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Ancient blue-green blooms

Abstract—Recent decades have seen a large increase in surface scums (blooms) of cyanophytes (blue-green algae and blue-green bacteria) in inland waters. These are potentially toxic to mammals, including humans, and have caused considerable public concern in Europe, Australasia, and North America. They are often associated with eutrophication, and much has been invested in their control. Not all blooms, however, are necessarily the results of human interference with lakes. Scattered paleolimnological evidence indicates that some blooms may be associated with pristine conditions, though this message has largely been ignored. Evidence is given here of a long history of blooms in Whitemere, U.K., from extraction and identification of specific carotenoids from dated sediment cores. Whitemere is representative of a large group of lakes in the West Midlands of the U.K. and is likely to be representative also of those similar postglacial kettle hole lakes in North America and Eurasia, which are groundwater fed with long retention times and thermally stratified. Blue-green blooms may thus be a normal feature of such lakes and not necessarily a pathology to be controlled.

Blue-green algal blooms are now very common. Many lowland lakes in Europe have carried, in some summers, warning signs against the dangers of toxicity (Codd 1984; Codd and Beattie 1991), and regulatory authorities are widely concerned about reducing the incidence of blooms and improving amenity (National Rivers Authority 1990). Conservation values have been reduced (Carvalho and Moss 1995). Even more serious are concerns about public water supply, for blooms are costly in water treatment (Hayes and Greene 1984). There has inevitably developed a culture in which blooms are universally vilified and associated with human alteration of catchments and discharge of effluents. Concern is often justified, but blooms are not always recent phenomena. Paleolimnological evidence sometimes reveals anthropogenic bloom incidence long before the modern period (Hutchinson et al. 1970; van Geel et al. 1994).

There also exists, however, a small amount of paleolimnological literature hinting at an even more ancient incidence of blooms, prior to human settlement. Often, these are associated with increased stabilization of the water column in warming climates. Zullig (1989) records an increase in cyanophyte pigments in the early Atlantic period, persisting to the mid-Holocene in the Soppensee and (1986) in the Preboreal and Boreal in the Lobsigensee. Fritz (1989) notes an expansion of *Oscillatoria* about 6000 B.P. in a small East Anglian lake. In Alberta, Lake Wabamum and other lakes have had prolonged incidence of large blue-green algal populations, waxing and waning with climate change and fire history in the surrounding prairie, but persisting as a constant feature (Schweger and Hickman 1989; Hickman and Schweger 1991). Compared with the number of lakes in the northern hemisphere, systematic paleolimnological investigations have been few, and those capable of revealing changes in blue-green algae, as opposed to diatoms, have been even fewer. If Lake Wabamum had blooms as normal features, perhaps many other lakes have had similar histories.

The North-West Midland meres, U.K. (Reynolds 1979), are well known for their cyanophyte blooms. The meres were formed around 10,000–14,000 yr ago on the glacial drift plain of Shropshire and Cheshire, by moraine damming, kettle hole formation, and the collection of meltwater in hollows, sometimes created by saline subsidence, in the hummocky landscape. Early bloom formation in them is reflected in a local expression—‘‘the breaking of the meres,’’ which is taken from a term formerly used in brewing to describe the rising of the wort (yeast) to the surface during fermentation (Phillips 1884). There are also literary references to such ‘‘breaking’’ in the seventeenth century (Webb 1928). Blooms in the historic period, however, might easily be attributed to local eutrophication from village sewage or farms, but they suggest the possibility of a much earlier origin. Were this the case, and because the meres are in no way unusual among thousands of small, stratified, groundwater-fed lakes on the glacial plains of the northern hemisphere, the commonly believed paradigm of blooms as inevitable pathological features of lakes might need to be revisited and approaches to lake restoration adjusted.

