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# Influence of depth and mixing regime on sedimentation in a small, fluctuating tropical soda lake

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*Abstract*

The historical sediment record of Lake Sonachi (Kenya) was used to study the influence of lake depth and mixing regime on patterns of sedimentation in a small, fluctuating tropical soda lake. Lake Sonachi last desiccated completely in the early nineteenth century and has fluctuated between 3- and 18-m lake depth over the past 115 yr. A freeze-core of offshore sediments describes recent lake history as a succession of meromictic episodes, represented by varved or subannually laminated muds, and holomictic episodes, represented by more coarsely layered muds. Two interbedded horizons of colloidal amorphous silica dated to a period of rising lake level after a prolonged lowstand were deposited by abiogenic, pH-driven precipitation from the water column and represent the instantaneous sequestering of an estimated 63 mg liter$^{-1}$ or possibly >50% of the lake's dissolved-silica reservoir. Changes in offshore sedimentation and inferred bottom dynamics over time indicate that sediment resuspension and focusing in Lake Sonachi occur mostly during infrequent events of deep circulation between the average mud deposition boundary depth at ~2 m and the chemocline depth at 4–5 m; wind-driven sediment redistribution across the lake floor is important only at lake depths of ≤3 m. Dry sediment accumulation has varied between 86 and 620 g m$^{-2}$ yr$^{-1}$ over the past 175 yr, with no relationship to lake depth but, on average, lower rates during meromixis (199 ± 90 g m$^{-2}$ yr$^{-1}$) than during holomixis (349 ± 152 g m$^{-2}$ yr$^{-1}$). Net organic carbon accumulation offshore varied between 0 and 92 g m$^{-2}$ yr$^{-1}$, with no significant relationship to either lake depth or mixing regime at the time of deposition. Sedimentary organic carbon content (5.7–26.9%) is negatively correlated with bulk sediment accumulation; 73% of this variation is accounted for by the clastic dilution of sedimented planktonic algal production with low-organic littoral sediments redeposited offshore.

Density stratification affects lake metabolism through its effects on oxygen distribution, hydrochemistry, nutrient cycling, benthic and planktonic production, and organic carbon mineralization (Hammer 1986; Kelts 1988; Talbot and Livingstone 1989; Miller et al. 1993). Consequently, the development and breakdown of density stratification accompanying lake-level fluctuation may be important drivers of long-term ecosystem dynamics in closed-basin lakes (Talling 1992; Jellison and Melack 1993). The interplay between mixing and stratification in saline lakes regulates carbon and nutrient cycling through its influence on deep-water oxygen renewal and on the areal distribution of sediment erosion, transport, and accumulation. Particularly in tropical saline lakes, combination of density stratification with high algal productivity and intense microbial activity can quickly deplete hypolimnetic oxygen reserves (Wood et al. 1984). Wind-driven resuspension of shallow-water sediments regenerates nutrients to the water column (Golterman et al. 1969) and promotes microbial degradation of previously buried organic matter (OM; Ritzrau and Graf 1992). Insight into the temporal and spatial relationships between lake level, mixing regime, and bottom dynamics in fluctuating tropical lakes is thus necessary for understanding their long-term evolution.

Sediment deposition, mixing, and redistribution rates in lakes depend on its texture and cohesiveness, the shear stress imparted on it by currents and waves, and the intensity of bioturbation relative to the rate of sediment accumulation (Lick 1982; Robbins 1982; Håkansson and Jansson 1983). While it may be difficult to calculate the exact effect of a particular change in lake level on the various vertical and horizontal components of sediment mixing, empirical relationships between basin morphometry and bottom dynamics (Håkanson 1977, 1982; Rowan et al. 1992; Blais and Kalff 1995) and between bottom dynamics and the preservation of sedimentary structure (Larsen and MacDonald 1993; but *see* Larsen et al. 1998) appear to have sufficient predictive power to suggest that sediment stratigraphy produces an accurate archive of past changes in mixing regime.

My study uses $^{210}$Pb-dated sediment cores from Lake Sonachi in Kenya to calibrate sedimentary signals of past changes in bottom dynamics against the historical lake-level record and then uses this validated sediment record to investigate patterns of sedimentation and the accumulation of organic carbon in relation to lake depth and mixing regime. In a companion paper, Verschuren et al. (in press) use fossil stratigraphies of algal pigments, diatoms, and invertebrates in

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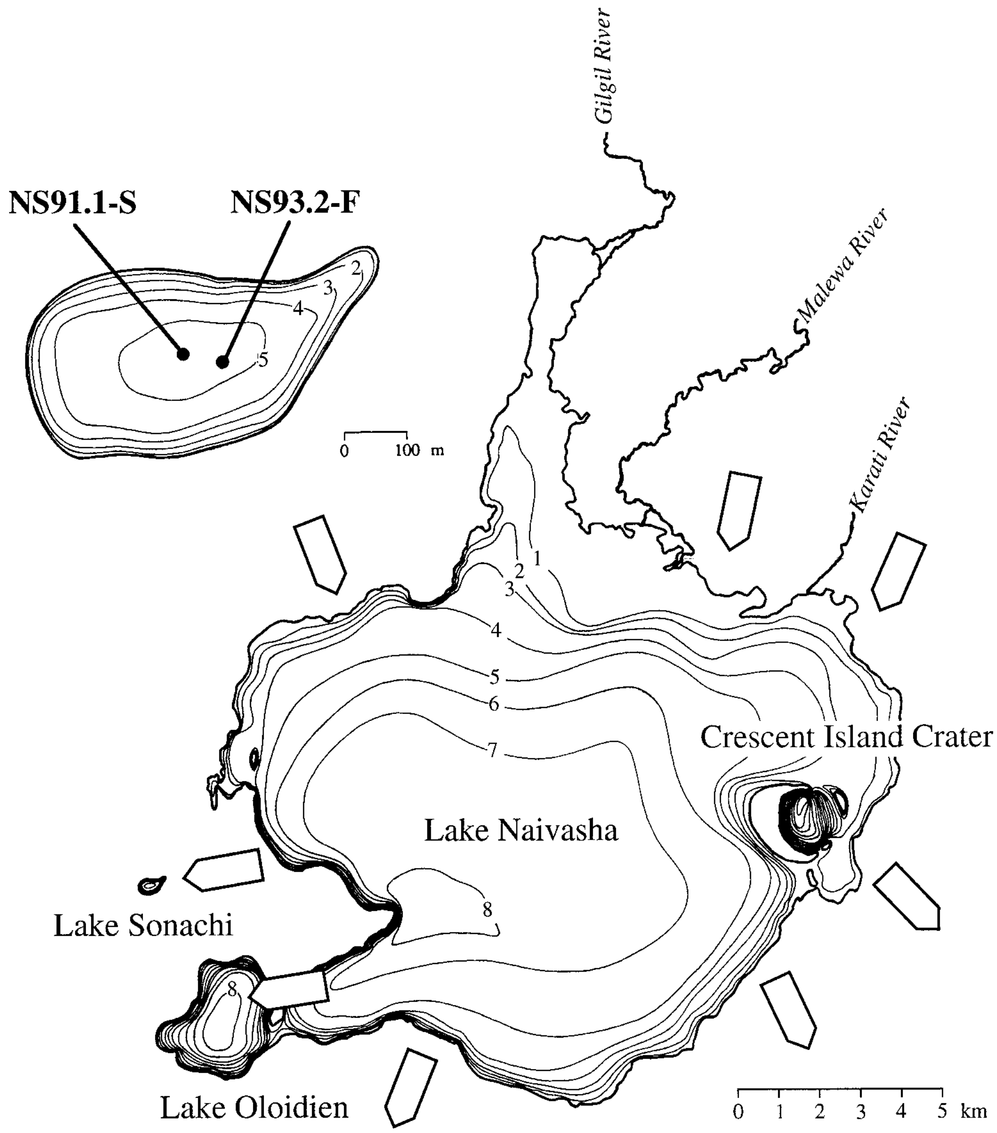


