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Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: II. Geochronologies and mass sedimentation rates based on ^{14}C and ^{210}Pb data

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Abstract

We established sediment geochronologies for cores from eight deltaic areas in Lake Tanganyika (the Lubulungu, Kabesi, Halembe, Malagarasi, Nyasanga/Kahama, Mwamgongo, Nyamusenyi, and Karonge/Kirasa River deltas), recording a range of watershed disturbance histories from the eastern margin of this African rift valley lake. Cores from currently disturbed sites on the central Tanzanian coast display remarkably uniform and low rates of sediment accumulation from the 18th century until the early 1960s, when a synchronous and dramatic rise in rates occurs. Through this same time interval sedimentation rates offshore from undisturbed Tanzanian watersheds either remain unchanged or decline. Further north, at disturbed sites along the northern Tanzania and Burundi coasts, the pattern of sedimentation rate increase is more complex. Although a mid-late 20th century increase is also evident in these sites, indications of earlier periods of increasing sediment erosion, dating from the mid-late 19th century, are also evident. Synchronous changes in sediment accumulation rates dating from the early 1960s may be the result of exceptionally wet years triggering an increase in the discharge of previously eroded and unconsolidated alluvium and stream/beach terrace deposits, previously accumulated in the deltas and stream valleys of impacted watersheds. Sedimentation rate impacts of deforestation on lake ecosystems are likely modulated by short-term climatic forcing events, which can impact the specific timing and location of sediment discharge to lakes.

Introduction

Accurate assessment of changes in lacustrine sedimentation rates is a critical component of any paleolimnologic study attempting to document patterns and timing of anthropogenically-induced erosion. At Lake Tanganyika, Africa, as in many parts of the world, considerable agronomic, remote sensing, and anecdotal information exists suggesting that human-induced deforestation accelerated during the 20th century, and that this deforestation is likely to have generated increased rates of soil erosion from watersheds around the lake (Bizimana and Duchafour 1991; Cohen et al. 1993; Bryant 1999). However, these earlier investigations provided no long-term historic information that could be used to explicitly demonstrate a long-term change in rates of soil erosion through comparison of modern with pre-20th century conditions.

In this study we provide geochronological data from cores collected by the Global Environmental Facility/Lake Tanganyika Biodiversity Project (GEF/LTBP), as well as other cores collected at Lake Tanganyika, which collectively constrain the timing of key depositional events, and document the history of changes in sediment mass accumulation on selected deltas of Lake Tanganyika. A complete discussion of the study rationale and core collection methods and locations is provided in the companion paper (Cohen et al. 2005a). Briefly, we selected coring sites to provide historic sedimentation rate information from the river deltas of watersheds spanning a range of deforestation levels and area, on the assumption that these were likely to be the most important variables for determining inter-site sedimentation rate variability over the time scales of this study (few hundred to few thousand years) (Table 1). Cores discussed here include both multicores collected in a 1998 expedition and several vibracores collected in 1997 (labeled with a 'V' suffix). All ^{210}Pb analyses on multicores were made on a designated core labeled with an 'R' suffix (i.e., LT-1998-82R), whereas ^{14}C samples were collected primarily from the parallel multicore barrel that was analyzed primarily for microfossil content, labeled with an 'M' suffix (i.e., LT-1998-2M).

The development of radiochemical techniques has provided tools for establishing geochronologies within bedded sediments, and for examining rates of sedimentary processes. The terms used to describe sedimentation on various time scales can be distinguished quantitatively when radiochemical techniques are used. Some naturally occurring radionuclides (e.g., ^{210}Pb) are very particle-reactive (i.e., rapidly sorbed onto particle surfaces) and have been successfully used to determine rates of sedimentary processes in a range of natural environments (Nittrouer et al. 1979; McKee et al. 1983; Appleby and Oldfield 1992). AMS ^{14}C measurements on terrestrially produced organic matter that settles out on lake deltas provides another approach to dating subrecent lake deposits. In this investigation we used a combination of both methods to produce the age models presented here and used in subsequent, companion papers in this volume.

Methods

In this study, our strategy was to select a single sampling site to represent each delta. This was in large part because of the expense and time-intensive nature of geochronological determinations. We recognize the possible problems with characterizing the sedimentation rate and rate change history in highly dynamic deltaic systems using a single site, but given limited resources, we decided that it was preferable to examine multiple deltas rather than multiple cores for fewer deltas in this initial study.

Table 1. List of investigated deltas and coring stations in this study.

