

Annual-scale (1930-1990) assessment of anthropogenic influences on the assemblage structure of Golden-Brown Algae (Chrysophytes) in Crawford Lake, Ontario, Canada

By

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ABSTRACT

Crawford Lake, situated within the Crawford Lake Conservation Area near Milton, Ontario, Canada, has unique characteristics that make it ideally suited to high-resolution paleoecological studies. The seasonally deposited varved sediments in the deep basin of this meromictic lake are currently being considered as a potential Global Boundary Stratotype Section and Point (GSSP) to mark the lower boundary of the proposed Anthropocene Epoch. Golden-Brown Algae (Chrysophyte) communities were examined at annual resolution in varves spanning 1930-1990 CE from freeze core CRW19-2FT-B2, collected from Crawford Lake in February 2019. Stratigraphically constrained cluster analysis showed major assemblage changes within this interval, with one of the highest magnitude changes occurring between varves deposited in 1952 and 1953, coinciding with the global effect of atmospheric nuclear armament testing on deposited isotope signatures, one of the key markers of the proposed Holocene-Anthropocene boundary. The post-1953 species assemblages within this lake were novel and differed greatly in composition compared to those examined from earlier in the 20th century. These changes in assemblage are attributed to increased industrial emissions and related effects of acid deposition on the lake's catchment, related to the Great Acceleration – the massive economic, industrial and demographic expansion beginning in the mid-20th century. The findings reported here reflect major changes in earth systems that the Anthropocene Working Group proposes to use to make the base of the Anthropocene Series, providing support for the laminated sedimentary sequence from Crawford Lake as a potential Anthropocene GSSP.

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INTRODUCTION

The current geologic epoch, the Holocene, began approximately 11,650 cal years before present, is defined by the development of the current, relatively warm, interglacial conditions (Walker et al., 2009). However, some researchers have argued that more recently the planet has become dominated by unique anthropogenic, or man-made, impacts at global, regional, and local scales (Doney et al., 2009; Paerl, 2006; Zalasiewicz et al., 2010). These impacts have been so extensive that there is evidence that they have become permanently incorporated into the geologic record (Zalasiewicz et al., 2014; Zalasiewicz et al., 2010). Despite considerable semantic baggage associated with the term, the label Anthropocene has been agreed upon for a new geologic epoch to directly follow the Holocene. As discussed below there has been considerable debate concerning a start date for the Anthropocene, but with a proposal from the Anthropocene Working Group (AWG) of the Sub-commission on Quaternary Stratigraphy a consensus has been reached to have this new epoch start in the mid-twentieth century (Subramanian, 2019).

The proposed establishment of the Anthropocene Epoch by the AWG has not been without considerable debate within the stratigraphic community. Some researchers are opposed to a new epoch being established to succeed the Holocene Interglacial, which starting only \sim 12,000 years ago is already of very short duration when compared with other epochs in the geologic time scale. Some argue that the Anthropocene should be defined as starting some thousands of years ago, coincident with increased and widespread agricultural activity. Others have suggested various milestones during the industrial revolution would be a more appropriate starting date. Finally, there is a significant contingent in the scientific community who believe that the Anthropocene should have a lower boundary in the mid-twentieth century, coincident with nuclear weapons testing and ‘the great acceleration’; a term referencing the large-scale increases in fuel consumption, fuel extraction, land and water use, food consumption due to a rapidly increasing population. These anthropogenic impacts have led to global environmental changes including changes to the global nitrogen cycle (Moomaw et al., 2010), changes with natural disasters

including increases in wildfires and changing cyclone tracks (Colbert et al., 2013; Williams et al., 2019), as well as acidification of ocean bodies and terrestrial lakes (Doney et al., 2009b). The prolific nuclear testing during this period have also led to global-scale changes in radioisotope abundance, adding another useful marker to define the lower boundary of the Anthropocene (Rafter and Fergusson, 1957).

To be a good candidate for the Anthropocene Global Stratotype Section and Point (GSSP), of which there are 11, the GSSP must preserve and show changes demonstrative of the global human impacts associated with the Anthropocene as well as be able to provide a precise and accurate datum for the base of the unit, be accessible, and be a site that will preserve these changes through time (Waters et al., 2018; Subramanian, 2019; Head, 2019, Anthropocene Working Group, 2020). Crawford Lake, located within the Crawford Lake Conservation Area, is a meromictic lake, and is considered a leading candidate to be selected as the Anthropocene GSSP. This meromictic, sheltered, relatively deep (~24m deep) lake is characterized by stratification between the upper and lower parts of the water column at ~15m depth. The deeper, more conductive, less oxygenated monimolimnion inhibits disturbances of the sediment-water interface by forces such as wave action or bioturbation. The undisturbed lake bottom is conducive for the preservation of microfossils and other proxy records within well-defined, seasonally-varved sediments. Although the lake sedimentary record spans the entire Holocene, this interval of laminated sediments spans from the Recent, back through the proposed mid-twentieth century Anthropocene-Holocene boundary to the late 13th or 14th century (Boyko-Diakonow, 1979; Ekdahl et al., 2004; Krueger and McCarthy, 2016). These varved sediments allow for paleolimnological studies at resolutions unmatched by studies of more homogenized core material that require the use of radioisotope core dating methodologies, where uncertainties within the calculated age-depth models based on number of half-lives and isotope activity within the sample often results in errors, a major difficulty when defining a GSSP based in the mid 20th century even with ²¹⁰Pb dating techniques.

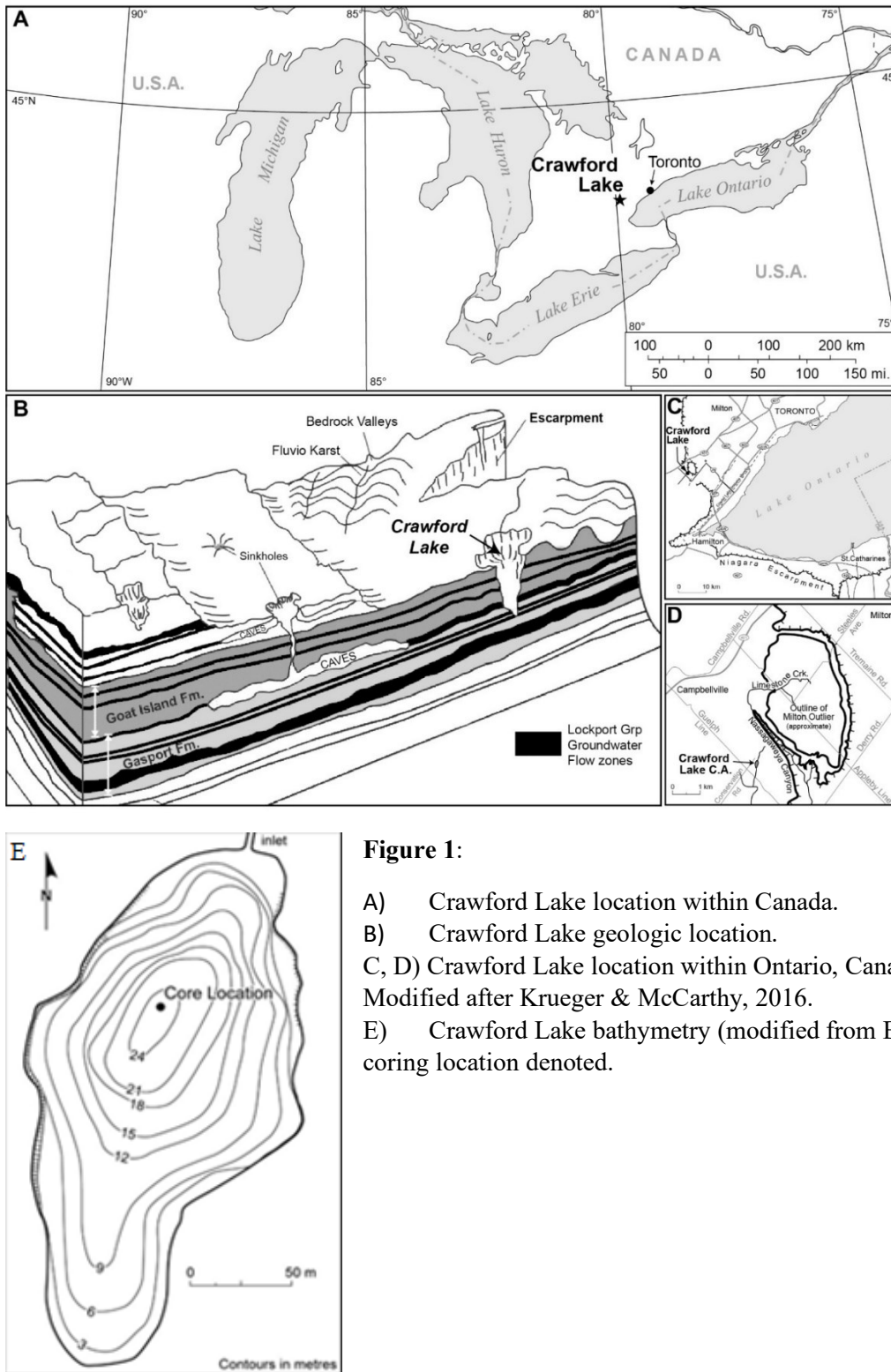


Figure 1:

