

## Littlefield Lake, Michigan: Carbonate budget of Holocene sedimentation in a temperate-region lacustrine system<sup>1</sup>

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### *Abstract*

Littlefield Lake is in a late stage of marl lake evolution characterized by reduced rates of carbonate precipitation. Long and short term carbonate budgets show that the volume of calcite in the lake basin is 3-7 times that expected from annual calcium depletion in the epilimnetic water. This Holocene decrease in carbonate production is also recorded as a gradual increase in the amount of organic and carbonate material in cores from the deep lake basin. Late-stage reduction in carbonate production is evidently a natural consequence of lakeward progradation of littoral marl benches, encroachment of terrestrial vegetation, and reduced colonization by carbonate-producing lake macrophytes.

Carbonate-precipitating lakes and associated marl sediment of nearly pure low-magnesium calcite fill depressions in glacial drift throughout temperate regions of the world. Both the water chemistry and ecology of such lakes have been investigated, primarily to determine the relative importance of physicochemical (e.g. Brunskill 1968, 1969; Terlecky 1974) and biochemical (e.g. Dean 1981; Gilbert and Leask 1981) processes in carbonate precipitation. Despite the obvious and intimate link between these processes and marl generation, lake deposits themselves have received comparatively little attention.

In addition to the paucity of sedimentary data, our knowledge of lake evolution is hindered by ambiguities surrounding the long term relation between primary productivity and carbonate formation. Wetzel (1970, 1975) and Manny et al. (1978) found that in marl lakes in Michigan and Indiana, except during early post-glacial sedimentation, when rates of autochthonous organic and carbonate deposition were high, periods

of high carbonate sedimentation generally coincided with periods of low organic matter accumulation. This inverse relation has been attributed to reduced photosynthetic efficiency as particulate carbonate adsorbs and complexes essential metallic and organic compounds and suppresses microbial nutrient regeneration (Wetzel 1970). Conversely, positive correlations between carbonate and organic matter accumulation have been reported for Canadian marl lakes (Hickman and Klarer 1981; Last 1982). Hickman and Klarer (1981) suggested that this direct relation reflects increased biological activity during warmer periods and enhancement of both physical and biological conditions necessary for carbonate production.

Thus two distinctly different trends in marl lake evolution have been inferred from sedimentary evidence. Neither of these models considers the influence of bog organic compounds which often come to overlie marl carbonates as terrigenous vegetation encroaches on littoral areas (e.g. Wetzel 1975). Because of infilling, marl lake sediment should record transitions from lacustrine carbonates and allochthonous organic matter to bog facies rich in autochthonous organic matter. If such a transition is typical of mature marl lakes, it should result in a significant decrease in carbonate production and a negative correlation between carbonate and organic matter in younger sediments.

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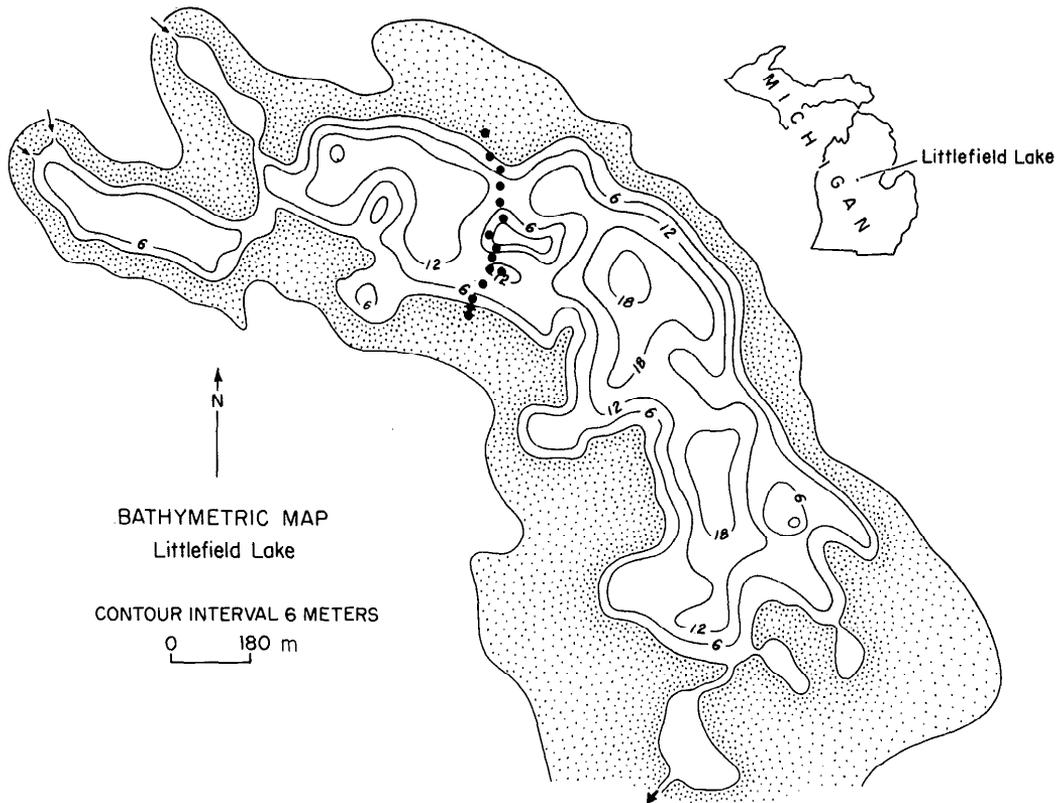


Fig. 1. Bathymetric-geologic map of Littlefield Lake. Stippled area is underlain by Holocene peat and marl which is in turn underlain and surrounded by glacial drift. Arrows—inlets and the outlet; ●—positions of the 15 cores in Figs. 3–6. (Bathymetry modified from Inst. Fish. Res. unpubl. rep.)