Delta	Station #	Lat. S. (decimal)	Long. E (decimal)	Water Depth (m)	Disturbance level/ catchment area
Lubulungu	LT-98-2	6.1653	29.7060	110	Low/small
Lubulungu	LT-98-12	6.1655	29.7178	126	Low/small
Kabesi	LT-98-18	5.9768	29.8167	75.0	Intermediate/intermediate
Kabesi	LT-97-61	5.9688	29.824	67.4	Intermediate/intermediate
Nyasanga/Kahama	LT-98-58	4.6883	29.6167	76.0	Low/very small
Mwamgongo	LT-98-37	4.6227	29.6332	95	High/very small
Nyamusenyi	LT-98-98	3.6193	29.3402	60	High/small
Karonge/Kirasa	LT-98-82	3.5835	29.3252	96	High/medium
Karonge/Kirasa	KAR #3	3.5917	29.3367	50	High/medium
Malagarasi	LT-97-14	5.1400	29.7328	73.1	Intermediate/large
Halembe	LT-97-57	5.7862	29.9325	75.8	Low/small

^{210}Pb dating

^{210}Pb analyses were used in this study to constrain sedimentation rates for the most recent parts of the cores collected, generally representing the 19th and 20th century histories of each delta studied. All ^{210}Pb analyses were conducted at Tulane University. The polonium method of Nittrouer et al. (1979) and McKee et al. (1983) was used in this study. Dried and ground sediments ($\sim$1–2 g) were weighed and transferred into a Teflon microwave digestion vessel (CEM model MRS-2000 microwave digestion system). Approximately 2 ml of double distilled water was added, followed by a known volume of ^{209}Po yield tracer (calibrated with NIST standard SRM-432). An acid solution was added (4 ml HNO_3, 4 ml HCl, and 2 ml HF) and the digestion vessel was sealed. A microwave apparatus was assembled, and a two-step digestion was used (30 min at 100 psi followed by 30 min at 80 psi). Samples were allowed to cool and were then transferred into a Teflon centrifuge tube and centrifuged at 2000 rpm for 15 min. The acid solution was decanted from any undissolved residue into a plating vessel. The pH was adjusted to 2.0 and the solution was electroplated onto a stainless steel planchet for 20 h. In addition, dry ground sediment samples for a subset of downcore intervals were sealed in vials and equilibrated for three weeks. Activities of radionuclides were determined using gamma spectroscopy on a closed-end coaxial well detector. Detector efficiencies as a function of material density for each radionuclide are determined from a series of standards covering the range of densities observed in the study area. Supported levels of ^{210}Pb were determined by measuring the gamma activity of ^{214}Pb (295 and 352 KeV) and ^{214}Bi (609 KeV). Self-absorption corrections were made on each sample following the technique of Cutshall et al. (1983).

An advection–diffusion model (Guinasso and Schink 1975) was used to obtain sedimentation rate information from the down core distribution of radionuclides. A geochronology was established from the downcore distribution of excess ^{210}Pb activities using a constant rate of supply (CRS) model (Appleby and Oldfield 1992). Within individual subsections of the cores that exhibit exponential decay (designated by separate correlation coefficients) sedimentation rates derived using constant initial concentration (CIC) and CRS models yield similar results. Geochronologies from ^{210}Pb data can be expressed in terms of sedimentation rates (mm yr^{-1}) or calendar years for event correlation. Mass sedimentation rates (g cm^{-2} yr^{-1}) can also be determined from the ^{210}Pb data, and to a lesser extent using ^{14}C data, with additional information about porosity and sediment density. Ultramodern ^{14}C data was used in preference to ^{210}Pb for devising an age model only in core LT-98-98R, where, as discussed below, the ^{210}Pb data suggest a violation of the assumption of constant rates of unsupported ^{210}Pb supply. Mass sedimentation rates calculated from ^{210}Pb, and to a lesser extent from ^{14}C data, allow us in the companion papers to present a number of the quantitative sedimentological and paleontological variables in terms of abundance per gram and as a flux (abundance per cm^2 per year). In considering these flux calculations, however, it is important to keep in mind that many of the sedimentation events that make up these records may be pulsed, with higher 'rates' representing those places and times when more such pulses occurred over the sampling intervals (years to decades). This scenario is likely on deltas, making fluxes less meaningful statistics. Thus, their interpretation should be treated cautiously.

^{14}C accelerator mass spectrometry (AMS) dating

Complications in the interpretation of ^{14}C age dates from bulk lacustrine organic matter produced in Lake Tanganyika arise from the fact that this stratified lake's deep monimolimnion acts as a reservoir for 'old' carbon (i.e., depleted through radiogenic decay of ^{14}C). This limits the utility of the ^{14}C method on autochthonous organic matter, requiring correction factors to be subtracted from the apparent ^{14}C age (e.g., Cohen et al. 1997), which themselves may vary over time as a result of variable entrainment of carbon from deep water. To avoid this problem we have limited our analysis to organic matter that was washed into the lake from terrestrial sources.

For this study, AMS ^{14}C dating was used to accomplish two goals:

(1) Provide direct age dates on older parts of cores. Most cores studied here are relatively young

and considerable uncertainty exists in radiocarbon ages for the past few centuries.

(2) Identify core tops as 'modern' based on the presence of an 'ultramodern' ^{14}C signature. Atmospheric nuclear testing greatly increased the amount of ^{14}C in the atmosphere, resulting in an easily detectable signal in organic matter of this age.