- A) Crawford Lake location within Canada.
 - B) Crawford Lake geologic location.
 - C, D) Crawford Lake location within Ontario, Canada.
- Modified after Krueger & McCarthy, 2016.
- E) Crawford Lake bathymetry (modified from Boyko, 1793) with coring location denoted.

Previous researchers have used the varved sediment record in Crawford Lake to unravel its paleolimnological history using many different bio-indicators. For example, the pollen, charcoal and diatom records have provided important information on the impact of past anthropogenic impacts ((Ekdahl et al., 2007, 2004; McAndrews and Boyko-Diakonow, 1989; Rybak and Dickman, 1988). Evidence of eutrophication, nearby fires, and associated pollen grains revealed using these proxies has provided evidence of the Indigenous habitation adjacent to the lake during the late 1200s to 1400s, as well as later 19th century European settlement (Clark and Royall, 1995; McAndrews and Boyko-Diakonow, 1989; McAndrews and Turton, 2008). Other surveys have investigated changes in tree coverage and climate throughout the area, with such studies focusing on the past ~1000 years ((Yu, 1997; Yu and Eicher, 1998; Yu and Wright, 2001). Despite the plethora of research carried out at Crawford Lake, very few studies have taken advantage of the annual-high-temporal resolution record afforded by the varved sediments to examine the paleolimnological record at annual resolution, with only Serack (2020) having studied the lake at annual resolution up to this point.

Some important proxies (e.g., chrysophytes) have not been widely analyzed at Crawford Lake to date. Prior to an investigation carried out by Gushulak *et al.* (2021), only stomatocysts, the resting life stage of chrysophytes, have previously been studied here (Rybak et al., 1987). Gushulak *et al.* (2021) examined both chrysophyte and diatom assemblages spanning the 19th and 20th centuries at sub-decadal resolution, showing major assemblage changes concomitant with the proposed Anthropocene lower boundary (2021).

Based on the success of the Gushulak *et al.* (2021) in demonstrating that scaled chrysophytes are a robust proxy for documenting paleoenvironmental change within Crawford Lake, and the annual-resolution varve chronology established by Serack (2020), the research presented here was carried out to analyze these chrysophyte communities at annual resolution in an interval bracketing the proposed mid-20th century Anthropocene-Holocene boundary (1930-1990) to determine more precisely the

paleolimnological onset and trajectory of the Great Acceleration in Crawford Lake, which will aid in the bid for the sedimentary record of this site being selected as the GSSP for the new epoch lower boundary.

Chrysophytes

Chrysophytes, sometimes referred to as golden-brown algae due to their photosynthetic accessory pigments of the same colour, are an increasingly important paleoecological bio-indicator. Of particular interest to paleoecologists are the scaled chrysophytes; chrysophyte species that create siliceous scales and spines to protect their soft cell body, which also preserve well within lakebed sediments. These species may be solitary or colonial, with their scales and spines bearing ornamentation allowing for identification to the species level from remains preserved within sediment cores. These species have been used as a robust proxy for environmental change, being sensitive to, and having been used to show changes in various environmental conditions such as pH (Cumming et al., 1992; Hadley, 2012), water salinity (Cumming et al., 1993; Zeeb and Smol, 1995), and trophic status (Siver and Marsicano, 1996), making them an ideal proxy to study changes in a lacustrine system such as Crawford Lake. Other than the work of Gushulak *et al.* (2020), chrysophyte studies within the lake have been limited to those done by Rybak and Dickman (1988) and Rybak *et al.* (1989), which implied eutrophication within Crawford lake in the late 1970's based on chrysophyte cyst assemblages and pigment ratios between different autotrophic groups. It was hypothesized within both of these papers that the late 1970's assemblage changes found within different groups may be due to eutrophication caused by a large increase in visitors and construction within the area.

METHODS

Study Area

Crawford Lake (43° 28' 06" N, 79° 56' 55" W), situated on dolomitic bedrock within the Crawford Lake Conservation Area in Milton, Ontario, features a maximum water depth of ~24 m, surface area of approximately 2.4 ha, and is at an elevation of 286 m above sea level. The deflection of wind from

nearby forests comprised of *Thuja*, *Betula*, *Ulmus*, *Quercus*, and *Pinus* (McAndrews & Boyko-Diakonow, 1989) and proximity to the Niagara Escarpment, as well as the general shape and depth of the lake, provides a sheltered environment conducive to creating a meromictic lake environment. This environment, with non-mixing bottom waters below a sharp chemocline at ~15 m water depth, reduces lake bottom bio-perturbation, allowing for seasonal varves to form within the lakebed sediments. Despite the general feature of meromictic lakes possessing a de-oxygenated monimolimnion, recent work by Heyde *et al.* (in revision) suggests the monimolimnion has observable quantities of dissolved oxygen within its waters, likely due to inflows of oxygenated groundwaters. Light-colored layers formed from precipitation of calcite during the Spring and Summer and dark, organic-rich layers are deposited during the fall and winter. The climate in the Halton region that encompasses Crawford Lake is humid continental, with average yearly temperature ~8.1°C and mean annual precipitation of ~1030mm between 1980 and 2018 (Hamilton, Ontario: Environment Canada, 2020). Previous research shows the lake to be alkaline, with higher specific conductance in the monimolimnion (Ekdahl *et al.*, 2007; Gushulak *et al.*, 2021).

Sample Collection

A two-faced freeze core was collected (CRW19-2FT-B2), 83 cm in length, using methods similar to the of Glew *et al.* (2001) in February of 2019 by Tim Patterson and associates, using ethanol and dry ice to freeze sediment along the length of a flat faced metal prism. The core was collected at a depth of ~24m, with sampling location shown in Figure 1, and transported frozen to Carleton University for subsequent processing and analysis. A scalpel was used to isolate and subsample adjacent light and dark bands varve couplets deposited each calendar year. Each varve-year was matched to the corresponding Gregorian year using the dating model developed by (Serack, 2020) (Figure 2). Sixty-one subsamples, corresponding to the years 1930 to 1990 CE were prepared for analysis of siliceous algae.

