Limnol. Oceanogr., 50(2), 2005, 629–635

The origin of the fluid mud layer in Lake Apopka, Florida

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Abstract

Since it switched from a macrophyte-dominated state to a turbid, algal-dominated state in 1947, Lake Apopka has developed a layer of flocculent sediments with characteristics of fluid mud covering most of the lakebed and averaging 47 cm in thickness in 1996. Waves in this large, shallow lake frequently resuspend the upper portion of the fluid mud and frustrate programs designed to decrease the trophic state. We tested two hypotheses for its origin, one that the fluid mud layer represents the buildup of organic materials that had accumulated since 1947, the other that it was derived primarily by the liquefaction of the underlying macrophyte-derived consolidated sediments. We examined (1) changes in the mean depth of the lake relative to changes in fluid mud thickness; (2) ^{210}Pb dating of the sediments; (3) organic matter budget for the lake; (4) inorganic particle budget for the lake; and (5) chemical markers of sediments produced during the macrophyte stage (biogenic silica from sponges, long-chain n-alkanes from macrophytes, and ^{13}C) in the fluid mud. The evidence indicates that a major portion of the fluid mud can be attributed to the liquefaction of underlying consolidated sediments that were produced during the macrophyte stage of the lake. It follows that the fluid mud layer is less a direct consequence of eutrophication than a consequence of enhanced wave action on the lakebed following the loss of macrophyte dominance in this lake.

Lake Apopka, Florida, has been a highly eutrophic lake for the past half century and has been considered as an example of cultural eutrophication. Several recent actions to reoligophy the lake have included the $100,000,000 purchase of adjacent farm lands by the state, development of an artificial marsh to remove phosphorus from the lake, and netting to remove gizzard shad (Lowe et al. 2001). A major impediment to a reversal in trophic state has been a layer of fluid mud (flocculent sediments) about 47-cm thick that covers 90% of the lake bed in this large (124 km^2) but shallow (mean depth = 1.7 m) lake. Large waves frequently resuspend the upper portion of the fluid mud, as well as a layer of meroplankton algae (Carrick et al. 1993) that grows on its surface, and result in high levels of total phosphorus, chlorophyll *a*, and suspended solids in the water (Bachmann et al. 1999). Living phytoplankton make up only 10% of the total suspended solids by weight in the water column, so it is the resuspended solids that make a significant contribution to the poor water clarity in this lake (Bachmann et al. 1999). Because of its importance to the limnology of the lake, we are interested in the origin of this sediment layer.

Lake Apopka is a classic example of the phenomenon of alternative stable states (Scheffer 1998). Historically the lake was dominated by macrophytes that covered about 85% of the surface area, and the water within the plant beds was reported to be clear (Clugston 1963). Starting in the fall of 1947, the macrophyte cover was rapidly lost and the lake waters lost their former clarity as phytoplankton became the dominant plant form and highly organic sediments were resuspended by wind-driven waves (Schelske et al. 1995). The cause of the switch has been attributed to nutrient inputs from a large marshy area on the north side of the lake that was diked off from the lake for agricultural production in the early 1940s. During wet periods, nutrient-rich water was pumped from the farms into the lake. An alternative explanation is that in 1947 hurricane winds (Schelske et al. 1995) or a tornado associated with the hurricane (Bachmann et al. 2001) uprooted aquatic macrophytes in a portion of the lake and initiated the switch to algal dominance. The macrophytes were all but eliminated by the early 1950s (Clugston 1963), and the turbid algal-dominated state has been stable up to the present time.

The flocculent surface sediments in Lake Apopka have an average bulk density of 1.02 g cm^{-3} (Bachmann et al. 1999). This puts them in the range for fluid mud, since Ross (1988) reported characteristic values of bulk density for fluid mud ranging from 1.01 to 1.10 g cm^{-3} depending on sediment composition and the state of agitation. Fluid mud can be defined as a mixture of mainly fine sediments with water that has practically no shear strength. While fluid mud layers were originally described for coastal systems, they have been found in inland lakes as well, including Lake Okeechobee, Florida (Mehta 1996).