An absence of these trends may indicate that a lake basin has not yet matured to this transition stage. Similarly, such transitions would not be discernible if an incomplete sediment column was recovered in cores or if sediment columns contained allochthonous units. The latter consideration may be particularly significant because it is now clear that two distinct facies may be deposited in these settings (Wetzel and Manny 1978; Murphy and Wilkinson 1980; Treese and Wilkinson 1982). Whereas littoral bench and lakemount deposits typically consist of autochthonous shelly and sandy algal micrites, basin center sediments commonly include allochthonous masses of carbonate from surrounding marl benches. Such basinal deposits consist of complex sequences of older sediment overlying younger (e.g. Wetzel and Manny 1978; Treese and Wilkinson 1982).

We here test these hypotheses through

analysis of cores from marl benches and the central basin of Littlefield Lake, a marl lake in south-central Michigan. The history of carbonate deposition in this lake is developed from a comparison of the present carbonate production rate with that calculated from the total volume of Holocene sediment in the lake basin and from observed changes in sediment composition with depth.

#### General setting

Littlefield Lake is a dimictic lake, about  $2.5 \times 0.5$  km, in a basin of several coalesced kettles in Isabella County, Michigan. A broad marl bench has formed along the entire shoreline and three well developed lakemounts have built to the lake surface (Fig. 1). Distributions and thicknesses of component Holocene facies strongly suggest that Littlefield Lake rapidly filled to its present

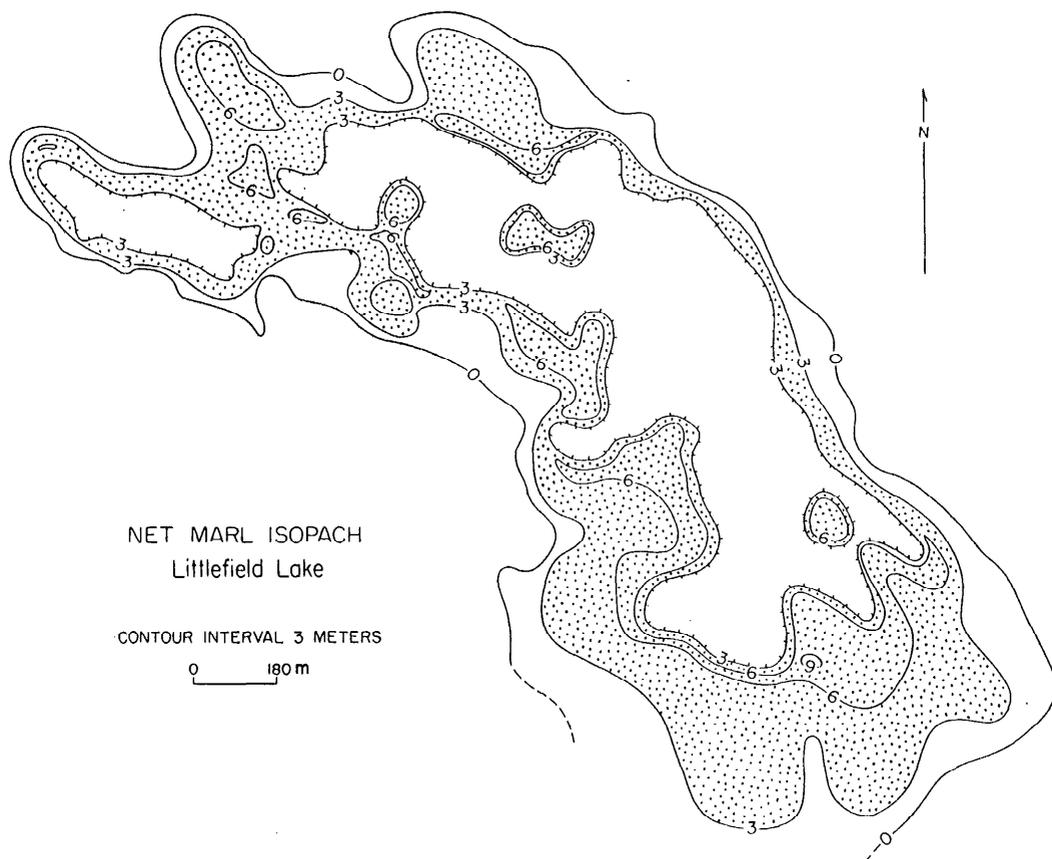


Fig. 2. Net marl isopach of Littlefield Lake, contoured from data of Davis (1903) and from this study. Stippled areas are underlain by marl sequences  $> 3$  m thick; these thicker sediment accumulations underlie lake margin benches and basin center lakemounts.

level soon after the retreat of Wisconsin ice and that lake levels and general patterns of sedimentation have changed little since (Murphy and Wilkinson 1980).