Dated materials consisted of terrestrial plant matter, to avoid the problems of carbon reservoir effects and reworking of older materials alluded to above. When possible, delicate leaves were used to minimize the likelihood of reworking.

All AMS dating was done at the Tandem Accelerator National AMS Laboratory at the University of Arizona. All ^{14}C dates are reported as both uncorrected radiocarbon years B.P. (relative to 1950, these are reported in the tables only), and as corrected calendar dates (A.D. or B.C., used in all graphics and sedimentation rate calculations). Calendar year estimates were made using Calib 4.3 (Stuiver et al. 1998a, b and http://calib.org/calib). For our age models and all subsequent illustrations, we used the mean of the highest probability interval provided by the Calib 4.3 calibration algorithm. For age determinations where multiple high probability (>5% relative area under probability distribution curve) dates were determined, we also provide the alternative age dates in Table 2. Because of the well-known difficulties in interpreting ^{14}C data for the period from 300 to 0 B.P. (i.e., radiocarbon B.P., 1950) we gave preference to ^{210}Pb chronologies when discrepancies arose between the two data sets. Unless otherwise indicated, all radiometric age dates were used to assign sample ages through polynomial best-fit age models.

Ultramodern (i.e., post-bomb) ^{14}C results can in principle be assigned age dates, based on the rise and subsequent decline in atmospheric ^{14}C that resulted from the history and timing of atmospheric nuclear testing and its cessation. We used the ^{14}C curves of Nydal and Lövseth (1983) and Levin and Kromer (1997) to estimate ages for our post-bomb samples. Given the uncertainty of these interpretations (and requisite extrapolation for samples younger than 1983) we present these interpretations only in Table 2. In cases where the ultramodern ^{14}C dates are from a single leaf sample, the age uncertainties are likely to be quite small, on the order of a few years.

Results

Core locality information

Details concerning the coring localities and site selection process used in this study are provided in Cohen et al. (2005a). For reference we provide a summary of that information here (Table 1). In addition to the 1998 GEF/LTBP multicores, a vibracore (LT-97-14V) collected in an earlier survey off the front of the Malagarasi River (8.5 km due west of the northern distributary channel of that river), is included in our ^{210}Pb analysis here. Several previously collected ^{210}Pb profiles are also referenced for comparison (Table 1).

^{210}Pb dating and sediment accumulation rates

^{210}Pb profiles for six cores are presented in Figures 1 through 6. One of the cores from the undisturbed Lubulungu area, LT-98-2M, was determined by radiocarbon measurements (discussed below) to be too old to obtain informative ^{210}Pb geochronologies, and the other core from this site LT-98-12M, had recent sedimentation rates (based on ^{14}C) that were too low in the 19th–20th centuries to warrant investigation by ^{210}Pb methods. Unsupported ^{210}Pb activities are relatively high in most of the cores (>20 dpm g^{-1}), allowing us to obtain comparatively long geochronologies – up to ~8 half-lives (180 years) in some cases, because detection limits of this method are <0.1 dpm g^{-1}. Downcore unsupported ^{210}Pb varies in systematic ways in almost all profiles, making them readily interpretable. One core, LT-98-98R (Nyamusenyi: Figure 5) shows an abrupt decrease in unsupported ^{210}Pb activity at ~30 cm, that cannot be readily interpreted with a ^{210}Pb age model, as discussed below.

The southernmost of the six ^{210}Pb-dated cores LT-98-18R (Kabesi: Figure 1), and LT-97-14V (Malagarasi: Figure 6), both from moderate disturbed watersheds, show abrupt and dramatic upcore changes in sediment accumulation rate, starting in the early 1960s (probably 1961/62), with relatively low and constant rates prior to this period. These rates are independent of water content, which is relatively invariant below about 1.5–2 cm through the core lengths analyzed. Core LT-98-58R (Nyasanga/Kahama: Figure 2), the one

Table 2. AMS ^{14}C sample identification numbers and analyses.