Fluid mud is generated by liquefaction of cohesive sedi-

Acknowledgments
This manuscript benefited from constructive comments provided by associate editor Jack Middelburg and two anonymous reviewers. Journal Series R-10245 of the Florida Agricultural Experiment Station, Gainesville, Florida.

ment beds by wave action or by an imbalance between settling and eddy diffusion near the bed. Wave-induced liquefaction of a cohesive sediment bed can be one of the main mechanisms for the formation of fluid mud in wave-dominated environments. At the upper surface of the fluid mud there is a region with a steep gradient termed the lutocline that forms the boundary between the water column and the unconsolidated sediments below (Vinzon and Mehta 1998). Waves provide an effective mechanism to maintain these sediments as unconsolidated below the lutocline.

Theories of accumulation—The first theory of origin was that the fluid mud layer in Lake Apopka represented the remains of dead algal cells that had been accumulating since the lake made its switch in 1947 (Schneider and Little 1969), and that this accumulation is the result of accelerating eutrophication (Reddy and Graetz 1991; Schelske 1997). A survey in 1968 found that the fluid mud averaged 10 cm in thickness and covered 90% of the lake bed (Schneider and Little 1969). These materials overlaid consolidated organic-rich sediments. The fluid mud layer increased to 32 cm in thickness in 1987 (Reddy and Graetz 1991) and 47 cm in 1996 (Schelske 1997). According to the accumulation theory, the consolidated sediments below the fluid mud layer represented sediments laid down during the macrophyte state, and the majority of the fluid mud layer represented sediments laid down since the loss of the macrophytes except for a small amount of macrophyte sediments generated at the time the lake made its switch to algal dominance. Subsequent investigators have used the boundary layer between the flocculent sediments and the underlying consolidated materials as a date marker (either 1945 or 1947) for paleolimnological studies and to calculate rates of phosphorus storage over time (Lowe et al. 1992; Schelske 1997).

We have previously questioned this untested theory (Bachmann et al. 2000), since there seem to be some inconsistencies. We do not see other examples of lakes with rapidly growing flocculent sediment layers, and also it did not seem likely that dead algal cells would resist decomposition and accumulate in a subtropical lake with frequent sediment resuspension into oxic waters. Whitmore et al. (1996) studied seven other Florida lakes and found that organic sediments were ''often grossly lacking because the basins are shallow, and frequent mixing, lack of stratification, and warm temperatures lead to breakdown of organic material.'' As we will document later, we also could see no indication that the mean depth of the lake was decreasing in response to an accumulation of flocculent sediments.

We have proposed a second theory suggesting that a substantial portion of the fluid mud layer in Lake Apopka has been formed by liquefaction of the underlying consolidated sediments (Bachmann et al. 2000). When waves act on the low-permeability mud bed, the porewater pressure increases, until the effective normal stresses vanish and the bed is fluidized. The wave normal pressures acting on the deformable bed induce shear stresses in the bed that can be large when compared with the flow-induced shear stresses (de Wit and Kranenburg 1997) and enough to break the bonds between the consolidated sediment particles. Waves become attenuated as energy is transferred to the breakdown of sediment structure. The breakdown may occur by soil piping, followed by the failure of the soil structure around the cavities, and a fluid mud layer is generated. The equilibrium thickness of this layer is determined by water parameters and mud properties (Vinzon and Mehta 1998; Li and Mehta 2001).

The purpose of this study is to use the available data to evaluate the two hypotheses on the origin of the fluid mud layer in Lake Apopka. We will specifically examine the following: (1) Does the mean depth of the lake decrease in response to increases in the thickness of the fluid mud layer? (2) Can ^{210}Pb dating be used to date the interface between the fluid mud and the consolidated sediments? (3) Does the lake produce an excess of organic matter over decomposition to account for the amount of organic material stored in the fluid mud? (4) Does the annual input of inorganic particles to the lake exceed the annual loss through the outlet by a sufficient amount to account for the amount of inorganic particles stored in the fluid mud?, and (5) Are there chemical and biological markers in the fluid mud that can distinguish it from the underlying macrophyte-dominated sediments?

