Environmental change controls of lacustrine carbonate, Cayuga Lake, New York

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ABSTRACT

Dated sediment cores from Cayuga Lake, New York State, document that biologically mediated precipitation of calcite has been controlled by environmental change, both natural and anthropogenic, over the past 10 000 yr. During the Holocene Hypsithermal (~9–4 ka [^{14}C]), Milankovitch forcing of summer insolation in the Northern Hemisphere resulted in a broad increase (to 55%), then decrease (to <5%), of calcite content in bottom sediment. Warmer summers resulted in earlier onset of thermal stratification of the water column, which increased the duration of primary production as well as the abundance of picoplankton, which in turn increased the amount of calcite precipitated. At the end of the Hypsithermal ca. 3500 yr ago, global cooling greatly reduced the amount of calcite precipitated. However, since A.D. 1940, calcite contents in Cayuga Lake sediments have risen up to ~20%. One hypothesis is that this recent increase in calcite is the result of cultural eutrophication (nutrient loading). However, this rise in calcite also closely tracks the anthropogenic rise of atmospheric carbon dioxide, suggesting a possible link to global environmental change. Further research on hard-water lake basins will be needed to test which of these two hypotheses is correct.

INTRODUCTION

The recent rise of anthropogenic carbon dioxide concentrations in the atmosphere (Keeling et al., 1989) has sparked considerable concern about future climates and how various Earth environments might respond to global environmental change. Mid-latitude lakes may be especially sensitive to environmental change, because seasonal water stratification and primary production are both strongly linked to seasonality. Of particular interest is the calcite precipitated from the surface of hard-water lakes, because it offers a potential high-resolution sediment archive of biotic and abiotic processes that operate in temperate lakes (Kelts and Talbot, 1990).

The purpose of this paper is to report initial results from a mid-latitude lake (Cayuga Lake, New York State) that illustrate links between biologically mediated precipitation of calcite and environmental changes, both natural and anthropogenic, during the past 10 000 yr. New data from Cayuga Lake document strong correlations between the amount of calcite preserved in bottom sediments and the natural warming-cooling trend of the Holocene Hypsithermal, as well as the rise of anthropogenic atmospheric carbon dioxide since at least A.D. 1940.

SETTING

Cayuga Lake is the second-largest of the Finger Lakes of central New York State (Fig. 1); it has a length of 60 km and a maximum water depth of 132 m (Oglesby, 1978). The lake formed as a glacial rock basin (tunnel valley?) coincident with Heinrich event H-1, ca. 14.4–13.9 ka (^{14}C) (Mullins and Hinchey, 1989; Mullins et al., 1996). Cayuga Lake is a mesotrophic, warm monomictic lake that stratifies thermally only once during the summer, and mixes continuously from fall through spring (Oglesby, 1978). Water residence times are on the order of 8–10 yr (Michel and Kraemer, 1995).

Many of the Finger Lakes now undergo "whiting events" (open-water precipitation of calcite) during summer months that greatly decrease water clarity (Effler et al., 1987). Thompson et al. (1997) convincingly demonstrated that calcite precipitated during whiting events in nearby Fayetteville Green Lake, New York, is mediated by the photosynthetic activity of cyanobacterial picoplankton, which create a high pH micro-