Fig. 1. Bathymetry of Lake Naivasha (in 1983, at 1,886 m above sea level) and Lake Sonachi (in 1990, at 1,884 m above sea level), with core localities and arrows indicating the direction of groundwater flow. Modified after Gaudet and Melack (1981), Åse et al. (1986), and Damnati et al. (1991).

Lake Sonachi sediments to study long-term dynamics of the biological communities inhabiting this fluctuating ecosystem.

## Methods

*Site description*—Lake Sonachi (00°46.80′S, 36°15.70′E) is a small (0.14 km$^2$) and shallow ($Z_{max}$ = 4.25 m in 1993) alkaline–saline crater lake located at 1,884 m above sea level in the semiarid Rift Valley of central Kenya. The site is also known as ''Naivasha Crater Lake'' (Beadle 1932; Jenkin 1932; Peters and MacIntyre 1976), ''Green Crater Lake'' (Damnati et al. 1991), and ''Crater Lake'' (Hecky and Kilham 1973). Lake Sonachi occupies the floor of a phreatomagmatic explosion crater (0.84 km$^2$) 3 km west of Lake Naivasha, a large (135 km$^2$ in 1993) but similarly shallow ($Z_{max}$ = 6 m) freshwater lake (Fig. 1). Highlands flanking the Rift Valley intercept much of the monsoonal rainfall destined for the region, so that annual rainfall averages only 680 mm (1951–1980; MacIntyre and Melack 1982; Åse et al. 1986), while annual evaporation is about 1,865 mm (1966–1982; Åse et al. 1986). The water balance of Lake Naivasha and its satellite basins Lake Oloidien and Crescent Island Crater is maintained against this strong moisture deficit by river input primarily from the Malewa River, which drains the Kinangop Plateau and wet highlands of the Nyandarua Range to the east. Lake Sonachi is maintained by local rainfall over its small crater catchment and a substantial component of subsurface flow from Lake Naivasha (Gaudet and Melack 1981; MacIntyre and Melack 1982; Darling et al. 1990). Historical depth soundings in Lake Sonachi, the first of which dates from 1929, are highly correlated ($r^2 = 0.95$, $P < 0.001$, $n = 15$), with contemporaneous $Z_{max}$ values for Lake Naivasha inferred from the bathymetry (Åse et al. 1986) and historical lake-level record (Verschuren 1996) of the latter basin. These data and field observations of synchronous lake-level change (MacIntyre and Melack 1982; Njuguna 1988) support hydrological evidence (Darling et al. 1990) for a strong groundwater connection between these two lakes and suggest that the 115-yr lake-level record of Lake Naivasha can be fully extrapolated to Lake Sonachi (Verschuren 1996).

The solute budget of Lake Sonachi is controlled by evaporative concentration at the lake surface and dissolution of sedimentary evaporites by percolating groundwater. Wind shelter afforded by the crater rim and forested inner crater slopes promote density stratification and create a steep chemocline most often located at 4–5-m depth ($n = 7$; MacIntyre and Melack 1982; Njuguna 1988). The mixolimnion undergoes a daily cycle of thermal stratification, in which a 2–3°C temperature gradient develops during the morning and is broken down by convective circulation at night. MacIntyre and Melack (1982) drew on 18 months of observation between 1969 and 1979 to classify Lake Sonachi as meromictic. However, the low lake level ($Z_{max} \leq 5$ m) prevailing since 1985 currently prevents chemical stratification from persisting year-round, with deep wind-driven mixing most likely to occur during the dry-season lowstand in February–March. Like other African soda lakes, the ionic composition of Lake Sonachi is dominated by sodium and bicarbonate, and both pH (9.0–10.3) and alkalinity (41–105 meq liter$^{-1}$) are high (Beadle 1932; Kilham unpubl. data; Melack 1981; Njuguna 1988). Surface-water conductivity ($K_{25}$) measurements collected since 1929 range from 3,000 to 11,550 $\mu$s cm$^{-1}$; years with good seasonal data coverage show annual conductivity variation to be ca. 1,000–2,000 $\mu$s cm$^{-1}$ (Verschuren 1996).

*Field techniques and subsampling of sediment cores*—Two cores of offshore sediments were recovered from near the center of Lake Sonachi in 1991 and 1993. Piston-core NS91.1-S (0.35 m) was collected in 4.7-m water depth using a rod-operated piston corer (Wright 1980) and was sectioned upright in the field in 1.0-cm increments with a fixed-interval sectioning device (Verschuren 1993). Freeze-core NS93.2-F (0.37 m) was collected in 4.3-m water depth using a wedge-shaped aluminum box filled with dry ice and ethanol (Renberg 1981). The corer was fitted lengthwise with profiled edges to recover four replicate frozen slabs of the sediment profile. During 12 min of in situ freezing, the corer was lodged firmly in a stiff clay horizon ca. 0.32 m below the sediment surface, which prevented sinking or other displacement. The freeze-core was returned from the field intact and processed in a walk-in refrigerator. It was cleaned, photographed, and sectioned with a miniature chisel in 50 increments of variable thickness (0.3–1.7 cm) while cooled on a bed of crushed dry ice. Increment boundaries were chosen to coincide with visible lithostratigraphic boundaries so that textural and geochemical data obtained from each increment would be representative of a well-defined sediment horizon and reflect a specific lake condition at the time of deposition. Because the freeze-coring operation had caused slight resuspension of flocculent muds at the sediment–water interface, I assigned the 0.0-cm depth level to the top of the uppermost undisturbed horizon. Replicate increment samples from two or more core slabs were combined to increase sample size where necessary; consistency of sampling among the four replicate slabs was ensured by making increment-boundary decisions in advance on 1 : 1 photographic prints of the planed slab surfaces. The sectioned samples were transferred to vials and allowed to melt during storage in the dark.

