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Preliminary interpretation of fossil pigment record from Crystal Lake, SK

This brief report outlines the main trends observed in the sediment record of fossil pigments, as well as a suite of geochemical indicators. These pigments provide the main colours seen in all plants (including aquatic ones) and are deposited in the lake sediments in proportion to the abundance of the algae and cyanobacteria (aka phototrophs) in the water column. The geochemical indicators tell us about the sources of two main elements, carbon (C) and nitrogen (N), which in turn are often related to changes in lake production and carbon sources (C), as well as nutrient inputs and N sources (N).

In general, the interpretation of the pigment record is reasonably straightforward – more fossil pigment means there was more algae in the lake. However, there are some instances where the interpretation is more complicated, such as changes in the fossil record due to pigment breakdown after burial, or changes in the location of the algae in the water column (here, deeper populations tend to be collected in the sediments better than populations near the lake surface). Fortunately, we have a "preservation index" which is a ratio of a very common pigment (chlorophyll a – the green you see in the world) to its degradation product (pheophytin a). If the preservation index is changing a lot, we need to be cautious about interpretation of the fossil record.

Interpretation of the elemental and stable isotope data (C, N) is more complex. In general, changes in proportions of C and N (as % dry mass) track the overall productivity of the lake; however, in some instances, changes in the input of organic and inorganic C can affect %C separate from changes in lake production. Similarly, changes in the deepwater oxygen content can aid in C and N (and pigment) preservation (thereby increasing %C, etc.). Finally, in some cases, organic matter content can change due to variation in wetland abundance, either within a lake or in its associated water sources.

In general, the ratio of C:N tells us about the source of elements, with aquatic organic matter (from algae and cyanobacteria) having a lower ratio (8-12) than terrestrial organic matter (20-35), although the input of carbonates (inorganic C) can increase the C:N ratio well beyond these values (>30 to 100s). Alternately, inputs of dissolved organic matter (DOM) from bog plants can exhibit abnormally low C:N (< 6). Stable isotopes of C ($\delta^{13}C$) vary in response to the main C source to the lake, with inorganic material (CO_2, or carbonates) having relatively high values (0 to -10‰) while terrestrial organic matter is intermediate (-20‰) and algae-rich organic matter from within the lake being even lower (-25‰ to -60‰), depending on whether the C is from respirated (recycled) CO_2 (-25‰ to -30‰) or methane (-35‰ to -60‰). Further, DOM from bog system can exhibit relatively low $\delta^{13}C$ (~ - 25‰).

At present, we are still awaiting estimates of sediment age from Flett Industries in Winnipeg. Consequently, we have presented the historical changes in terms of sediment depth (cm), with the deeper material being older than the shallow material. This burial depth refers to the depth of the layer of sediments below the sediment-water interface (i.e., the bottom of the lake). As a result, we can only make very approximate estimates as to the timing of the changes seen in the sediment record. We will update these dates when we get the age estimates over the coming months.

Fossil pigments

Overall, analysis of the sediment record suggests that there has been some increase in the primary production of Crystal Lake, with most of the changes likely associated with land-use changes in the catchment immediately adjacent to the lake that affect the inputs of nutrients or organic matter (see appended Fig. 1).

In particular, there is evidence of an approximate doubling in abundance of several groups of algae, at a depth of about 30 cm in the core, resulting in a marked changed in the total production of primary producers (panels H, I in Fig. 1). In most southern Saskatchewan grassland lakes, this would normally correspond to the onset of intensive agriculture in the catchment of the lake (ca. 1930s) or a profound change in cottage density adjacent to the lake. In more boreal locations, increased production might correspond to the advent of deforestation, particularly if tree removal were permanent, or a change in the optical environment due to wetlands drainage.

Historical changes are greatest for chemically-stable pigments from cryptophytes (often a spring group; panel C) and chlorophytes (aka green algae, including *Chara*; D), with less marked changes in diatoms (spring taxa; B), total cyanobacteria (summer taxa; F), and colonial (Nostocales) cyanobacteria (summer taxa; G). In general cryptophytes and chlorophytes do well in spring conditions (low light) or in moderately-stained waters (also lower light).