The water comes from subaqueous springs and from three small streams which enter two daughter lakes to the northwest; the outlet flows through a daughter lake at the southeastern end of the lake basin (Fig. 1). The water entering this system is saturated with respect to calcium carbonate due to percolation through the surrounding calcareous glacial drift. Terrigenous siliciclastic and carbonate debris entering from the northwest via the three streams are largely trapped in small deltas as the streams enter the daughter lakes. Thus the lake deposits are composed mainly of extremely pure calcite, which atomic absorption spectroscopy

and X-ray diffraction analyses indicate contain 2–3 mol %  $MgCO_3$ . Small amounts of aragonite are present as mollusc shells, and minor amounts of quartz, pyrite, feldspar, and occasional illite and chlorite as a clay-sized fraction (Murphy and Wilkinson 1980).

We selected Littlefield Lake for study because it (and its drainage basin) has remained relatively unmodified by human development and because the data needed for carbonate budget calculations have been obtained during several recent studies of water chemistry (Dustin et al. 1986), surficial sediment geochemistry (Treese et al. 1981; Owen and Wilkinson 1983), and sediment facies distributions (Murphy and Wilkinson 1980; Treese and Wilkinson 1982). The system is also of historical in-

Table 1. Areas and volumes of water and sediment in the Littlefield Lake basin. Total basin refers to the original water-filled volume of the lake basin following retreat of Wisconsin ice.

	Surface area ( $10^3 \text{ m}^2$ )	Present vol ( $10^6 \text{ m}^3$ )
Epilimnetic water	7.99	5.86
Hypolimnetic water	4.65	1.73
Total water	7.99	7.59
Total sediment	17.45	5.79
Total basin	17.45	13.38

terest because it was among the first temperate region marl lakes to be investigated (Davis 1900, 1903).

#### Long term carbonate budget

We made two preliminary maps to determine net Holocene sediment thicknesses. One was a map of elevations on the Pleistocene drift surface, based on data from U.S. Geological Survey topographic measurements, from Davis (1903), and from our own study. The other was a map of Holocene and Pleistocene units from USGS topography and from a bathymetric map of Littlefield Lake (Inst. Fish. Res. unpubl. rep.). A net Holocene sediment isopach was then derived by calculating differences in elevations of these two surfaces (Fig. 2). This method allows for reasonable estimates of Holocene sediment thickness in areas of low data density with a probable accuracy to  $\pm 1$  m. Fine-grid graph paper was then superimposed over the bathymetric and sediment

thickness maps (Figs. 1, 2), and the areas between isopachs and isobaths were determined. From these data, the volumes of Holocene sediment and water were calculated for the lake basin (Table 1).

In Littlefield Lake, the average depth to the thermocline during summer stratification is 10 m (Murphy and Wilkinson 1980) and the volume of epilimnetic water during summer carbonate production is  $5.86 \times 10^6 \text{ m}^3$  (Table 1). Most carbonate is precipitated and deposited on broad shallow benches which surround the lake. Because of the greater sedimentation rate around the lake margin and shallow lakemounts (Fig. 2), the area of the lake basin has decreased more rapidly than its volume. Water now covers 46% of the original lake area but occupies 57% of the original basin volume. This difference implies that the rate at which the volume of epilimnetic water has decreased is proportional to the rate of decrease in area and not of total water volume. Because facies boundaries within the sedimentary fill of the lake basin are horizontally persistent (Murphy and Wilkinson 1980), the average Holocene depth to the thermocline has probably remained at about 10 m; hence, the average Holocene volume of epilimnetic water during carbonate precipitation has been  $9.28 \times 10^6 \text{ m}^3$ .

We collected 15 cores, extending from the sediment-water interface to the surface of underlying terrigenous sand and gravel along a north-south transect to determine sedi-

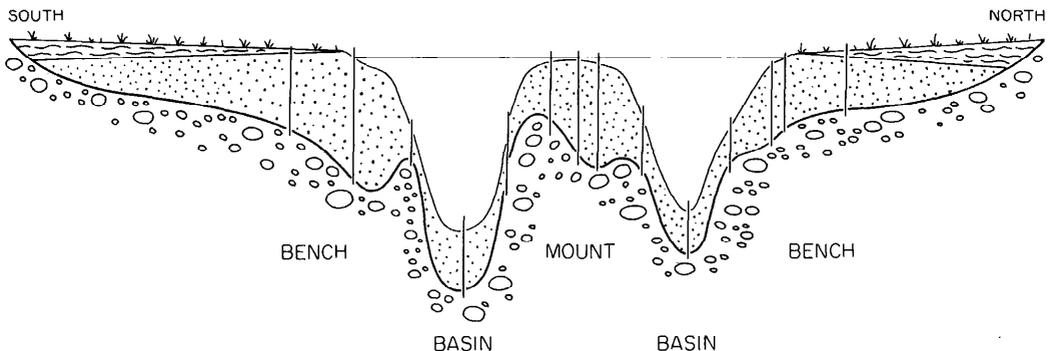


Fig. 3. Section through Littlefield Lake showing the distribution of Holocene sediment. Solid lines—cores in Figs. 4, 5, and 6; wavy lines—peat accumulations along the lake margin; stippled area—marl sediment; open area—presently occupied by water. Note thicker sediment accumulation over lakemounts and along lake margins. Section location shown in Fig. 1.

