



Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: III. Physical stratigraphy and charcoal analysis

Manuel R. Palacios-Fest^{1,*}, Andrew S. Cohen², Kiram Lezzar², Louis Nahimana³ and Brandon M. Tanner²

¹*Terra Nostra, Tucson, AZ 85741, USA;* ²*Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA;* ³*Département des Science de la Terre, Université de Burundi Bujumbura, Burundi 2700;* *Author for correspondence (e-mail: terra_nostra_mx@yahoo.com.mx)

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Abstract

Documenting the history of catchment deforestation using paleolimnological data involves understanding both the timing and magnitude of change in the input of erosional products to the downstream lake. These products include both physically-eroded soil and the byproducts of burning, primarily charcoal, which arise from both intentional and climatically-induced changes in fire frequency. As a part of the Lake Tanganyika Biodiversity Project's special study on sedimentation, we have investigated the sedimentological composition of seven dated cores from six deltas or delta complexes along the east coast of Lake Tanganyika: the Lubulungu River delta, the Kabesi River delta, the Nyasanga/Kahama River delta, and the Mwamgongo River delta in Tanzania, and the Nyamusenyi River delta and Karonge/Kirasa River delta in Burundi. Changes in sediment mass accumulation rates, composition, and charcoal flux in the littoral and sublittoral zones of the lake that can be linked to watershed disturbance factors in the deltas were examined. Total organic carbon accumulation rates, in particular, are strongly linked to higher sediment mass accumulation from terrestrial sources, and show striking mid-20th century increases at disturbed watershed deltas that may indicate a connection between increased watershed erosion and increased nearshore productivity. However, changes in sedimentation patterns are not solely correlated with the 20th century period of increasing human population in the basin. Fire activity, as recorded by charcoal accumulation rates, was also elevated during arid intervals of the 13th–early 19th centuries. Some differences between northern and southern sedimentation histories appear to be correlated with different histories of human population in central Tanzania in contrast with northern Tanzania and Burundi.

Introduction

Understanding the impact of watershed deforestation on lake ecosystems requires the determination of changes in both the quality and quantity of sediment being discharged into the lake. The

stratigraphic analysis of well-dated cores from deltaic regions of lakes, where sediments are initially discharged, provides critical data for interpreting the timing and magnitude of these impacts (e.g., deforestation, change in sediment composition in the lake). In large lakes, where human

impacts vary greatly between influent watersheds, paleolimnologic studies can also provide a means of comparing sedimentologic responses of watershed deforestation across a spectrum of pre-existing watershed characteristics and impact levels. For example, a combination of watershed size and magnitude of deforestation may be responsible for changes in sediment inundation that in turn will impact the ecosystem affecting life patterns (e.g., species ecological replacement).

Here, we describe the physical stratigraphy of cores collected by the Lake Tanganyika Biodiversity Project's Special Study on Sedimentation Impacts. A companion paper by Cohen et al. (2005a) describes the background and rationale for this study, and provides location maps, site characteristics and coring techniques used to obtain the cores described here. Another companion paper describes the geochronology and age models used here (McKee et al. 2005). Briefly, the cores described here were collected from a series of river deltas along the eastern margin of Lake Tanganyika, which span a spectrum of watershed disturbance and size characteristics. These deltas lie offshore from the following rivers (in order from south to north): the Lubulungu River (low disturbance, small-sized drainage area: 50 km², central Tanzanian coastline), Kabesi River (medium disturbance, medium-sized drainage area: 120 km², central Tanzanian coastline), Nyasanga/Kahama Rivers (low disturbance, very small-sized drainage area: 3.8 km², northern Tanzanian coastline) and Mwamgongo River (high disturbance, very small-sized drainage area: 7.7 km², northern Tanzanian coastline), Nyamusenyi River (extremely high disturbance, small-sized drainage area: 30 km², northern Burundi coastline), and Karonge/Kirasa Rivers (extremely high disturbance, medium-sized drainage area-combined area 162 km², northern Burundi coastline (see Figures 1–5 and Table 1 of Cohen et al. 2005a).

Watersheds were characterized as currently experiencing low, medium or high levels of disturbance based on the proportion of mature forest/woodland cover existing in the watershed. *Low disturbance* areas have forest/woodland cover in both the delta plain and upland portions of the watershed, with extremely limited or no agricultural/grazing activity. *Medium disturbance* watersheds have extensive agricultural development in the lowland and/or delta plain regions of the

watershed, but retain forest, woodland, or mixed woodland/grassland cover in their uplands, with the entire watershed retaining between ~25 and 75% forest/woodland cover. *High disturbance* areas are regions where >75% forest/woodland cover has been removed. The two deltas in Burundi are additionally characterized as 'extremely highly' disturbed because these watersheds have undergone extensive surface slope failure.

Materials and methods

Numerous multicores were collected at each delta during this study, of which only a small number could be analyzed in detail. We selected the best cores for use in this study, based on a combination of likelihood of providing continuous records, quality and quantity of indicator materials, and comparability of coring stations vis-a-vis their distances from shore and water depths. Three splits from each core were sampled, normally at 3-cm intervals, for loss-on-ignition, sedimentological (granulometric and micropaleontologic) and palynological analysis. The 3-cm sampling interval used corresponds to the mean depth of bioturbation and sample time averaging observed in X-radiographs of deltaic cores from Lake Tanganyika. A total of 109 samples were prepared for each analysis.

For this exploratory investigation, a simple set of informative and inexpensive indicators was chosen. Granulometric analysis (grain size) provides indications of significant changes in the nature of eroded materials within a watershed and the strength of sediment delivery systems to the coring site. Because total carbonate content in most cores was low (<1%), the contribution of non-terrestrial sources of coarser-grained particles in these cores is probably negligible. Water content and bulk density were measured as supporting data for interpreting sedimentation rates. Total carbonate content and total organic matter were measured as probable indicators of benthic secondary productivity, terrestrial/aquatic productivity and organic matter flux.

The full age spectral data, associated probabilities, and standard errors for each age date, along with discussion of occasional discrepancies between ¹⁴C and ²¹⁰Pb age dates, age models, and sediment accumulation rate estimates used in this study are discussed elsewhere (McKee et al. 2005). The ¹⁴C

dates presented in this paper are calendar-year age estimates (age B.P. in parentheses, relative to 1950 A.D.) based on the median values of the ^{14}C probability spectra derived from each uncalibrated age date. ‘Ultramodern’ (i.e., post-bomb) ^{14}C dates, in conjunction with ^{210}Pb age models constrain the ages of the upper parts of most of the cores. Sediment accumulation rate estimates are based on ^{210}Pb profiles except for those intervals that predate the ^{210}Pb time scale (last 150 years). Where significant discrepancies exist between ^{210}Pb and ^{14}C age estimates we have favored the former, because of the well known uncertainties in ^{14}C geochronology for the last few hundred years.

All sedimentologic splits were prepared for granulometric and micropaleontologic analysis using the USGS freeze–thaw technique (Forester 1991), modified by Palacios-Fest (1994). Approximately 10–20 g wet weight was used for each sample. For granulometric analysis, samples were wet-sieved in a set of three sieves of $>1\text{ mm}$, $>106\ \mu\text{m}$ and $>63\ \mu\text{m}$ mesh sizes to obtain the coarse, medium and fine sand fractions.