Although chemically-unstable (labile) markers of siliceous algae (diatoms, chrysophytes, some dinoflagellates) and total phototrophs (chlorophyll a; J) show a marked increase in the uppermost 5-10 cm of the sediments (material deposited in past 10-30 yr), these changes also correspond to changes in the preservation environment (panel L) suggesting that the recent changes in sedimentary pigment content arises from degradation of unstable compounds once they have been buried in the mud. Consistent with this interpretation, we see no evidence of recent increases in algae or cyanobacteria in individual biomarkers, or in the chemically-stable metrics of total primary production (H, I). Further, as a result of potential post-depositional changes, we urge caution in interpreting the elevated concentrations of most pigments in the uppermost sediments (1 cm, ~1-2 yr).

The irregular presence of low-levels of the pigment from purple sulfur bacteria (okenone; panel K) is consistent with generally low oxygen levels in the deepest water of Crystal Lake. That said, the concentrations of okenone are very low relative to those seen in other lakes that are either permanently stratified, or which have very limited oxygen in deeper waters. Purple sulfur bacteria are photosynthetic and require the presence of both light and hydrogen sulfide (H_2S), a chemical produced during organic matter degradation. Sulfur bacteria are killed by oxygen, so only occur in anoxic (no oxygen) environments. When an anoxic layer is illuminated, we often see very high levels of okenone due to purple sulfur bacteria. In the case of Crystal Lake, the low concentrations (and high associated variability among samples) suggest that there are relatively few times when conditions are optimal for sulfur bacteria. By this, we infer either that the deep waters were not perpetually anoxic, or that light rarely penetrated to anoxic habitats (deep waters, sediments).

Patterns of geochemical change are complex and do not provide an unambiguous interpretation as to the causes of historical changes in Crystal Lake. Overall, C:N ratios (panel Q) are relatively stable, exhibiting a narrow range from 10:1 to 12:1 (by mass). These values are characteristic of organic material derived from algae or cyanobacteria, or DOM from bogs (6-12), rather than terrestrial organic matter (20-25), or the elevated influx of carbonates to the sediments (values >30-100s).

Normally, increases in lake production are recorded by both an increase in pigment concentration and an increase the %C (panel M) and %N (O) content of the sediments. However, in the case of Crystal Lake, Sediment analysis suggests that organic matter deposition was actually greater in deeper (older) sediments than in shallow (younger) sediments, with higher %C and %N below 30-35 cm. These patterns suggest overall higher lake production earlier in the historical record, a pattern opposite to that recorded by pigments.

Consistent with this interpretation, analysis of C stable isotopes ($\delta^{13}C$; panel N) confirms that values are characteristic of elevated production in the older time periods (below ca. 30 cm). Normally in prairie lakes, an increase in primary producer abundance results in a decline in $\delta^{13}C$ due to an increased photosynthetic use of respired CO_2 ($\delta^{13}C$ of respired CO_2 is -25 to -30‰) rather than atmospheric CO_2 ($\delta^{13}C$ of atmospheric CO_2 is -5 to -10‰). To date, all lake analyzed in the Canadian Prairies have shown that increased primary production has been marked by elevated C content (%C) *and* declines in $\delta^{13}C$ values. However, at present, we believe that Crystal Lake may represent a different lake type, one highly influenced by lakeshore or upstream bogs (see below).

Historical variation in N stable isotope values ($\delta^{15}N$; panel P) suggest a substantial change in N sources over the period of time encompassed by the Crystal Lake sediment core (likely ~150 yr). Below 30 cm burial depth, $\delta^{15}N$ values are usually near 0‰. These values are similar to those associated with sources of atmospheric N (i.e., fixed N; also ~0‰), either from N_2-fixing cyanobacteria within the lake or from terrestrial vegetation (alder, juniper, bog plants, etc.). Given the relatively low abundance of potentially N_2-fixing cyanobacteria deep in the cores (canthaxanthin; panel G), we feel that a terrestrial or bog source is most likely.

$\delta^{15}N$ values increased to 2-3‰ in sediments shallower than 30-35 cm, and remained stable until the uppermost 10 cm, after which they drop ~1‰. In other agriculturally-impacted regions, the increase in $\delta^{15}N$ is associated with increased N influx to the lake, often from farm fertilizers or other major changes in source of N to the lake (e.g., septic systems). While increased farm fertilizer may underlie the increase in $\delta^{15}N$ in the upper half of the Crystal Lake core, it is also worth noting that much higher values of $\delta^{15}N$ were also recorded deep in the core (ca. 55-60 cm burial depth), during an era that likely precedes the onset of regional farming or fertilizer application. Given the high negative correlation between %N and $\delta^{15}N$ ($R^2 = 0.43$), we infer that a common mechanism is altering both N content and source.