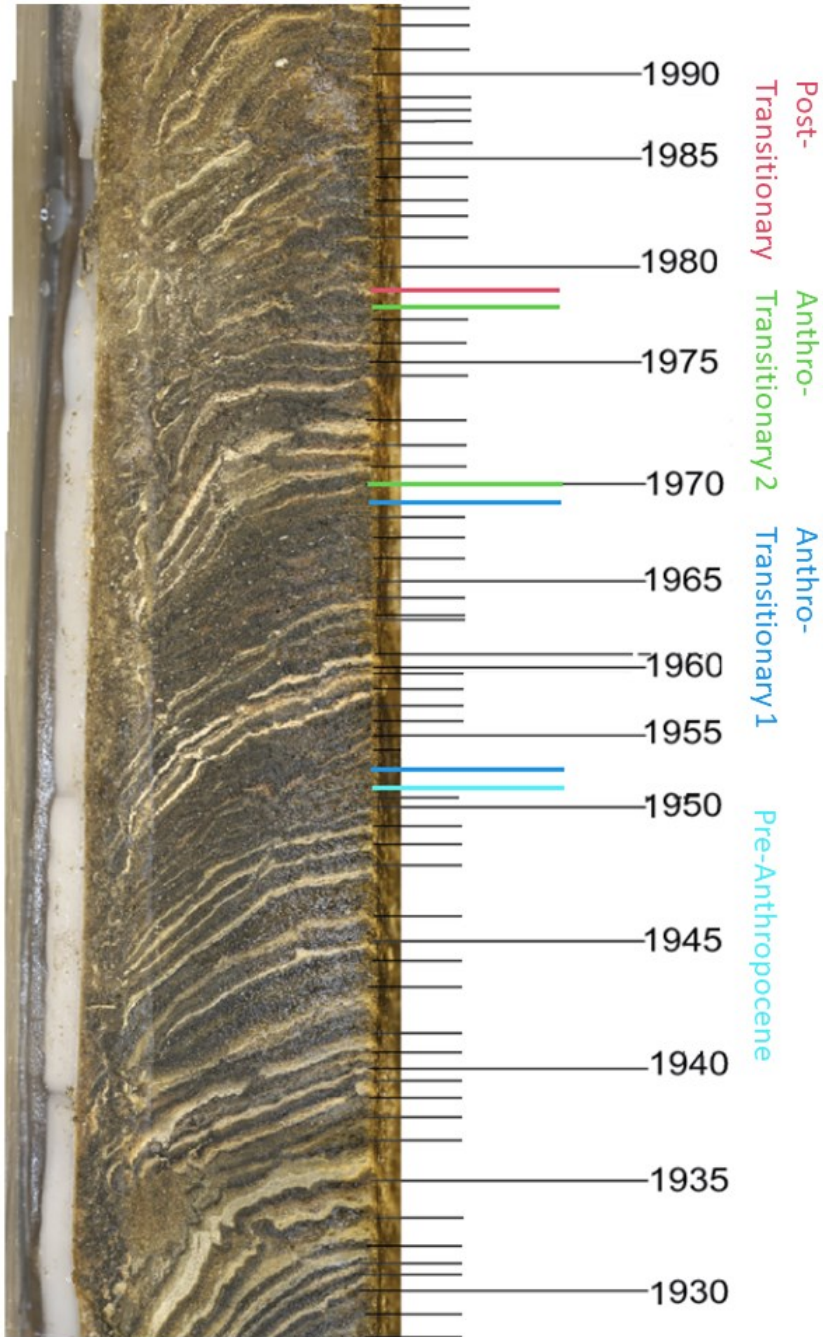


Figure 2: Studied core section. Significant stratigraphic zones are labelled, as well as boundaries of those zones; see Results for more information. Varve thickness and composition appears to vary with zone; Anthro-Transitional Zone 1, proposed to be the zone most impacted by acid deposition, appears to have the most concentration of dark organic matter relative to light (carbonate) bands.

Chrysophyte Analysis

Each subsample was processed for analysis of siliceous algae following a protocol similar to that described by Battarbee *et al.* (2001). For this methodology, ≤ 0.1 g of sample from each varve-identified year was treated with 10% HCl to remove carbonates, and then washed with distilled water numerous times (~10 washes) until the supernatant reached the pH of the distilled water, to reduce the concentration of dissolved calcium, and increase the pH of the samples. These samples were then treated with 30% H₂O₂ to remove organic matter from the samples, and subsequently were again put through a series of washes. These siliceous slurries were then plated in a series of dilutions onto coverslips and allowed to dry for ~12-18 hours on a warming tray before being affixed onto microscope slides using Cargille Meltmount™ 1.704. The slides were examined under an Olympus BX51 microscope at 1000x oil-immersion magnification, to identify chrysophyte scales to species level, with statistically significant populations of ~400 scales counted for each (Patterson & Fishbein, 1989) (Table 1). The identity of scales of certain species that did not present easily-observable, taxon-defining ornamentation under these standard light microscope conditions were verified using scanning electron microscopy. Previously prepared sample slurries were pipetted onto scanning electron microscope stubs topped with double-sided carbon tape and left to dry overnight. The samples were examined using a Tesca VegaII XMU scanning electron microscope using images created by both secondary electron and back-scattered electrons. Scales were identified using images and descriptions found within taxonomic literature (Siver, 1991). The chronology of examined samples was the varve-year inferred chronology established by Serack (2020) (Figure 2).

Statistical analysis

Scale abundance of the statistically significant taxa (Fishbein and Patterson, 1993; Patterson and Fishbein, 1989) were plotted using Tilia v. 2.0.2 (Grimm, 2004). A stratigraphically constrained cluster analysis (CONISS) was performed on scale relative abundance data. This analysis provides clusters based on an incremental sum of squares method and Euclidean distance, considering only stratigraphically

adjacent samples to better represent groups through the history of the sediment record (Grimm, 1987). Separate zones marked through CONISS were validated using a broken stick model using the *rioja* package (Juggins, 2020) within R studio (R Core Team, 2020). Non-metric multidimensional scaling (NMDS) was performed on square-root transformed species abundance data (n=61), using Bray-Curtis Dissimilarity as distance within R studio using the *vegan* package (Oksanen et al., 2020), to view assemblage and species data with reduced dimensions, and allow for visualization of data within a two-dimensional graphical interpretation; as such, the NMDS bi-plot allowed for reinforcement of results obtained from CONISS through visualization of the groups in a reduced dimensional space.

Species	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944
<i>Mallomonas pseudocoronata</i>	0.875	0.745	0.807	0.808	0.911	0.914	0.717	0.862	0.700	0.794	0.719	0.745	0.761	0.746	0.743
<i>Mallomonas tonsurata</i>	0.022	0.172	0.166	0.160	0.061	0.059	0.148	0.089	0.203	0.082	0.227	0.221	0.231	0.217	0.182
<i>Mallomonas striata</i> <i>var. serrata</i>	0.051	0.023	0.017	0.012	0.003	0.020	0.050	0.022	0.030	0.019	0.018	0.007	0.000	0.007	0.007
<i>Mallomonas acaroides</i> <i>var. acaroides</i>	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.002	0.000	0.000	0.005	0.010	0.000	0.000	0.000
<i>Synura curtispina</i>	0.022	0.003	0.005	0.012	0.010	0.005	0.032	0.010	0.018	0.051	0.005	0.005	0.002	0.017	0.030
<i>Synura echinulata</i>	0.017	0.053	0.005	0.005	0.016	0.000	0.045	0.010	0.050	0.044	0.018	0.005	0.002	0.012	0.005
<i>Synura petersenii</i>	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.005	0.005	0.007	0.002	0.000	0.030
<i>Mallomonas elongata</i>	0.012	0.003	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
<i>Synura spinosa</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<i>Synura uvella</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000
<i>Spiniferomonas</i> spp.	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.000
<i>Chryso-sphaerella</i> spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL COUNTS	415	396	404	401	313	409	378	406	400	413	392	412	415	401	401

Table 1.1: Relative scale abundance and total scale count data (1930-1944).

Species	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
<i>Mallomonas pseudocoronata</i>	0.676	0.751	0.645	0.448	0.581	0.915	0.900	0.771	0.521	0.466	0.181	0.531	0.500	0.610	0.488
<i>Mallomonas tonsurata</i>	0.152	0.205	0.282	0.071	0.085	0.022	0.054	0.093	0.156	0.233	0.080	0.103	0.104	0.093	0.080
<i>Mallomonas striata</i> <i>var. serrata</i>	0.012	0.002	0.011	0.007	0.000	0.000	0.005	0.020	0.031	0.037	0.213	0.088	0.032	0.002	0.012
<i>Mallomonas acaroides</i> <i>var. acaroides</i>	0.000	0.000	0.011	0.000	0.010	0.000	0.002	0.000	0.005	0.000	0.000	0.002	0.007	0.000	0.002
<i>Synura curtispina</i>	0.110	0.002	0.020	0.305	0.242	0.052	0.012	0.086	0.209	0.205	0.109	0.098	0.150	0.189	0.249
<i>Synura echinulata</i>	0.007	0.002	0.000	0.145	0.031	0.010	0.024	0.027	0.050	0.046	0.075	0.110	0.136	0.075	0.105
<i>Synura petersenii</i>	0.034	0.027	0.027	0.017	0.041	0.000	0.002	0.000	0.028	0.014	0.331	0.068	0.070	0.026	0.059
<i>Mallomonas elongata</i>	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.002
<i>Synura spinosa</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
<i>Synura uvella</i>	0.000	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000
<i>Spiniferomonas</i> spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000
<i>Chryso-sphaerella</i> spp.	0.000	0.010	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000
TOTAL COUNTS	408	414	440	406	413	401	410	407	422	438	414	409	412	428	410

Table 1.2: Relative scale abundance and total scale count data (1945-1959).