AA#	Core# (LT-98)	Material[a]	Depth (cm)	$\delta^{13}C$	Fraction modern	1σ	^{14}C age B.P.	1σ	Preferred calendar age A.D. (B.C.) & % prob.	Alternate calendar age(s) &% prob.
32722	2M	p.f.	3–4	−26.2	0.9564	0.0071	360	60	1543 ± 102 (2σ)	–
29099	2M	t	19–20	−27.9	0.8844	0.0045	985	40	1067 ± 81(2σ)	–
32721	2M	p.f.	34–35	−26.8	0.7321	0.0049	2505	55	(622 ± 83) (1σ) 80.1	(771 ± 116) (1σ)13.5
32726	2M	t	42–43	−28.3	0.6008	0.0043	4095	55	(2636 ± 63) (1σ)	
56833	12M	c	1–2	−25.0[b]	0.8299	0.0155	1500	150	556 ± 137 (1σ)[c]	–
36834	12M	c	2–3	−25.0[b]	0.8720	0.0124	1100	110	965 ± 87 (1σ)[c]	–
56835	12M	i	2–3	−25.0[b]	0.9776	0.0123	180	100	1859 ± 28 (1σ) 24.5	1726 ± 55 (1σ) 46.5
30558	12M	l	3–4	−27.2	0.9679	0.0064	260	55	1767 ± 38 (1σ) (2σ) 76.2	1657 ± 31 (1σ) 40.7
33152	12M	p.f.	9–10	−25.4	0.8709	0.0205	Contaminated			
33153	12M	p.f.	36–37	−23.3	0.9392	0.0133	500[d]	110	1431 ± 50 (1σ) 65.1	1341 ± 39 (1σ) 32.0
30559	18M	p.f.	1–2	−25.8	1.1327	0.0131	Post-bomb (early 90s)			
33150	18M	p.f.	18–19	−20.9	0.8767	0.014	Contaminated			
33151	18M	p.f.	39–40	−25.3	0.8723	0.0126	Contaminated			
30561	58M	p.f.	2–3	−18.4	1.0343	0.0088	Post-bomb (early 50s)			
32719	58M	p.f.	18–19	−25.2	0.9647	0.0086	290	70	1563 ± 119 (2σ) 87.0	1765 ± 31 (1σ) 10.9
32728	58M	p.f.	37–38	−27.8	0.9744	0.0071	210	60	1759 ± 133 (2σ) 80.1	1930 ± 22 (2σ) 12.9
30560	37M	p.f.	3–4	−27.8	1.1450	0.0079	Post-bomb (early 90s)			
32720	37M	p.f.	30–31	−24.6	0.9616	0.0067	315	55	1555 ± 45 (1σ) 73.6	1629 ± 14(1σ) 23.0
32724	37M	p.f	43–44	−24.4	0.09469	0.0071	440	60	1454 ± 41 (1σ) 87.9	1607 ± 7 (1σ) 8.2
30562	98A	l & s	9–10	−28.0	1.1367	0.0064	Post-bomb (early 90s?)			
	98A	g.f.	18–19	−17.6	1.3192	0.0073	Post-bomb (mid-late 70s?)			
	98A	1& s	34–35	−20.0	1.2276	0.0088	Post-bomb (late 50s/ early 60s)			
30563	82M	p.f.	3–4	−26.3	1.14	?	Post-bomb (early 90s?)			
	82M	P.f.	6–7	−24.2	1.1399	0.0138	Post-bomb (early 90s)			
32729	82M	g.f.	27–28	−13.9	0.9487	0.0141	420	120	1487 ± 191(2σ)96.5	

% Prob. = relative area under probability distribution for calendar ages where alternative ages are presented.
[a]Abbreviations for organic material: p.f. = indetermined terrestrial plant fragment, t = twig, l = leaf, l & s = leaf plus seed, g.f. = grass fragment, c = charcoal, i = insect fragment.
[b]Very small sample size necessitated an assumed correction; [c]material likely reworked; and [d]maximum age possibly contaminated.

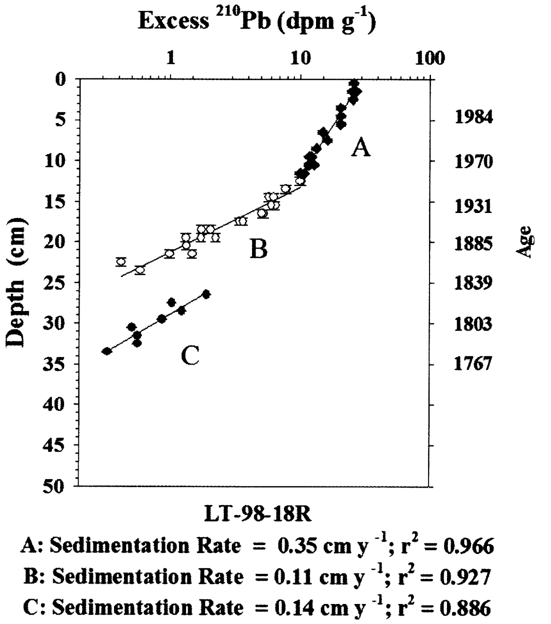

Figure 1. Unsupported ^{210}Pb profile for Core LT-98-18R, Kabesi River delta.

low disturbance site multicore for which we were able to obtain a ^{210}Pb profile, showed no such changes, with unsupported ^{210}Pb activity decreasing exponentially downcore, consistent with relatively constant sediment accumulation rates throughout the ^{210}Pb-dated interval. A 1997 vibracore (LT-97-57V-not shown) collected offshore from a low disturbance Halembe River delta area of north of the Mahale Mountains yielded

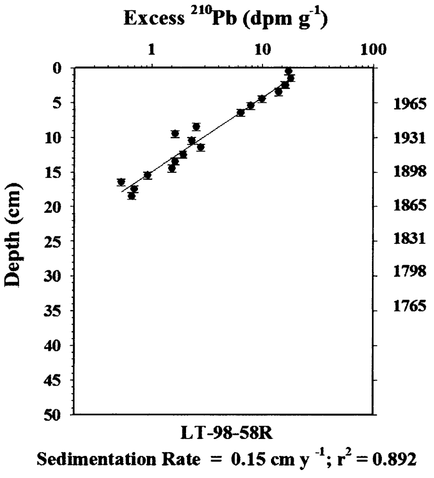

Figure 2. Unsupported ^{210}Pb profile for Core LT-98-58R, Gombe River delta.

slightly declining sedimentation rates over the ^{210}Pb-dated interval.

