
1965-1966	20	0	0	1	8
1964	33	7	3	0	7
1963	24	9	0	0	7
1962	26	3	0	0	8
1960-1961	27	8	0	2	7
1958-1959	26	6	0	0	12
1957-1958	21	5	1	0	6
1956	52	5	2	0	13
1954-1955	15	3	0	0	4
1953-1954	21	7	0	1	9
1952	51	6	0	0	17
1951	56	10	1	0	12
1950	48	7	0	5	20
1949	33	3	0	1	28
1948	52	6	1	4	23
1947	72	7	2	1	14
1946	65	7	1	7	23
1945	62	7	0	4	8
1944	50	6	1	4	8
1943	40	13	4	5	4

1941-1942	63	5	2	4	10
1940	59	6	0	4	6
1939	70	3	3	2	9
1938	84	1	3	1	16
1937	74	5	2	3	23
1936	69	4	1	2	6
1935	43	5	0	2	4
1934	20	4	0	0	7
1933	16	3	0	0	5
1932	20	4	0	1	9
1931	4	0	0	0	1
1930	14	0	0	0	3
1929	13	0	0	0	2
1928	6	1	0	0	0
1927	10	3	0	0	2
1926	17	2	0	0	1
1925	12	0	0	1	3

Table 4: Unscreened diatom population counts of *Caloneis bacillum*, *Cocconeis placentula*, *Cyclotella distinguenda*, *Cymbella neocistula*, and *Cymbella cymbiformis* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Caloneis bacillum</i>	<i>Cocconeis placentula</i>	<i>Cyclotella distinguenda</i>	<i>Cymbella neocistula</i>	<i>Cymbella cymbiformis</i>
1985	4	2	31	0	1
1984	1	1	42	2	1
1983	2	1	43	4	0
1982	1	1	43	3	0
1981	3	0	21	3	1
1980	1	0	60	1	0
1979	2	2	35	4	1
1978	3	0	25	0	0
1977	5	3	34	8	1
1976	1	1	36	3	0
1974-1975	3	8	22	3	0
1973	5	2	17	1	0
1972	0	0	25	3	2
1971	1	1	29	0	2
1970	5	1	27	0	1
1969	0	0	65	0	1
1968	4	1	34	0	0
1967	2	2	40	0	2
1965-1966	2	0	20	0	3
1964	2	0	66	2	2
1963	0	0	94	0	1
1962	4	1	113	0	0
1960-1961	0	1	120	2	2
1958-1959	4	0	64	6	3
1957-1958	1	0	96	4	4
1956	3	0	57	2	0
1954-1955	2	0	99	4	1
1953-1954	1	0	110	2	2
1952	2	0	74	5	2
1951	3	1	75	4	6
1950	1	0	63	0	7
1949	1	0	34	0	4
1948	1	1	25	1	4
1947	2	0	38	2	7
1946	2	1	34	1	4
1945	4	1	35	3	6
1944	3	2	59	11	0
1943	4	0	35	8	2
1941-1942	5	0	50	7	3
1940	3	1	89	9	2

1939	5	0	24	11	2
1938	1	2	15	6	2
1937	2	1	12	6	1
1936	2	2	33	3	1
1935	1	0	81	4	0
1934	1	0	96	6	1
1933	0	2	126	2	2
1932	0	0	122	4	0
1931	0	0	127	1	0
1930	0	1	92	3	1
1929	0	0	106	1	0
1928	0	0	94	0	0
1927	1	2	128	6	1
1926	0	0	119	3	1
1925	1	0	128	1	0