*Analytical procedures*—Water content (% $H_2O$ by weight), porosity (% $H_2O$ by volume), dry density (dry weight ml$^{-1}$ wet mud), and bulk composition (% dry weight) of both cores were determined by measuring the weight loss from 1.00-ml samples after drying overnight at 105°C, burning at 550°C, and ashing at 1,000°C, respectively (Bengtsson and Enell 1986). Loss-on-ignition data from NS93.2-F were corrected for the dry weight of dissolved solids (TDS) in interstitial ice using the TDS of melted and filtered clear ice above the sediment–water interface; this correction was significant only in the uppermost 6 cm of highly porous surface muds. Total carbon (TC) and total inorganic carbon (TIC) were measured by coulometry on 24 samples selected to cover the full range of TC and TIC values represented in the core profile; total organic carbon (OC) was obtained by subtracting TIC from TC. OC in the remaining 26 samples was calculated using a calibration of OC against OM content as determined by weight loss at 550°C (% OM $= 1.90 \cdot$ % OC $+ 3.86$, $r^2 = 0.93$, $n = 24$). Poor correlation between TIC and percent carbonate ($CaCO_3$) values obtained by weight loss at 1,000°C ($r^2 = 0.33$, $n = 24$) precluded similar calculation of TIC from loss-on-ignition data; presumably, a significant part of weight loss at 1,000°C is due to variable release of $H_2O$ bound to clay lattices (Dean 1974). Coarse OM and sand-sized mineral particles were quantified by dispersing the sediment matrix overnight in 0.25% Calgon, digesting in 10% KOH for 30 min, and rinsing through a 74-$\mu$m sieve. The retained residue was transferred to ashless filter paper and analyzed by loss-on-ignition methods, as above (Digerfeldt 1986). Depending on sediment porosity, the minimum concentrations that allowed reliable quantification of coarse particles were 0.4–1.7% of the organic fraction and 0.1–1.1% of the mineral fraction. Amorphous silica, which included both biogenic silica derived from diatoms and abiogenic colloidal silica, was measured using the wet alkaline extraction method (DeMaster 1981) with a 1% $Na_2CO_3$ solution. Authigenic minerals in selected sediment horizons were identified using smear-slide, scanning electron microscopy (SEM), x-ray diffraction, and electron microprobe (EDS-EM) analyses.

Sediment chronology and accumulation rates were determined by measuring $^{210}$Pb activity through its granddaughter isotope $^{210}$Po, with $^{208}$Po added as an internal yield tracer. Sample preparation was modified from Eakins and Morrison (1978), and activity was measured for 48–120 h in an alpha-spectrometry system. Supported $^{210}$Pb activity was estimated as the asymptote of total activity at depth, and unsupported activity was determined by subtracting average supported

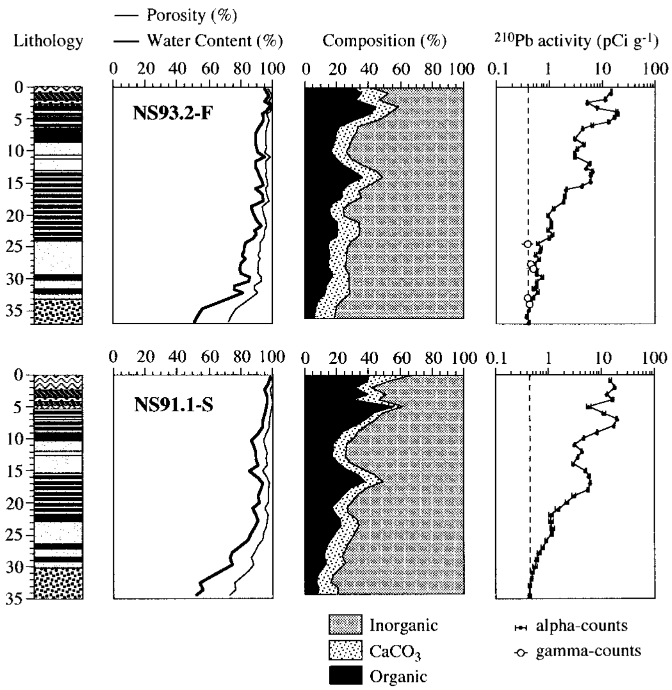


Fig. 2. Comparison of freeze-core NS93.2-F (upper panels) and piston-core NS91.1-S (lower panels) from Lake Sonachi showing the high degree of similarity in core lithology, water content, sediment composition, and $^{210}$Pb activity. Composition data for NS93.2-F are shown integrated over 1-cm increments as for NS91.1-S. $CaCO_3$ content is based on weight loss at 1,000°C and may overestimate its true value (*see Methods*). Counting errors on total $^{210}$Pb activity measured by alpha spectrometry are generally smaller than symbol size. (*See Fig. 3 for a legend to core lithology.*)

activity from total activity measured at each sample level. Estimates of supported $^{210}$Pb were also obtained independently by gamma spectrometry and were used to confirm the lowermost occurrence of unsupported $^{210}$Pb in NS93.2-F. Sediment age and sedimentation rates were calculated according to the constant-rate-of-supply (c.r.s.) model (Appleby and Oldfield 1978), with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford 1990). For each individual NS93.2-F core increment deposited since 1883, lake depth at the time of deposition was calculated by linking the historical lake-level record of Lake Naivasha to sediment age derived from $^{210}$Pb dating. Evaluation of sedimentation patterns in relation to lake depth excludes the core section below 26 cm core depth, deposited before 1883. Evaluation of sedimentation patterns involving $^{210}$Pb-derived accumulation rates excludes horizons identified to reflect event deposition, and core increments below 30.7 cm, where counting uncertainty assumes a substantial (>30%) fraction of the obtained values.

## Results

*Core correlation and chronostratigraphy*—Offshore surface sediments in Lake Sonachi consist of 32 cm highly porous organic muds overlying a stiff horizon of low-organic clays (Fig. 2). Porosity exceeds 95% in the upper 22–25 cm of the cores, decreasing sharply below that level to about 75% at the bottom. OM content decreases from values of 31–56% near the sediment surface to 7–9% in the bottom clays, with three distinct subsurface maxima evident in both cores. The inorganic component of recent Lake Sonachi sediments consists of clay- or silt-sized particles derived from microcline, orthoclase, and plagioclase, 4–63% amorphous silica, and 8–18% low-Mg calcite. Sand-sized (>74 $\mu$m) grains of angular quartz, obsidian, and pumice make up 10% of the mineral matrix in the bottom clays but not more than 2% in the overlying lacustrine muds. Coarse (>74 $\mu$m) organic debris of terrestrial or semiaquatic origin (*Acacia* leaflets, grass charcoal, and sedge seeds) comprises 2–3% of total OM in the bottom clays but occurs only erratically and in trace amounts (<1%) higher up.

