Chrysophycean cysts: indicators of eutrophication in the recent sediments of Frains Lake, Michigan, U.S.A.

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Abstract

The recent sediments of Frains Lake, Michigan contain a rich and well preserved association of chrysophycean cysts. Forty one forms are revealed by scanning electron microscopy (SEM) and light microscopy (LM). Taxonomic descriptions and SEM micrographs are provided for the dominant forms. The three dominant taxa throughout the sediments, *Cysta minima, C. modica* and *C. subbavaricum*, do not show significant shifts in proportional abundance associated with European settlement and the onset of cultural eutrophication. However, certain subdominant taxa do show clear trends. Density counts indicate a dramatic decline in cyst concentration (by volume and by dry mass) and a sharp increase in absolute accumulation (net annual influx) following settlement.

The Frains Lake profile of chrysophycean cysts is compared to sequences of other North American and European temperate lakes. The utility of chrysophycean cysts as paleoenvironmental indicators is considered on the basis of these results.

Introduction

Chrysophycean flagellates (Division Chrysophycophyta) are an important component of the phytoplankton in a wide range of lacustrine systems. Their siliceous fossil remains are often abundant and well preserved in lake sediments. Chrysophycean algae deposit two types of fossils: vegetative scales, and cysts (statospores) which may be produced asexually or sexually (Sandgren 1981). Scales have been used increasingly for paleolimnological study (Battarbee *et al.* 1980; Cronberg 1980; Munch 1980; Smol 1980; Tippett 1964). Despite the abundance of cysts in many lake sediments, they have been severely under-utilized as paleoecological indicators. This stems in part from the difficulty of determining which species produce the preserved cysts, and in part from the lack of a complete morphological taxonomy of fossilized cysts. However, the need to develop the use of cysts in paleolimnological work has been cited repeatedly (e.g., Nygaard 1956; Leventhal 1970; Adam 1980).

Chrysophycean cysts are abundant throughout the Holocene sediments of Frains Lake, Michigan. Recent historical changes in the trophic status of the lake are well documented and clearly reflected by sediment geochemistry (Davis 1976) and by microfossil flora and fauna (Kerfoot 1974; Carney 1982). Thus, the Frains Lake fossil material should be particularly appropriate for assessing the utility of chrysophycean cysts as paleolimnological indicators. The purpose of this paper is to: 1) provide SEM photographs and descriptions of the major cyst forms of Frains Lake, 2) correlate cyst stratigraphy with the known shifts in trophic status of the lake, and 3) compare the Frains Lake cyst sequence with profiles from other temperate lakes.

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Study site

Frains Lake (42°20'N, 83°37'W) is located approximately 19 km northeast of Ann Arbor, Michigan. It is a small (6.6 ha, 200 m wide by 500 m long) temperate dimictic lake which has become highly eutrophic (Davis 1976; LaZerte 1978). The single symmetrical basin reaches a maximum depth of 10 m (Fig. 1). The watershed is 18.4 ha in area (Davis 1976) and there are no direct inflowing streams. Water enters the lake as rain and runoff from the surrounding slopes. One outlet drains from the north side periodically.

The history of native Indian and European settlement in the Frains Lake watershed has been described in detail elsewhere (Carney 1982). The most important point is that *ca.* 1830 land in the region was extensively cleared for farming by European settlers and has been cultivated continuously since then (Davis *et al.* 1971). In the 1930s a pig farm was established directly south of Frains Lake.

Materials and methods

A 10-m core was recovered from the center of the lake on 23 May, 1980. Samples to be used for counting were placed in 100 ml beakers containing a 1:9 solution of concentrated sulfuric acid and nitric acid. Diatom frustules and chrysophycean cysts were cleaned according to the method described by Patrick & Reimer (1966). Procedures for other sediment analyses and core dating are detailed in Carney (1982). Specimens were identified and enumerated at 950× with a Leitz Ortholux microscope (N.A. = 1.32). For chrysophycean cyst identification primary references were Nygaard (1956), Leventhal (1970), Huber-Pestalozzi (1941) and Gritten (1977). Density counts (one per level) were obtained by enumerating all diatoms and chrysophycean cysts within exactly one half the total area of the cover glass. Proportional counts (three per level) were made by taking a horizontal transect across the center of the slide until 500 diatom valves (and all chrysophycean cysts in the same fields) were identified.