Data sources and methods

Water depths and fluid mud thicknesses—There have been three major studies of the Lake Apopka sediments involving physical and chemical measurements made on cores taken on grid patterns covering the entire lake (Schneider and Little 1969; Reddy and Graetz 1991; Schelske 1997). In addition Schelske (1997) has used a number of paleolimnological measurements on selected cores from the lake. We have used the results of these studies to test our hypotheses. To determine trends in lake mean depth, we took advantage of the fact that water depths in Lake Apopka have been measured with high precision on four occasions between 1968 and 1996. In June 1996, Schelske (1997) located 46 sampling stations on an equal area grid using a global positioning system. An infrared optical detector (Myers and Schelske 2000) was used to locate the interface between the soft, flocculent sediments and the overlying water, and the water depth at each station was measured to the nearest centimeter. We determined the lake level on each of their sampling days using U.S. Geological Survey (1958–1997) records and adjusted the measured water depths to an elevation of 20.1 m National Geodetic Vertical Datum (NGVD) to be consistent with the other studies of lake depths. The mean depth was calculated as the mean of the 46 adjusted depth measurements. We also calculated the mean of the 46 measurements of fluid mud thickness as determined by Schelske (1997) at the same stations.

In June 1989 the depth of water was measured at 329 points on a grid 609.6 m on a side using a fathometer (Danek and Tomlinson 1989). A side-by-side comparison of the fathometer readings with a photoelectric device that detects the surface of the fluid mud determined that the fathometer could accurately detect the sediment–water interface. The investigators used two water level recorders to correct each depth measurement to an elevation of 20.1 m. We determined the mean of their 329 depth measurements.

In June 1987 Reddy and Graetz (1991) determined both water depth and the thickness of the fluid mud at a grid of 90 stations spaced about 1,220 m on a side. They used a photoelectric device to detect the sediment–water interface. We used U.S. Geological Survey records of water levels on the sampling days to correct their water depth measurements to an elevation of 20.1 m and calculated the means of the measurements of water depth and fluid mud thickness.

In March 1968 Schneider and Little (1969) took sediment cores at 90 stations on a grid 1,220 m on a side like that used by Reddy and Graetz (1991) and recorded the thickness of the fluid mud. They also placed buoys 152 m apart on lines between the grid points and used them to guide a boat running at a constant speed and used a fathometer to chart water depths and lake bottom contours. These depths were used to construct a bathymetric map with a lake elevation of 20.3 m. We determined the lake volume with planimetry, and the mean depth was calculated and corrected to an elevation of 20.1 m.

Following Vinzon and Mehta (1998), we calculated the equilibrium height of the lutocline for a point at the center of Lake Apopka for the median wind velocity (5.8 m s^{-1}) and for the wind velocity that is exceeded only 10% of the time (10.7 m s^{-1}) (Bachmann et al. 1999). The wave heights and periods were calculated with the Sverdrup-Munk-Bretscheider (SMB) shallow-water wave model (U.S. Army Coastal Engineering Research Center 1984) with an effective fetch of 5,131 m and an average depth over the fetch of 1.72 m. In calculating the lutocline height (Vinzon and Mehta 1998) we used sediment properties from Schelske (1997) and took the water depth at the station as 1.57 m. The mean volumetric concentration of the suspended solids at the surface of the floc was 13 g L^{-1}, and the corresponding settling velocity of the flocs was taken as 0.1 mm s^{-1} based on the literature (van Rijn 1993; Gowland et al. in press). A bottom roughness of 0.05 m^{-1} was adopted according to the experiments reported in Vinzon and Mehta (1998). Based on the mean loss on ignition of the sediments of 0.687, the particle or granular density was taken as 1,500 kg m^{-3} according data for Florida lakes reported in Gowland et al. (in press).

^{210}Pb dating—Schelske (1997) made measurements of ^{210}Pb and ^{137}Cs in slices of sediment cores taken at 10 stations distributed across Lake Apopka. We used his ^{210}Pb data in the constant rate of supply model of Appleby and Oldfield (1978) to calculate the date at the bottom of the fluid mud layer.