$^{210}$Pb activity in both cores shows nonmonotonic behavior superimposed on a strong pattern of exponential decay (Fig. 2). The c.r.s. dating model assumes that deviations from exponential decline with depth reflect fluctuations in the rate of local sediment accumulation (Appleby and Oldfield 1978). Allowing for the on average lower time resolution of core NS91.1-S (~5.9 vs. ~3.5 yr in NS93.2-F), strong similarity between the two $^{210}$Pb activity profiles suggests that patterns of sedimentation through time at the two core sites were similar. Mean values of total $^{210}$Pb activity obtained by alpha spectrometry at the bottom of each core (0.41 ± 0.02 pCi $g^{-1}$ in NS93.2-F, $n = 4$; 0.45 ± 0.01 pCi $g^{-1}$ in NS91.1-S, $n = 2$) are nearly identical to mean supported $^{210}$Pb activity in NS93.2-F obtained by gamma spectrometry (0.49 ± 0.06 pCi $g^{-1}$, $n = 5$; Fig. 2), indicating that both cores contain a complete inventory of unsupported $^{210}$Pb. Similar values for the cumulative unsupported $^{210}$Pb inventory (8.62 pCi $cm^{-2}$ in NS93.2-F; 9.82 pCi $cm^{-2}$ in NS91.1-S) and for the local sedimentary $^{210}$Pb flux (0.32 and 0.34 pCi $cm^{-2}$ $yr^{-1}$) suggest comparable focusing of sediment and $^{210}$Pb to both core sites. Strong correlations between the time-normalized OM stratigraphies of NS93.2-F and NS91.1-S ($r^2 = 0.71$, $P < 0.001$), despite differences in coring and subsampling procedures, confirm spatial uniformity of temporal variation in sedimentation patterns and suggest that both cores can be considered representative for the history of offshore sedimentation in Lake Sonachi. Stratigraphic marker horizons near the sediment surface are situated 2.5 cm higher in NS93.2-F than in NS91.1-S (Fig. 2) due to assignment of the 0.0-cm level in NS93.2-F to the uppermost undisturbed horizon. Consistent depth–age relationships were obtained by setting the collecting date for NS93.2-F to 1988, which is the age at 2.5-cm depth in NS91.1-S. Results presented here focus on the data from freeze-core NS93.2-F because of its superior time resolution and strict correspondence of sampled increments with visible sedimentary structure.

*Lithology and geochemistry*—Offshore surface sediments in Lake Sonachi consist of alternating sections of dark brown finely laminated muds and lighter colored coarsely laminated muds (units I–III; Fig. 3). Stiff low-organic clays at the bottom of the core (unit 0) constitute a desiccation horizon formed by oxidation and compaction of older lacustrine deposits during a prolonged period of subaerial exposure. This sandy clay breccia contains clasts of finely laminated clayey

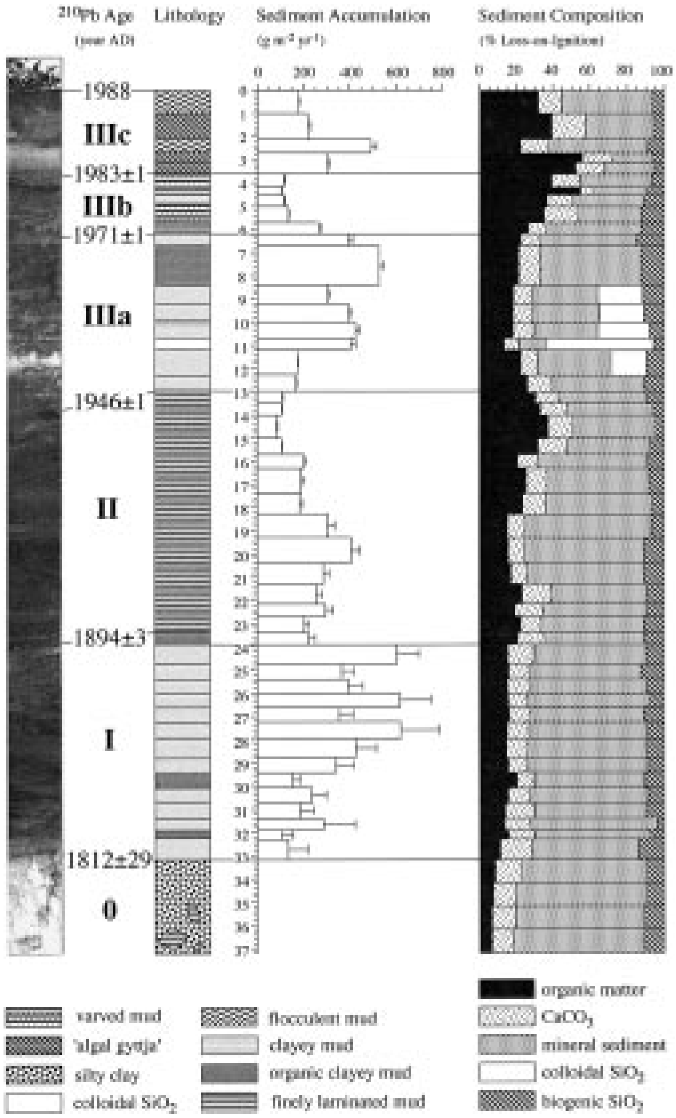


Fig. 3. Stratigraphy, lithology, and zonation of core NS93.2-F from Lake Sonachi with bulk composition data and $^{210}$Pb-inferred rates of sediment accumulation for the 50 sampled horizons. The photograph shows a representative section of the core profile, while mean thickness of lithological horizons is based on four to six measurements across the width of the core.

muds, remnants from an earlier lacustrine phase that were reworked and incorporated in a seasonally inundated dry lake bed.

Unit I (33.2–23.4 cm in NS93.2-F) is comprised of the coarsely laminated muds deposited between lake filling in the early nineteenth century and about 1890. Color differences between adjacent horizons are rather inconspicuous, except for two that have a 3–5% higher OM content (Fig. 3). Unit II (23.4–13.0 cm) was deposited between 1890 and 1945 and consists almost entirely of finely laminated (~1 mm) muds with alternating dark reddish-brown, dark grayish-brown, or black laminae. The overall dark color of this unit correlates with a relatively high OM content (20–36% vs. 15–20% for unit I).

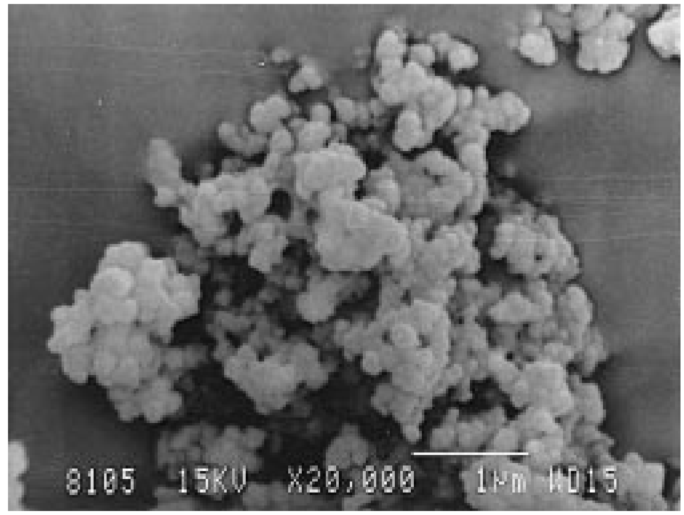


Fig. 4. SEM image of colloidal amorphous silica precipitated abiogenically out of the water column during lake-level rise in the late 1950s and early 1960s. Scale bar = 1 $\mu$m.