Core LT-98-37R, from the highly disturbed Mwamgongo River watershed (Figure 3) shows a change in linear sedimentation rates also in the early 1960s. Mass accumulation rate calculations for this core (Figure 7) indicate a more complex history, with low rates prior to the mid-19th century, an abrupt rise in the 1860s, followed by an interval of late 19th–20th century stabilization, prior to a second rise in the early 1960s.

The ^{210}Pb profile of core LT-98-98R (Nyamusenyi River, Figure 5) is extremely difficult to interpret because of its nonlinear decline in unsupported ^{210}Pb activity, and segments of more or less constant activity over 5–10 cm stratigraphic intervals. Judging solely from the ^{210}Pb data it might be assumed that this record results from either physical disturbance of the core during recovery. Alternatively it might be thought that discrete and very massive sedimentation pulses were deposited on top of one another, separated by hiatal surfaces (the lowermost of which, at about 30 cm, would be of considerable age), with massive bioturbation and or slumping within constant ^{210}Pb zones. However, parts of this interpretation are at odds with other evidence. The multicore was observed to be in excellent condition in terms of lack of evident core artifacts at the time

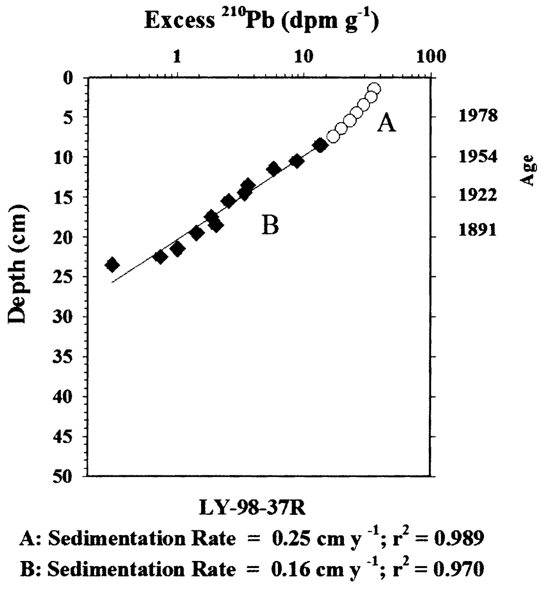

Figure 3. Unsupported ^{210}Pb profile for Core LT-98-37R, Mwamgongo River delta.

of recovery. The physical stratigraphy of the core shows it to be laminated or microlaminated and lacking massive bioturbation or slump features. And the core's ultramodern ^{14}C profile is both stratigraphically coherent (i.e., younger dates consistently over older ones) and entirely post-bomb (Table 2). Although it is possible, and perhaps likely, that the stratigraphy of this core is the result of massive, pulsed events, these events appear to be entirely confined to the last ~50 years. The most plausible explanation for these discrepancies is that the assumption of a constant rate of unsupported ^{210}Pb supply is incorrect in the Nyamusenyi core, perhaps as a result of sediment inputs from other rivers in the region. Evidence for long-distance transport of Ruzizi River sediments from the north end of Lake Tanganyika towards the Burundi core sites is discussed elsewhere (Msaky et al. 2005), and this could provide a likely source of sediment with potentially very different ^{210}Pb inventories.

Like LT-98-37R, core LT-98-82R (Karonge/Kirasa Rivers, Figure 4) also shows a pattern of both a dramatic mid-20th century rise (possibly synchronous with the 1961/2 event seen further south) and an early episode of rising and then declining rates in the 19th century. An additional, previously studied Karonge River delta core (KAR #3) provided a very similar record to LT-98-82R, also suggesting rapidly rising mass accumulation rates in the mid-20th century (Wells et al. 1999).

Mass accumulation rates (MAR) vary substantially both between core sites and within cores. The highest rates overall occur in LT-98-98R (Nyamusenyi) and the late 20th century portion of LT-98-82R (Karonge/Kirasa), both very highly disturbed sites. The higher absolute rates encountered in LT-98-98R probably arise from the fact that whereas the drainage area of the Karonge/Kirasa valley is about 5× larger than the Nyamusenyi, the Karonge/Kirasa sediment is being distributed over a delta platform about 10× larger than the Nyamusenyi. Very low MARs are observed at Kabesi and Malagarasi (LT-98-18R and LT-97-14V) prior to the 1960s, Nyasanga/Kahama (LT-98-58R) throughout its record, and Mwamgongo (LT-98-37R) prior to the 19th century. The low MARs in the early part of the Kabesi (LT-98-18R) record are particularly notable given the relatively large drainage basin area and delta distribution platform for that system. These low rates for the drainages of the Mahale Mountains are also