Inorganic particle budget—We calculated external inputs of inorganic particles to the lake and losses through the outlet to compare with estimates of the rate of accumulation of inorganic sediments in the fluid mud layer. Since the lake is primarily fed by groundwater and has no surface streams that could supply inorganic particles, we examined data on the drainage water pumped from the adjacent muck farms. For the period 1988–1992 we obtained 338 measurements of total suspended solids in the waters pumped into the lake from the farms using the U.S. Environmental Protection Agency storage and retrieval (STORET) database. To be conservative we assumed that all of the particles were inorganic, though the muck soils of the farms are highly organic. The average concentration of particles was multiplied by the average annual amount of water pumped into the lake for the years 1989–1994 as reported by the St. Johns River Water Management District (SJRWMD). Loss of inorganic particles through the outlet was estimated by multiplying their average concentration in the lake times the average outflow volume from the lake (U.S. Geological Survey 1996) for the years 1958–1996. The total suspended solids in the lake waters were estimated from 120 monthly measurements made by SJRWMD from 1987 to 1996. According to Schelske et al. (1995), 36% to 49% of the total suspended solids in the water column consisted of inorganic materials, so we multiplied the average total suspended solids in the lake by 43% to estimate the inorganic content. Net accumulation of inorganic particles in the sediments in units of kilograms per year was found as the difference between inputs and outputs. For comparative purposes we converted our net sedimentation rates to units of centimeters per year by multiplying with a conversion factor based on the ratio of the average depth of the fluid mud layer (47 cm) to the total weight of the inorganic particles in the fluid mud layer (8.13×10^8 kg) as determined by Schelske (1997).

Chemical markers in sediments—We used the results of past paleolimnological studies to determine whether the composition of the fluid mud was similar to that of the sediments laid down prior to 1947 during the macrophyte stage. For example, Kenney et al. (2002) used measurements of sponge biogenic silica concentrations in selected sediment cores from Lake Apopka to differentiate between sediments laid down during periods of macrophyte dominance and periods of phytoplankton dominance. They noted that in Lake Apopka submersed macrophytes would provide the dominant substrate for freshwater sponges due to a lack of other solid substrates for attachment. Their data were taken from cores collected by Schelske (1997), who used a procedure described by Conley and Schelske (1993) to measure sponge biogenic silica concentrations in sections of sediment cores taken from Lake Apopka in 1995 and 1996. There were 93 measurements made on sections from 15 cores used in the sediment survey and 108 measurements made on sections of cores from nine stations that he also used for radiometric dating purposes (historic stations). We sorted the samples into fluid mud and macrophyte-based sediments using the fluid mud depths determined by Schelske (1997) and determined the mean concentrations of silica attributed to freshwater sponge spicules.

Silliman and Schelske (2003) used ratios of long-chain n-alkanes to short-chain n-alkanes in Lake Apopka sediment samples to distinguish sediments produced by macrophytes from those produced by phytoplankton. They explain that long-chain n-alkanes with 27, 29, and 31 carbons represent the remains of aquatic macrophytes, while the short-chain n-alkanes with 17 and 19 carbons are produced by phytoplankton. They studied two of the historic cores collected by Schelske (1997) with five sections from his core LA9-95 and three sections from his core LA-2H-96. Using Schelske's classification of fluid mud versus consolidated sediments, we grouped the samples by sediment type and found the means

Table 1. Average water depths adjusted to a surface elevation of 20.1 m and thickness of fluid mud between 1968 and 1996. Standard errors for fluid mud means given in parentheses. See text for data sources.

Year	Water depth (m)	Fluid mud thickness (cm)
1968	1.5	10 (2.1)
1987	1.5	32 (2.1)
1989	1.5	NA
1996	1.7	47 (2.9)

NA, not applicable.

and standard errors for the concentrations of long-chain and short-chain n-alkanes in the two sediment types.

Gu and Schelske (2004) used differences in stable carbon isotope ($\delta^{13}C$) ratios to identify sources of various carbon pools in Lake Apopka samples. We used the values in their table 1 to find the average $\delta^{13}C$ of the particulate organic carbon in the water column. For the macrophyte-derived sediments we found the average $\delta^{13}C$ for the organic matter samples in their sediment core extending from 40 to 80 cm in depth, and for the fluid mud layer we used the average $\delta^{13}C$ of their core samples extending from 0 to 35 cm in depth. On the assumption that the fluid mud contained a mixture of organic carbon from the water column and the consolidated sediments, we used the following equation to find the fraction of the organic carbon in the fluid mud that was derived from the underlying macrophyte-derived sediments.

$$f \times \delta^{13}C_{MAC} + (1 - f) \times \delta^{13}C_{POC} = \delta^{13}C_{FM} \qquad (1)$$

where f is the fraction of the fluid mud carbon from the macrophyte-derived sediments and $\delta^{13}C_{MAC}$, $\delta^{13}C_{POC}$, and $\delta^{13}C_{FM}$ are the $\delta^{13}C$ values for the macrophyte-derived sediments, the particulate organic carbon in the water column, and the organic carbon in the fluid mud, respectively.