Unit III (13.0–0.0 cm) is comprised of both coarsely and finely laminated muds. Subunit IIIa (13.0–6.2 cm) represents sedimentation from 1945 to 1970 and consists of coarsely laminated ochreous and dark-brown muds interbedded by two horizons of a pale gel-like material. The lower horizon has an amorphous-silica content of 63% (Fig. 3) and was determined by SEM and EDS-EM to consist mostly of abiogenic colloidal silica (Fig. 4). The ochreous color, pale mottling, and high silica content (≥30%) of adjacent muds (12.3–8.4 cm; Fig. 3) suggest significant admixture of colloidal silica throughout this section. Positive correlation of amorphous-silica content with concentrations of the fossil diatom pigment diatoxanthin in the remainder of the core ($r^2 = 0.28$, $P < 0.001$, $n = 40$) suggests that fossil diatom frustules may be the normal source of silica in Lake Sonachi sediments (Verschuren et al. in press). Linear regression of silica concentration vs. diatoxanthin ($y = 0.89 + 0.77x$) yielded estimates of 5–12% for the diatom component of amorphous-silica concentrations in the section 12.3–8.4 cm, from which the colloidal component was calculated to represent ~57% of bulk dry sediment at 11.2–10.7-cm depth and 19–28% in adjacent muds (Fig. 3).

Subunit IIIb (6.2–3.6 cm) is mainly composed of two sections of finely laminated muds deposited in the mid-1970s and early 1980s when Lake Sonachi was meromictic (MacIntyre and Melack 1982), separated by a 4-mm-thick horizon of unlaminated brown mud. The upper half of each laminated section contains a few carbonate varve couplets (Anderson et al. 1985) of dark organic mud alternating with low-Mg calcite (Fig. 3); in both of these sections, the $^{210}$Pb-inferred period of varve deposition (3 and 2 yr) matches the number of varves counted. Subunit IIIc (3.6–0.0 cm) was deposited after 1983 under the current holomictic regime. It consists of three horizons of an olive-green gelatinous material alternating with flocculent muds containing aggregates of partly decomposed algae. The gelatinous horizons, here identified as ''algal gyttja,'' are extremely porous (99.4–99.7% $H_2O$ by volume) masses of sedimented cyanobacteria

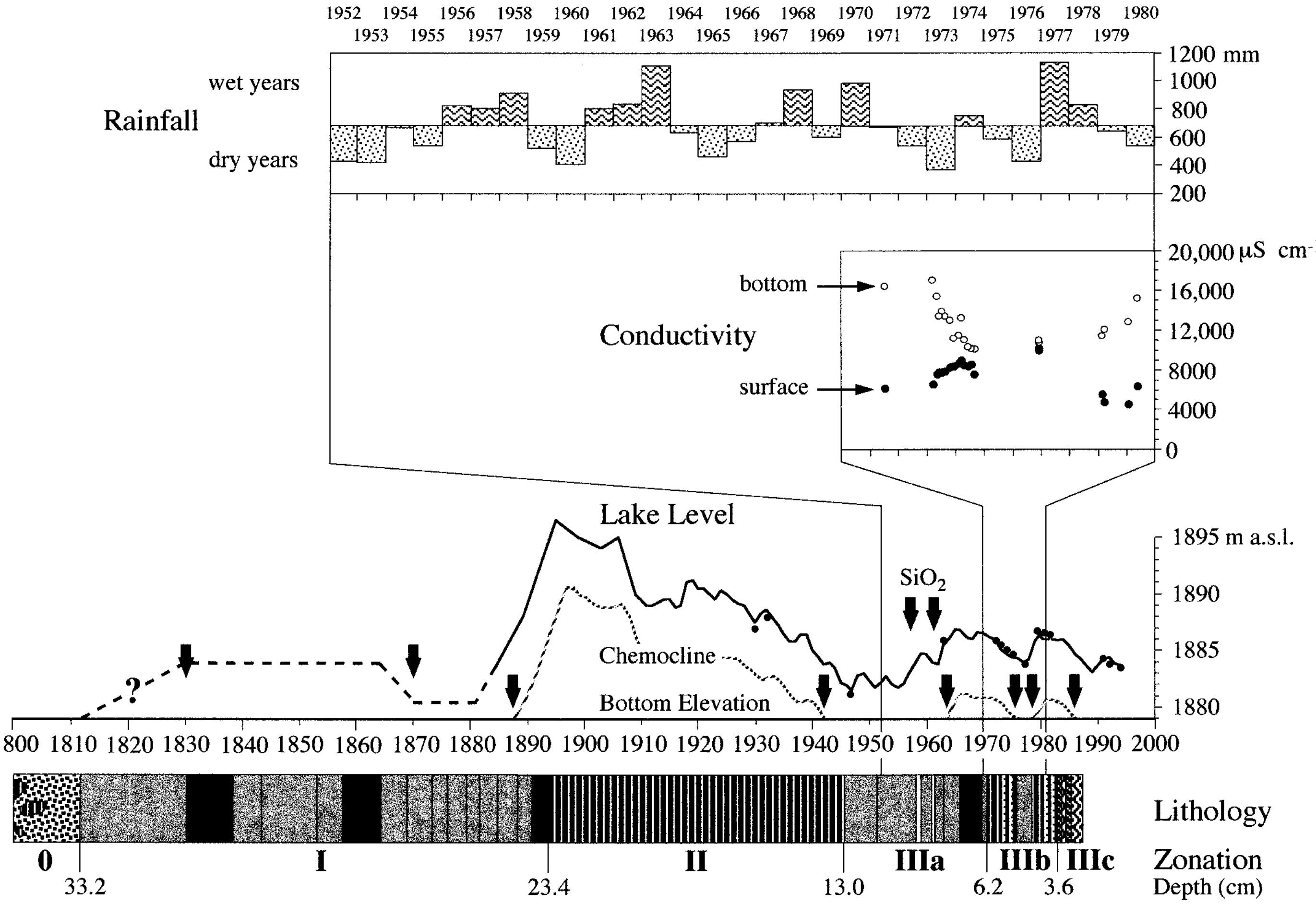


Fig. 5. Comparison of Lake Sonachi core NS93.2-F lithology with the historical lake-level record of Lake Naivasha (Åse et al. 1986; Verschuren 1996), depth soundings in Lake Sonachi (black dots; from various sources), and field data on density stratification and local rainfall (MacIntyre and Melack 1982; Nicholson et al. 1988; Njuguna 1988). Arrows point to historical events anchoring the $^{210}$Pb-inferred sediment chronology, cf. Table 1. Core depth is transformed to fit the linear time axis; compare with Fig. 3.

in a matrix of bacteria and fungal hyphae. Interpreted to represent event deposition of cyanobacterial blooms, these horizons are prone to collapse to a fraction of their current thickness (4–11 mm) under the accumulating weight of new sedimentation.

$^{210}$Pb-inferred rates of bulk sediment accumulation range from 86 to 620 g $m^{-2}$ $yr^{-1}$, with low rates generally coinciding with OM maxima and high rates coinciding with OM minima (Fig. 3). The only apparent exception to this relationship occurs in the upper half of unit I (28.8–23.9 cm), where OM content is constant at 15% (OC $\sim$ 6%), while accumulation rates vary by a factor of two between adjacent horizons. $^{210}$Pb-inferred accumulation rates for the colloidal-silica and algal gyttja event horizons underestimate their true rate of sedimentation, due to the disproportionate influence of admixed recycled sediments (and associated $^{210}$Pb) on measured $^{210}$Pb activity in these highly porous materials.