All samples for loss-on-ignition (LOI) were prepared using the technique described in Bengtsson and Enell (1986) and Boyle (2004). This involves step-wise heating and reweighing of samples to 105, 550, and 925 °C for the determination of water content, organic matter LOI [$0.40 \times$ conversion factor for total organic carbon (TOC)], and inorganic matter LOI [$0.12 \times$ conversion factor for total inorganic carbon (TIC)], respectively. Data are presented as both abundance per gram and as a flux ($\text{mg cm}^{-2}\text{ yr}^{-1}$) based on component proportions and mass accumulation rates, and are plotted against time for easier comparison between core sites.

Charcoal abundance was estimated as the number of charred particles per gram retained on the $>106\ \mu\text{m}$ sieve fraction only, where most of the volume was concentrated, as an indicator of total abundance. This coarser charcoal fraction provides a good indication of local, within-watershed production, as opposed to long-distance aerial transport. We calculated abundance both as number per gram and as a flux ($\# \text{ cm}^{-2}\text{ yr}^{-1}$).

Results

[Note: cores are described from South to North. For details on core sites, see Cohen et al. (2005a)]

Lubulungu delta cores, LT-98-2M and LT-98-12M, central Mahale Mountains region, Tanzania (low disturbance, small-sized drainage area)

Two cores were collected from the west-central part of the Lubulungu River delta, LT-98-2M and LT-98-12M. Core LT-98-2M was collected in 110 m of water depth in the central plain of the delta, about 1.5 km offshore and west of the Mahale Mountains National Park, Tanzania. Swimming copepods and clear water at the sediment/water interface indicate that the sediment surface was undisturbed during collection. However, ^{14}C geochronologic data, discussed in McKee et al. (2005) suggests that this core site was an area of either non-deposition or erosion over the last few hundred years. The core consists of 49 cm of alternating massive sandy clay and clay (partly laminated in the lower 10 cm), either with shell fragments or plant remains, or occasionally both (Figure 1). A notable fining upwards of sediments occurs above 35 cm, about 700–600 B.C. (2650–2550 B.P.) (Figure 2). A secondary fining event occurs higher in the core, above about 25 cm. Assuming continuous sedimentation, this would correspond to about 400–500 A.D. (1550–1450 B.P.), although it is possible that substantial hiatuses exist in this record, given these fining trends and the long interval covered by the core. Both TOC and TIC measurements show increases in the LT-98-2M core. Concentration and mass accumulation rates change, with notable increases in TOC and TIC mass accumulation rates starting about 100 B.C. (2050 B.P.), shortly before the first appearance of calcareous fossils in the core. These trends correlate with upcore granulometric changes to finer textures. Total organic carbon (TOC) values remain high ($\sim 5\%$) throughout the rest of the core, whereas TIC values (reflecting mollusc fragments, and to a lesser extent, ostracode concentrations) decline after $\sim 1100\text{ A.D.}$ ($\sim 850\text{ B.P.}$). Both granulometric and geochronologic data suggest that this change in TIC is probably a result of initial increases in calcium carbonate availability and/or preservation and later productivity of carbonate-producing organisms, followed by siliciclastic dilution caused by higher rates of mud input. Charcoal concentration is extremely low ($<5\text{ particles cm}^{-2}\text{ yr}^{-1}$) before 1 A.D. (1950 B.P.). Between ~ 1 and 100 A.D. (1950–1850 B.P.),

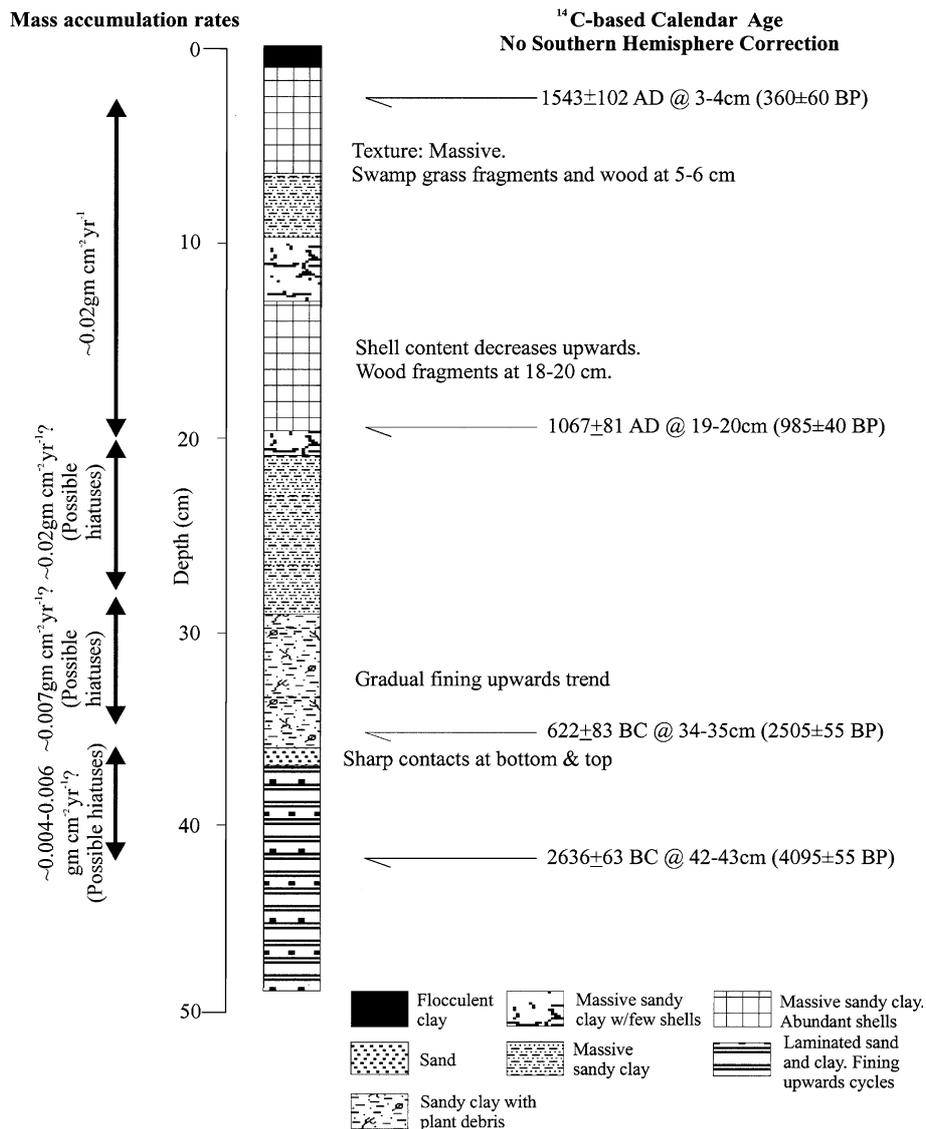


Figure 1. Lithostratigraphy of core LT-98-2M, central Lubulungu delta, 110 m water depth. Total core length 49 cm. See Cohen et al. (2005a, Figure 2) for location and bathymetric map.

accumulation rates increased in the upper part of core LT-98-2M. Charcoal increase coincided with the first occurrences of ostracodes and molluscs in the core, and greatly accelerating after ~1200–1300 A.D. (750–650 B.P.). Higher charcoal concentrations are evident from 13th to early 19th centuries in this and several of our other core records (cores LT-98-12M, LT-98-18M and LT-98-58M). Charcoal concentrations probably reflect regional aridity and increased fire activity, in accord with other records showing periods of

extremely arid conditions and low lake levels during portions of the Little Ice Age (Cohen et al. 1997; Nicholson 1999; Verschuren et al. 2000; Alin et al. 2002; Alin and Cohen 2003).