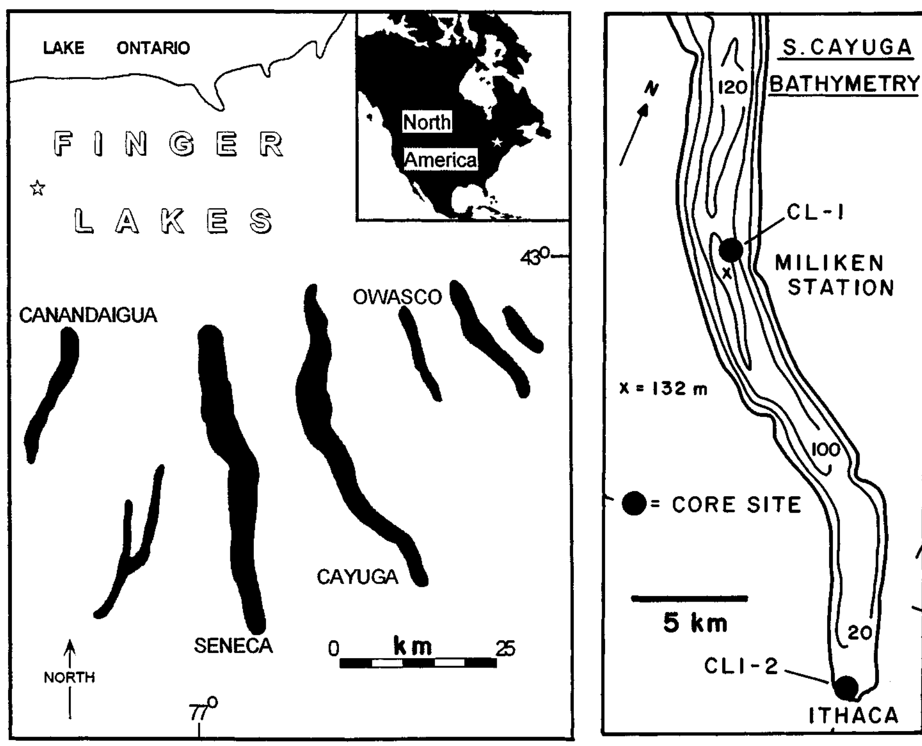

Figure 1. Left: Index map of eastern Finger Lakes region, New York State; study area is in southern half of Cayuga Lake. Right: Bathymetry of southern half of Cayuga Lake illustrating core locations; bathymetry is from Mullins et al. (1996).

TABLE 1. RADIOCARBON DATA

Sample no.	Depth (cm)	Material	Lab+	Corrected ^{14}C age	$\delta^{13}C$ (‰)
Piston Core	CL-1				
CL-1	430	Wood	AA-19536	5954 ± 75	-25.6
CL-1	45	Wood	USGS	1056 ± 53	-27.7
CL-2*	230	Wood	USGS	2473 ± 56	-29.3
CL-2*	376	Pine Cone	USGS	4324 ± 60	-26.5
Hand Core	CLI-2				
CLI-2	340	Wood	TX-8493	1110 ± 80	-27.1
CLI-2	994	Wood	AA-19537	5988 ± 66	-27.7
CLI-2	1490	Bulk organics	AA-21303	10958 ± 94	-25.5

Note: All ages, with the exception of CLI-2/340, are AMS (acceleration mass spectrometer) dates.

* Transferred to CL-1 via $CaCO_3$ correlation.

+ AA—University of Arizona Radiocarbon Facility; TX—University of Texas Radiocarbon Facility; USGS—Date provided by U.S. Geological Survey, Reston, Virginia (T. Kraemer).

environment around their cells, leading to epicellular precipitation of calcite. Hodell et al. (1998) documented that calcite precipitation in nearby Lake Ontario is highly correlated to lake temperature, but is also dependent upon primary productivity and the abundance of picoplankton.

METHODS

Sediment cores were collected from two localities in Cayuga Lake: (1) near the area of maximum water depth in the southern half of the lake, and (2) at the southern terminus of the lake near Ithaca (Fig. 1). At the deep-water site (CL-1), a 5.4-m-long piston core and a 1-m-long box core were collected from surface vessels. At the southern end of the lake (CLI-2), a 15-m-long sediment core was collected by hand using a 3-cm-diameter soil sampler.

Age control for the two long cores was established by radiocarbon dating of terrestrial organic material (with the exception of one bulk organic date; Table 1). Age models for the cores were developed by linear extrapolation between radiocarbon data points, which were then converted to calendar years following Bartlein et al. (1995). Age control for the box core is based on identification of a bomb spike in ^{137}Cs profile data (A.D. 1963) at 17–18 cm below the lake floor, as well as ^{210}Pb data. (Tom Kraemer, U.S. Geological Survey, 1996, written commun.).