For SEM examinations, the same acid-cleaned samples from sediment depths of 90, 200, 405, 435, 525 and 620 cm were used. A series of serial dilutions from each sample was air-dried onto glass surfaces epoxied to aluminum stubs and coated with gold in a Hummer Junior sputter coater (Technics). Cysts were examined and photographed at an accelerating voltage of 25 kV with a JEOL model JSM-35C scanning electron microscope at the Biology Department of the University of Texas at Arlington. Although all the above-listed sediment samples were examined for cyst morphotypes, almost all photography was done on pre-settlement material (525 and 620 cm) that was largely free of inorganic debris. The cysts pictured here are representative of the morphology of those form-species throughout the sediment core.

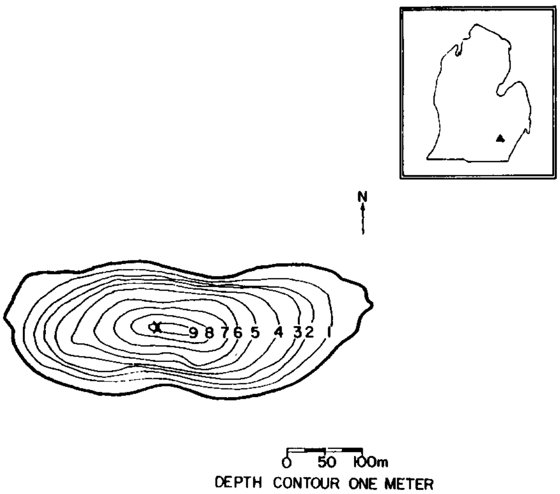


Fig. 1. Frains Lake, with depth contours (in meters). The × indicates where the core for this study was taken. Inset: lower peninsula of Michigan. The triangle marks the location of Frains Lake.

Results and discussion

Morphology of dominant cysts

A careful scanning electron microscope examination of the Frains Lake sediments has resulted in the identification of 41 distinct cyst morphotypes. Some of these correspond to previously defined form-species (Nygaard 1956; Leventhal 1970; Gritten 1977), but many represent new types. In keeping with the primarily stratigraphic emphasis of this paper, only the dominant morphotypes that figure prominently in the stratigraphic analysis are illustrated here. These SEM micrographs serve to remove any future ambiguity when comparing the Frains Lake stratigraphy to that of other lakes. *Cysta teres, C. subastroidea* and *C. microcarpa* are not illustrated here because they conform quite well to Nygaard's (1956) descriptions. A complete paleocyst flora of Frains Lake will be published separately (Sandgren & Carney, in prep.) after we complete an SEM investigation of the Lake Gribsø material from which most original light microscopical descriptions have been derived (Nygaard 1956).

As is to be expected, individual cysts within fossilized populations show considerable morphological variability which is probably related to developmental maturity and the nutrient status of the encysting cell (Sandgren 1981). The observed variability relates especially to cyst diameter, the extent of development of the pore collar, and surface ornamentation. The amount of variability within a cyst population representing a discrete biological species is unknown, and is currently under investigation. The present identifications are based on SEM micrographs of a large number of individuals (in most instances), and is in consideration of the morphological diversity that has been observed in past studies of statospore development (Cronberg 1973, 1980; Sandgren 1980a, b, 1981).