Core LT-98-12M was collected in 126-m water depth, about 500 m northeast of core LT-98-2M (1.2 km from shore), on a narrower and deeper portion of the delta front. Unlike LT-98-2M, the top of core LT-98-12M appears to be ‘modern’, although 19–20th century sediment accumulation rates at this site have been very low, and the

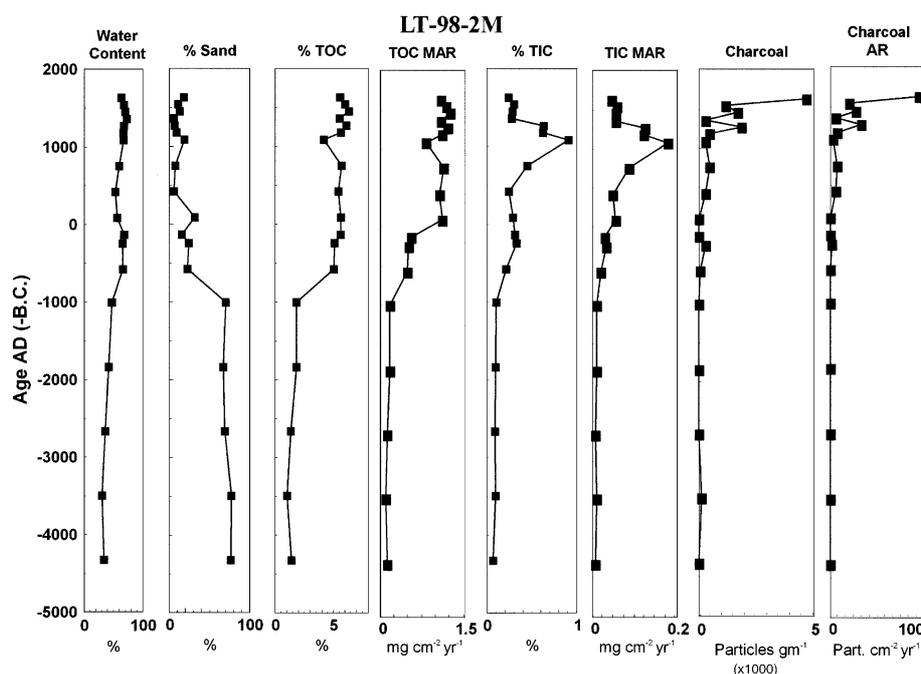


Figure 2. Sedimentologic and charcoal profiles for core LT-98-2M.

temporal sampling resolution as a result was not as good as in other intervals. Core LT-98-12M consists of 40 cm of massive sandy clay, alternating with either mollusc fragments or plant debris or wood fragments, or occasionally both (Figure 3). In general, sediments coarsen upwards, mostly through the upper 10 cm (18–20th centuries) (Figure 4). Low concentrations of sand occur throughout the lower portion of LT-98-12M, with generally higher values evident after the early 18th century. LT-98-12M displays high TOC values and low TIC values throughout the core. Both vary only slightly, in ways that are not evidently correlated with other variables. Total organic carbon (TOC) and TIC MARs decline dramatically at the top of the core as a consequence of overall steep declines in sedimentation rates since the late 18th century. A decrease in charcoal abundance and major decline in accumulation rate occurs above 30 cm (early 16th century?), with low values persisting up to 15 cm (late 17th–early 18th century). This is followed by a rise in charcoal concentration in the upper part of the core. However, this increase appears to be largely an artifact of the low background sedimentation rates; when calculated as an accumulation rate charcoal flux shows a secondary rise in the mid-late 18th century

followed by declines to very low levels at the top of the core.

Kabesi delta core, LT-98-18M, north Mahale Mountains region, Tanzania (intermediate disturbance, medium-sized drainage area)

Core LT-98-18M was collected about 1.5 km offshore of the Kabesi River mouth, in 75-m water depth. The core top contained a live gastropod (*Paramelania iridescens*) in living position, indicating perfect recovery of the sediment–water interface and oxic conditions at the core site. The core consists of 42 cm of brown massive mud (Figure 5), which display an increasing proportion of sand in the uppermost ~12 cm of the core (from <0.95 to 2.48%), coincident with a 3- to 4-fold increase in sedimentation rates dating from the early 1960s (Figure 6). Total organic carbon (TOC) concentrations range between 4 and 5%, and decline gradually but systematically above 20 cm, ~1899. However, TOC accumulation rates rise dramatically after the early 1960s, in concert with overall increasing sedimentation rates. Total inorganic carbon (TIC) content increases slightly at the same time, but is low throughout the core.