Results

Water depths and fluid mud thickness—In the period from 1968 through 1996 the mean depth of the lake did not decrease (Table 1), but remained about the same or even increased. At the same time the average thickness of the fluid mud layer increased from 10 to 47 cm (Table 1). The fluid mud thicknesses measured in the 3 yr studied were all significantly different from each other. If the fluid mud represented primarily new materials deposited during the algal stage since 1947, then the mean depth would have decreased by an amount equivalent to the increase in thickness of the fluid mud layer. These data do not support the hypothesis that the fluid mud layer primarily consists of sediments laid down since 1947. Instead they support the hypothesis that they were formed by a liquefaction of previously consolidated sediments laid down during the macrophyte stage prior to the late 1940s with a smaller contribution of more recent sedimentary materials.

The fluid mud thicknesses as measured by Schelske (1997) were highly variable from place to place in the lake and ranged from 1 to 136 cm with 80% of the values between 13 and 96 cm. Thus, our calculations of the equilibrium lutocline heights (fluid mud thickness) due to wave action of 25 to 39 cm (Table 2) are within the range of values observed in Lake Apopka. Since our calculations were made for the center of the lake, different thicknesses might be expected at other locations due to varying wind fetches and water depths. This indicates that once the macrophytes were lost after 1947 and waves started to be generated in the lake, they were able to produce and keep the observed fluid mud in suspension below the lutocline.

Table 2. Lutocline height (H_e) calculated for the center of Lake Apopka based on wave heights and periods expected for the median wind velocity and the wind velocity exceeded 10% of the time.

Wind velocity ($m\ s^{-1}$)	Wave period (s)	Wave height (m)	H_e (cm)
5.8	1.62	0.20	25
10.7	2.00	0.33	39

^{210}Pb dating—The ^{210}Pb dates for the bottom of the fluid mud layer in the 10 cores averaged at 1947; however, the range in dates was considerable from 1895 to 1969 with a standard deviation of 23 years. Because of the wide scatter of the results, we agree with Schelske (1997), who concluded that ^{210}Pb dating could not be used for determining the year in which the sediments in the fluid mud started to accumulate. Among his reasons for discounting the ^{210}Pb dates was the fact that the diking of the farms reduced the surface area of the lake and thus changed the annual amount of atmospheric deposition to the lake. This violates the major assumption of a constant rate of supply of excess ^{210}Pb to the depositional sites in the lake. Schelske did use the distribution of ^{210}Pb with depth in the fluid mud layer to date the various levels by assuming that the bottom of this layer represented 1945.

The distribution of ^{210}Pb with depth in the fluid mud layer tended to be uniform (Schelske 1997) rather than show the usual exponential decrease with depth found in lakes with undisturbed sediments and constant rates of sedimentation. There are two ways that these types of curves might have been generated. One would involve vertical mixing within the fluid mud layer and the other exponentially increasing rates of sedimentation. Schelske (1997) assumed the latter and concluded that sedimentation rates were increasing exponentially in the decades since 1947. We disagree because there are no data to indicate that sedimentation would have increased in that manner. Since fluid mud is a suspension rather than a cohesive sediment, it is subject to movements in response to passing waves that could provide some vertical mixing within the layer (Mehta 1996). During storm events, resuspension of sediments would also contribute to vertical mixing. Likewise this type of mixing within the fluid mud layer could explain the lack of a strong peak in ^{137}Cs (Schelske 1997), representing the maximum rate of deposition in the early 1950s.

Primary production versus community respiration—In another paper (Bachmann et al. 2000), we tested the hypothesis

Table 3. Average concentrations (mg g^{-1}) of sponge biogenic silica and average concentrations (μg g^{-1}) of long-chain and short-chain *n*-alkanes in sections of sediment cores from Lake Apopka grouped by sediment type (fluid mud versus consolidated sediments) and core type. Standard errors are in parentheses. Sponge biogenic silica data are from Kenney et al. (2002), and *n*-alkane data are from Silliman and Schelske (2003).