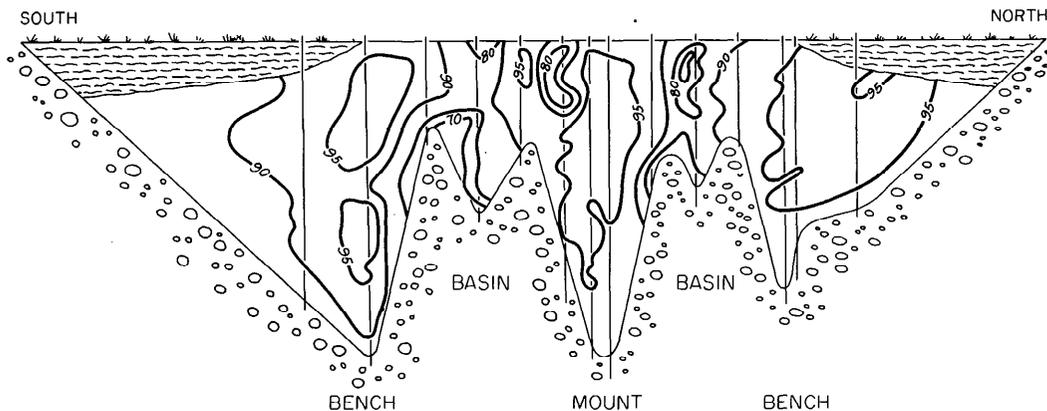


Fig. 4. Section through Holocene sediment in the Littlefield Lake basin hung on the Holocene sediment surface (largely the sediment-water interface), with isopleths of carbonate content as dry wt %  $\text{CaCO}_3$ . Wavy lines (here and in Figs. 5 and 6)—Holocene peat. The purest carbonate ( $>95\%$   $\text{CaCO}_3$ ) occurs as lakemount and lake margin bench sequences.

ment composition (Fig. 1). Each was split and sampled at 30-cm intervals except where abrupt facies changes necessitated closer spacing. The amount of carbonate, organic, and siliceous material (diatom frustules, feldspar, and clay minerals) was determined by loss on ignition (e.g. Dean 1974); the precision of these determinations is  $\pm 2\%$  for carbonate and  $\pm 1\%$  for organic and siliceous matter. Because core spacing was not even across this transect (Fig. 3), isopleths of carbonate, siliceous, and organic components were then constructed (Figs. 4, 5, and 6) and the sectional areas of differing carbonate purity measured as a function of depth below lake level (Table 2).

We used data from Guillet (1969) to determine sediment water content as a function of marl sediment composition:  $W = 111.53 - 0.572C$  where  $W$  is wt % water and  $C$  is wt % carbonate in dry sediment, with a highly significant correlation coefficient ( $P < 0.01$ ). On the basis of carbonate content, the average water content of Littlefield Lake sediment is 57.6% by weight. We then calculated the total mass of carbonate in the lake basin from the total volume of sediment (Table 1) using an average water content of 58%, an average carbonate content of 93% (Table 2), and a carbonate density of  $2.7 \text{ g cm}^{-3}$ . The mass of  $\text{CaCO}_3$  in Littlefield Lake sediments is  $61.0 \times 10^{11} \text{ g}$ .

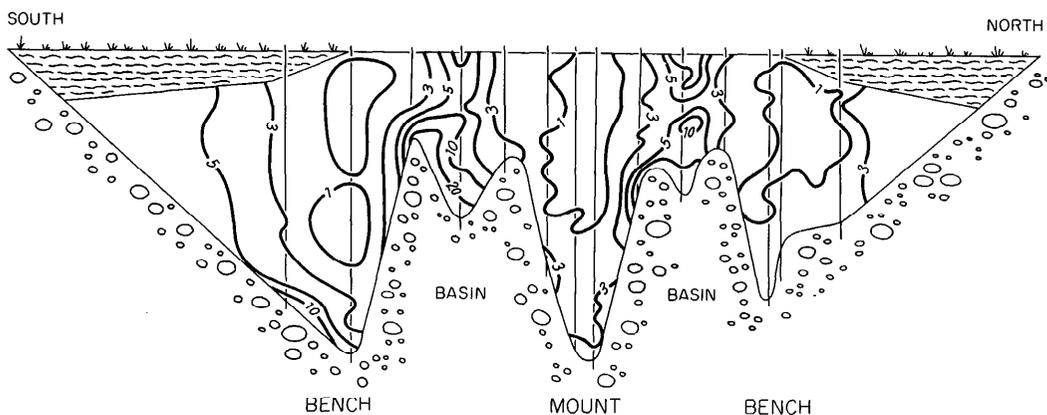


Fig. 5. As Fig. 4, but of siliceous components. These are most concentrated in sediment filling deeper lake basins.