## Discussion

*The sediment record of mixing regime, lake level, and climate: Unit I*—The time of lake filling inferred from $^{210}$Pb dating of the unit 0–I boundary (A.D. 1812 $\pm$ 29 yr in NS93.2-F and 1815 $\pm$ 8 yr in NS91.1-S) corresponds favorably with precolonial documentary records, indicating severe drought in equatorial East Africa from the late 1700s to the 1820s–1830s and a return to wetter conditions after that (Nicholson 1995). Absence of millimeter-scale (i.e., subannual) lamination in unit I sediments suggests a holomictic mixing regime, but preservation of distinct centimeter-scale structure implies that bioturbation must have been insignificant. Nineteenth-century Lake Sonachi may have been chemically stratified for most of the year, with sporadic events of complete circulation occurring only after chemocline erosion during the dry season. High bacterial oxygen demand for the degradation of sedimented cyanobacterial blooms (Verschuren et al. in press) together with poor water-column circulation must have led to persistent bottom anoxia that kept the offshore lake floor permanently inhospitable to benthic invertebrates. Inferred holomixis and low to intermediate lake depth (Fig. 5) agree with the precolonial historical evidence indicating that nineteenth-century lake levels throughout East Africa were below average twentieth-century levels (Nicholson 1995). The near-desiccation of lakes Naivasha and Sonachi during the 1870s and early 1880s recorded in oral traditions of the local Maasai (Sikes 1936) is expressed in the sediment record by the fluctuating rates of sediment accumulation at the top of unit I (Fig. 3), evidence for shifting sedimentation patterns with episodic redistribution of shallow-water sediments across the lake floor (Dearing 1983; Hilton 1985).

*Unit II*—The $^{210}$Pb-inferred date of 1894 $\pm$ 3 yr for the transition from coarsely laminated to finely laminated deposits at the unit I–II boundary agrees with the documented major transgression of Lake Naivasha between 1883 and 1894 (Fig. 5) following a decade of above-average rainfall (Nicholson 1995). Assuming that deepest seasonal mixing at that time was comparable to the chemocline depth of 4–5 m observed recently, the increase in lake depth from 4 to 17 m must certainly have initiated permanent chemical stratification. A 6-m drop of lake level in 1906–1910 failed to disrupt meromixis but did temporarily reverse the trend toward lower rates of sediment accumulation (Fig. 3). Lake level remained stable for two decades, then by 1930 started a progressive decline that culminated in the historic lowstand of 1946 and a lake depth of only 2.5 m (Fig. 5). The loss of fine lamination at the unit II–III boundary reflects disruption of meromixis shortly before the lowstand was reached.

*Subunit IIIa*—Coarsely laminated muds of subunit IIIa were deposited between the late 1940s and about 1970, covering a period of initially low and then increasing lake depth (Fig. 5). The two interbedded horizons of colloidal silica are dated to 1958.6 and 1961.0 $\pm$ 0.5 yr, coincident with known periods of above-average rainfall in 1956–1958 and 1961–1963 (Nicholson et al. 1988) that caused the two-step lake-level rise from a depth of 3 m in 1956 to 7 m by 1964 (Fig. 5). This microamorphous, anhydrous silica precipitates abiogenically from silica-saturated, high-pH waters when down-mixing of large freshwater inputs depresses pH to $<$9 (Iler 1991) and is the recognized precursor of the bedded chert found in ancient alkaline–saline playa deposits worldwide (Jones et al. 1967, 1977). High dissolved-silica concentrations are common in African soda lakes (Talling and Talling 1965) due to the ready supply from hydrolysis of silicate minerals in volcanic soils, and a near-constant regime of strong evaporative concentration (Eugster and Jones 1968; Jones et al. 1977). Lake Sonachi water chemistry as recorded in the 1970s (1,670–2,520 $\mu$M or 77–116 mg liter$^{-1}$ Si and pH 9.0–10.3; Kilham unpubl. data; MacIntyre and Melack 1982; Njuguna 1988) was favorable for abiogenic silica precipitation to occur; hence, conditions are certain to have been favorable in the 1950s following three decades of negative water balance (Fig. 5). The total sedimentary silica flux resulting from these precipitation events is estimated as $\sim$31.3 mg cm$^{-2}$, the sum of colloidal-silica concentrations in the two pale horizons and in the ochreous mud below them; colloidal silica present in ochreous mud higher up the profile is interpreted to represent redeposition from elsewhere. In the water depth of $\sim$5 m prevailing at the time, the two precipitation events represent instantaneous sequestering of $\sim$63 mg liter$^{-1}$ dissolved silica from the water column, or possibly $>$50% of the lake's dissolved-silica reservoir.

Although the depth of 7 m reached by 1964 was sufficient for formation of a present-day chemocline, meromixis does not appear to have been reestablished until about 1970 (Fig. 5). Failure of stratification to persist year-round before that time suggests that the density contrast between bottom and surface waters was too weak. The large drainage basin (2,378 km$^2$) and substantial river inflow to Lake Naivasha amplify its lake-level response to positive rainfall anomalies, a response that the small crater basin (0.84 km$^2$) of Lake Sonachi is lacking. From 1964 to 1967, local Rift Valley rainfall was below average (Fig. 5), but elevated Malewa River discharge associated with exceptional rainfall and aquifer recharge in 1961–1963 continued to make important contributions to the water balance of Lake Naivasha (Vincent et al. 1979; Gaudet and Melack 1981). If the mid-1960s highstand of Lake Sonachi was indeed sustained by groundwater-driven adjustment to the level of Lake Naivasha rather than local rainfall, continuous input of salt-charged groundwater (MacIntyre and Melack 1982), combined with strong evaporation and below-average freshwater input at the lake surface, may have delayed meromixis by preventing the development of stable density stratification.

*Subunits IIIb and IIIc*—Comparison of subunit IIIb lithostratigraphy with field data for 1970–1980 (MacIntyre and Melack 1982; Njuguna 1988) confirms millimeter-scale lamination in modern Lake Sonachi sediments as a reliable marker for meromixis and reveals remarkably fine detail in the lake's sediment record. Lake Sonachi started this period with stable density stratification and preservation of fine laminations (Fig. 5). Below-average rainfall in 1972–1973 and again in 1975–1976 reduced lake depth from 7.5 to 5 m and gradually eroded the chemocline. By November 1976, surface and bottom conductivities were nearly identical, and chemical stability was very low (MacIntyre and Melack 1982; Fig. 5). Although field data for 1975–1978 are scarce, meromixis must have been lost shortly before or soon after November 1976 and not reestablished until 1978 or early 1979 after 2 yr of heavy rainfall in 1977–1978 had again increased lake depth to 7.5 m (Fig. 5). In agreement with these field data, the 4-mm-thick unlaminated horizon representing this short-lived holomictic phase is dated to 1975.7–1978.5 $\pm$ 0.5 yr. Restoration of meromixis by 1979 is expressed in a new sequence of finely laminated sediments. Meromixis was lost once more by the mid-1980s after lake depth again dropped to $<$5 m, and finely laminated sediments were replaced by the coarsely layered muds and decomposing algae deposited under current holomixis (Fig. 5).