		Fluid mud		Consolidated sediments	
Core type	Variable	*n*	Average	*n*	Average
Historic	Biogenic silica	62	10.1 (0.4)	46	12.8 (0.4)
Survey	Biogenic silica	76	16.1 (0.8)	17	18.2 (1.7)
Historic	Long-chain alkanes	4	1.4 (0.09)	4	1.9 (0.19)
Historic	Short-chain alkanes	4	0.16 (0.022)	4	0.06 (0.001)

that there was a surplus of organic matter produced in the lake by using the diel oxygen method to estimate gross production and community respiration in Lake Apopka. We also reanalyzed the results of five other studies of primary production in this lake. In all studies combined, community respiration exceeded gross production on 60 out of 76 days sampled. Out of the six studies, five showed negative net production and only one was positive; however, only two of the studies showed a net production statistically different from zero, and both of those showed negative net production. None of the studies support the hypothesis (Schelske 1997) that there is a surplus of organic carbon accumulating in the lake each year. In fact in recent years the lake seems to be consuming more carbon than is being produced. We have proposed (Bachmann et al. 2000) that with the loss of the macrophytes, the wind develops large waves that are able to resuspend organic sediments laid down during the macrophyte phase and that increased exposure to dissolved oxygen in the water column has resulted in accelerated decomposition of stored organics from the sediments.

Since the Bachmann et al. (2000) paper was published, Schelske et al. (2003) have published an analysis of their light and dark bottle measurements made at midday that were included in the Bachmann et al. (2000) study. When they use the standard method for estimating daily photosynthesis they found an average daily areal gross production of 2.06 mg C m^{-3} d^{-1} and an average daily areal community respiration of 6.68 mg C m^{-3} d^{-1}. These results indicate an average daily areal gross production of -4.62 mg C m^{-3} d^{-1}. This is in excellent agreement with the value of -4.57 mg C m^{-3} d^{-1} found by Bachmann et al. (2000); however, they went on to reject their measurements and used some unorthodox techniques to conclude the lake was not heterotrophic. We disagree with their approach and will address it elsewhere.

Inorganic particle budget—The mean concentration of total suspended solids in the water pumped from the muck farms was 72.6 g m^{-3} (SE = 4.9), and the average annual water load was 6.21×10^7 m^3 (SE = 1.7×10^7) for an annual load of particulates of 4.5×10^6 kg. Since it also includes organic materials, it is most likely an overestimate of the loading of inorganic particles. The mean concentration of total suspended solids in the lake water was 79 g m^{-3} (SE = 7.5) (Bachmann et al. 1999), so with a 43% inorganic content the inorganic suspended solids concentration would be 34.0 g m^{-3}. With an annual average outflow through the outlet of 6.21×10^7 m^3, the lake would be exporting 2.3×10^6 kg yr^{-1} of inorganic particles. The net retention of inorganic particles would be 2.2×10^6 kg yr^{-1} or an equivalent sedimentation rate of 0.1 cm yr^{-1} if we assume all of the particles in the water pumped from the muck farms are inorganic. The estimated net retention would be less to the extent that the pumped particles were organic rather than inorganic.

For comparison Schelske et al. (2000) made the assumption that the fluid mud represented sediments accumulated since 1945 and used the ^{210}Pb distribution in cores of these flocculent sediments with four different sets of assumptions to estimate the rate of accumulation of dry and organic sediments in Lake Apopka over the period 1986–1995. If we take inorganic sedimentation as the difference between total and organic sedimentation, their estimates of inorganic sediment accumulation range from 16.3×10^6 to 26.3×10^6 kg yr^{-1} or sedimentation rates of 0.9 to 1.5 cm yr^{-1}. Our inorganic particle budget indicates that the net accumulation of inorganic particles is only 8% to 13% of these amounts. These findings support the idea that the fluid mud layer incorporates a significant amount of sedimentary material laid down prior to 1947.

Chemical markers in sediments—The average concentrations of sponge biogenic silica in the fluid mud were slightly less than those in the consolidated sediments (Table 3). The differences were statistically significant at the 5% level of significance only for the historic cores. The average concentrations of sponge biogenic silica in the fluid mud and consolidated sediments were not different for the survey cores or for the historic and survey cores combined. Even for the historic cores the average concentration of sponge biogenic silica in the fluid mud was 79% of that in the consolidated sediments. Since the sponge biogenic silica is a marker for sediments produced in the macrophyte stage, these results support the liquefaction hypothesis for the origin of the fluid mud.