The 1-m-long box core from site CL-1 was sampled at 1 cm intervals (average ~2 yr), whereas the 5.4-m-long piston core from this site was sampled every 10 cm (average ~135 yr). The 15-m-long core from site CLI-2 was sampled at a 25 cm interval, or approximately every 180 yr. Subsamples ($n = 214$) were then analyzed for dry weight percent total organic matter and total carbonate content by loss on ignition at 550 °C and 1000 °C, respectively (Dean, 1974); based on replicate analyses, error is <0.5%.

Correlation coefficients were calculated (Pearson's r) that produce a standardized statistic (+1 to –1) that is not scale dependent. Holocene records were digitized at 500 yr intervals over the past 10 000 yr, whereas data sets covering the past 200 yr were digitized at an average of 4.4 yr.

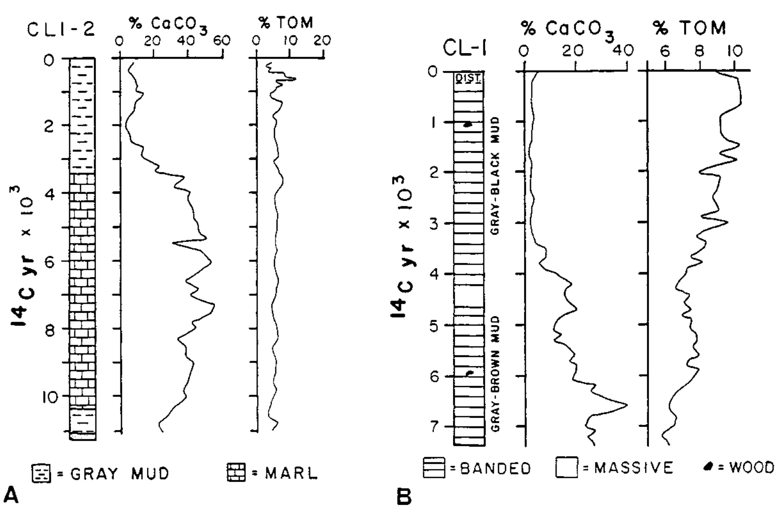

Figure 2. Lithostratigraphy and dry weight percent calcium carbonate and total organic matter (TOM) content versus radiocarbon age for (A) 15-m-long core CLI-2 and (B) 5.4-m-long core CL-1 (see Fig. 1).

RESULTS

Shallow-Water Site CLI-2

The 15-m-long sediment core recovered from the southern terminus of Cayuga Lake (Fig. 1) consists of an 8-m-thick sequence of light gray marl (>30% calcium carbonate) overlain by 6 m, and underlain by 1 m, of dark-gray mud (Fig. 2A). Oogonia (reproductive organs of the aquatic macrophyte *Chara*) are present throughout the length of the core, indicating that this site has remained within the shallow photic zone for at least the past 11 000 ^{14}C yr. Accumulation rates in the core vary from ~100 to 300 cm/1000 yr.

When plotted against a radiocarbon time scale, results from core CLI-2 (Fig. 2A) indicate that marl deposition occurred from ca. 10.3 ka (end of the Younger Dryas cold interval) to ca. 3.5 ka (end of the Holocene Hypsithermal warm interval). Maximum calcite content of 55% in the marl at ca. 7.2 ka (^{14}C) drop to values of <5% in the overlying dark gray mud. The overall curve for calcite in core CLI-2 displays a broad increase then decrease throughout the marl, although smaller scale anomalies are also apparent (Fig. 2A). However, total organic matter (TOM) values are relatively invariant.

Deep-Water Site CL-1

Sediments recovered in the 5.4-m-long piston core at this deep-water (108 m) site consist of laminated, gray-brown to gray-black muds. Radiocarbon data indicate that the sediments in this core extend back to ca. 7.3 ka (^{14}C) (Fig. 2B) at an essentially linear accumulation rate of ~80 cm/1000 yr.