The stratigraphic record of past lake level and mixing regime in Lake Sonachi is anchored at the sediment surface and 10 marker horizons (Fig. 5: arrows), six of which are supported by independent historical evidence and four of which can be linked to the historical lake-level record by assuming constancy of chemocline depth through time (Lowe et al. 1997). Excellent agreement between the $^{210}$Pb-inferred ages of marker horizons and the documented or estimated age of changes in sedimentation patterns that created them (Table 1) demonstrates the accuracy of Lake Sonachi's sediment record as an archive of lake history. The rich detail of this sediment record can be attributed to the high fre-

Table 1. Comparison of $^{210}$Pb dates and documented or estimated (brackets) dates for historical events anchoring the lithostratigraphy of Lake Sonachi freeze-core NS93.2-F.

| Date | Event | Reference | Sedimentary evidence | $^{210}$Pb date |
|---|---|---|---|---|
| (1985) | Meromixis to holomixis | Chemocline depth | Fine to coarse lamination | 1983.1 ± 0.4 |
| 1978–1979 | Holomixis to meromixis | MacIntyre and Melack 1982 | Coarse to fine lamination | 1978.5 ± 0.5 |
| 1976 | Meromixis to holomixis | MacIntyre and Melack 1982 | Fine to coarse lamination | 1975.7 ± 0.5 |
| (1963) | Holomixis to meromixis | Chemocline depth | Coarse to fine lamination | 1971.1 ± 0.5 |
| 1961–1963 | High rainfall | Nicholson et al. 1988 | Colloidal-silica deposition | 1961.0 ± 0.5 |
| 1956–1958 | High rainfall | Nicholson et al. 1988 | Colloidal-silica deposition | 1958.6 ± 0.6 |
| (1942) | Meromixis to holomixis | Chemocline depth | Fine to coarse lamination | 1946.6 ± 0.7 |
| (1888) | Holomixis to meromixis | Chemocline depth | Coarse to fine lamination | 1894.0 ± 2.5 |
| ca. 1870 | Start of extreme lowstand | Sikes 1936 | Fluctuating accumulation | 1869.1 ± 5.2 |
| ca. 1830 | Lake filling | Nicholson 1995 | Start lacustrine sedimentation | 1811.6 ± 28.6 |

quency of changes in mixing regime and bottom dynamics, particularly in recent decades. Its excellent preservation resulted from a combination of basin-morphometric and physical factors that protect Lake Sonachi's offshore sediment–water interface against both wind-driven and biological disturbance.

*Patterns of sedimentation*—Empirical sedimentation models based on wave theory (Håkanson 1977, 1982; Johnson 1980; Rowan et al. 1992) combined with Lake Naivasha peak wind speed values of 20–25 knots (~10–12 m s$^{-1}$; Åse et al. 1986) predict that wind-driven sediment disturbance in Lake Sonachi would be limited to water depths of 1–2 m even without the benefit of topographic wind shelter. In addition, the ellipsoid bathymetry of Lake Sonachi (Fig. 1) restricts areas of wind-driven sediment erosion and transport to a narrow littoral zone unless $Z_{max}$ falls below 2 m. Thus, peripheral wave action (Hilton et al. 1986) can only have been an important agent of sediment redistribution in the initial stage of lake filling and during the 1870s lowstand (Fig. 5). In a lake as small as Lake Sonachi, most sediment redistribution occurs during infrequent episodes of deep turbulent mixing below the critical depth of sediment accumulation (i.e., water depth at the boundary between the zones of sediment accumulation and transport; Håkanson and Jansson 1983) under normal wind regimes (Pennington 1974; Dearing 1997). In hydrologically stable lakes, this focusing mechanism is similar to peripheral wave action in that within-lake variation of sediment accumulation will show a positive correlation with local water depth (Hilton 1985). In fluctuating lakes, it predicts a negative relationship between offshore sediment accumulation and lake depth, $Z_{max}$: accumulation should be higher during lowstands because sediments from a greater area of shallow lake bottom affected by resuspension are focused into a smaller zone of undisturbed accumulation (Oldfield 1977; Digerfeldt 1986). This prediction is not realized in the Lake Sonachi record ($r^2 = 0.025$, $P = 0.4$, $n = 38$) because of at least two confounding factors. First, episodic wind-driven redistribution of sediments across the lake floor during the 1870s lowstand caused local rates of accumulation to fluctuate independent of lake level (Figs. 3, 5). Second, at the short time scales dealt with in this study, the relationship between accumulation and lake depth may be modified by transient dynamics, such as would occur if inundation of peripheral mudflats enhanced offshore transport during episodes of rising lake level. The Lake Sonachi record does show a clear relationship between sediment accumulation and mixing regime, however, with on average lower accumulation during meromixis (199 ± 90 g m$^{-2}$ yr$^{-1}$, $n = 18$) than during holomixis (349 ± 152 g m$^{-2}$ yr$^{-1}$, $n = 24$, $P < 0.001$).

Empirical relationships between lake morphometry and mixing depth in freshwater lakes (Kling 1988; Gorham and Boyce 1989) predict that oxycline depth in Lake Sonachi should be about 7–9 m (7.7 ± 0.8 m) rather than 4–5 m as observed. The two factors contributing to reduced mixing depth in Lake Sonachi are topographic wind shelter and density stratification. Expressed as the ratio between rim height above the water surface and effective fetch in the dominant wind direction, Lake Sonachi ranks among the most sheltered of East African crater lakes (Melack 1978, 1981). In the context of offshore bottom dynamics, the important role of wind shelter is that it limits the frequency and intensity of deep-mixing events that resuspend materials below the average boundary depth of sediment accumulation. Density stratification also contributes to reduced shear stress of turbulent mixing at the sediment–water interface, so that sediment disturbance is limited, and sedimentary structure is preserved in lake depths as shallow as 3 m, such as occurred during the 1940s lowstand. With regard to bottom dynamics, stability of the Lake Sonachi chemocline (Melack 1981; MacIntyre and Melack 1982) restricts such resuspension to mixolimnetic bottom areas, thus creating a clear lateral threshold boundary between the zones of transport and accumulation. In the sediment record, this threshold is manifested by the sharp changes in sediment accumulation rate at the stratigraphic boundaries between phases of holomixis and meromixis (Fig. 3).