Species	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
<i>Mallomonas pseudocoronata</i>	0.366	0.215	0.179	0.391	0.623	0.544	0.493	0.273	0.336	0.551	0.157	0.082	0.160	0.798	0.603
<i>Mallomonas tonsurata</i>	0.083	0.110	0.055	0.077	0.035	0.059	0.067	0.032	0.063	0.060	0.017	0.019	0.100	0.058	0.062
<i>Mallomonas striata</i> var. <i>serrata</i>	0.044	0.020	0.025	0.011	0.002	0.002	0.002	0.005	0.002	0.019	0.002	0.002	0.017	0.007	0.002
<i>Mallomonas acaroides</i> var. <i>acaroides</i>	0.002	0.000	0.000	0.000	0.062	0.084	0.182	0.052	0.347	0.222	0.763	0.693	0.167	0.104	0.176
<i>Synura curtispina</i>	0.371	0.322	0.184	0.120	0.155	0.131	0.108	0.278	0.139	0.085	0.024	0.026	0.328	0.000	0.017
<i>Synura echinulata</i>	0.100	0.110	0.085	0.036	0.030	0.052	0.062	0.076	0.044	0.017	0.000	0.002	0.095	0.027	0.014
<i>Synura petersenii</i>	0.032	0.222	0.468	0.366	0.092	0.128	0.086	0.285	0.065	0.039	0.036	0.165	0.044	0.007	0.126
<i>Mallomonas elongata</i>	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.005	0.000	0.000	0.000
<i>Synura spinosa</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<i>Synura uvella</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.090	0.000	0.000
<i>Spiniferomonas</i> spp.	0.002	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<i>Chryso-sphaerella</i> spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.002	0.000	0.000	0.000
TOTAL COUNTS	410	410	402	366	401	406	406	407	432	414	413	417	412	415	421

Table 1.3: Relative scale abundance and total scale count data (1960-1974).

Species	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
<i>Mallomonas pseudocoronata</i>	0.665	0.304	0.541	0.603	0.218	0.101	0.156	0.108	0.077	0.043	0.079	0.038	0.043	0.100	0.110	0.126
<i>Mallomonas tonsurata</i>	0.019	0.049	0.054	0.031	0.063	0.065	0.053	0.059	0.048	0.053	0.061	0.029	0.031	0.100	0.088	0.049
<i>Mallomonas striata</i> var. <i>serrata</i>	0.000	0.005	0.007	0.017	0.051	0.077	0.089	0.111	0.061	0.085	0.042	0.036	0.012	0.040	0.017	0.015
<i>Mallomonas acaroides</i> var. <i>acaroides</i>	0.277	0.477	0.244	0.291	0.653	0.749	0.694	0.708	0.804	0.802	0.799	0.882	0.909	0.744	0.758	0.778
<i>Synura curtispina</i>	0.005	0.036	0.037	0.031	0.000	0.002	0.000	0.000	0.002	0.002	0.007	0.000	0.000	0.007	0.002	0.005
<i>Synura echinulate</i>	0.014	0.027	0.022	0.019	0.012	0.005	0.010	0.009	0.005	0.010	0.010	0.007	0.000	0.007	0.015	0.025
<i>Synura petersenii</i>	0.012	0.090	0.090	0.009	0.000	0.000	0.000	0.005	0.002	0.005	0.002	0.005	0.005	0.002	0.007	0.000
<i>Mallomonas elongata</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000
<i>Synura spinosa</i>	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<i>Synura uvella</i>	0.002	0.005	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.002
<i>Spiniferomonas</i> spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<i>Chryso-sphaerella</i> spp.	0.005	0.007	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TOTAL COUNTS	415	411	410	423	412	415	418	424	413	414	407	416	419	402	409	406

Table 1.4: Relative scale abundance and total scale count data (1975-1990)

RESULTS

Twelve scaled chrysophyte taxa were identified within the core taken for this study, of which five reached abundances of >20% in at least one sample (Table 1). The stratigraphically constrained CONISS cluster analysis resulted in recognition of four distinct paleoenvironmental units identified as the: Pre-Anthropocene Zone (1930-1952); Anthro-Transitional Zone 1 (1953-1969); Anthro-Transitional Zone 2 (1970-1978); and Post-Transitional Zone (1979-1990) (Figure 3). Based on Euclidean distance between zones in the CONISS analysis, the most distinctive group is the Post-Transitional Zone, with the second-largest degree break based on magnitude of distance being the upper boundary of the Pre-Anthropocene group.

The 1930-1952 Pre-Anthropocene Zone is characterized by the large proportion of *Mallomonas pseudocoronata* Prescott found within the zone with *Mallomonas tonsurata* Teiling being the second most dominant species of the interval. Combined, these two species generally provide more than 90% of the scales observed within this interval.

The Anthro-Transitional Zone 1, from 1953 to 1969 is defined by a large increase of *Synura* species, *Synura curtispina* Asmund, *Synura echinulata* Korshikov and *Synura petersenii* Korshikov, changing from <10% abundance in most years within the Pre-Anthropocene Zone to becoming the species present in highest abundance. This zone also has a reduced relative of abundance of *M. pseudocoronata*, which shows a general decreasing trend with time.

The Anthro-Transitional Zone 2 (1970-1978) has the lowest relative abundance of *Mallomonas striata* var. *serrata* Harris and Bradley, which is present in all zones, and is defined by the decrease of *Synura* species compared to the previous zone as well as the appearance of *Mallomonas acaroides* var. *acaroides* in appreciable quantities.

The Post-Transitional Zone, characterizing Crawford Lake from 1979 to 1990 has the lowest relative abundance of all taxa other than *M. acaroides* var. *acaroides* and *M. striata* var. *serrata* within all

zones; the *Synura* species make up less than 5% scale abundance through this time interval. This zone is comprised mostly of scales belonging to *M. acaroides* var. *acaroides*, which makes up greater than 70% scale abundance within this zone.