Whitemere, in North Shropshire (2°52′W, 52°53′N; National Grid Reference SJ 415330), is a typical kettle hole lake with annual cyanophyte blooms, usually dominated by *Anabaena circinalis* and *Microcystis aeruginosa* (Kilinc 1995). It has an area of 25.5 ha, a maximum depth of 17 m, and a monomictic thermal regime. Conductivity is high (300–350 μs cm^{-1}), alkalinity is moderate (1.7 ± 0.1 meq liter^{-1}, and pH ranges from 6.7 to 9.8. Soluble reactive and total phosphorus concentrations span 0.5 to $>$1.0 mg liter^{-1}, which is not atypical of stratified meres in the region (Reynolds 1971; Moss et al. 1994, 1997). There are no point sources of eutrophication and no surface inflows. The mere is fed by groundwater, which has low phosphorus concentrations (Kilinc 1995) and is groundwater drained. Winter inorganic nitrogen concentrations range from 0.5 to 1.5 mg N liter^{-1}, and inorganic nitrogen is depleted in summer. Bioassays (Hameed et al. in press) suggest that algal yield is then limited by nitrogen.

Sediment cores were taken with a Mackereth corer (Mackereth 1958) from a flat area of lake bottom under 7 m of water to avoid possible complications of sediment slumping in the precipitous hole that contains the deepest water. Cores reached the junction of the lake sediment and the glacial clay. Radiocarbon-dated organic lake sediment from close to the bottom had an age of 6540 ± 80 B.P. (SRR-5687), and a further radiocarbon date of 860 ± 70 B.P. (SRR-5686) was obtained at 130 cm. These dates are unlikely to be affected by carbonate effects, for carbonate comprised at most 3% of the dry sediment in the lower part of the core and was lower

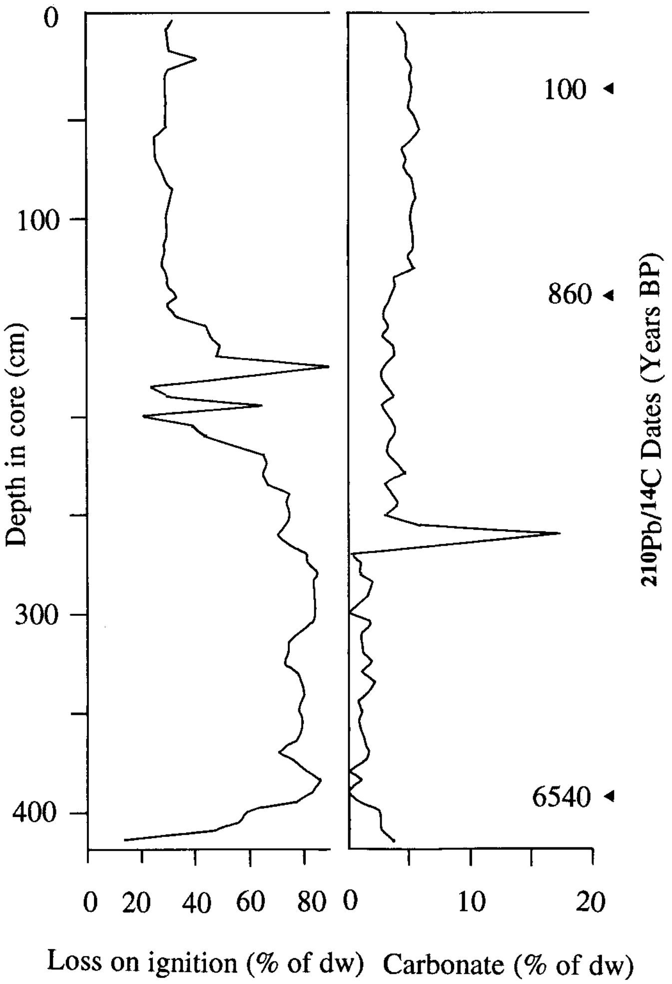

Fig. 1. Loss on ignition and carbonate profiles for a core of sediment taken from Whitemere, U.K.

at the level of the earliest date, while organic content was nearly 80% (Fig. 1). A single high value of carbonate at 255 cm was not replicated in other cores and is associated with a piece of mollusc shell. Sediment from the period from around 7000 B.P. to the time of the earliest substantial post-glacial biological activity in the area (around 10500 B.P., Reynolds 1979) is absent from the cores, perhaps because the lake level was much lower in that period or because of sediment focusing over what may then have been a greater-than-at-present slope of the basal deposits. ^{210}Pb was used to date recent sediments.