Cyst descriptions

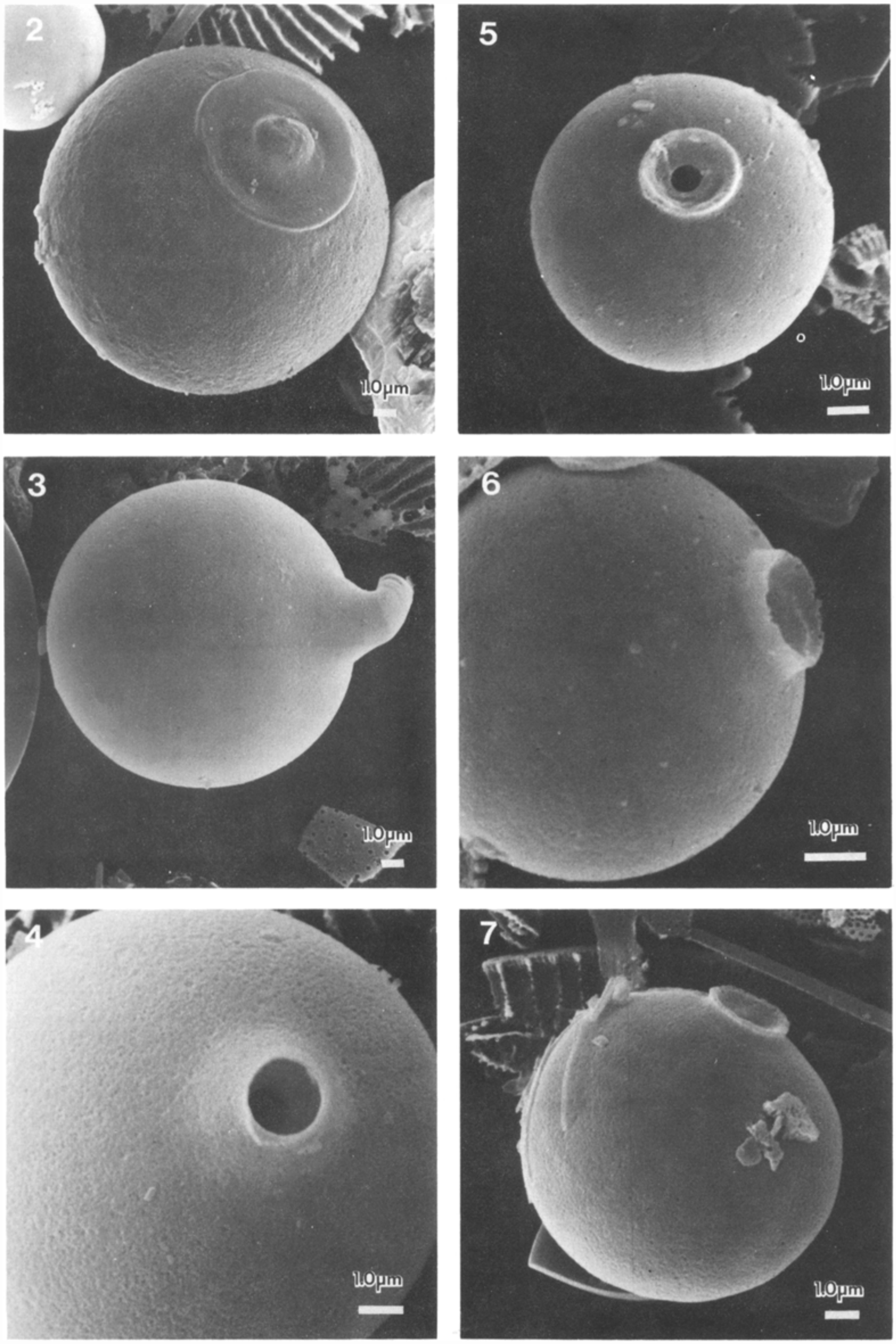
1. Cysta cingens Nygaard (?) (Fig. 2): The cysts of this species observed in Frains Lake sediments are larger in diameter (15.2–16.5 μm) than those described by Nygaard, but have the same distinctive profile under the light microscope. The very broad (up to one third the cyst diameter) and low collar has an erect outer margin and a gradually descending inner margin. The interior of the collar grades into a raised, nipple-like protrusion of plug material obscuring the pore. It is this protrusion that gives the cyst its characteristic profile. The cyst surface is very slightly textured or granulate.