Table 5: Unscreened diatom population counts of *Cymbella dorsenotata*, *Denticula kuetzingii*, *Encyonema silesicum*, *Encyonema minutum*, and *Encyonema neogracile* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Cymbella dorsenotata</i>	<i>Denticula kuetzingii</i>	<i>Encyonema silesicum</i>	<i>Encyonema minutum</i>	<i>Encyonema neogracile</i>
1985	0	5	7	5	4
1984	0	12	7	4	1
1983	1	6	10	5	5
1982	0	4	9	7	3
1981	0	1	12	4	2
1980	0	5	4	2	0
1979	0	4	6	3	4
1978	0	2	8	2	2
1977	0	11	14	10	7
1976	0	3	9	5	2
1974-1975	0	5	6	4	6
1973	0	13	7	9	4
1972	1	8	7	5	0
1971	0	7	7	10	0
1970	0	15	7	8	0
1969	0	5	3	5	0
1968	0	13	4	6	3
1967	0	10	1	6	5
1965-1966	0	2	0	3	2
1964	0	5	6	5	10
1963	0	4	1	4	9
1962	0	10	2	6	4
1960-1961	0	4	4	5	2
1958-1959	0	7	10	9	4
1957-1958	0	9	2	5	3
1956	0	10	9	8	5
1954-1955	0	7	4	5	0
1953-1954	0	5	5	3	2
1952	0	7	6	7	1
1951	0	13	10	5	1
1950	0	8	8	6	0
1949	0	4	7	5	3
1948	0	8	6	6	2
1947	0	9	6	4	0
1946	0	3	1	0	3
1945	0	7	9	0	0
1944	0	10	7	3	0
1943	0	8	8	4	0
1941-1942	1	19	13	4	0
1940	0	4	4	3	0

1939	0	7	8	2	0
1938	0	6	10	0	0
1937	0	11	7	1	2
1936	2	4	4	2	0
1935	0	1	3	3	0
1934	0	0	1	2	0
1933	0	2	0	0	0
1932	0	4	6	0	1
1931	0	1	0	0	0
1930	0	0	0	0	0
1929	0	1	0	0	0
1928	0	0	0	0	0
1927	0	3	1	2	0
1926	0	1	3	0	1
1925	0	2	0	0	0

Table 6: Unscreened diatom population counts of *Encyonopsis reichardtii*, *Eunotia circumborealis*, *Eunotia mucophila*, *Fragilaria construens* var. *constrictum*, and *Fragilaria delicatissima* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Encyonopsis reichardtii</i>	<i>Eunotia circumborealis</i>	<i>Eunotia mucophila</i>	<i>Fragilaria construens</i> var. <i>constrictum</i>	<i>Fragilaria delicatissima</i>
1985	3	0	0	6	35
1984	1	2	0	12	23
1983	2	4	1	23	37
1982	4	0	0	35	40
1981	1	3	0	11	49
1980	3	0	0	9	33
1979	3	0	0	7	54
1978	2	7	0	9	53
1977	7	6	0	25	35
1976	3	2	1	12	83
1974-1975	7	7	0	15	40
1973	11	6	0	30	28
1972	15	4	0	28	34
1971	7	4	0	5	60
1970	9	5	0	5	32
1969	4	5	0	0	30
1968	10	4	0	0	57
1967	8	2	1	0	83
1965-1966	0	0	0	0	140
1964	4	4	2	3	75
1963	0	4	1	0	59
1962	1	1	0	0	19
1960-1961	3	3	0	0	23
1958-1959	9	1	0	1	27
1957-1958	5	1	1	1	13
1956	7	3	0	3	41
1954-1955	3	2	0	0	12
1953-1954	8	3	0	0	22
1952	3	3	0	0	20
1951	4	6	0	0	36
1950	1	3	0	0	43
1949	3	3	0	0	44
1948	5	5	0	0	62
1947	4	3	1	0	36
1946	2	2	0	0	53
1945	5	2	0	0	58
1944	4	8	0	1	41
1943	1	4	0	1	67
1941-1942	2	7	3	0	41

1940	1	3	0	1	22
1939	3	3	0	1	49
1938	2	4	0	3	60
1937	2	8	1	2	51
1936	0	2	0	2	66
1935	0	1	0	1	30
1934	1	0	0	0	48
1933	0	0	0	0	25
1932	0	0	0	0	15
1931	0	0	0	0	5
1930	0	0	0	0	15
1929	1	0	0	0	24
1928	0	1	0	0	13
1927	1	0	0	0	43
1926	1	0	0	0	17
1925	1	0	0	0	18