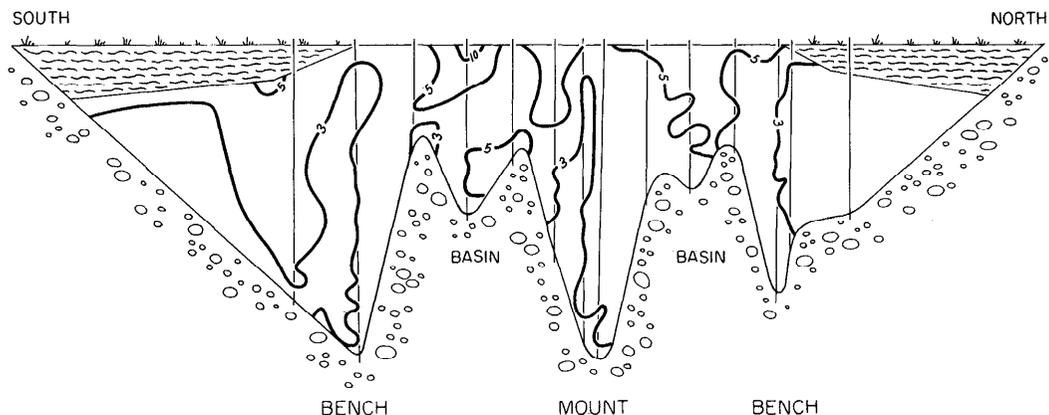


Fig. 6. As Fig. 4, but of organic components. Organic material is most concentrated in sediment filling deeper lake basins.

The maximum age of Holocene deposits was determined by  $^{14}\text{C}$  analysis of organic debris at the bottoms of four cores. The age of the oldest marl (that immediately overlies the dated organic material) is about 11,500 B.P. (Table 3). The epilimnetic water volume has averaged  $9.28 \times 10^6 \text{ m}^3$  over this period while  $61.0 \times 10^{11} \text{ g}$  of carbonate has accumulated. Hence, the long term annual carbonate production rate, as  $\text{g CaCO}_3$

$\text{m}^{-3}$  of epilimnetic water per year, is about  $57.1 \text{ g m}^{-3} \text{ yr}^{-1}$ .

#### Short term carbonate budget

To compare annual variations in water chemistry to the history of carbonate deposition in this basin, we did various chemical analyses at monthly intervals for 15 months between 1978 and 1979 (Dustin et al. 1986). Changes in calcium concentration

Table 2. Proportions of Littlefield Lake sediment, by  $\text{CaCO}_3$  content, cored in the transect of Fig. 1. Data expressed as square meters of the  $3,029 \text{ m}^2$  of the sediment in the section of Figs. 4-6. The median sediment carbonate content is about 93%  $\text{CaCO}_3$  and the purest marl occurs about 1.5 m below lake level. This position corresponds to the crest of the marl bench slope; landward, carbonate is diluted with organic debris from subaerial swamps; basinward, sediment contains increasing amounts of organic and siliceous debris.

Elevation relative to lake level (m)	% $\text{CaCO}_3$								Total
	100-98	98-96	96-94	94-92	92-90	90-80	80-70	70-60	
1.5			12.2	32.9					45.1
0.5		10.7	115.0	198.6					324.3
-0.5	12.5	88.5	103.1	170.5	4.6	1.3			380.5
-1.5	47.9	119.9	83.3	94.3	25.0	4.3	0.3		375.3
-2.5	20.7	142.7	67.7	87.8	4.9	5.5			329.3
-3.5		127.5	70.8	89.4	4.3	0.6			392.6
-4.5		111.0	90.6	53.4	2.4	0.3			257.7
-5.5		71.7	90.3	51.2	11.9	3.4			228.5
-6.5		15.9	107.1	69.8	22.6	7.3			222.7
-7.5		2.4	57.0	16.2	35.7	10.7	9.8		131.8
-8.5			6.4	38.4	35.4	16.5	4.0		100.7
-9.5			0.6	14.6	21.7	12.8	5.8	0.3	55.8
-10.5				4.9	22.0	14.6	8.8	6.4	56.7
-11.5				0.9	20.7	27.1	5.8	4.6	59.1
-12.5					10.7	22.9	31.3	6.1	71.0
-13.5					2.4	27.8	5.8	5.5	41.5
-14.5						15.6	7.9	3.7	27.2
-15.5						8.5	7.6	0.6	16.7
-16.5						4.3	4.6	0.6	9.5
-17.5						0.9	0.6	1.5	3.0

Table 3.  $^{14}\text{C}$  dates for organic debris at the base of four cores taken in Littlefield Lake. WF—Wood fragment; MPD—macerated plant debris. Average age is 11,530 years.

Sample	Depth (m)	$^{14}\text{C}$ (‰)	Age (B.P.)
2-cm WF	8.7	$-761.9 \pm 3.5$	$11,530 \pm 410$
MPD	8.9	$-771.3 \pm 3.4$	$11,950 \pm 390$
3-cm WF	8.6	$-750.3 \pm 3.7$	$11,160 \pm 290$
MPD	9.6	$-760.3 \pm 29.0$	$11,480 \pm 1,200$

are particularly important in this regard in that AAS analyses of Ca concentrations, accurate to 0.1 ppm, record periods of carbonate precipitation and dissolution (Fig. 7). These data were used to calculate a modern annual Ca and  $\text{CaCO}_3$  budget for the lake (Table 4). The average Ca concentration in shallow epilimnetic water during the 32-week period when the lake is stratified decreases from 43.7 ppm to 40.7 ppm; this 3.0-ppm depletion corresponds to the removal of  $18.0 \times 10^6$  g of Ca, or  $45.0 \times 10^6$  g of  $\text{CaCO}_3$ , per year (Table 4). During this