From ca. 7.3 to 3.4 ka (^{14}C), calcite content varies from a maximum of 40% at 6.6 ka to a minimum of 8% at 3.4 ka (Fig. 2B). However, during the past 3400 yr (^{14}C), calcite contents have always been less than a background level of 5%. This drop in calcite accumulation in core CL-1 at 3.4 ka (^{14}C) (Fig. 2B) coincides with the cessation of marl deposition at site CLI-2 at ca. 3.5 ka (^{14}C) (Fig. 2A). TOM values in core CL-1 display an up-core increase from ~6% to 10%.

Results from the box core recovered at site CL-1 indicate that between 100 and 70 cm below the lake floor, calcite values are always <5% (Fig. 3), as they have been since ca. 3.4 ka (^{14}C). However, between 70 and 28 cm, calcite contents increase to 10%, and in the upper 28 cm of box core CL-1, calcite contents rise rapidly from 8% to 20% (Fig. 3). TOM values similarly show an up-core increase.

On the basis of ^{137}Cs and ^{210}Pb data, calcite values increased above 5% for the first time prior to the 20th century and then rose rapidly beginning ca. A.D. 1940 (Fig. 3). The only significant anomaly in calcium carbonate content over this

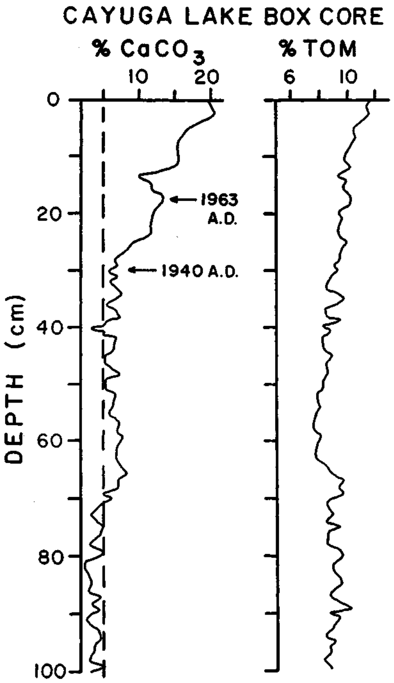

Figure 3. Dry weight percent calcium carbonate and total organic matter (TOM) content versus depth for box core CL-1 (see Fig. 1). Date of A.D. 1963 is based on direct ^{137}Cs and ^{210}Pb data, whereas date of A.D. 1940 is based on linear extrapolation from A.D. 1963.

interval occurred during the middle to late 1960s, a time of cool and dry (shorter) summer conditions (Yarnal and Leathers, 1988).

DISCUSSION

Holocene Hypsithermal

The broad rise and fall of calcite content recorded in shallow-water core CLI-2 (Fig. 2A) occurred during the mid-Holocene Hypsithermal (ca. 9–4 ka [^{14}C]). The Hypsithermal is a well-known climatic interval (Pielou, 1991) when mean summer surface temperatures in the Northern Hemisphere were 2–3 °C warmer than today because of an increase in solar radiation (~8% at 43°N) driven by Milankovitch orbital elements (COHMAP, 1988). This association between the broad warming-cooling trend of the Hypsithermal and calcite precipitation in Cayuga Lake is illustrated by comparing calcite contents in core CLI-2 (in calendar years) with a smoothed ice core $\delta^{18}O$ (temperature proxy) record from the Renland site in Greenland (Larsen et al., 1995), as well as an insolation curve for the latitude (43°N) of the Finger Lakes (Berger, 1978). Both the Cayuga and Greenland curves display a broad increase between ca. 10 and 7 ka (calendar years), followed by a broad decrease between ca. 7 and 3.5 ka (Fig. 4). For the past ~3500 calendar years, both curves are relatively constant, with the exception of the past ~200 yr when there are rapid increases. The correlation coefficient (*r*) between Cayuga Lake calcite content and