Table 7: Unscreened diatom population counts of *Fragilaria pararumpens*, *Fragilaria tenera*, *Gomphonema lateripunctatum*, *Gomphonema coronatum*, and *Gomphonema truncatum* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Fragilaria pararumpens</i>	<i>Fragilaria tenera</i>	<i>Gomphonema lateripunctatum</i>	<i>Gomphonema coronatum</i>	<i>Gomphonema truncatum</i>
1985	9	30	12	0	0
1984	14	14	21	2	3
1983	11	12	22	1	1
1982	15	12	29	0	2
1981	8	11	18	0	0
1980	10	10	21	2	0
1979	9	9	19	0	0
1978	13	11	28	0	1
1977	17	12	30	0	0
1976	12	6	24	1	1
1974-1975	15	14	35	0	1
1973	34	16	29	1	5
1972	18	20	41	1	0
1971	38	13	30	1	1
1970	22	17	42	1	5
1969	8	22	15	0	0
1968	33	12	30	0	3
1967	29	5	26	1	3
1965-1966	24	6	9	0	0
1964	26	10	19	0	0
1963	8	26	22	0	0
1962	18	15	27	1	0
1960-1961	14	16	21	0	1
1958-1959	12	30	37	0	0
1957-1958	13	17	25	0	0
1956	16	28	27	0	4
1954-1955	6	5	26	0	1
1953-1954	8	14	21	0	2
1952	11	23	14	0	0
1951	27	16	32	0	0
1950	20	12	38	0	0
1949	16	16	38	0	0
1948	19	18	24	0	0
1947	19	14	29	0	0
1946	16	14	18	0	1
1945	11	11	21	0	0
1944	7	9	29	0	0
1943	15	22	14	0	1
1941-1942	7	12	13	0	2
1940	5	6	10	0	2

1939	13	22	15	0	1
1938	14	21	5	0	0
1937	12	16	7	1	1
1936	5	7	8	0	3
1935	10	11	6	0	0
1934	4	5	6	0	0
1933	2	3	0	0	0
1932	1	1	1	0	0
1931	2	1	0	0	0
1930	0	2	0	0	0
1929	0	0	0	0	0
1928	1	1	0	0	0
1927	5	4	4	0	0
1926	0	0	2	0	1
1925	0	1	1	0	2

Table 8: Unscreened diatom population counts of *Gomphonema micropus*, *Lindavia antiqua*, *Lindavia bodanica*, *Meridion circulaire*, and *Navicula radiosa* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Gomphonema micropus</i>	<i>Lindavia antiqua</i>	<i>Lindavia bodanica</i>	<i>Meridion circulaire</i>	<i>Navicula radiosa</i>
1985	1	0	45	6	9
1984	5	0	53	14	13
1983	2	2	34	8	20
1982	3	0	38	8	16
1981	6	0	23	11	9
1980	2	2	43	6	13
1979	2	3	36	8	8
1978	2	1	22	5	9
1977	1	3	36	10	16
1976	4	0	30	5	9
1974-1975	12	0	19	12	10
1973	19	0	22	16	11
1972	14	2	30	12	7
1971	18	1	21	11	10
1970	13	2	21	18	12
1969	6	1	99	6	9
1968	7	0	32	18	15
1967	10	0	28	10	15
1965-1966	3	0	59	6	6
1964	4	0	64	13	10
1963	3	0	129	1	6
1962	1	0	124	12	7
1960-1961	6	0	141	11	4
1958-1959	7	0	115	6	6
1957-1958	7	0	141	8	6
1956	5	0	46	15	13
1954-1955	9	3	195	4	4
1953-1954	5	2	121	7	5
1952	6	5	94	3	10
1951	9	4	5	6	19
1950	15	3	20	9	15
1949	14	4	15	6	13
1948	8	1	8	15	17
1947	12	4	11	18	18
1946	9	1	10	12	7
1945	12	3	8	12	21
1944	14	5	19	17	6
1943	9	1	12	16	5
1941-1942	7	0	23	18	7
1940	10	0	66	15	4