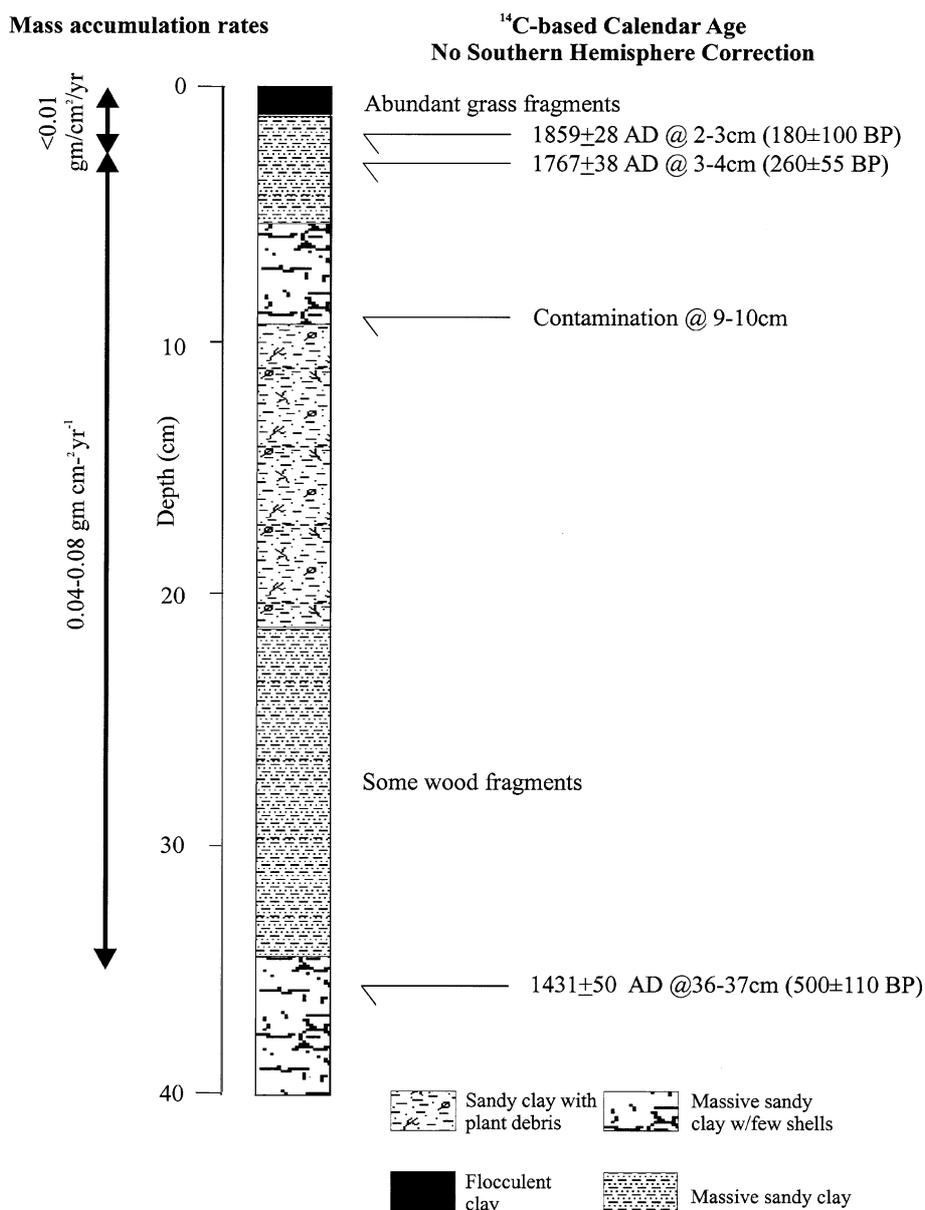


Figure 3. Lithostratigraphy of core LT-98-12M, central Lubulungu delta, 126 m water depth. Total core length 40 cm. See Cohen et al. (2005a, Figure 2) for location and bathymetric map.

As with the TOC record, the relatively uniform TIC concentration throughout the core actually represents a major increase in accumulation rates of calcium carbonate over the past ~40 years at this site. For TIC, this probably represents *in situ* carbonate production, since there is no source of CaCO_3 -particulate matter in the Kabesi watershed. In the case of TOC, the increase may reflect increased aquatic organic matter accumulation,

increased terrestrial organic inputs, or some combination of the two. LT-98-18M contains relatively low concentrations of charcoal, and accumulation rates are also low. Charcoal concentrations and accumulation rates decline fairly continuously from the base of the core (mid-18th century) until the mid-20th century, at which time they begin to rise again, followed by an abrupt decline in the late 1980s.

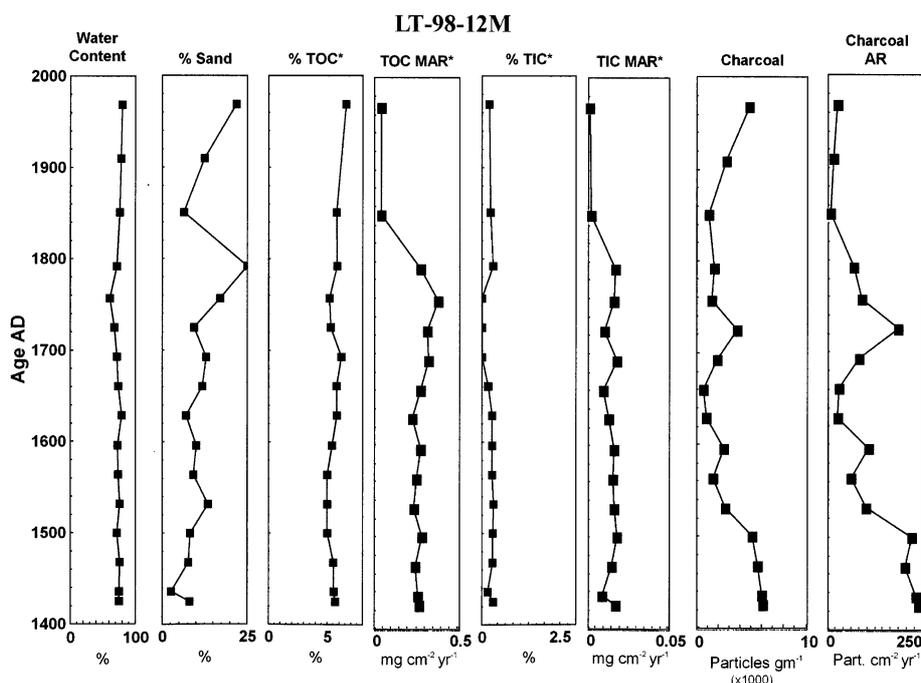


Figure 4. Sedimentologic and charcoal profiles for core LT-98-12M. *Available sample material from the 1910 horizon was too small to obtain accurate TOC and TIC measurements.

Nyasanga/Kahama deltas core, LT-98-58M, northern Tanzania (low disturbance, very small-sized drainage area)

Core LT-98-58M was collected in 76-m water depth, about 300 m offshore from Gombe Stream National Park and the Nyasanga/Kahama coastal sand belt. The precise coring site was located on a topographic bench on an otherwise steep slope, thus allowing for fine sediment accumulation. The core consists of 39 cm of brownish to dark gray clays (Figure 7). Sediments alternate between laminated silty clay and massive clay with carbonate layers and shell fragments, and display a slight coarsening upwards above ~16 cm (~1898) (Figure 8). LT-98-58M displays moderately high (2.5–4%) TOC levels throughout the core, with no systematic trends evident in either concentration or accumulation rate. Total inorganic carbon (TIC) concentration is relatively high compared to other cores, although measured as an accumulation rate it is intermediate. Total inorganic carbon (TIC) is also very variable throughout the core, with higher values in the mid-18th century, a drop in the late 18th century and then a marked rise in

the early 18th century. Following this period, there was marked decline in the mid-19th century followed by a significant rise after 1920 in both concentration and accumulation rate. Charcoal abundance is extremely high in the LT-98-58M core and rises to extraordinary levels at the core top, with the highest flux rates observed in any core studied. This result is unexpected, as the area is protected from intentional burning today (high values occur both pre- and post-1968, the date of National Park establishment). Very high values occur in samples from both the late 18th/early 19th century, and the late 20th century. Much lower concentrations and accumulation rates occur from the mid-19th to mid-20th century, although these values are still high in comparison with other core localities. The high values of the late 20th century suggest that charcoal must be transported by flotation over distances exceeding that separating this study site from the park boundary (i.e., several kilometers), or alternately, that wildfire within the park is for some reason anomalously high. We consider the latter explanation unlikely, because the difference between park and ‘non-park’ in terms of watershed land usage and seasonal