Presently, we favour a hypothesis that historical changes in land use have altered the input or production of dissolved organic matter (DOM) by mosses or other bog-associated plants and that these events in turn have affected the water clarity, chemistry, and production of Crystal Lake. Analysis of satellite images shows the presence of bog-like ecosystems in the areas north and west of the lake. It is possible that similar bogs may have surrounded the shoreline of Crystal Lake or that, in the past, water from upstream bogs contributed substantially to the lake inflow. Normally, bogs have a high proportion of mosses (typically *Sphagnum* spp.) that produce a highly coloured (brown) organic acid material (DOM) that greatly restricts light penetration into the lake. This low-light environment reduces primary production by algae and cyanobacteria, and selects for algae that can withstand low light, high DOM environments (cryptophytes, chlorophytes, some cyanobacteria). However, the high concentrations of DOM also precipitate and sink to the lake bottom, resulting in highly organic sediment (high C, high N) with a relatively low C:N ratio. Thus, high historical inputs of DOM would explain the relatively low primary production by algae, yet the high %C and %N in contemporaneous sediments.

If these bogs sources of DOM were removed or diverted, the lake would become clearer and more hospitable to algae and cyanobacteria, resulting in higher deposition of pigments from primary producers, but potentially lower overall organic matter content of sediments (less DOM precipitated). Further, plant growth in bogs is often highly limited by the supply of N, therefore bogs often have numerous N_2-fixing plants. Leachate from these N_2-fixing plants would produce the low $\delta^{15}N$ values recorded deep in the core (~0‰), but when bogs were lost, the $\delta^{15}N$ values would rise rapidly to values characteristic of drier land habitats. Essentially, this is the pattern seen in Crystal Lake.

Taken together, it appears that the loss of historical bogs from the catchment of Crystal Lake may have changed in the optical and chemical environment of the water, leading to many of the changes observed in the cores (increased algal production, lower organic matter sedimentation, change in N source). However, further historical (land use) and hydrological research will be required to confirm these hypotheses. In particular, analysis of aerial photographs and historical drainage patterns could reveal the extent to which regional bogs have been drained, and their potential effect on Crystal Lake. Similarly, analysis of census data for the region could provide information on the historical changes in farm fertilizer application, as well as the rates of development of cottaging.

Bottomline

Crystal Lake appears to have become moderately more productive over the course of the time represented by the sediment core (ca. 150 yrs). Overall, production of the lake increased relative to background levels probably in the early-to-mid 20th-century (ca. 30 cm depth) when cryptopytes (C) and green algae (D) increased. In general, there is limited evidence for sudden changes in lake status during the past 1-3 decades (0 to 10 cm depth) with relatively stable concentrations of chemically-robust biomarkers of total production (H, I). At present, it appears that these historical changes are most consistent with alterations in land use that may have both mobilized nutrient inputs to the lake from agriculture or cottaging and/or altered the inputs of dissolved organic matter from bog-associated plants. At present, it is not possible to make a definitive distinction between these mechanisms (and both may occur), although we note that changes in bog abundance are likely to produce geochemical patterns more consistent with those seen in the sediments of Crystal Lake.

Once we have the estimates of sediment age, we will replot the data according to age. Such a chronological presentation will provide insights as to the timing of past changes and may help identify the relative importance of farming, cottaging, and bog drainage as causes of the observed changes.

Please let us know if you have any questions.