same period, there is a slight increase (0.2 ppm) in hypolimnetic Ca concentrations due to the dissolution of settling  $\text{CaCO}_3$  particles and, possibly, from input from subaqueous springs. Consequently, the net Ca removal from the lake is  $17.7 \times 10^6$  g, or  $44.3 \times 10^6$  g  $\text{CaCO}_3$ , per year (Table 4). Thus, the short term annual carbonate production rate, as g  $\text{CaCO}_3$   $\text{m}^{-3}$  of epilimnetic water per year, is about  $7.56$  g  $\text{m}^{-3}$   $\text{yr}^{-1}$  (Table 5). Given the rate and an average Holocene epilimnetic volume of  $9.28 \times 10^6$   $\text{m}^3$ , this calcium flux corresponds to  $8.07 \times 10^{11}$  g of carbonate precipitation over the past 11,500 years (Table 5).

#### Long vs. short term rates

Data on Littlefield Lake sediment and water volumes and compositions indicate that the basin contains  $>7$  times the amount of  $\text{CaCO}_3$  that would be anticipated based on modern calcium fluxes from epilimnetic water (Table 5). Analysis of the errors inherent in estimates of lake basin geometry, sediment volume, age, and composition, and

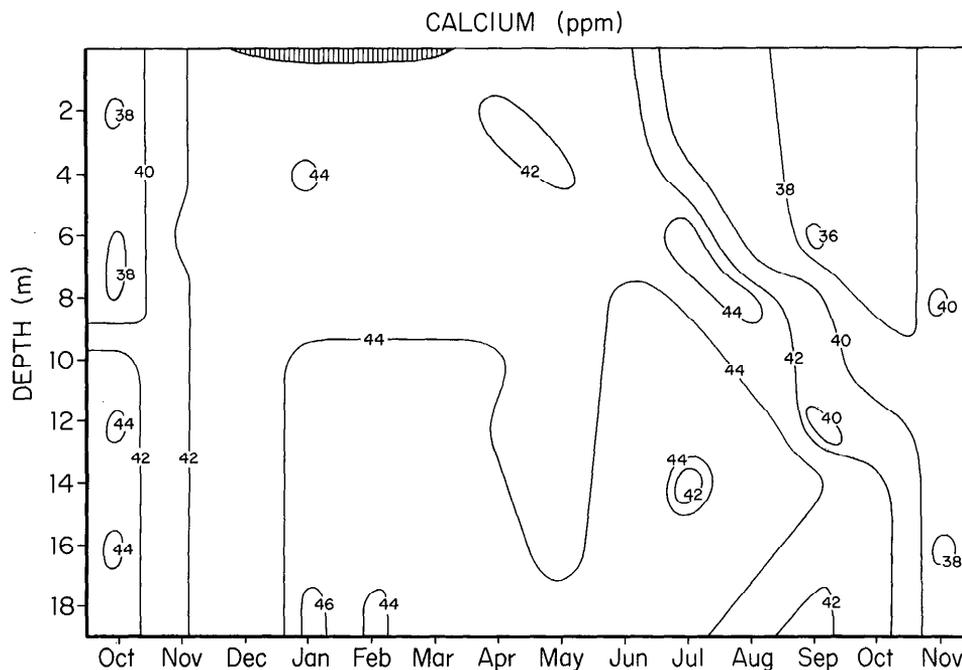


Fig. 7. Present annual variation in calcium concentrations in Littlefield Lake. Note uniform concentrations during fall and spring overturns (November and May), slight hypolimnetic enrichment during the winter isothermal period, and epilimnetic depletion during summer stratification as the thermocline migrated from 6 to 10 m. Striped lines—ice cover.

Table 4. Modern calcium and carbonate budget for Littlefield Lake.

	Measured Ca (ppm)	Mass Ca	Mass CaCO <sub>3</sub>	Annual flux (10 <sup>6</sup> g)	
		(10 <sup>6</sup> g)		Ca	CaCO <sub>3</sub>
Isothermal period (20 weeks)					
Water vol. <10 m	43.7	256	640		
Water vol. >10 m	43.7	75.6	189		
Total		332	829		
Stratified period (32 weeks)					
Epilimnion (<10 m)	40.7	238	595	-18.0	-45.0
Hypolimnion (>10 m)	43.9	75.9	190	+0.3	+0.7
Total		314	785	-17.7	-44.3

present carbonate production rate suggests that this difference is much too large to be the result of cumulative error. One other possible explanation is that the lake was precipitating a large amount of Ca received from subaqueous springs. This would amount to a hidden Ca cycle not apparent in epilimnetic concentrations, causing a significantly larger CaCO<sub>3</sub> production than that inferred from Ca depletion. Although we have no way of testing this possibility directly, the amount of Ca introduced from such a source can be constrained by the water chemistry data (Fig. 7). In particular, because essentially no carbonate production occurs during colder months when marl lakes are isothermal (Ludlam 1969; Kelts and Hsu 1978), any Ca input from subaqueous springs should be manifested as an increase in Ca concentration during this period. Megard (unpubl. rep.) observed this exact situation in several other carbonate-producing lakes. In order to estimate the *maximum* amount of Ca which could be supplied in this manner, we must make three assumptions: that

the lake is in a steady state with respect to Ca concentrations (i.e. the mass of Ca lost during summer carbonate production is replaced by recharge during the winter isothermal period); that Ca recharge is entirely from subaqueous springs (i.e. no Ca is made available from the dissolution of carbonate particles at depth; probably an unrealistic assumption considering the undersaturated nature of deep lake waters, but one that overestimates subaqueous calcium sources); and that the rate of subaqueous Ca input remains relatively constant throughout the year.