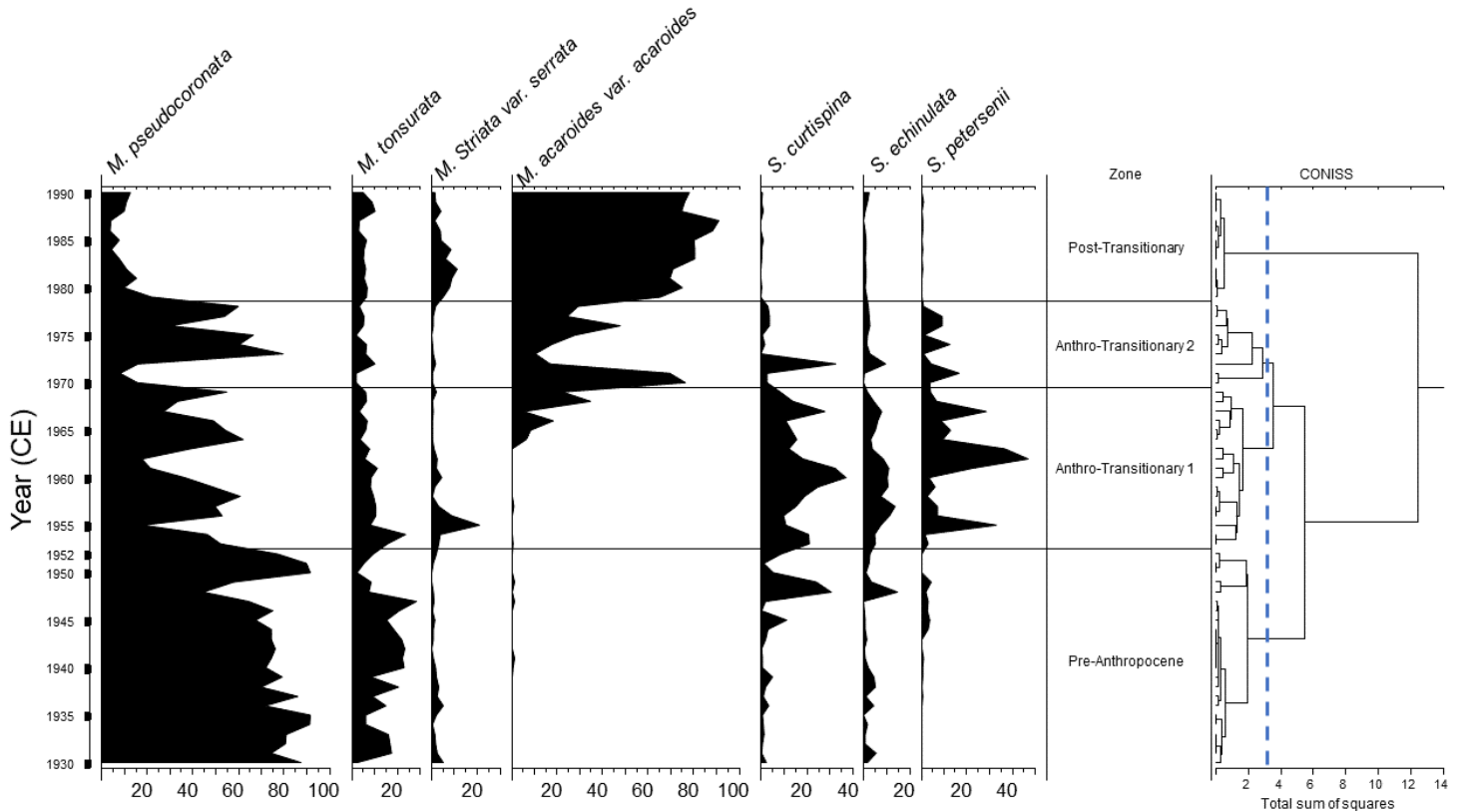
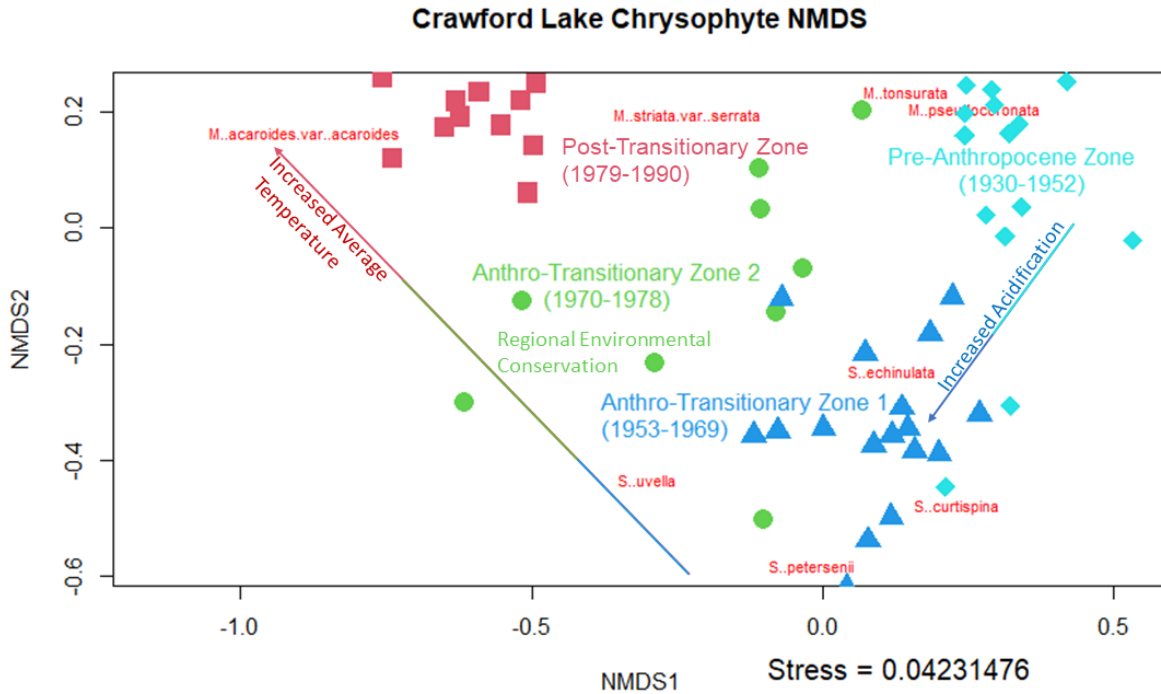


Figure 3: Stratigraphic diagram depicting the chrysophyte community of Crawford Lake from 1930-1990. Splits denoting zones, derived from the accompanying CONISS, are marked by horizontal lines occur with upper boundaries at 1952, 1969, and 1978. The vertical dashed line represents the division between clusters of samples with and without statistical significance.

Non-metric multidimensional scaling (NMDS) analysis shows that the assemblages belonging to the Post-Transitional Zone plotted in quadrant II, plot close to *Mallomonas acaroides* var. *acaroides*, also in quadrant II (Figure 4). The Anthro-Transitional Zones rank to quadrant IV, with Zone 1 ranking further along the positive x axis than Zone 2. The first Anthro-Transitional Zone plots within the same

area in space as *S. echinulata*, *S. petersenii*, *S. curtispina*, and *Synura uvella* Ehrenberg. The second of these zones plots between the first and the Post-Transitional Zone. The Pre-Anthropocene Zone ranks



generally in quadrant I, plotting near the *Mallomonas* species *tonsurata* and *pseudocoronata*.

Figure 4: NMDS plot of yearly assemblages and species. 1930-1952 assemblages appear as cyan diamonds, 1953-1969 assemblages appear as blue triangles, 1970-1978 assemblages are represented by green circles, 1979-1990 assemblages are represented as red squares. Model fit stress <0.045. Arrows represent general trends in assemblage evolution, with text describing believed causes.

DISCUSSION

General Description

Statistical analysis of the scaled chrysophyte population data within Crawford Lake showed three distinct paleoenvironmental shifts through the 1930-1990 interval that resulted in development of four distinct assemblages. Using high-resolution annual subsampling afforded by the unique annually deposited varves that characterize sedimentation in Crawford Lake, these significant paleoenvironmental

shifts were narrowed to precise year boundaries; 1952-1953, 1969-1970, and 1978-1979. The general trend in the chrysophyte communities within Crawford Lake is a shift from *M. pseudocoronata*, the most abundant *Mallomonas* species over the early to mid 1900's to *M. acaroides* as the most abundant species in the late 1900's, with colonial *Synura* species appearing with high scale abundance in the mid-twentieth century (Fig 3).

From the bottom boundary of the studied section of core spanning 1930 to 1952 (the Pre-Anthropocene Zone) the scaled chrysophyte community was comprised almost entirely of *M. pseudocoronata* and *M. tonsurata*. Both species have similar environmental preference ranges, including similar preferences for lake water conductivity (~120-190 μ S), temperature (~15°C), and total phosphorus (~23-33 μ g/L) within lacustrine systems as well as preferring alkaline waters, as found within Crawford Lake, situated on dolomitic limestone (Siver, 1991).