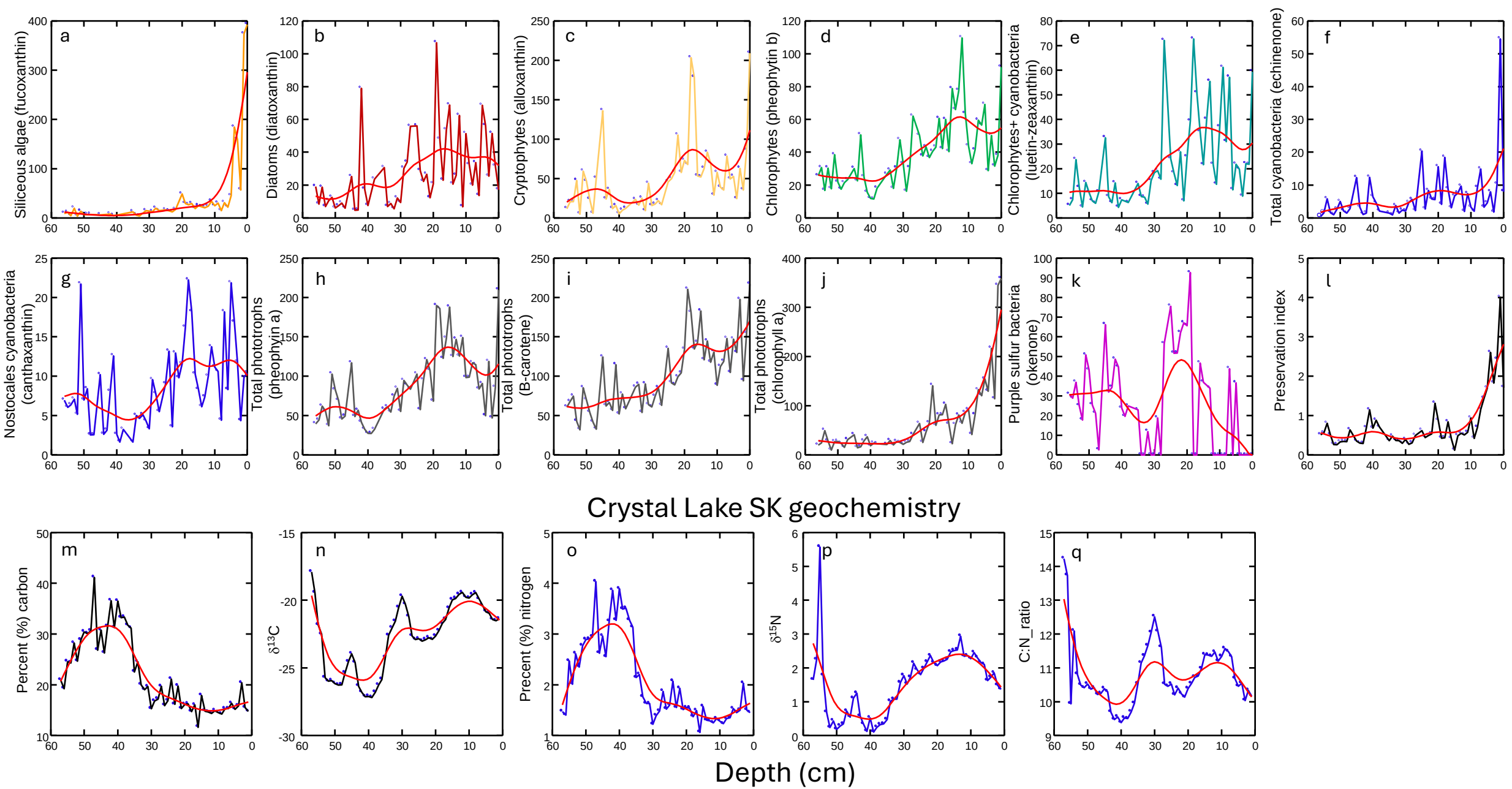
Cheers

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Crystal Lake SK fossil pigments
a
Siliceous algae (fucoxanthin)
b
Diatoms (diatoxanthin)
c
Cryptophytes (alloxanthin)
d
Chlorophytes (pheophytin b)
e
Chlorophytes+ cyanobacteria (luetin-zeaxanthin)
f
Total cyanobacteria (echinenone)
g
Nostocales cyanobacteria (canthaxanthin)
h
Total phototrophs (pheophyin a)
i
Total phototrophs (B-carotene)
j
Total phototrophs (chlorophyll a)
k
Purple sulfur bacteria (okenone)
l
Preservation index
Crystal Lake SK geochemistry
m
Percent (%) carbon
n
δ13C
o
Precent (%) nitrogen
p
δ15N
q
C:N_ratio
Depth (cm)