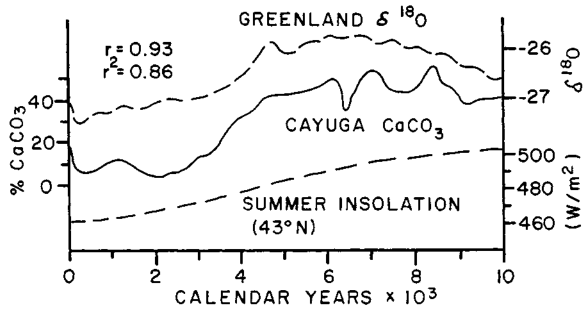

Figure 4. Comparison of first-order trends in $\delta^{18}O$ (ice) values from Renland site in Greenland (Larsen et al., 1995) and insolation curve for lat 43°N (Berger, 1978), with $CaCO_3$ results from Cayuga Lake core CLI-2; *r* values are for $CaCO_3$ versus Greenland $\delta^{18}O$ (upper left).

Renland $\delta^{18}O$ values is 0.93. This correlation, plus the relationship between Cayuga calcite and insolation (Fig. 4), suggest a causal link between the precipitation of calcite in Cayuga Lake and hemispherical temperature change during Holocene time.

Schleske and Hodell (1991) and Hodell et al. (1998) documented (via stable isotope studies) a strong relationship between higher historical summer temperatures and increased calcite precipitation for Lake Ontario (~50 km north of Cayuga Lake). However, they argued that temperature is only part of the explanation, and further suggested that the amount of calcite precipitated is controlled by the onset of stable thermal stratification of the water column. During warmer summers, thermal stratification of temperate lakes occurs earlier (and lasts longer), which extends primary production and the abundance of picoplankton while decreasing the solubility of calcite. Combined, these factors result in greater production of calcite from hard-water lakes.

In Cayuga Lake, the broad warming-cooling trend of the Holocene Hypsithermal may have first increased, then decreased, the length of the summer photosynthetic period, which in turn increased and then decreased the amount of calcite precipitated. This interpretation for Cayuga Lake is supported by stable isotope data from Seneca Lake (immediately west of Cayuga Lake; Fig. 1) that have documented a positive relationship between increased calcite contents and enriched $\delta^{13}C$ values for calcite during the Holocene (Anderson et al., 1997), which would be expected during extended photosynthesis because of the preferential removal of ^{12}C by phytoplankton (Hollander and McKenzie, 1991).

Past 200 yr

Over the past ~3500 yr, the first time that calcite contents in Cayuga Lake sediments rose above the background value of 5% was prior to A.D. 1900, which was followed in ca. A.D. 1940 by an exponential increase of calcite to today's value of ~20% (Fig. 3). This unprecedented increase of biologically mediated calcite precipitation in Cayuga Lake during the past ~3500 yr could be due to a number of factors. One potential explanation is that it is a simple diagenetic trend. However, this seems unlikely because calcite contents deeper in the sediment column in Cayuga Lake are twice as high (40%) as they are at the lake floor (Figs. 2B and 3).

Another possible explanation is anthropogenically linked environmental change. Schleske and Hodell (1991) and Hodell et al. (1998) found a very similar rise in calcite content in sediments from nearby Lake Ontario. They argued that this recent increase in calcite precipitation was the result of cultural eutrophication (phosphorous loading), which began after A.D. 1850 due to deforestation and agricultural practices, and then increased exponentially after A.D. 1940 due to urbanization (sewage and detergent loads).