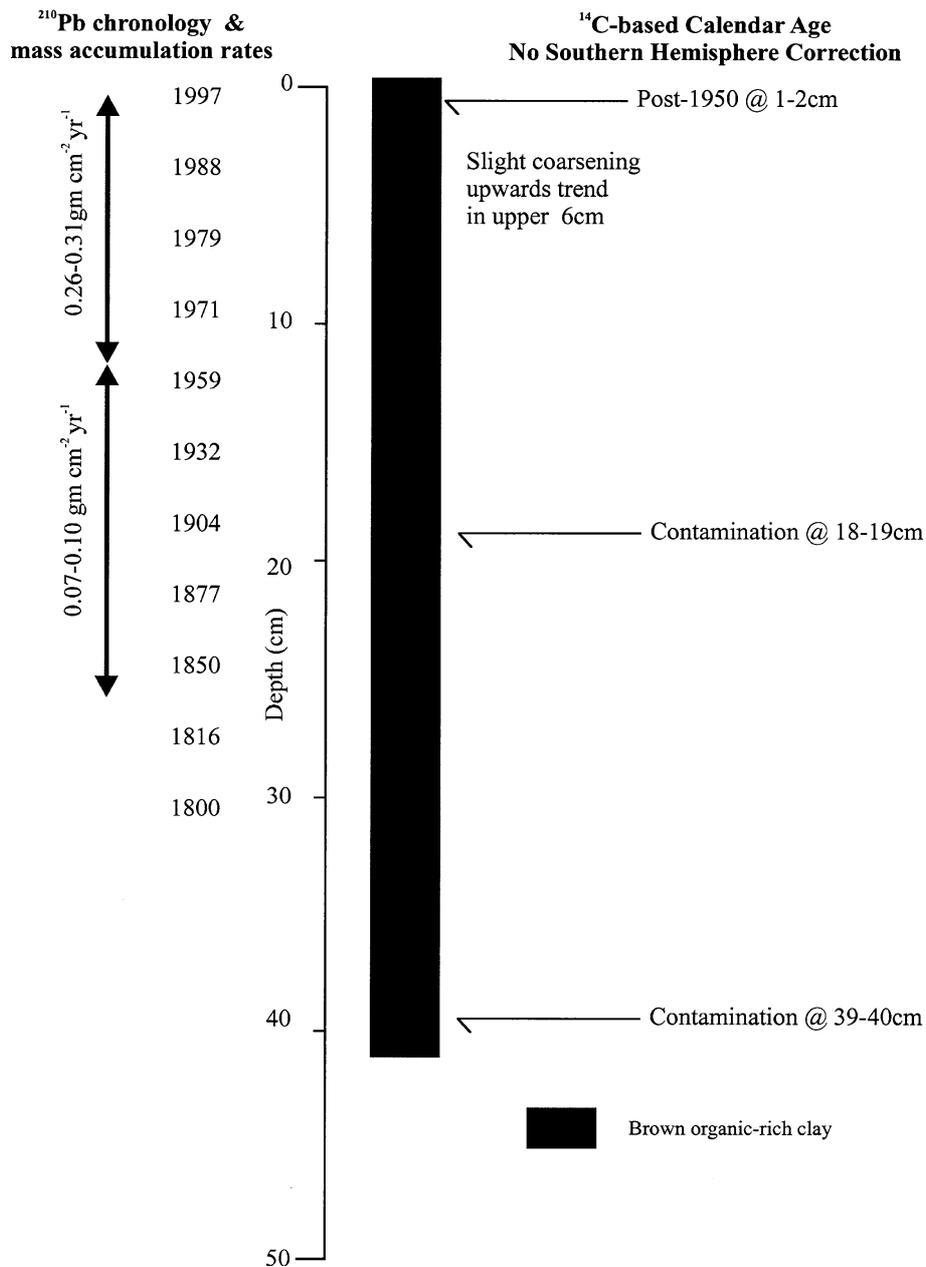


Figure 5. Lithostratigraphy of core LT-98-18M, Kabesi River delta, 75 m water depth. Total core length 42 cm. See Cohen et al. (2005a, Figure 3) for location and bathymetric map.

burning is dramatic in this area. This signal of sediment input for floating fractions from areas outside of the immediate vicinity of this small delta is also evident in the pollen record of this site, discussed in the companion paper by Msaky et al. (2005).

Mwamongo delta core, LT-98-37M northern Tanzania (high disturbance, very small-sized drainage area)

Core LT-98-37M was collected in 95-m water depth about 300 m offshore from the Mwamongo

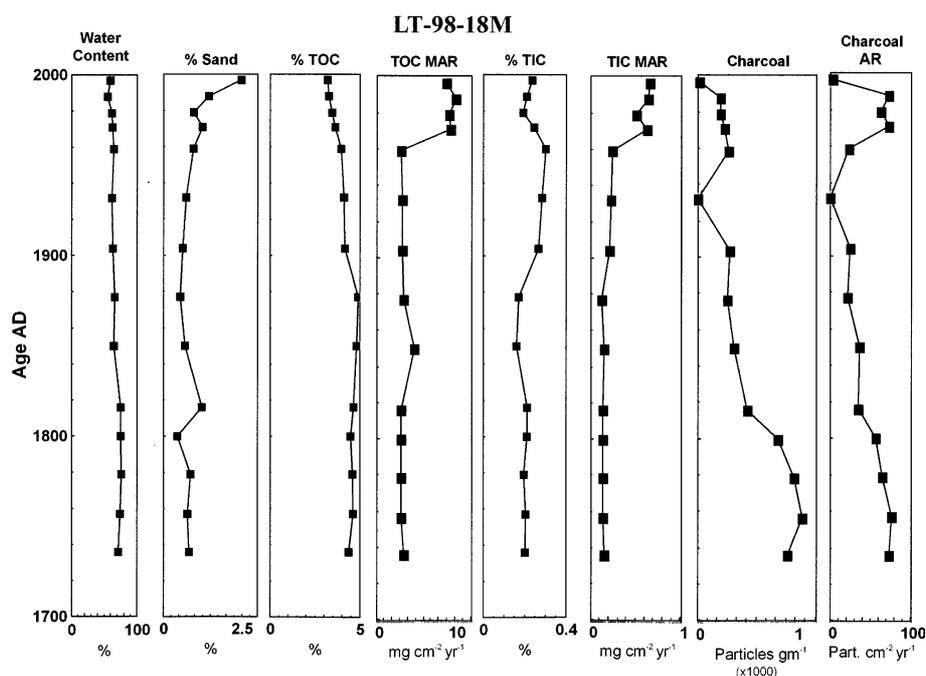


Figure 6. Sedimentologic and charcoal profiles for core LT-98-18M.

River, north of Gombe Stream National Park, Tanzania. Like the Nyasanga/Kahama site, this coring location was a flat bench on an otherwise steep slope. The overall core condition and core top sediment–water interface preservation were excellent. The sediment/water interface consists of flocculent clay with abundant live copepods, ostracodes and snails. The core consists of 45 cm of brownish clays (Figure 9). Alternating massive silty clay and dark sandy organic clay occur throughout, along with carbonates, and the core displays a slight fining upwards. A striking transition to reddish clays near the core top was observed in this core and the other cores collected from the Mwamgongo delta. Similar color changes occur at the tops of cores from other disturbed Tanzanian and Burundian delta cores, and probably indicate high rates of eroded, lateritic soil accumulation, which accumulated so quickly that the reduction interface is well below the sediment–water interface. An upcore decrease in the proportion of coarse sand occurs in LT-98-37M, with pronounced declines near the base of the core (15th century) and then gradually through the early 19th century, after which sand content rises

slightly (Figure 10). This grain size trend closely parallels sediment mass accumulation rates (coarser sediments = higher rates). LT-98-37M displays high values of TOC throughout the core (~4% average, with one sample from the early 1970s reaching nearly 7%). Total organic carbon (TOC) accumulation rates are moderate compared with other cores in the lower part of the core (15–16th centuries) then decline to low levels and rise again to intermediate levels during the 19th century. LT-98-37M also displays some of the highest TIC values seen in any core (2–4%). Their pattern of higher concentrations and accumulation rates in the lower part of the core, dropping to low levels in the middle of the core, and then rising again in the upper part of the core mirrors TOC, except that the dramatic rise in TIC (late 19th century) and its subsequent decline (1940s) occur somewhat earlier for TIC than TOC. Moderately high values of charcoal concentration and accumulation rates exist throughout the core. Charcoal accumulation is relatively high prior to the mid-16th century, then declines to much lower levels through the 18th century, and rises again during the late 19–20th centuries.