2. Cysta curvicollis Nygaard (Figs. 3 and 4): This form is characterized by the smooth or micro-textured cyst body and a distinctly elongate, hooked collar. The collar base is conico-convex; specimens from which the collar has been broken off reveal a flattened rim of silica surrounding the pore within the collar base (Fig. 4). The cylindrical collar extension hooks in an abrupt but variable angle of up to 90° to its base. Cyst diameter ranges from 10.5 to 14 μm in the specimens observed. This cyst is undoubtedly produced by the type variety of the common planktonic alga *Dinobryon cylindricum* Imhof.

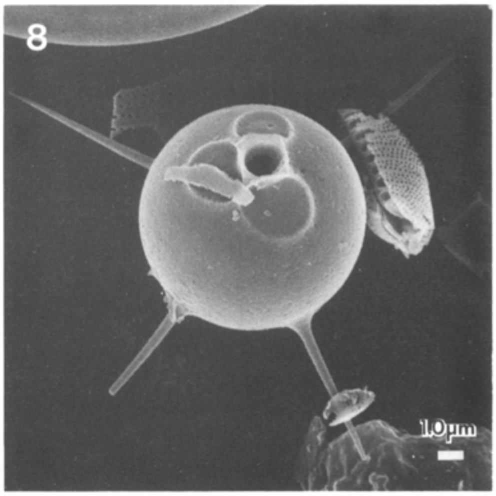
3. Cysta minima Nygaard and *Cysta modica* Nygaard (Figs. 5 and 6): These species are characterized by a smooth or micro-textured cyst surface and a short cylindrical collar. In the Frains Lake material the collar is abruptly erect on the outer margin, and ends in an irregular, acute apex. The inner collar margin typically descends abruptly to a flattened rim surrounding the pore. Some cysts show irregular ridges or thickenings around the inner base of the collar, and most cysts exhibit a spiral ridge of silica ascending the inner collar surface (Fig. 6). In this study, cysts 4.0–7.0 μm in diameter were termed *C. minima,* and cysts 7.0–8.6 μm in diameter were counted as *C. modica.* The observed SEM size range of these cysts is 5.6–8.6 μm in diameter. Whether these two unspecialized cyst forms represent only one or many vegetative cell species remains to be verified by observations on encysting populations of living cells.

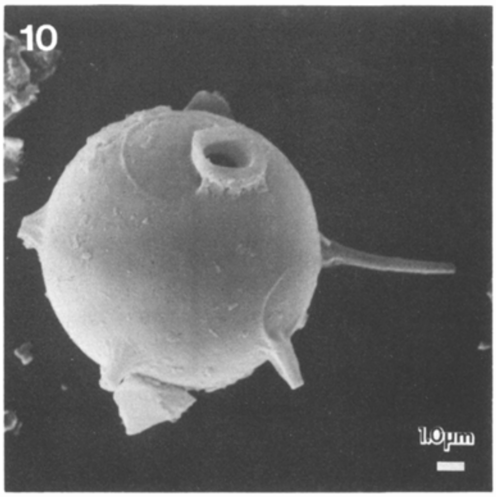
4. Cysta subbavaricum Nygaard (Fig. 7): These cysts conform well with Nygaard's description. The cyst is 8.9–10.5 μm in diameter, has a micro-textured surface, and a short collar that is medially constricted. Pore morphology in the Frains Lake material is unknown.