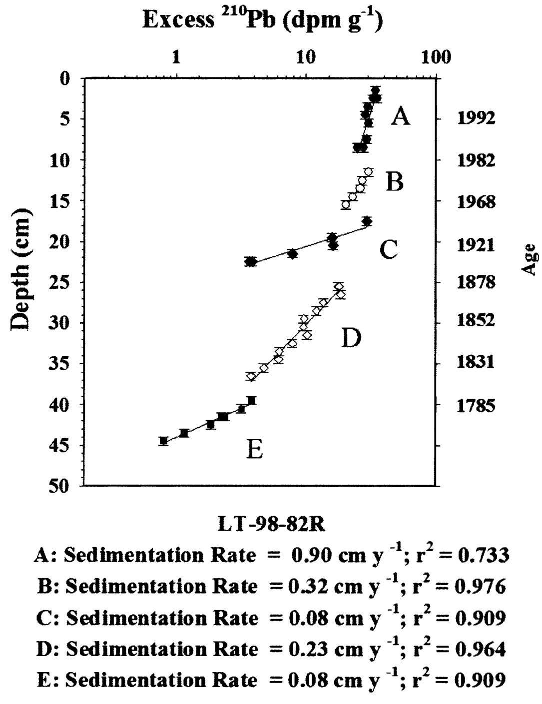

Figure 4. Unsupported ^{210}Pb profile for Core LT-98-82R, Karonge/Kirasa Rivers delta.

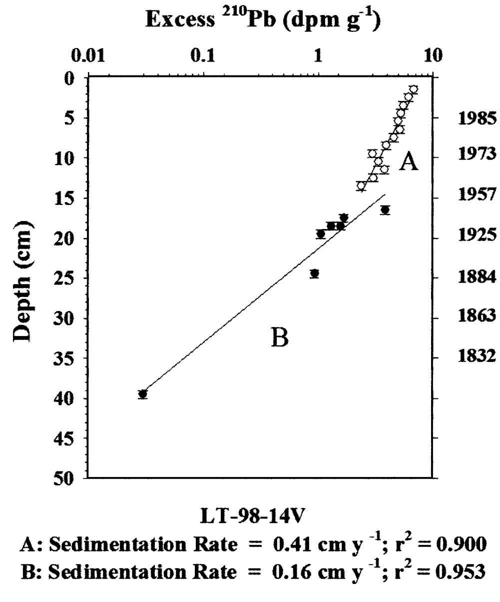

Figure 5. Unsupported ^{210}Pb profile for Core LT-98-98R, Nyamuseni River delta.

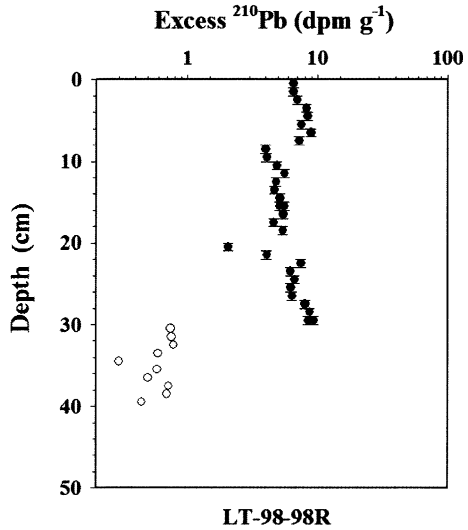

Figure 6. Unsupported ^{210}Pb profile for Core LT-97-14V, Malagarasi River delta.

evidenced in a ^{210}Pb profile from vibracore LT-97-61V (not shown), also from the Kabesi River delta, and in the presence of either hiatal surfaces or very slow sediment accumulation rates on the Lubulungu River delta platform further south (core LT-98-2R and LT-98-12R). Low absolute rates in the Malagarasi River delta system (LT-97-14V) prior to the mid-20th century probably reflect the combination of a large upstream sink for sediments at the confluence of several of the river's major tributaries (the Malagarasi wetlands) coupled with the very large delta platform over which sediments are being distributed.

The Mwamgongo core (LT-98-37R) is the only site that displays clear evidence for MAR increasing prior to the mid-20th century without any reversal. This increase is followed by a secondary rise in the early 1960s, simultaneous with numerous other indications of land-use change and alterations in lake ecology (Alin et al. 2002). Three of the deltas with MAR changes whose ages can be well constrained (Kabesi-LT-98-18R, Malagarasi-LT-97-14V and Mwamgongo LT-98-37M) show a striking synchroneity of rate increases starting in the early 1960s. The increase in mid-20th century MARs at Karonge/Kirasa (LT-98-92R) may also correspond to this date, although the dating of the rise at this location is less well constrained. In both LT-98-18R and LT-97-14V, these MARs remain at greatly elevated levels after that time, whereas LT-98-82R and LT-98-37R show declines near the top of the core (1980s to early 1990s). LT-98-82R also displays an intriguing mid-19th century rise and subsequent decline after the late 19th century, which does not pick up again until the mid-20th century rise. The Nyamusenyi core (LT-98-98R) displays a more complex pattern of increase, with the highest rates occurring more recently, although the uncertainties about the age model for LT-98-98R discussed earlier argue that this profile should be interpreted cautiously. Vertical uniformity in an unsupported ^{210}Pb profile can also be interpreted to represent vertical mixing or homogenization of the upper sediments, particularly through bioturbation.