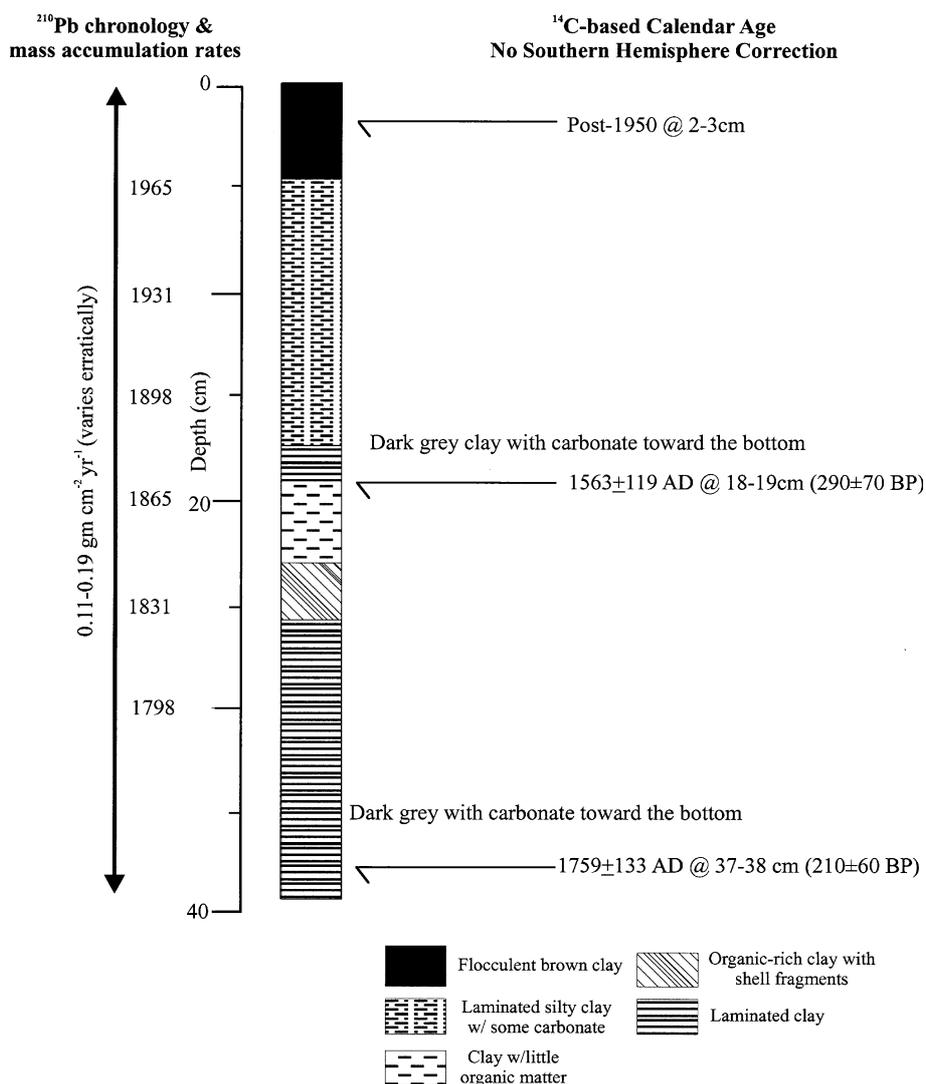


Figure 7. Lithostratigraphy of core LT-98-58M, Nyasanga/Kahama Rivers delta, 76 m water depth. Total core length 39 cm. See (Cohen et al. 2005a, Figure 4) for location and bathymetric map.

Nyamusenyi delta core, LT-98-98M, northern Burundi (high disturbance, small-sized drainage area)

Core LT-98-98M was collected in 60-m water depth, about 100 m north of the Nyamuseni River discharge point and approximately 200 m offshore. The core site is on the proximal part of an elongate spur or ridge extending off the delta, which, based on its shape, may be a small structural high. The core and core top were in excellent condition at recovery. The core consists of 37 cm of alternating brown sandy clay and micaceous

clay, with or without plant debris (Figure 11). The sediment-water interface consists of clayey sand. Apart from a transition from sand to clay-dominated sediment at the base of the core, there are no clear grain-size trends through the core (Figure 12). Core LT-98-98M displays relatively constant and moderately high concentrations (2–4%) of TOC throughout the core, coupled with consistently low TIC concentrations (reflected in the near absence of shelly fossils in this core). Abundant root fragments near the base of the core (late 1950s–early 1960s) indicate the rapid accumulation of reworked soils, consistent with the

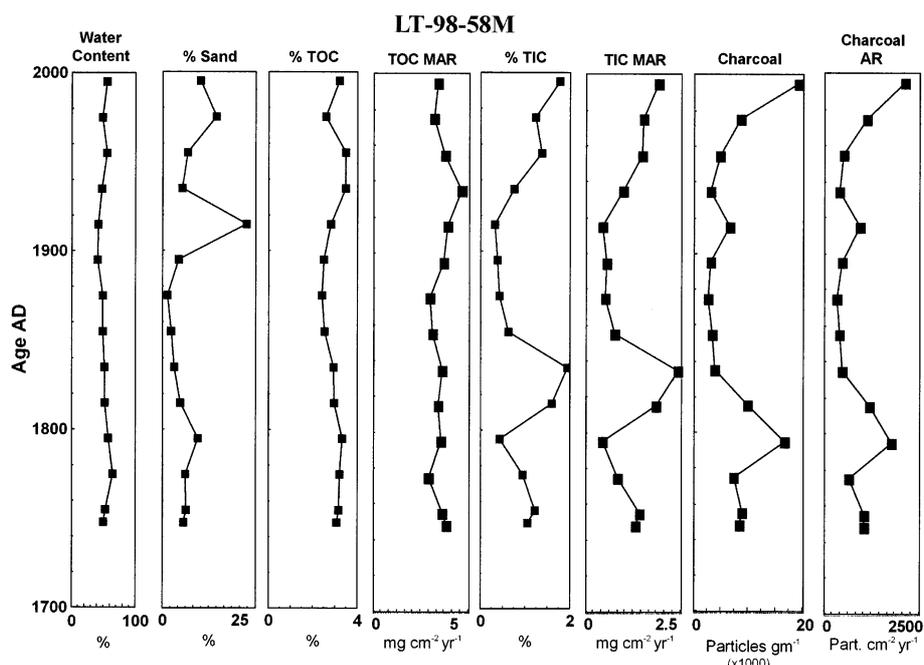


Figure 8. Sedimentologic and charcoal profiles for core LT-98-58M.

inference of increased soil erosion rates starting at that time discussed elsewhere (McKee et al. 2005). Accumulation rates of both TOC and TIC show an initial rise in the early 1960s, then remain relatively stable through the early 1990s, and then increased dramatically after the early 1990s. Small, needle-shaped rosettes of aragonite, formed in the water column, are extremely abundant in the surficial sediments of this area and probably represent the bulk of the TIC observed in these sediments. The increased flux in this aragonite may reflect increasing primary productivity rates in surface waters accompanying the increasing sediment input, a phenomenon observed at the mouths of other rivers in the Tanganyika basin that discharge large volumes of nutrients (Castañeda et al. 1999). Based on sedimentation rate changes, this nutrient enrichment was probably underway after the early 1960s, and increased dramatically in the 1990s. Core LT-98-98M displays relatively constant charcoal concentrations and gradually rising accumulation rates prior to the early 1980s. Peak charcoal concentrations and accumulation rate in the early 1980s were followed by a dramatic decline after the 1980s, probably reflect the declining availability of forest cover for burning

within this watershed, as conversion to agricultural and disturbed lands was more or less completed.