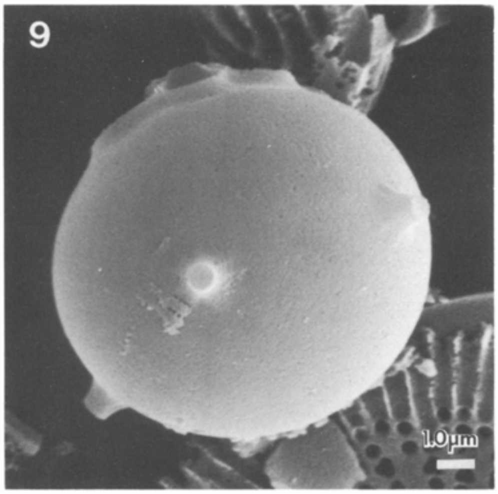
5. Cysta splendens sp. nova (Figs. 8, 9 and 10): This very characteristic new form has a micro-textured cyst surface with 4–5 long, acute spines symmetrically arranged in the posterior hemisphere. Spine length is variable, ranging from short (1 μm) and blunt (broken?) to 0.75–1.5 times the cyst diameter in length. Observed cyst diameter ranged from 9.6–11.5 μm. The cyst collar is surrounded by 3, 4 or 5 circular girdles of 'pseudo-collars' arranged regularly and often fusing laterally to one another and to the collar. The Frains Lake material shows great variability in the degree of development of these annular rings. The collar itself is short cylindric or occasionally medially constricted, and has a rounded apex in mature specimens. There is no or only a very narrow rim surrounding the pore within



Figs. 2–7. Fig. 2: Cysta cingens Nygaard (?). *Fig. 3: Cysta curvicollis* Nygaard. *Fig. 4: Cysta curvicollis* Nygaard. A higher magnification photograph of a specimen on which the collar has broken off. Note the 'chamber-like' conformation of the collar base and the planar rim of silica surrounding the pore. *Fig. 5: Cysta minima* Nygaard. A polar view showing the structure of the pore and the planar region inside the collar. *Fig. 6: Cysta modica* Nygaard. A lateral view showing the irregular apex of the collar and the spiral ridge of silica ascending the interior surface of the collar. *Fig. 7: Cysta subbavaricum* Nygaard.







Figs. 8–10. Fig. 8: Cysta splendens sp. nova. Polar view showing pore morphology and spine arrangement on a mature cyst. *Fig. 9: Cysta splendens* sp. nova. Lateral view of a cyst in which 'pseudo-collars' are wel developed and spines are very short or broken. *Fig. 10: Cysta splendens* sp. nova. Polar view of a cyst similar to that in Fig. 8. Note the appearance of the collar region; a faint pseudo-collar is present and the collar is medially constricted.

the collar. These cysts might easily be confused with *Cysta macrospinosa* Nygaard on the light microscopical level but for the pseudocollars.

Stratigraphy

European settlement and concomitant cultural eutrophication of Frains Lake are clearly indicated by the sediments. The settlement horizon, located at 410 cm in the profundal sediments, is reflected by a shift from highly organic greenish gyttja to a greyish clayey sediment. It is also indicated by a sharp increase in *Ambrosia* accumulation (Davis 1976), an abrupt shift in zooplankton community composition (Kerfoot 1974) and a marked change to diatoms characteristic of eutrophic lakes (Carney 1982).

Chrysophycean cysts are abundant and well preserved throughout the Frains Lake profundal core. Very few vegetative scales were encountered during LM counting and in a special search with the SEM (John Smol, personal communication). Three taxa, *Cysta minima, C. modica* and *C. subbavaricum,* are the clear dominants at all levels (Fig. 11). As discussed in the taxonomic section, these taxa simply reflect different size ranges of round cysts with short, cylindrical collars. *Cysta minima* is significantly more abundant proportionately in the post-settlement sediments ($P \ll 0.001$) according to Scheffé's S-method ($n = 42$, d.f. $= 13, 28$) while *C. subbavaricum* decreases significantly above the settlement horizon ($P \ll 0.001$). Nonetheless, these taxa do not reflect settlement as clearly as the other microfossils. These relatively nondescript round