Figure 7 shows the temporal pattern of change in sediment accumulation rates based on ^{210}Pb and supplementary ^{14}C results through the study area. The 1961 inflection in sediment accumulation rates is particularly striking, as it is observed in three very widely separated and geomorphically different regions. It is also noteworthy that indications of 19th century increases are restricted to the northern coring sites.

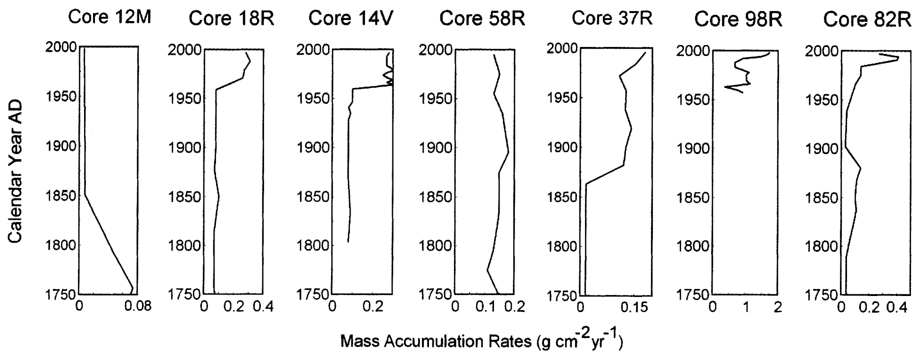

Figure 7. Comparisons of mass accumulation rate (MAR) profiles for six dated deltas, 1750–1998.

AMS ^{14}C dating

AMS ^{14}C data are presented in Table 2. Radiocarbon analyses demonstrate that the top of core LT-98-2M, on the platform of the Lubulungu River delta, is not modern. This coring site is well removed from any channels associated with this delta, suggesting that this is a hiatal area of nondeposition rather than active erosion. Core LT-98-2M displays extremely slow rates of average sediment accumulation (0.005–0.024 g cm^{-1} yr^{-1}), more typical of offshore sills of Lake Tanganyika, although the rate increases substantially after ~100 B.C. Core LT-98-12M, from a nearby site on this same delta, experienced very slow rates (0.007–0.07 g cm^{-1} yr^{-1}) throughout its history, and these rates declined to their modern and lowest levels between the late 18th and mid-19th centuries. Given the core site's location on a large, distal bench (removed from regular sediment input), it may be that this site has experienced pulsed intervals of sedimentation (corresponding to a few decades around the radiometrically-dated horizons, separated by unrecognized hiatuses). This interpretation is consistent with the presence of some reworked older material dated near the LT-98-12M core top (Table 2).

Eight ultramodern age dates (i.e., ^{14}C values greater than 1950, corrected for 20th century fossil fuel input of radiogenically 'dead' carbon, and implying sample formation after the onset of large-scale atmospheric nuclear testing) for cores LT-98-18M, LT-98-58M, LT-98-37M, LT-98-82M, and LT-98-98M are all consistent with the age models derived from the ^{210}Pb. For several of the cores, it is not possible to identify with precision an ultramodern 'date' from these data, given both analytical uncertainties and uncertainties about the post-test ban falloff in atmospheric ^{14}C for this part of the world. With two exceptions (LT-98-58M at 8–19 cm and LT-98-82M at 27–28 cm), other ^{14}C age determinations are consistent with ^{210}Pb age models and provide additional control for the geochronology of the lower parts of several cores. In the two cases where ^{14}C dates are not in agreement with the ^{210}Pb age model, we have adopted the latter for our age model and assumed the former to represent reworked older material.

Discussion

Sediment geochronologies primarily covering the past few hundred years from deltaic areas around Lake Tanganyika reveal that significant increases in mass accumulation rates of terrestrial sediments have occurred offshore from all investigated watersheds that are currently moderately to severely deforested (Figure 8). Conversely, in watersheds that show no sign of current disturbance, sedimentation records point to low and either uniform or declining sedimentation rates over the same time period. In the southern two rivers showing varying degrees of modern disturbance, the Kabesi and Malagarasi (LT-98-18R and LT-97-14V respectively) these increases are strictly mid-20th century phenomena, most probably dating to the early 1960s. At Mwamgongo (LT-98-37R, Mwamgongo River delta) and Karonge/Kirasa (LT-98-82R) this mid-20th century MAR rise is also observed, again most probably having occurred in the early 1960s. However at both Mwamgongo and Karonge/Kirasa, indications of 19th century increases are also evident. Collectively these data point to a north–south difference in disturbed watershed history during the 19th century, but a more coherent pattern of change in the mid-20th century.