Karonge/Kirasa deltas core, LT-98-82M, northern Burundi (high disturbance, medium-sized drainage area)

Core LT-98-82M was collected in 96-m water depth, 1.2 km west of the Karonge and Kirasa delta, on a broad, gently dipping slope. The core and core top were both in excellent condition at recovery. The core consists of 46 cm of alternating dark gray and gray, laminated or massive clays (Figure 13). The core shows a notable upcore decline in sand concentration, with brief reversals accompanying periods of increased sedimentation rates (Figure 14). Relatively constant and high TOC concentrations (slightly more abundant proportionately than at the nearby LT-98-98M) occur throughout the core. Total organic carbon (TOC) accumulation rate changes reflect overall sediment accumulation rate changes, with a major increase in TOC MAR after the early 1960s

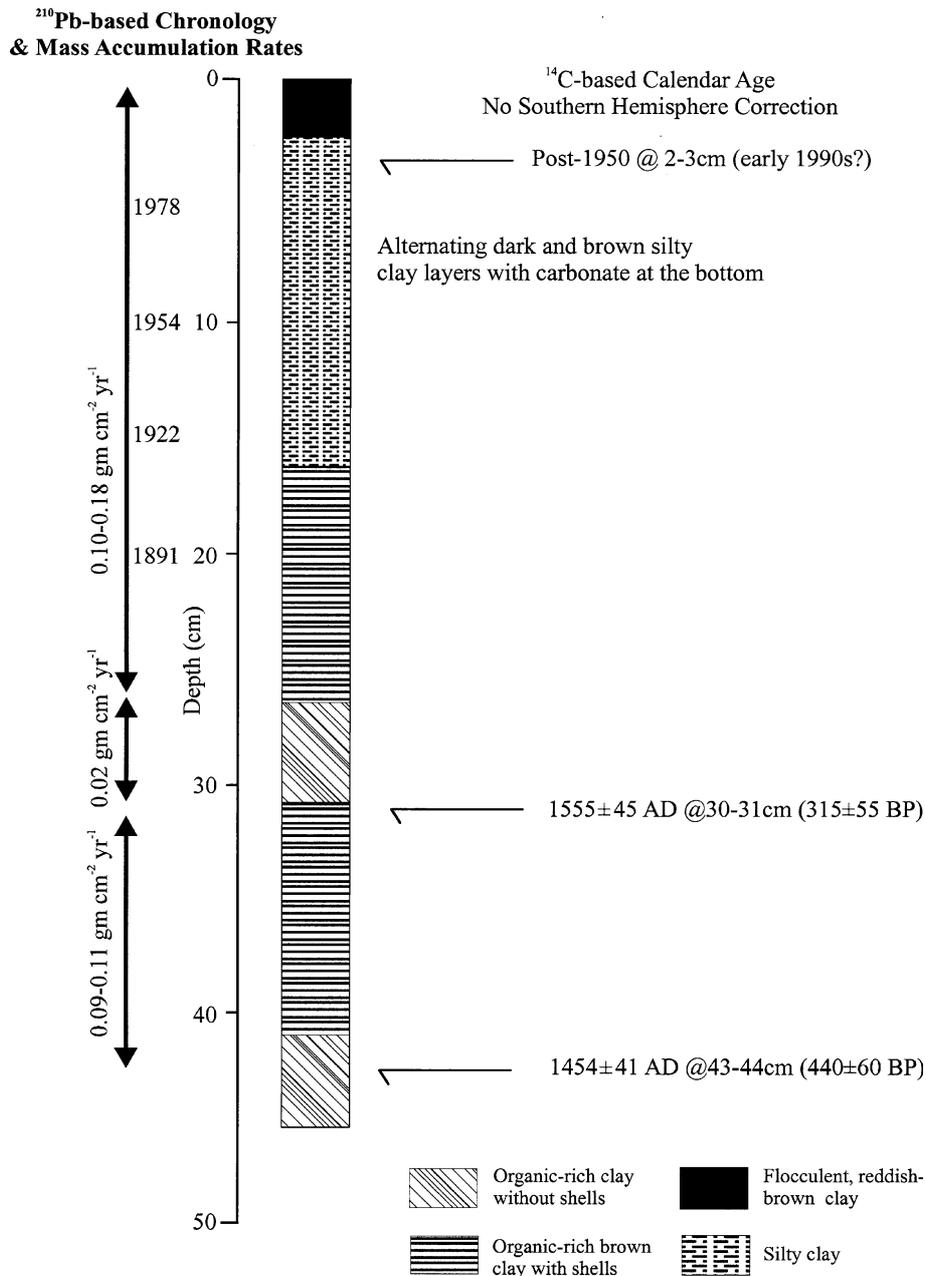


Figure 9. Lithostratigraphy of core LT-98-37M, Mwamgongo River delta, 95 m water depth. Total core length 45 cm. See (Cohen et al. 2005a, Figure 4) for location and bathymetric map.

reflecting background increases in sedimentation rates (Figure 14). Total inorganic carbon (TIC) concentration is also relatively constant throughout the core, with the exception of an interval in the mid-19th century, when concentration and accumulation rates rise significantly. As with TOC, TIC MARs rise again to high levels starting in the early 1960s.

As with LT-98-98M, abundant visible terrestrial plant debris throughout the upper part of LT-98-82M suggests that the TOC increase is primarily driven by allochthonous organic matter coming from terrestrial sources. Somewhat surprisingly, given the highly disturbed nature of this watershed, core LT-98-82M contains a relatively low abundance of charcoal throughout much of

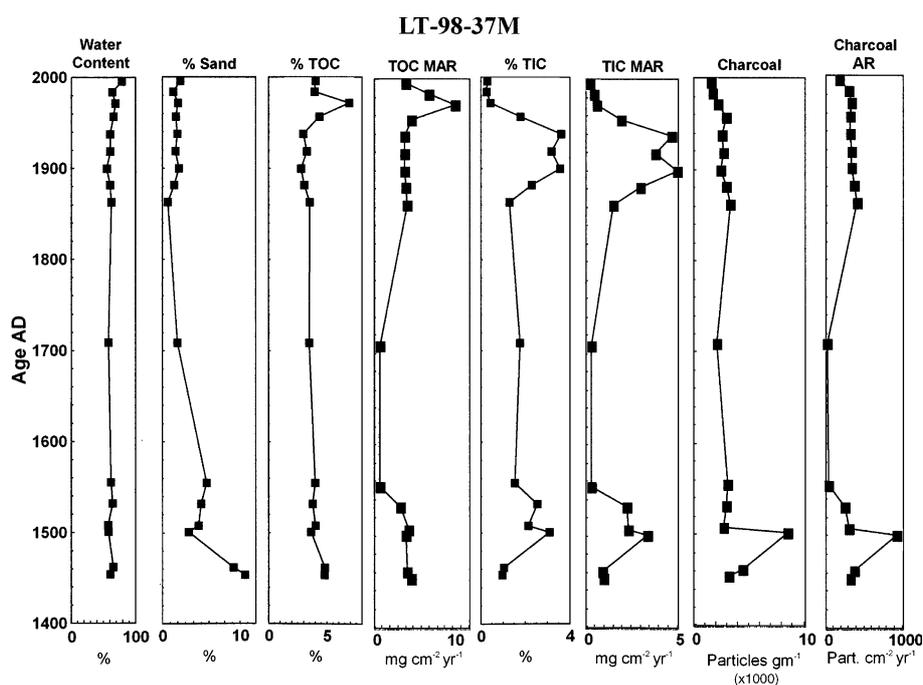


Figure 10. Sedimentologic and charcoal profiles for core LT-98-37M.

the core, mirroring low accumulation rates, except for two levels (36 and 27 cm = early-mid-19th century) and towards the core top (late 20th century).