The average concentrations of long-chain n-alkanes, a marker of macrophyte remains, in the fluid mud were less than those in the consolidated sediments (Table 3); however, the differences were not statistically significant ($p = 0.054$). With a larger sample size the difference most likely would be significant. An important point is that the average concentration of long-chain n-alkanes in the fluid mud is about 73% of that in the consolidated sediments. The concentrations of short-chain n-alkanes, markers of an algal origin, were about 2.6 times higher in the fluid mud than in the consolidated sediments (Table 3). The difference was statistically significant ($p = 0.05$) and reflects the contribution of algal remains to the sediments since the switch to the algal-dominated state.

The average $\delta^{13}C$ signature for the fluid mud of -20.1 (SE $= 0.9$) does not match the average $\delta^{13}C$ of the particulate organic carbon in the water column of -13.8 (SE $= 0.1$) but is greater than the average fluid mud $\delta^{13}C$ of -24.5 (SE $= 0.1$). The results of applying Eq. 1 indicate that the macrophyte-derived sediments contribute 59% of the ^{13}C to the fluid mud. This supports the idea that the underlying macrophyte-derived sediments have made a significant contribution to the organic carbon in the fluid mud layer.

Discussion

The mean depth data do not support the theory that the fluid mud layer consists primarily of dead algal cells laid down since the lake switched to a phytoplankton-dominated state in the late 1940s. Rather than decrease by 37 cm between 1968 and 1996 to match the increase in thickness of the fluid mud layer during this time period, the mean depth stayed about the same. This could not be due to sediment compaction because the fluid mud is a suspension supported by water and not the underlying sediments. We recognize that it is hard to put an error term on the mean depths, so that we cannot make a statistical test, yet great care was taken in the four mapping efforts and the expected change of about 0.4 m is large compared with the mean depth of 1.5 m. These data seem to support the alternative explanation that a substantial portion of this layer consists of a reworking and resuspension of the consolidated sediments laid down during the macrophyte phase prior to 1947. The role of the wave action over soft beds is well documented (Li and Mehta 2001), and it was shown that the generated waves in Lake Apopka are enough to generate lutoclines with a thickness of the order of the observed ones. Because of the unique history of Lake Apopka, we agree with Schelske (1997) that lead dating could not be used to date the interface between the fluid mud and the consolidated sediments.

When we looked at the budget of organic and inorganic substances, we found that there was insufficient material accumulating since 1947 to account for the mass of the fluid mud layer. We cited an analysis of several past studies of primary production and community respiration that indicated that Lake Apopka is actually heterotrophic, consuming more organic matter than it produces. We also found that the input of inorganic materials to the lake seemingly is too small to account for the storage of inorganic particles in the fluid mud layer.

We also looked for characteristics of the sediments that would identify them as being produced during the macrophyte- or the phytoplankton-dominated states. Because there was reason to believe that there was some vertical mixing in the fluid mud layer, the presence of, say, diatom remains of species characteristic of open water plankton at the bottom of the fluid mud layer would not necessarily rule out the fluidization hypothesis. However, the presence of markers characteristic of the macrophyte phase in the fluid mud would indicate that there was an admixture of consolidated sediments in the fluid mud layer. We did find two markers of the macrophyte period in the fluid mud layer in substantial amounts. The concentrations of long-chain n-alkanes and of biogenic sponge silica in the fluid mud were 73% and 79% of the concentrations found in the consolidated sediments. The $\delta^{13}C$ data also provide support for the hypothesis that the fluid mud contains significant amounts of liquefied consolidated sediments laid down during the macrophyte phase and that they do not represent the accumulation of dead algal cells since 1947.

In summary, we made several tests of the hypothesis that the fluid mud layer in Lake Apopka represented the buildup of organic materials that had accumulated since the macrophytes were lost in 1947. We looked for changes in the mean depths of the lake, evidence of a surplus of plant production over community respiration to account for storage rates of organic matter in the fluid mud layer, evidence that inputs of inorganic particles to the lake exceeded exports to the extent that they could account for the storage rates of inorganic matter in the fluid mud, and for markers of sediments produced during the macrophyte stage (biogenic silica from sponges and n-alkanes from macrophytes) in the fluid mud. The results did not support the hypothesis. The evidence indicates that a major portion of the fluid mud can be attributed to the liquefaction of underlying consolidated sediments that were produced during the macrophyte stage of the lake. It follows that the fluid mud layer is less a consequence of eutrophication than a consequence of enhanced wave action on the lakebed following the loss of macrophyte dominance in this lake.

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Received: 18 May 2004
Accepted: 4 November 2004
Amended: 16 November 2004