Carotenoid pigment remains were used as signatures for cyanophyte abundance, for they are diverse, often specific to algal taxa, and readily preserved in sediment (Leavitt 1993). Pigments were exhaustively extracted in serial aliquots of acetone, and chlorophylls and their derivatives were removed by transferral into ether to avoid interference of their spectra with those of carotenoids (Young et al. 1989). The acetone had been washed with sodium chloride solution to ensure that any polar xanthophylls moved to the ether. Pigments were separated with reversed-phase high-performance liquid chromatography (HPLC), based on the methods of Young et al. (1989). A Waters 990 controller was used with an on-line diode-array detector and Waters 990 software for the recording of chromatograms and integration of peak areas. Separation was on a Zorbax ODS (octadecalylsilyl) 5-μm reversed-phase column (25 × 4.6 mm), and separation conditions were as in Table 1.

Table 1. Separation conditions for carotenoid pigments from a core taken from Whitemere, U.K. Solvent A; acetonitrile/water (9 : 1); Solvent B, ethyl acetate.

Time (min)	%A	%B	Conditions	Flow rate (ml min^{-1})
0	100	0	Injection	1
25	0	100	Linear	1
30	0	100	Isocratic	1

Measurements were made at 10-cm intervals along the sediment core. The HPLC was calibrated with a β-carotene standard solution. Pigments were identified by their spectra and retention times and by comparison, with extracts taken from known algal monocultures of representative cyanophytes, diatoms, and green algae. The identification of apolutein is tentative, but the spectral characteristics of the compound strongly support its identification.

Amounts of pigment were expressed per unit organic content (Fig. 2) to avoid problems of dilution with clastic material entering from the catchment (Swain 1985). Cyanophyte pigments were abundant throughout the length of the core, but because carotenoids differ in their lability, it is not possible to infer cyanophyte dominance solely from absolute abundance in the pigment assemblages. However, β-carotene is produced by all algal taxa and echinenone, by virtually only the cyanophytes. Both are relatively well preserved to similar degrees (Leavitt 1993). The amount of echinenone in the Whitemere core exceeded half the concentration of β-carotene in most subsamples, suggesting that cyanophytes comprised a significant proportion of the algal biomass. Fucoxanthin was present only in the surface-sediment samples. It is produced by diatoms, frustules of which were abundant in the upper 200 cm of sediment (though not in the lower 200 cm). Absence of fucoxanthin from subsurface sediments, within the upper 200 cm, is likely to be due to its high lability (Repeta 1989).

Most carotenoid types had peak concentrations between 300 and 400 cm, minima around 200 cm, and increases above this depth. Loss-on-ignition profiles (Fig. 1) suggest that the sediment laid down around 200 cm corresponds to a period of disturbance in the catchment. Loss-on-ignition values fluctuate much more widely in this part of the core than elsewhere in it; this feature is common to several cores taken and is paralleled in cores taken from another lake (Colemere) in the area (McGowan 1997). High pigment concentrations in the lower part of the core suggest that conditions for preservation were good, and the existence of laminations in this region of the core suggests that the lake may then have been meromictic (having a permanently unmixed deep layer) or mixed to a lesser degree than in the present day. The near absence of diatoms below 200 cm is consistent with this. Planktonic diatoms are disfavored by