The first two assumptions require that the total amount of Ca entering the lake from subaqueous springs during the 20-week isothermal recharge period be equal to the total amount lost during the stratified period, or  $17.7 \times 10^6$  g (Table 5). The last assumption requires that the total mass of Ca entering the lake from subaqueous springs during the 32-week stratified period of carbonate production be  $17.7 \times 10^6$  g  $\times$  32/20, or  $28.3 \times 10^6$  g. If this Ca were all precipitated, then a maximum of  $70.7 \times 10^6$  g of CaCO<sub>3</sub> could accumulate per year as a result of a subaqueous Ca source. Adding this to the mass flux of CaCO<sub>3</sub> in the original budget ( $44.3 \times 10^6$  g CaCO<sub>3</sub>, Table 4) and converting the result to g CaCO<sub>3</sub> m<sup>-3</sup> of epilimnetic water per year indicates that the maximum possible production rate of CaCO<sub>3</sub> would be  $19.6$  g m<sup>-3</sup> yr<sup>-1</sup>. This rate corresponds to a total Holocene production of  $20.9 \times 10^{11}$  g of CaCO<sub>3</sub> (Table 5), a value still only about a third of the amount of carbonate actually in the lake basin.

Although it is likely that some Ca does

Table 5. Long and short term annual carbonate production rates in Littlefield Lake. For comparison, all are expressed as annual rates (mass of carbonate per cubic meter of epilimnetic water per year) and as Holocene rates (total mass of carbonate in the lake basin).

	Long term rate based on total carbonate	Short term rate based on annual Ca flux	Short term rate based on hidden Ca source
Annual rate (g m <sup>-3</sup> yr <sup>-1</sup> )	57.1	7.56	19.6
Holocene rate (10 <sup>11</sup> g)	61.0	8.07	20.9

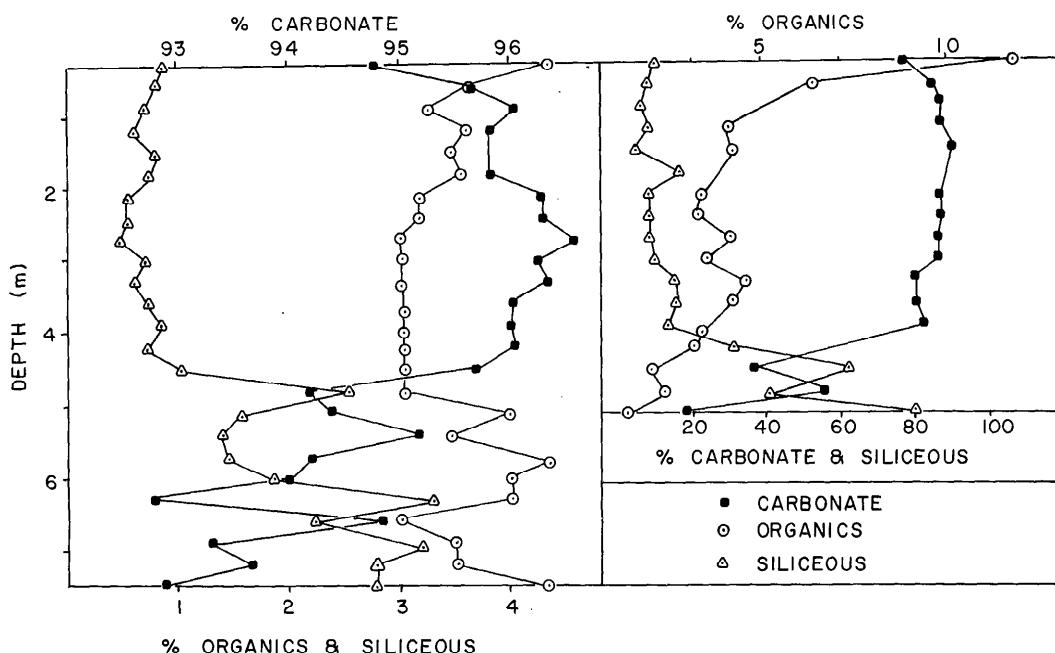


Fig. 8. Variation in the concentration of organic, carbonate, and siliceous components in two Littlefield Lake cores. Left core is typical of shallow water lake margin bench and lakemount sequences; right core is typical of deeper basin center sequences. The distribution of siliceous components decreases upward in both sequences, reflecting the progressive vegetation of the drainage basin and the decreased influx of terrigenous material during basin filling. The distribution of carbonate and organic components is similar in the two sequences. The decrease in organic matter toward the top of the shallow water core merely records the encroachment of a vegetated bench surface with basin filling. A similar decrease in the top of the deep water core, however, records a general decrease in the amount of carbonate relative to organic material deposited over the entire lake basin.

enter the lake from springs, the amount involved probably is much less than that calculated above. The primary mechanism of Ca removal/recharge most likely involves summer carbonate precipitation on shallow marl benches surrounding the lake and winter carbonate dissolution in cold, undersaturated waters. No attempt was made to include this process in budget calculations, since it could not be distinguished from Ca recharge due to subaqueous springs; however, if any carbonate dissolution does occur, then the estimated short term production rates are too high because they include some Ca that is recycled rather than being removed as sediment, and the difference between short and long term rates is even larger. On the basis of all available data, there apparently has been a significant reduction in the rate of carbonate production in Littlefield Lake during Holocene time.