1939	9	0	13	15	8
1938	6	0	19	4	7
1937	6	0	19	8	11
1936	4	0	38	8	2
1935	1	0	108	5	3
1934	0	0	104	5	2
1933	0	0	152	7	1
1932	2	0	135	4	7
1931	0	1	240	0	0
1930	0	0	193	0	4
1929	0	0	114	2	3
1928	0	0	162	0	0
1927	1	0	133	8	5
1926	2	0	166	2	3
1925	0	0	165	4	2

Table 9: Unscreened diatom population counts of *Navicula angusta*, *Nitzschia recta*, *Nitzschia gracilis*, *Nitzschia microcephala*, and *Placoneis explanata* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Navicula angusta</i>	<i>Nitzschia recta</i>	<i>Nitzschia gracilis</i>	<i>Nitzschia microcephala</i>	<i>Placoneis explanata</i>
1985	2	4	5	1	1
1984	1	5	4	1	2
1983	4	4	6	0	3
1982	9	1	0	0	1
1981	5	5	6	2	3
1980	3	0	2	0	1
1979	5	7	11	3	0
1978	4	7	9	4	2
1977	11	4	6	2	4
1976	2	2	6	1	0
1974-1975	6	6	12	2	3
1973	4	9	6	0	5
1972	5	6	10	0	8
1971	3	4	8	0	6
1970	8	5	4	0	4
1969	3	3	1	0	2
1968	2	3	3	0	5
1967	3	6	4	0	5
1965-1966	1	1	3	0	0
1964	3	7	0	0	0
1963	4	4	3	0	1
1962	1	0	1	0	3
1960-1961	0	2	0	0	1
1958-1959	0	1	0	0	4
1957-1958	0	2	1	0	2
1956	1	1	3	0	0
1954-1955	2	1	0	0	0
1953-1954	1	1	1	0	3
1952	2	1	3	0	0
1951	1	2	5	0	0
1950	0	0	1	0	0
1949	4	11	8	0	3
1948	0	6	1	0	0
1947	5	4	1	0	1
1946	0	6	5	0	2
1945	3	2	0	0	2
1944	0	1	2	0	0
1943	0	3	2	0	0
1941-1942	3	0	0	0	1
1940	2	0	1	0	0

1939	3	5	5	4	0
1938	2	3	5	1	0
1937	7	1	5	3	0
1936	2	0	3	2	0
1935	2	1	3	1	0
1934	1	0	1	0	1
1933	2	0	0	1	0
1932	3	0	2	1	1
1931	0	0	0	0	0
1930	1	1	0	0	0
1929	1	0	0	0	0
1928	0	0	0	0	0
1927	2	0	0	0	0
1926	4	0	1	0	0
1925	1	0	0	1	2

Table 10: Unscreened diatom population counts of *Rossithidium duthiei*, *Starosirella leptostauron*, *Sellaphora bacillum*, and *Sellaphora pupula* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Rossithidium duthiei</i>	<i>Starosirella leptostauron</i>	<i>Sellaphora bacillum</i>	<i>Sellaphora pupula</i>
1985	9	2	5	2
1984	8	0	6	5
1983	7	2	5	1
1982	10	1	3	4
1981	16	0	5	4
1980	3	2	3	0
1979	9	2	3	1
1978	9	1	2	3
1977	6	3	4	6
1976	12	1	2	1
1974-1975	7	1	3	8
1973	4	4	2	5
1972	8	3	3	3
1971	5	3	4	3
1970	3	3	5	4
1969	7	0	1	2
1968	4	4	4	5
1967	6	2	2	3
1965-1966	7	4	2	1
1964	6	0	7	0
1963	11	0	3	0
1962	5	0	4	2
1960-1961	1	0	5	0
1958-1959	5	1	4	0
1957-1958	4	0	2	2
1956	2	2	1	1
1954-1955	0	2	3	0
1953-1954	5	2	3	0
1952	8	2	2	0
1951	8	3	0	3
1950	15	3	1	1
1949	16	11	6	3
1948	10	13	2	1
1947	12	18	4	3
1946	29	7	1	0
1945	10	4	5	3
1944	8	3	2	0
1943	6	1	5	2
1941-1942	7	4	4	1
1940	11	3	6	1
1939	18	5	4	2