The basal boundary of the chrysophyte subgroup of assemblages found from 1953 to 1969 (Anthro-Transitional Zone 1), correlates well with the potential mid-twentieth century Anthropocene-Holocene boundary and is distinct from the previous zone by a large increase in the relative scale abundance of the *Synura* species; *S. echinulata*, *S. petersenii*, and *S. curtispina*. These species make up a large combined fraction of this zone's scale assemblages, and are generally known to be colony-forming species that bloom on or under the thermocline within lacustrine systems (Siver, 2003). Although these taxa generally bloom at deeper depths than other scaled chrysophyte species, they require light for photosynthetic activities. It is hypothesized that there was an increase in lake water clarity, a conjecture also supported by previous studies (e.g., Ekdahl *et al.*; (2004, 2007), which found an increase in benthic diatom taxa at this time. Benthic diatoms are commonly found within the littoral zones of lakes, generally attached to detritus, macrophytes, and lakebed substrates, while also still requiring enough light to maintain photosynthetic activity. This increase in both benthic diatom taxa, as well as *Synura* chrysophyte species which are generally found lower within the water column would be consistent with a decrease in light attenuation within the waters of Crawford Lake through that time interval. The increase of colonial

Synura species has been found to increase since pre-industrial times even in other areas considered minimally-disturbed (Mushet et al., 2018). These changes within minimally disturbed lakes may imply global changes to algal communities due to anthropogenic impacts.

The second Anthro-Transitional Zone, from through the 1970-1978 interval is defined by the appearance of *M. acaroides* var. *acaroides* in appreciable quantities, a decrease in the overall relative abundance of *Synura* taxa within the lake and has the lowest abundance of *M. striata* var. *serrata* within the studied core section. The decrease in abundance of *Synura* species compared to the abundance of *Mallomonas* species suggests a shift in water clarity to more turbid waters that were common earlier within the history of Crawford Lake.

The Post-Transitional Zone, spanning from 1979 until the upper horizon of the sampled section of the core in 1990, shows *M. acaroides* var. *acaroides* as the most abundant scaled chrysophyte taxon in general within this time period, having replaced *M. pseudocoronata* as the most abundant *Mallomonas* taxon. Both *Mallomonas* species that were present in the highest relative abundance within the core, *M. pseudocoronata* and *M. acaroides* var. *acaroides* are believed to have similar environmental preferences and optima, however *M. acaroides* var. *acaroides* has been described as preferring waters more alkaline than even *M. pseudocoronata* prefers (Siver, 1991). With the greatly diminished abundance of *Synura* taxa within this period, it is believed that these waters were less clear than the waters even in the 1930's.

Major Changes

The two largest magnitude changes between assemblage zones, based on the CONISS results occurred in 1952 and 1978. The 1952 shift is coincident with the proposed Anthropocene Epoch lower boundary, and the 1978 shift occurred after chrysophyte community transitions, which may be related to changes made to the catchment following the acquisition of Crawford Lake by Conservation Halton in 1970 to form the Crawford Lake Conservation Area, as well as a reduction in airborne industrial emissions within both Canada and the United States following the introduction of more stringent

environmental regulations in the 1970's. The probable main driver of the 1952 assemblage shift to favouring *Synura* species was an increase in water clarity, related to increased acid deposition from increased post-WWII industrialization, including the increased mining and ore smelting within the general region as well as increased human settlement, urban expansion, and increased motor vehicle usage and ownership (Steffen et al., 2011). The resultant lake water acidification was one of the major anthropogenic impacts on aquatic environments and a facet of the rapidly-increased human consumption that the Great Acceleration entails. The 1978 shift is hypothesized to have been caused by the opposite effect. The lake waters became less clear due to a significant reduction in acid deposition within the region caused primarily by emissions legislation changes, as well as the acquisition of the Crawford Lake area into lands protected by Conservation Halton (Meyer-Jacob et al., 2020, 2019; National Air Pollution Surveillance Program, 2020).

Although Crawford Lake is a highly-buffered system, overlaying a dolomitic limestone basement, it may be the acidification impacts on the soils within the catchment of Crawford Lake that caused the changes to the water clarity of Crawford Lake. Acidification impacts on the catchment may have resulted in the binding of compounds, such as humic compounds, which would normally contribute to the dissolved organic carbon (DOC) of nearby lacustrine systems (Hruška et al., 2009; Monteith et al., 2007). The peak of acid deposition within this region had occurred by 1970 and was due primarily to large emissions of sulphur and nitrogen oxides from industrial emitters both locally in Ontario and from upwind sources in the industrial heartland of the US (National Air Pollution Surveillance Program, 2020). Other studies have found similar trends in *Synura* species abundance related to DOC content within the water column (Hadley, 2012). The recovery from this period of clear water termed by some as “water re-browning”, has been reported from many other well-buffered, as well as chronically acidic lakes, that suffered from similar anthropogenic acid impacts (Meyer-Jacob et al., 2020, 2019). During this same interval when anthropogenic acid deposition impacted the lake, reforestation was also occurring in the

immediate area of Crawford Lake, which may have contributed to the increase of water-clarity through reduction in erosion and sediment export into the nearby waters (Keller and Fox, 2019).

The large chrysophyte assemblage shift that occurred in 1978 coincides with the re-emergence of *Mallomonas* species in high abundances. Although this change was most likely primarily brought about by water re-browning after recovery from acid impacts, it may also have been partly driven by Crawford Lake's incorporation into the Crawford Lake Conservation Area, or in part to climate change as the region has experienced increasing average annual temperatures over the past ~150 years. For example, replacement of *M. pseudocoronata* with *M. acaroides* var. *acaroides* has been observed in northern Saskatchewan lakes that have been impacted by climate warming (Mushet et al., 2017). Other changes in water chemistry, such as an increase in $p\text{CO}_2$, have also been shown to impact chrysophyte communities which lack carbon-concentrating molecules such as RuBisCO (Wolfe and Siver, 2013). The large-scale and ever-increasing concentrations of atmospheric CO_2 related to massive industrial expansion throughout the world during the Great Acceleration provides another possible anthropogenic impact on the Chrysophyte community. The combination of climate change and water chemistry shifts potentially brought about by anthropogenic impacts suggests the preserved communities within the sediments of Crawford Lake are representative of global industrialization trends as well as the associated anthropogenic impacts on the global environment. The apparent impacts, as well as the abruptness and magnitude of change between the groups above and below this boundary may be enhanced due to the greatly increased local human impacts in the form of increased visitors and construction in the area, as was also discussed by Gushulak *et al.* (2021) and Rybak and Dickman (1988)

CONCLUSIONS

The varved sediments of Crawford Lake have been used to identify changes within the contained scaled chrysophyte algal community at a highly precise annual resolution, with CONISS and NMDS identifying four distinct zones within the sedimentary record: the Pre-Anthropocene Zone (1930-1952); Anthro-Transitionary Zone 1 (1953-1969); Anthro-Transitionary Zone 2 (1970-1978); and the Post-

Transitional Zone (1979-1990). The main changes observed within this system is the increase, within Anthro-Transitional Zone 1, and decrease, within Anthro-Transitional Zone 2, in abundance of colonial *Synura* taxa, as well as the eventual replacement of *M. pseudocoronata*, the most abundant scale-bearing species within the Pre-Anthropocene Zone before 1952 with *M. acaroides* var. *acaroides*. Of these changes, the appearance of novel, *Synura*-dominated assemblages, was coincident with the proposed Holocene-Anthropocene boundary. This change, despite being observed within a highly-buffered lake system, is believed to be caused by acid impacts resultant from increased anthropogenic emissions of the Great Acceleration. Furthermore, the scaled chrysophyte paleoecological record of Crawford Lake appears to track multiple anthropogenic stressors associated with the Great Acceleration and the Anthropocene such as environmental acidification, climate change, and potentially increased CO₂ emissions. The clear record of anthropogenic impacts associated with the Great Acceleration recorded by the scaled chrysophyte community, in tandem with other indicators of the Great Acceleration and Anthropocene such as ²³⁹Pu isotope analysis, and proxies such as spheroidal carbonate particles that can be observed at annual resolution within the varved sediments of Crawford Lake present these sediments as a strong candidate for the Holocene-Anthropocene boundary and a suitable record of human-industrial impact on the environment (Waters et al., 2018; Head, 2019).