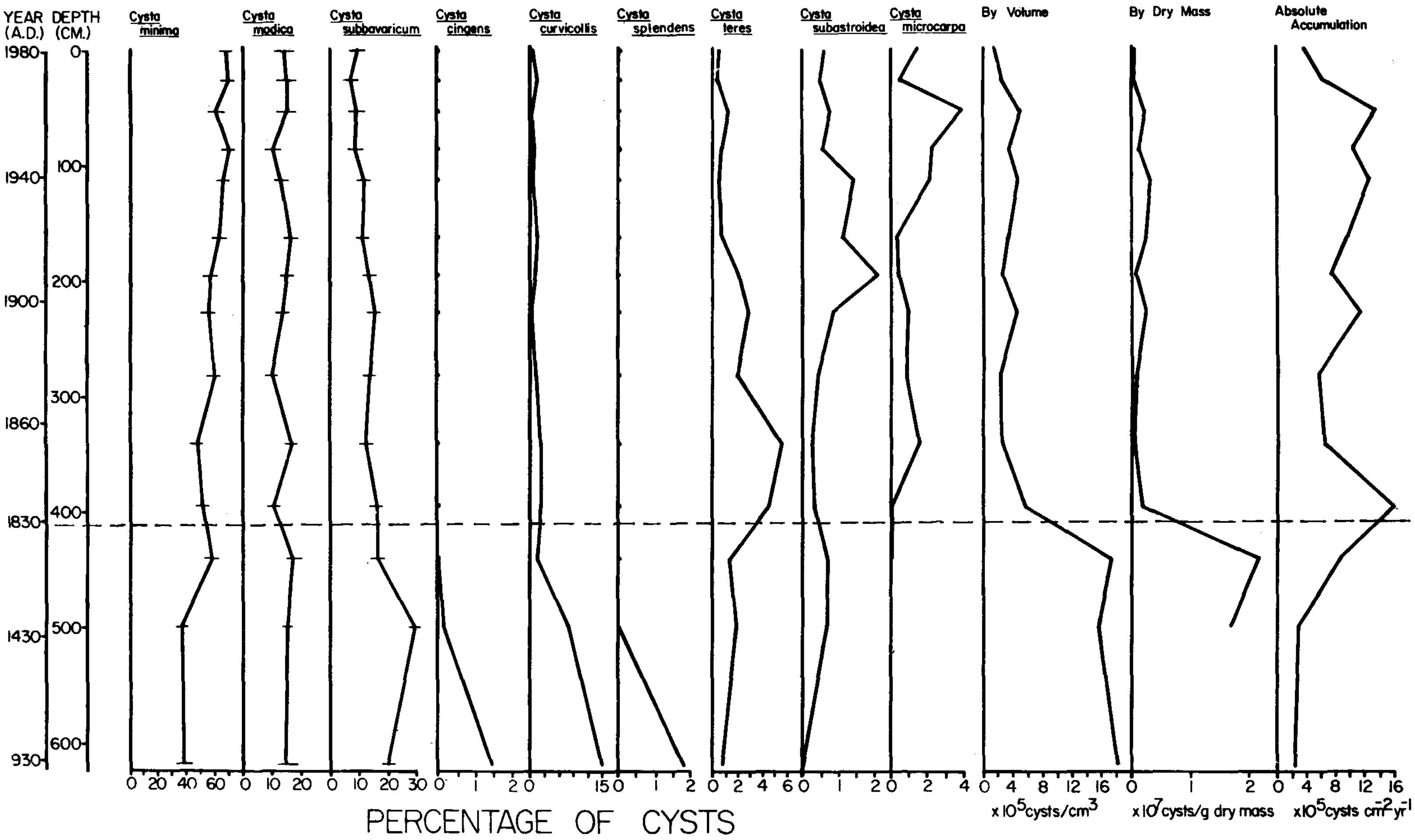


Fig. 11. Stratigraphic profiles for selected chrysophycean cyst forms, and cyst concentration and net annual accumulation. The dashed line indicates the European settlement horizon. 95% confidence limits for *C. minima*, *C. modica* and *C. subbavaricum* were calculated from the proportional replicates on the basis of multiple Bernoulli trials and multinomial distributions (Mosimann 1965). All other profiles are based on density counts.

forms commonly dominate cyst microfossil remains (Nygaard 1956; Leventhal 1970); the fact that they may be produced by different species makes their use problematic.