A notable feature of the increased 20th century MARs in most of our core records is that the rise in most locations is not simply a brief pulse, but rather, represents a sustained increase in sediment yields off the watershed for the past 40 years. At locations offshore of medium to large deltas, an increase in sedimentation rates (3- to 10-fold) was observed for the period subsequent to 1961. This observation implies that whatever mechanism is called upon for accelerating sediment yields must accommodate the existence of a relatively large 'reservoir' of stored sediment, probably more than is held in temporary storage on hillslopes alone. Our observations are consistent with the hypothesis that a short-duration triggering mechanism, possibly the extremely high rainfall and rising lake level events of 1961/62 documented for this region, initiated the formation of gulleys in previously stored alluvial plain and lake-terrace sediments, which ring many low relief areas of Lake Tanganyika. This effect would be enhanced in deltas adjacent to large alluvial plains and/or extensive high stand lake terraces, consistent with our observations at the Kabesi and Malagarasi River deltas. The implications of these historical interpretations are discussed more fully in the summary paper of this study (Cohen et al. 2005b).

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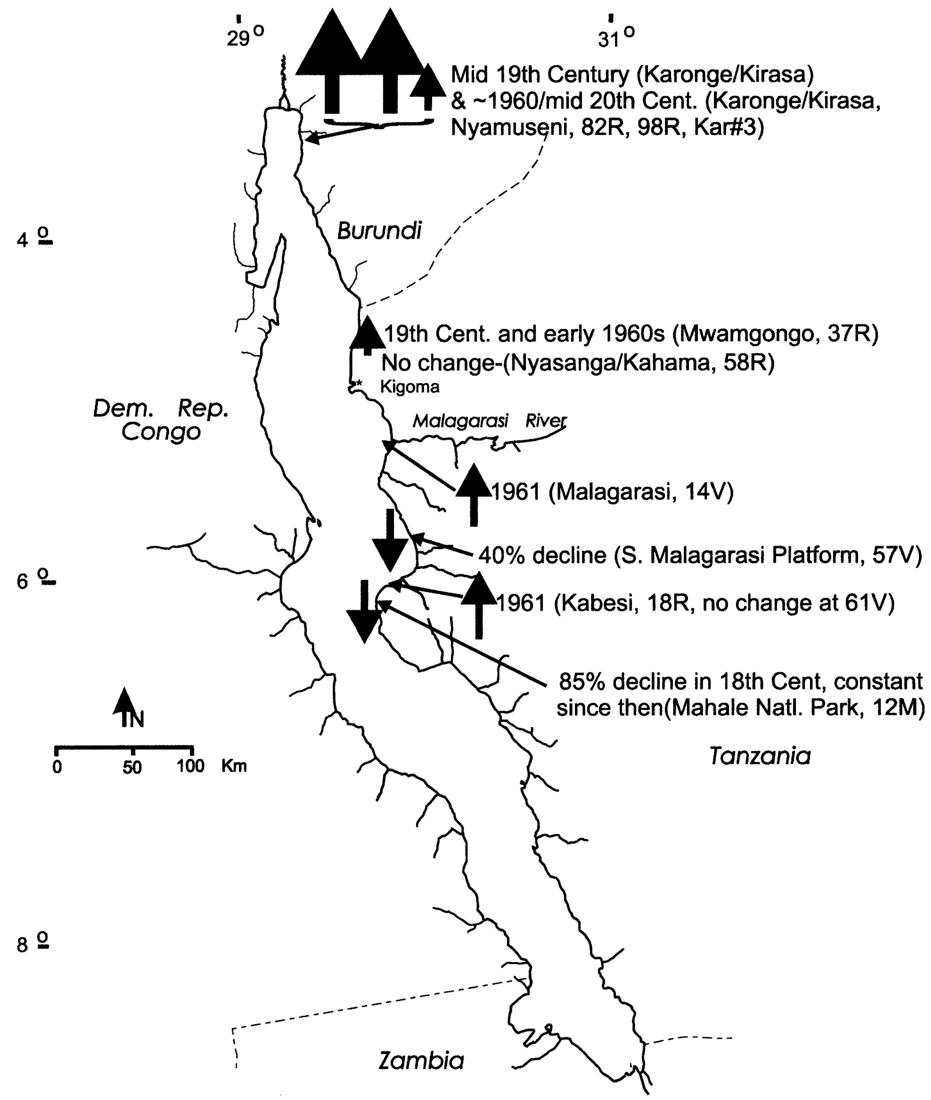

Figure 8. Relative changes and timing of MAR changes for deltas investigated in this and prior studies. Arrow sizes indicate the relative magnitude of change, with upwards pointed arrows indicating significant 19th–20th century increases and downwards pointed arrows indicating significant decreases.

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