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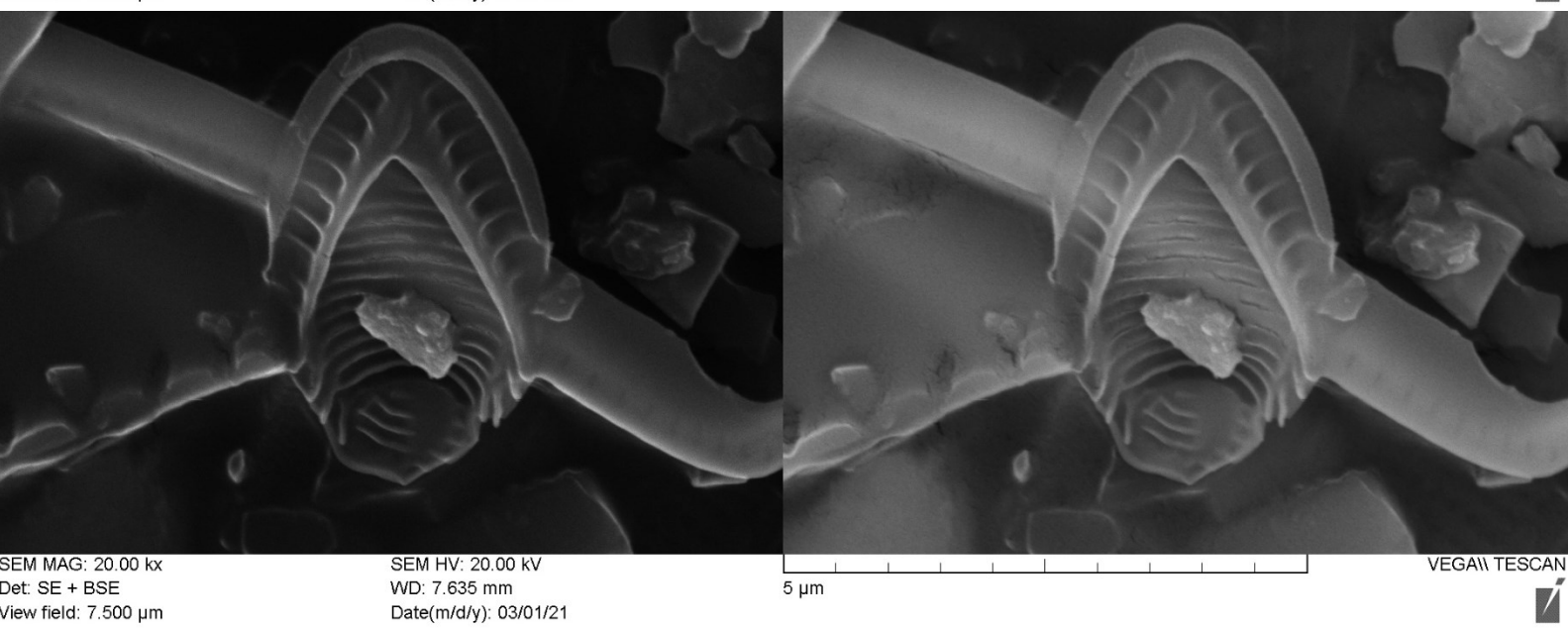
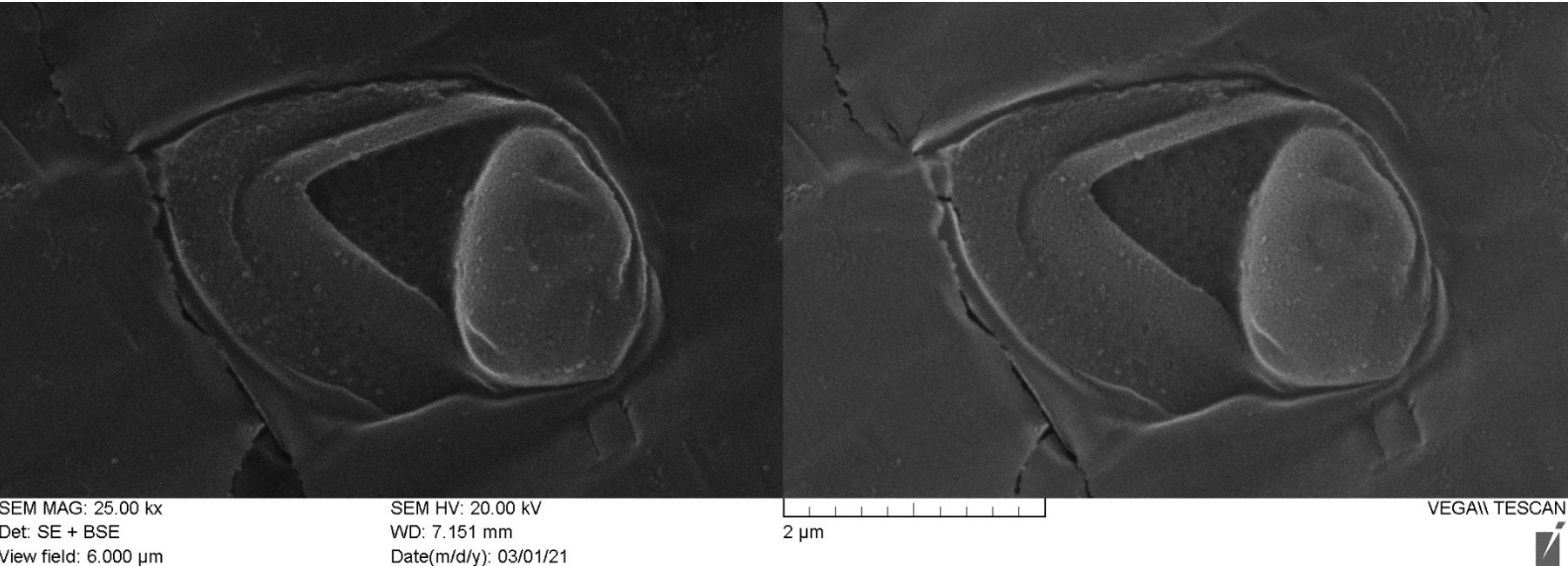
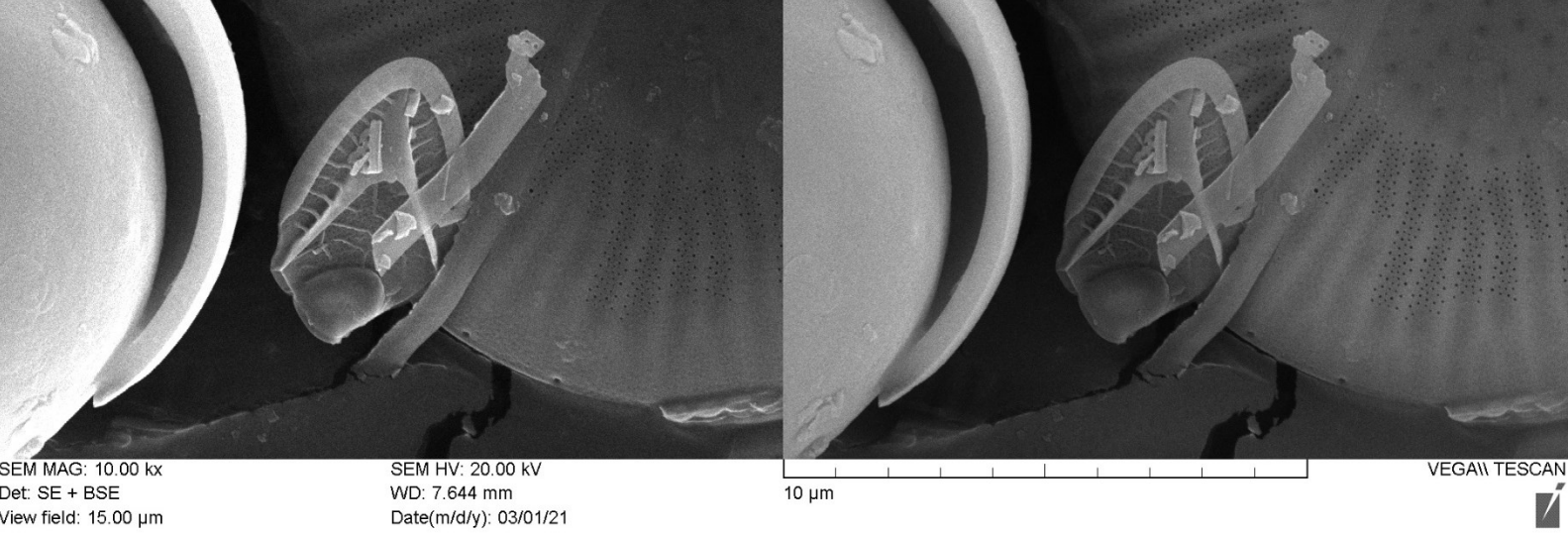
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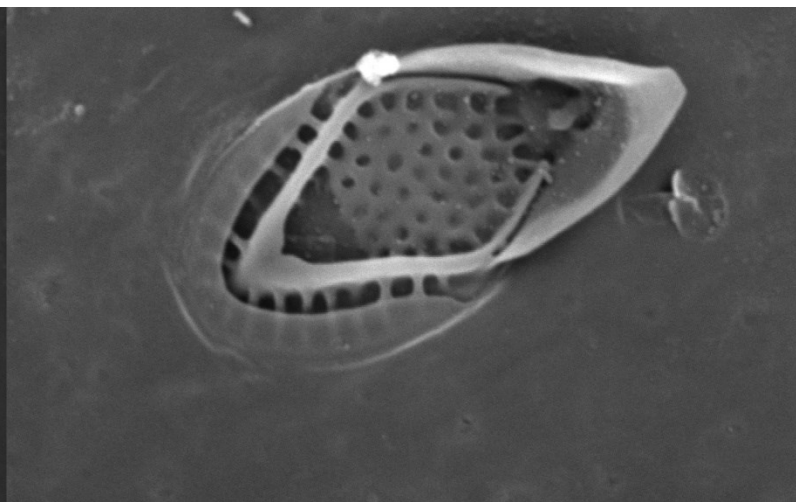
Appendix 1: Representative Scale Micrographs