#### *Sedimentological evidence*

Facies distributions and transitions in Littlefield Lake cores are in agreement with reduced rates of carbonate production as suggested from long and short term carbonate budgets. In general, most marl lakes are filled with sediment deposited in two general settings. Shallow benches and lakemounts are sites of rapid accumulation of nearly pure coarse-grained carbonate. This material is largely generated in situ as encrustations on lacustrine macrophytes such as charophytes, which are particularly important in Littlefield Lake (Murphy and Wilkinson 1980). Sediment in deeper basinal settings, however, is more siliceous, and organic-rich hemipelagic mud may contain allochthonous masses of nearshore marl containing *Chara* cortical tubules.

Changes in the abundance of carbonate,

siliceous, and organic components in shallow and deep water sediment are similar but, in the case of organic material, for different reasons. Siliceous material is composed largely of epiphytic diatom frustules (e.g. Davis 1903), feldspar, and clay minerals (e.g. Murphy and Wilkinson 1980). Manny et al. (1978) reported that early post-glacial shallow water sediment in other marl lakes may contain abundant siliceous material overlain by units containing greater amounts of organic and carbonate components. In particular, they suggested that greater amounts of siliceous material in sediment older than 10,200 years record greater terrigenous input before early stabilization of watershed soils by vegetation. Basinal and nearshore sequences in Littlefield Lake show a similar trend (Fig. 8) and probably record a similar process.

Increasing organic and decreasing carbonate contents toward the tops of deep and shallow water cores, however, record very different effects. Virtually all nearshore sediment shows decreasing amounts of carbonate material and increasing amounts of organic material toward the surface (Fig. 8). Although it might be argued that this change reflects the decreasing rate of carbonate production suggested from the carbonate budgets, the included organic material consists largely of allochthonous fragments of terrigenous vegetation, indicating that this increase in organic content merely reflects encroachment of swamps and bogs on the vegetated bench surface. The migration of sedimentary environments during bench progradation has a greater influence on nearshore facies than do changes in carbonate production.

A similar argument cannot be made for the upward increase in the organic content of basinal sediments (Fig. 8) because the lake centers are far enough from the lake margins so that the sediment composition would not be likely to record a few tens of meters of basinward shoreline migration. Since basinal muds consist of the finer fraction of sediment generated in nearshore settings, their composition is more nearly an average sample of the amount of carbonate and organic material generated in the lake basin as a whole. Muds have become in-

creasingly organic as Holocene sediment has infilled lake margins, as areas of swamp-bog vegetation have expanded, and as areas of carbonate precipitation have contracted.

Evidently, as littoral areas become restricted and areas suitable for the growth of carbonate-producing macrophytes such as *Chara* become reduced, areas of subaerial terrigenous vegetation expand giving rise to an increased input of allochthonous organic debris. Studies of similar peatlands have shown that bog-swamp vegetation may rapidly remove up to 60% of dissolved nutrients (including Ca) from water percolating into lake basins (e.g. Verry and Timmons 1982). Thus the establishment, stabilization, and gradual encroachment of terrestrial vegetation on littoral areas of marl lakes are particularly effective in limiting carbonate production. As lake basins fill, marl lakes evolve from calcium-rich, alkaline lacustrine systems to calcium-depleted, acidic systems dominated by a decrease in the rate of carbonate production and an increase in organic matter production.

### Conclusions

Long term and short term carbonate budgets demonstrate that Littlefield Lake is now in a late stage of evolution characterized by reduced rates of carbonate production. The mass of calcite in the lake basin could not have formed at the contemporary precipitation rate, even allowing for a significant source of calcium from subaqueous springs. Moreover, if calcium recycling by sediment dissolution is important, the difference between the total measured carbonate mass and that inferred from the annual precipitation rate is even larger.

Carbonate sediment is rapidly deposited in nearshore areas, while deeper basins are filled by sediment derived from shallower zones. This difference in sediment source and depositional process gives rise to different sedimentary sequences. The Holocene decrease in carbonate production is reflected only in the relative amount of organic and carbonate matter in deep lake sediment. Conversely, similar changes in sediment composition in other lake basins may record dissimilar processes in these two depositional settings, and this may have led

to some of the confusion in the literature concerning relationships between carbonate and organic contents of marl sediments.

Reduction in the rate of carbonate precipitation in temperate-region marl lakes is a natural consequence of the lakeward progradation of nearshore marl benches, expansion of areas of terrestrial vegetation, increased rates of calcium removal from percolating water, reduced areas suitable for carbonate producing macrophytes, and reduced surface areas and epilimnetic water volumes.

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