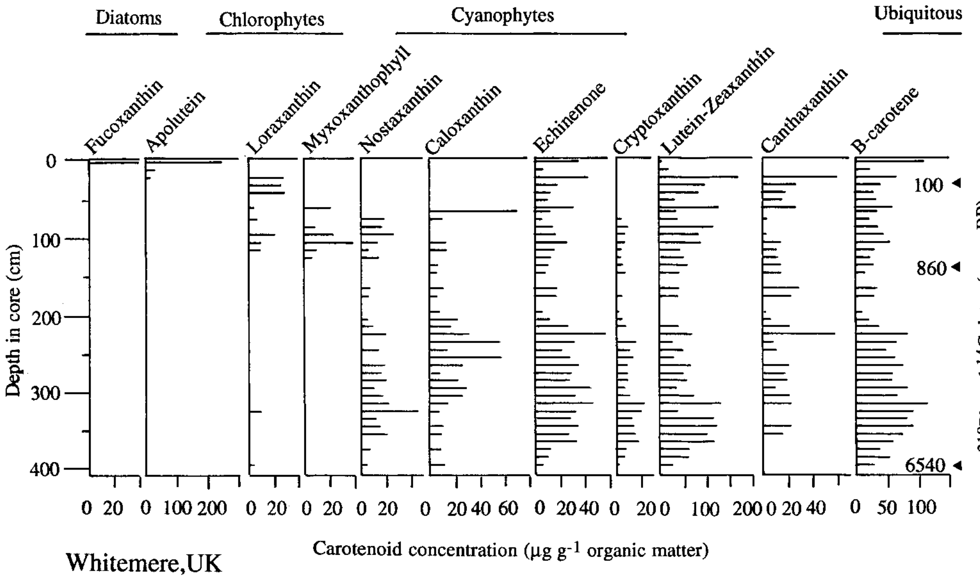

Fig. 2. Carotenoid concentrations in micrograms per gram organic weight of sediment from a core taken from Whitemere, U.K. Algal groups indicated by particular pigments are shown.

still conditions, and the alkaline conditions associated with biogenic meromixis lead to ready dissolution of diatom frustules.

Similar patterns in specific and total carotenoids were found in cores from another lake in the area, Colemere (McGowan 1997), suggesting that the Whitemere core shows regional rather than isolated characteristics. The main features of the regional history that need interpretation are thus a high thermal stability, possibly meromixis, from at the latest 6500 B.P. to perhaps 1500 B.P., then a period of disturbance of the catchment, associated with the large swings in loss of ignition in the core. The ^{210}Pb dates suggest a steady sedimentation rate, below the immediate surface layers, of about 1.5 mm yr^{-1}, which is similar to that inferred from the radiocarbon date obtained from 130 cm. Steady values of loss on ignition from the surface to about 150 cm (Fig. 1) suggest that the period of disturbance ended about 1000 B.P. Extrapolations of sedimentation rates indicate it began around 1500 B.P. at the earliest. There followed greater stability in the catchment, though with a more vigorous mixing regime in the lake, until the present. There is evidence, from diatom remains, of a recent eutrophication, but the predominance of cyanophyte pigments throughout the core indicates that this has been superimposed on a natural state in which cyanophyte blooms were normal features.

Several mechanisms may have changed the mixing regime between 1000 and 1500 B.P. First, as the basin filled with sediment, the surface area to depth ratio would have increased, increasing the effectiveness of the wind fetch; second, a general cooling that set in after about 3000 B.P. (Godwin 1975) may have eventually resulted in mixing; and third, removal of forest in the late Iron Age (Beales 1980; Twigger and Haslam 1991) would also have increased the effectiveness of wind mixing. This mixing may also have led to somewhat decreased preservation of carotenoids by exposing the pigments for longer periods to oxygenated water. A return to higher carotenoid concentrations in the period since 1000 B.P. may reflect increased nutrient loading as the catchment was developed for agriculture.

Strongly stratified conditions clearly favor cyanophyte blooms (Reynolds and Walsby 1975), as do low N to P ratios (Shapiro 1990) and low free CO_2 concentrations (Talling 1976). Whitemere can have provided these conditions throughout its history, both before settled human contact and after it. Recent eutrophication is likely to have been nitrogen driven, for the groundwater inflow concentrations of phosphorus are two orders of magnitude lower than those in the lake even at present (Kilinc 1995). Phosphorus is released into the hypolimnion from the sediment in summer but is not depleted in the epilimnion. This is most likely explained by vertical movements of cyanophytes and dinoflagellates between the hypolimnion and epilimnion (Moss et al. 1997). Concentrations decrease in winter as mixing reoxidizes the sediment surface, but they remain high throughout the water column, as there is little washout through the groundwater drainage.

Such conditions (stratification; moderate alkalinity leading to reduced free carbon dioxide concentrations during summer photosynthesis; and groundwater hydrology leading to the possibility of phosphorus accumulation) must be common among the hundreds of thousands of small lakes set in glacial drift deposits in the Northern hemisphere. We might therefore surmise that many lakes have cyanophyte blooms that originate from conditions that might be exacerbated by human activities but are not necessarily dependent on them.

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