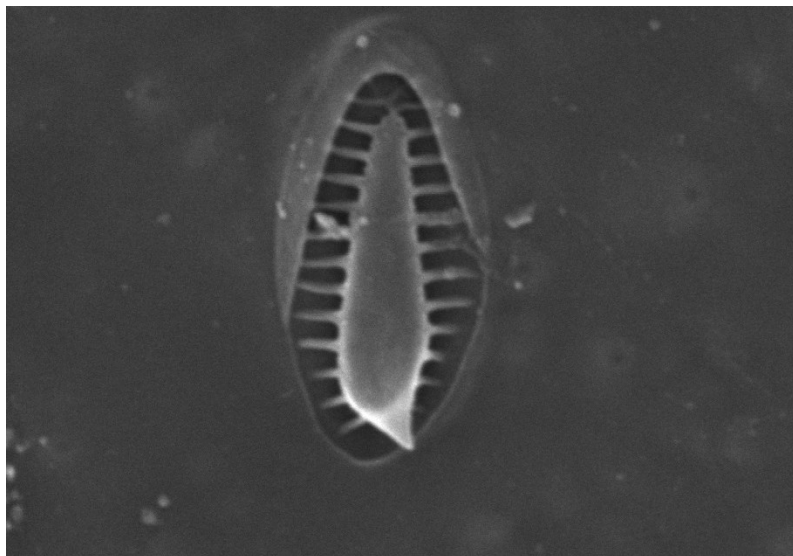
SEM MAG: 10.00 kx
 Det: SE + BSE
 View field: 15.00 µm

SEM HV: 20.00 kV
 WD: 11.66 mm
 Date(m/d/y): 03/01/21



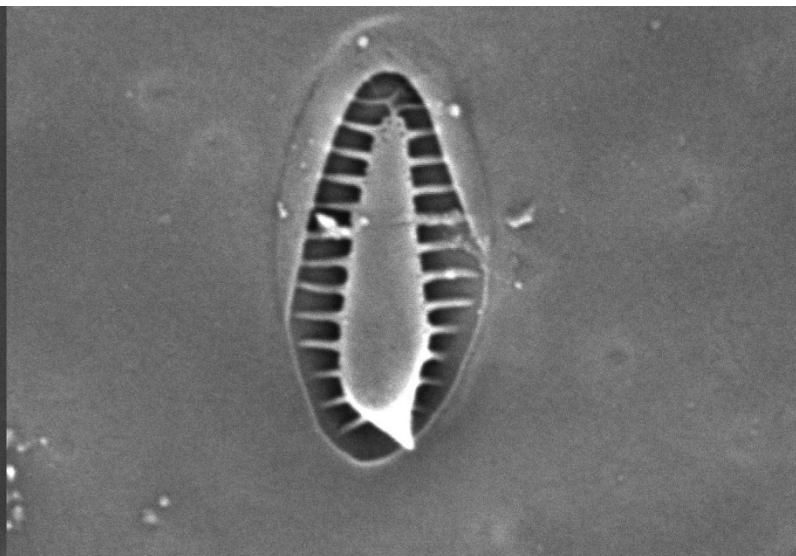
10 µm

VEGA\ TESCAN



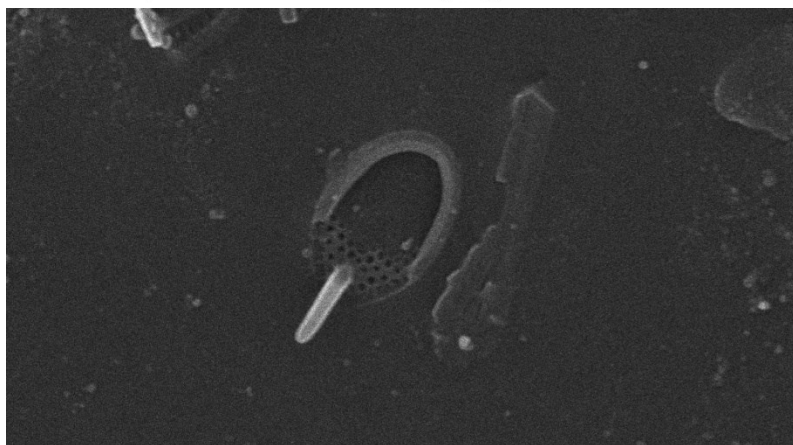
SEM MAG: 20.00 kx
 Det: SE + BSE
 View field: 7.500 µm

SEM HV: 20.00 kV
 WD: 7.102 mm
 Date(m/d/y): 03/01/21



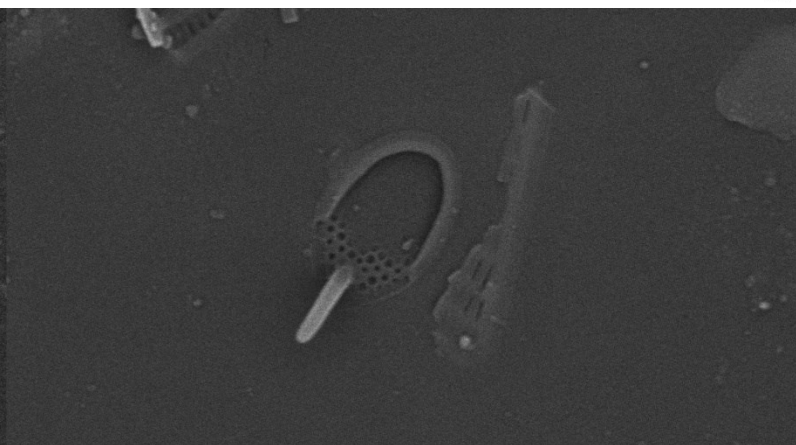
5 µm

VEGA\ TESCAN



SEM MAG: 10.00 kx
 Det: SE + BSE
 View field: 15.00 µm

SEM HV: 20.00 kV
 WD: 7.150 mm
 Date(m/d/y): 03/01/21



10 µm

VEGA\ TESCAN



Above: 1 – *Mallomonas acaroides* var. *acaroides*, 2 – *Mallomonas tonsurata*, 3 – *Mallomonas striata* var. *serrata*, 4 – *Mallomonas pseudocoronata*, 5 – *Synura petersenii*, 6 – *Synura curtisipina*