1938	17	4	1	1
1937	14	4	1	0
1936	9	4	3	2
1935	5	0	2	1
1934	2	0	1	0
1933	3	0	0	0
1932	2	1	0	0
1931	0	1	0	0
1930	2	0	0	0
1929	5	0	0	0
1928	4	0	0	0
1927	1	0	2	0
1926	4	0	0	0
1925	3	1	3	1

Table 11: Unscreened diatom population counts of *Ulnaria acus*, *Ulnaria capitata*, *Ulnaria delicatissima*, and *Ulnaria ulna* at a near-annual resolution from 1925-1985 at Crawford Lake

	<i>Ulnaria acus</i>	<i>Ulnaria capitata</i>	<i>Ulnaria delicatissima</i>	<i>Ulnaria ulna</i>
1985	1	0	52	0
1984	2	0	24	5
1983	1	0	44	1
1982	1	0	32	2
1981	1	0	53	4
1980	0	0	62	3
1979	0	0	65	1
1978	0	1	66	4
1977	0	0	45	3
1976	0	0	39	4
1974-1975	0	0	40	1
1973	2	0	32	15
1972	0	1	37	7
1971	0	1	25	5
1970	0	0	28	10
1969	0	0	37	0
1968	2	0	38	11
1967	3	0	40	6
1965-1966	1	0	76	3
1964	0	1	28	4
1963	0	1	33	3
1962	0	0	6	2
1960-1961	0	0	4	0
1958-1959	0	0	7	3
1957-1958	0	0	8	1
1956	0	0	24	3
1954-1955	0	0	6	0
1953-1954	0	0	11	2
1952	0	0	20	1
1951	0	0	21	0
1950	0	0	20	2
1949	3	0	34	2
1948	0	1	35	1
1947	0	1	33	4
1946	1	1	49	2
1945	0	0	61	4
1944	0	1	53	5
1943	0	0	79	7
1941-1942	0	0	50	4
1940	1	2	36	6
1939	0	0	57	4
1938	0	0	74	0
1937	0	0	68	5

1936	0	0	97	0
1935	0	0	62	2
1934	0	0	84	1
1933	0	0	54	2
1932	0	0	62	0
1931	0	0	26	0
1930	0	0	71	0
1929	0	0	164	0
1928	0	0	120	2
1927	0	0	74	0
1926	0	0	59	0
1925	0	0	57	0

Appendix C: Diatom taxa abbreviations used in figure 12 (NMDS)

Table 12: Diatom species abbreviations used in the NMDS figure (Fig. 12). The first two letters of the genus name followed by the first letter of the species name were used to develop the abbreviations.

Diatom Species	Abbreviation Used
<i>Achnantheidium minutissimum</i>	ACM
<i>Amphora lybica</i>	AML
<i>Asterionella formosa</i>	ASF
<i>Brachysira microcephala</i>	BRM
<i>Cocconeis placentula</i>	COP
<i>Cyclotella distinguenda</i>	CYD
<i>Cymbella neocistula</i>	CYN
<i>Denticula kuetzingii</i>	DEK
<i>Encyonema silesiacum</i>	ENS
<i>Encyonema minutum</i>	ENM
<i>Encyonema lunatum</i>	ENL
<i>Encyonopsis reichardtii</i>	ENR
<i>Eunotia circumborealis</i>	EUC
<i>Fragilaria construens. var. constrictum</i>	FRC
<i>Fragilaria delicatissima</i>	FRD
<i>Fragilaria pararumpens</i>	FRP
<i>Fragilaria tenera</i>	FRT
<i>Gomphonema lateripunctatum</i>	GOL
<i>Gomphonema micropus</i>	GOM
<i>Lindavia bodanica</i>	LIB
<i>Meridion circulaire</i>	MEC
<i>Navicula radiosa</i>	NAR
<i>Navicula angusta</i>	NAA
<i>Nitzschia recta</i>	NIR
<i>Nitzschia gracilis</i>	NIG
<i>Placoneis explanata</i>	PLE
<i>Rossithidium duthi</i>	ROD
<i>Starosirella leptostauron</i>	STL
<i>Sellaphora pupula</i>	SEP
<i>Ulnaria delicatissima</i>	ULD
<i>Ulnaria ulna</i>	ULU