Density stratification in Lake Sonachi, whether permanent or seasonal, also prevents nighttime convective circulation from adequately supplying oxygen to water depths exceeding ~2 m (MacIntyre and Melack 1982). Together with high benthic oxygen demand for bacteria-meditated degradation of sedimented cyanobacteria, this led to the persistent bottom anoxia that has prevented zoobenthos from colonizing the offshore lake bottom both during meromictic and holomictic phases. Preservation of distinct layering in the highly unstable surface muds deposited in 4.25-m water depth today (Figs. 3, 5) supports the inferred insignificance of both physical mixing and bioturbation during earlier holomictic epi-

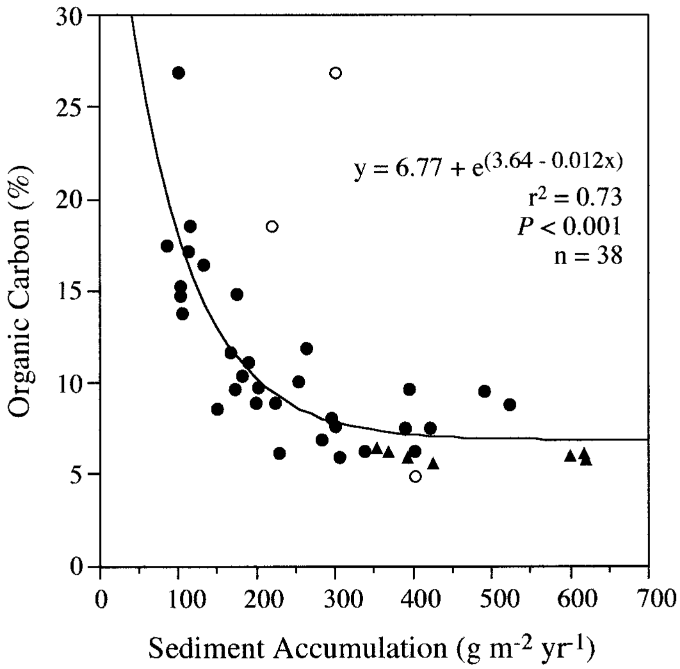


Fig. 6. Nonlinear relationship between sedimentary organic carbon content and sediment accumulation rate in core NS93.2-F. Triangles represent low-organic muds deposited during the extreme 1870s–1880s lowstand, when sediments were redistributed across the lake floor. Open symbols are passive data points representing algal gyttja and colloidal-silica event horizons.

sodes (pre-1890, 1945–1970). The little mixing that does occur may partly be due to the inherent instability of a stack of extremely porous (0–6.2 cm: 96.5–99.7%) sediment horizons with variable composition.

*Accumulation and preservation of organic carbon*—The organic carbon content of Lake Sonachi sediments deposited since lake filling in the early nineteenth century is on average higher in sediments deposited during meromixis (12.0 ± 4.9%, $n = 18$) than those deposited during holomixis (8.8 ± 4.8%, $n = 27$, $P < 0.05$). In the portion of the core deposited since 1883, no correlation was found between organic carbon content and lake depth ($r^2 = 0.01$, $P = 0.5$, $n = 35$) nor between organic carbon accumulation and lake depth ($r^2 = 0.04$, $P = 0.2$, $n = 34$). Detrending of the organic carbon profile does not improve the correlation, discounting the possibility that lack of relationship would be due to the overprint of a diagenetic gradient. Instead, it may indicate that the permanent bottom anoxia irrespective of lake depth or mixing regime limited the influence of oxygen on carbon mineralization rates through time.

Excluding colloidal-silica and algal gyttja event horizons, organic carbon concentration and bulk sediment accumulation (Fig. 3) display an inverse relationship that appears to point to clastic dilution (Dean and Gorham 1976) as a possibly prominent control on the organic carbon content of offshore Lake Sonachi sediments. The relationship can best be described by a negative exponential function ($r^2 = 0.73$, $P < 0.001$, $n = 38$; Fig. 6) that reaches an asymptotic value of ~6% OC at high rates of sediment accumulation. Sediments deposited during the 1870s lowstand, when $Z_{max} \leq 2$ m caused repeated resuspension and redistribution across the lake floor, have ~6% OC irrespective of accumulation rate (Figs. 3, 6). Hence, it can be inferred that (1) the clastic materials by which autochthonous, pelagic organic carbon production is diluted before burial are redeposited littoral sediments containing 6% organic carbon, and (2) this asymptotic OC value represents relatively stable species of organic carbon that survived microbial degradation despite frequent resuspension into an oxygenated water column. Subtracting this inferred lateral organic carbon flux from total accumulation offshore yields estimates for the preserved net accumulation of pelagic organic carbon between 0 g C $m^{-2}$ $yr^{-1}$ during the 1870s lowstand and 9.2 g C $m^{-2}$ $yr^{-1}$ during meromixis at high lake level around 1900. Very low OC values in unit 0 (2.0–2.8%) reflect the advanced OM mineralization occurring during subaerial exposure of lacustrine sediments upon complete desiccation of the lake floor.

*Implications for paleoclimate reconstruction from the sediments of fluctuating lakes*—The results of this study prompt four conclusions relevant to the use of sediment stratigraphies from fluctuating lakes to infer past climatic variability at short time scales. First, even though the stratigraphy of recent Lake Sonachi sediments accurately recorded the changes in bottom dynamics resulting from climate-driven changes in lake level and mixing regime, quantitative reconstruction of lake depth at this time scale clearly requires an intimate understanding of the hydrology and physical limnology of the studied system and of the sedimentological thresholds that create the observed sedimentary structure (Valero-Garcés and Kelts 1995; Dearing 1997). For example, the 1956–1958 and 1961–1963 high-rainfall episodes were recorded in the form of colloidal-silica horizons only because a long-lasting period of negative water balance had driven the dissolved-silica concentration to supersaturation; comparable rainfall variability in the late 1960s and 1970s failed to cause silica precipitation but instead, triggered establishment or disruption of meromixis.

Second, the assumption of constancy of chemocline depth through time (Lowe et al. 1997) appears to be a viable first approximation of reality but may be affected by hysteresis between depth and mixing regime, such as occurred at Lake Sonachi in the 1960s when contributions of saline groundwater flow to the hydrological balance exceeded those of local rainfall.

Third, preservation of fine lithological structure in lake-sediment records does not require meromixis but can also occur in shallow holomictic conditions when wind-driven turbulence is reduced through wind shelter or intermittent density stratification, and bioturbation is prevented by bottom anoxia.

Fourth, at the scale of system dynamics examined in this study, clastic dilution appears to be the principal determinant of sedimentary organic carbon content in fluctuating lakes. Correlation of organic carbon content with lake depth is lacking, and its correlation with mixing regime is a consequence of reduced profundal sediment accumulation, rather than improved preservation, during meromixis. This result implies that the widely used facies models based on classification of petroleum source-rock environments (Eugster and

Hardie 1978; Demaison and Moore 1980; Kelts 1988; Talbot 1988), which attribute gradients in sedimentary organic carbon content primarily to differences in production or preservation, may not apply to soda-lake environments at this scale of events. The strength of the relationship between organic carbon content and bulk sediment accumulation suggests that OC might be used as a predictor of accumulation rate in lake-sediment records, at least for phases of lake history during which bottom anoxia is maintained. In wind-stressed, aerobic depositional environments where random resuspension and redistribution dominate sediment focusing, organic carbon content becomes independent of net accumulation rate. When complete desiccation occurs, subaerial oxidation on the dry lake floor eventually leaves only the most refractory OM intact.

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