Many subdominant taxa, however, do show clear trends associated with settlement. *Cysta cingens, C. curvicollis* and *C. splendens* all occur almost exclusively in the pre-settlement sediments (Fig. 11). Other pre-settlement taxa not shown are *Cysta obliqua* and cyst number 3 (author's designation). *Cysta teres, C. subastroidea* and *C. microcarpa* increase proportionately and in absolute accumulation with settlement (Fig. 11). Other post-settlement taxa include morphotypes resembling *Cysta globata, C. granulosa, C. vermicularis, Mallomonas caudata* and *Uroglena soniaca.*

Only the studies of Nygaard on Lake Gribsø (1956) and Leventhal on Lago di Monterosi (1970) have provided detailed information on the composition and abundance of cyst forms in relation to lake trophic status. There are no strikingly similar patterns of cyst deposition in relation to eutrophication between these two lakes and Frains Lake. However, certain taxa show comparable trends. In Lago di Monterosi and Frains Lake, *Cysta cingens* had a greater proportional abundance in less eutrophic phases. *Cysta curvicollis* peaked in Lake Gribsø immediately prior to forest clearance, and occurred in the relatively oligotrophic period of Frains Lake. This is logical since *Dinobryon cylindricum,* which produces *C. curvicollis,* is generally found in cool oligotrophic or mildly eutrophic waters (Huber-Pestalozzi 1941). *Cysta macrospinosa,* which occurred in the less eutrophic periods of Lago di Monterosi, may represent the same species as *C. splendens* (see taxonomic section), which was found in the pre-settlement depths of the Frains Lake sediments. The post-settlement peaks of many Frains Lake cysts are comparable to trends for Lake Gribsø forms. *Cysta minima, C. subastroidea* and *C. vermicularis* all occurred during more eutrophic periods of both lakes. *Cysta microcarpa,* another Frâins Lake post-settlement taxon, occurred during a period of nutrient enrichment in Llyn Padarn, and only while Llyn Peris was influenced by mining (Elner & Happey-Wood 1978).

The results of density counts reveal interesting and important trends. Densities by volume and by dry weight both decrease dramatically above the settlement horizon, while absolute accumulation, or net annual influx, increases above this depth (Fig. 11). Leventhal (1970) stated that the Chrysophyceae are generally more abundant in nutrient-poor waters. Moss (1979) found that chrysophycean cysts were more abundant in the less eutrophic phases of Strumpshaw Broad, England. While the net annual influx of cysts in Frains Lake does increase with settlement, the proportion of cysts to diatoms is three times greater during the pre-settlement period. These results lend some support to Leventhal's statement.

Conclusion

This study indicates that while chrysophycean cysts are presently somewhat difficult to use as stratigraphic indicators, they may be utilized, with due caution, to help interpret lake history. The fact that chrysophycean cysts are commonly abundant and often the best-preserved microfossils behooves us to develop their use. The following work is especially needed. The priority is to study the encystment process and identify cysts for additional common chrysophycean species. Critical stratigraphic analysis must include thorough SEM work and careful quantitative counts with the light microscope. This is particularly important because the best prospects for the use of cysts as paleoenvironmental indicators appear, at present, not to lie with the usually morphologically nondescript dominants, but with the more distinct subdominant forms.

Summary

1. The occurrence of the dominant chrysophycean cysts (statospores) in the recent sediments of Frains Lake is documented by scanning electron microscope (SEM) photographs and a quantitative stratigraphic profile.
2. Cultural eutrophication is not clearly reflected by shifts in the three dominant cyst forms, but is marked by changes in subdominant forms.
3. Future progress in the use of chrysophycean cysts as paleoenvironmental indicators will require: a) coupling of cyst forms with the appropriate species, b) careful identification using SEM, and c) quantitative stratigraphic work with both dominant and rarer forms.

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