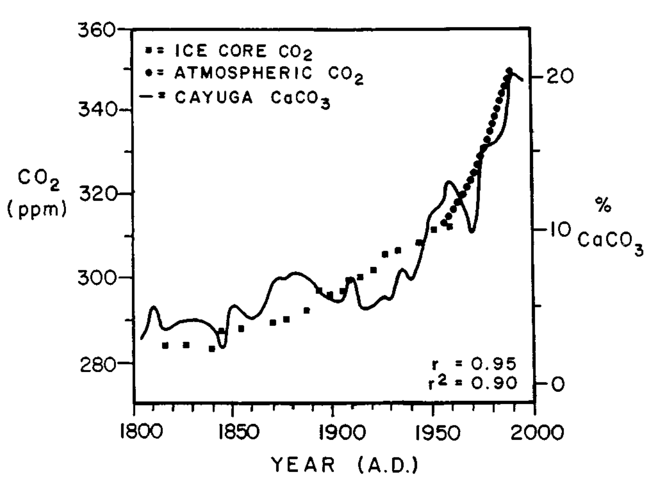

Figure 5. Comparison of atmospheric carbon dioxide concentrations (Neftle et al., 1985; Keeling et al., 1989) over the past 200 yr with calcite data from Cayuga Lake box core CL-1 (see Fig. 1) versus calendar years.

Cultural eutrophication is also a potential hypothesis for the recent rise in calcite content in Cayuga Lake sediments. The initial rise prior to A.D. 1900 could have been due to deforestation and agricultural activities, which began ca. A.D. 1810 and peaked by the late 1880s (Oglesby, 1978). Cayuga Lake also became more eutrophic during the 1940s. Oglesby (1978) speculated that this was a response to phosphate detergent loading because there was no coincident increase of either population growth or agricultural activity in the Cayuga Lake watershed. Although phosphorous loading is a reasonable hypothesis, New York State banned the use of phosphate detergents in A.D. 1973 (Oglesby, 1978), yet calcite precipitation has continued to increase from A.D. 1973 to 1996 (Fig. 3), despite the relatively short (8–10 yr) water residence time for Cayuga Lake. Calcite contents in sediment deposited ca. A.D. 1973 were 14.5% versus 19.6% for A.D. 1996 (Fig. 3).

As an alternative to the cultural eutrophication hypothesis, I suggest a working hypothesis centered around the recent anthropogenic rise of global atmospheric carbon dioxide. There is a remarkably strong correlation ($r = 0.95$) between calcite content in Cayuga Lake sediments and the anthropogenically linked rise of atmospheric carbon dioxide during the past 200 yr (Neftel et al., 1985; Keeling et al., 1989) (Fig. 5).

Botanists have known for decades that plants grow faster in carbon dioxide–rich environments due to increased rates of photosynthesis (Kimball et al., 1993). Although most hard-water lakes typically have higher concentrations of total carbon dioxide than the overlying atmosphere (Wetzel, 1975), this may not always be true for the lake's surface at times of maximum productivity (blooms). For the marine environment, Riebesell et al. (1993) showed that carbon dioxide can be a limiting nutrient for primary production, particularly during intense blooms. In the lacustrine environment, Thompson et al. (1997) demonstrated that calcite precipitation is a direct consequence of the photosynthetic activity of cyanobacterial picoplankton, which is reflected in the parallel increases of both calcite and TOM in the Cayuga box core. A question that needs to be resolved is whether or not anthropogenic inputs of carbon dioxide to the atmosphere since A.D. 1940 have stimulated picoplankton production (and thus calcite precipitation) during times of intense spring to summer blooms.

We are currently examining the detailed record of calcite precipitation over the past 150 yr in the remaining ten Finger Lakes in an attempt to determine if the Cayuga Lake record is a regional or local response. As part of this study, linkages will be tested between calcite precipitation and regional historical climate (temperature and seasonality) data, as well as the record of paleoproductivity via stable isotope analyses of both calcite and organic matter. We will also examine the sediment record for phosphorous loading and compare it with historical records of cultural activity on a lake by lake basis. If the cultural eutrophication hypothesis is correct, we would expect to see considerable temporal variability in the sediment record of eleven different lake basins which have independent watershed histories. However, if the global change hypothesis is correct, we would expect to see a more or less synchronous regional response as a consequence of broad-scale environmental change. Also needed will be data on carbon dioxide concentrations in the epilimnion of hard-water lakes and the overlying atmosphere at times of intense picoplankton blooms and whiting events.

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