Intersite comparisons and discussion

Total organic carbon (TOC) values ranged between ~3–7% in all cores, with the notable exception of the lowermost portion of LT-98-2M (pre ~500 B.C./~2450 B.P.), which was sandy and TOC-poor. This interval, unrecorded in any other cores, may have been a period of substantially lower lake levels. This evidence for lower lake levels in the LT-98-2M core is consistent with earlier studies (Haberyan and Hecky 1987; Casanova and Hillaire-Marcel 1992; Cohen et al. 1997), all of which suggest a probable closure of the Ruzizi River outflow from Lake Kivu to Lake Tanganyika for an extended portion of the Late Holocene. These earlier studies suggested that the rise in Lake Tanganyika water level that accompanied the opening of Lake Kivu occurred at some time between 100 and 800 A.D. (1850–1150 B.P.). However, the results from this study

imply that at least some outflow began earlier, between 1000 and 600 B.C. (2950–2550 B.P.). In large part, these discrepancies probably result from our age model uncertainties for the lake's paleohydrologic history during the 1000 B.C. (2950 B.P.) and 1000 A.D. (950 B.P.) interval. Major paleolimnologic changes consistent with erratically rising lake levels, beginning prior to 620 B.C. (2570 B.P.) (this study) and largely completed by 580 A.D. (1370 B.P.) (Alin and Cohen 2003) suggest that inflow from Lake Kivu probably increased incrementally during this time.

Systematic increases in TOC accumulation rates are evident from all of the highly disturbed watershed cores. This increase occurs abruptly in the 1960s in the Kabesi River core from central Tanzania (LT-98-18M). At the more northerly, disturbed sites with multi-century records (LT-98-37M and LT-98-82M) this 1960s rise is also evident, but is preceded by a more gradual increase, starting in the 19th century. In contrast, no such increase in TOC accumulation rate is evident in either of the undisturbed core sites, at Lubulungu (LT-98-12M) or Nyasanga/Kahama (LT-98-58M), with the LT-98-12M core actually showing a

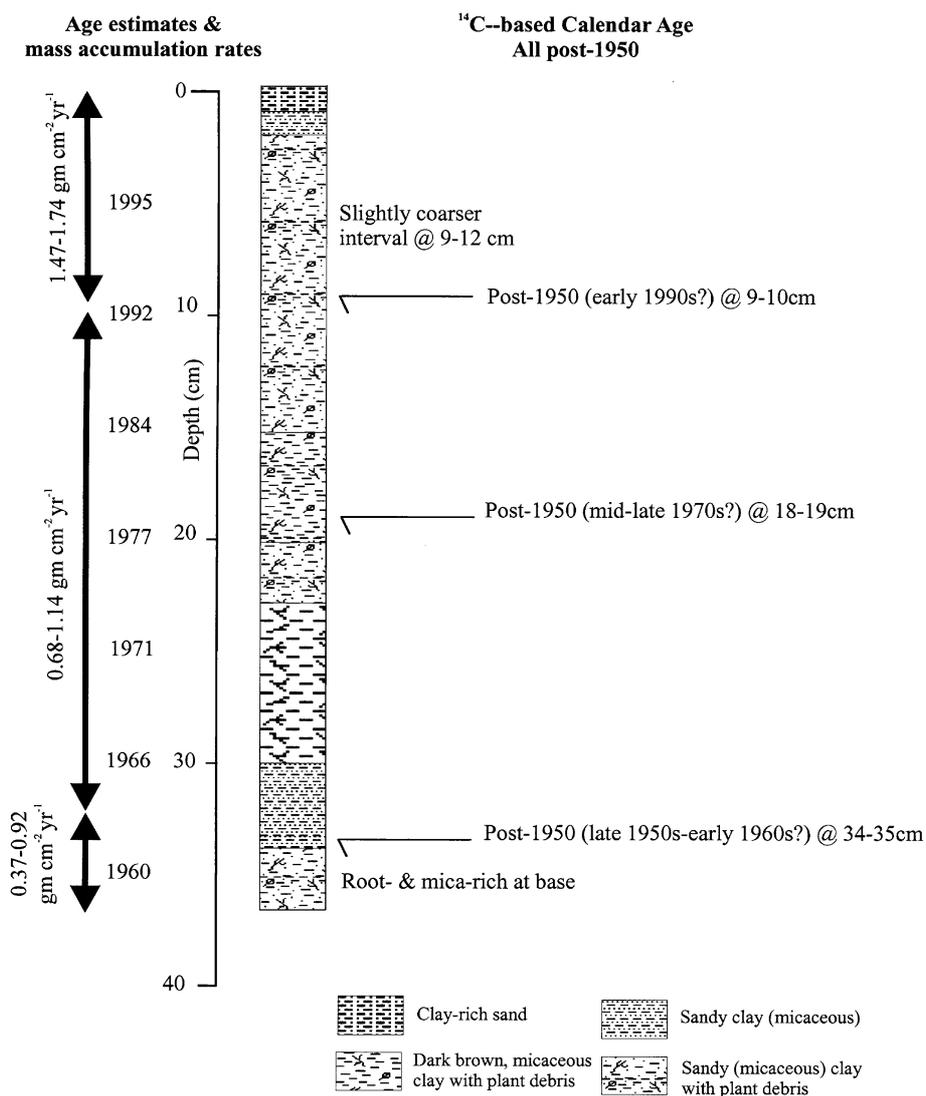


Figure 11. Lithostratigraphy of core LT-98-98M, Nyamusenyi River delta, 60 m water depth. Total core length 37 cm. See Cohen et al. (2005a, Figure 5) for location and bathymetric map.

significant decline in TOC MARs after the late 18th–early 19th century.

Total inorganic carbon (TIC) concentrations were very low (<1%) in all cores from the central Tanzania and Burundi deltas (LT-98-2M, 12M, 18M, 98M and 82M). At site LT-98-2M, the near absence of TIC sedimentation prior to 1000 B.C. (2950 B.P.), and its gradual increase through 100 A.D. (1850 B.P.) is consistent with the interpretation of Lake Kivu closure discussed above, since that lake is the primary source of calcium carbonate (and dissolved solutes in general) to modern Lake Tanganyika.

Total inorganic carbon (TIC) concentrations were substantially higher in both northern Tanzanian coast cores (LT-98-58M and 37M) than in the other cores examined. These intersite differences probably reflect overall lower fluxes of siliciclastic sediments into the areas offshore from these smaller watersheds, resulting in lower degrees of dilution of carbonate sedimentation. Mass accumulation rate changes in TIC through the core records for the moderately disturbed site at Kabesi (LT-98-18M) and the very highly disturbed sites in Burundi (LT-98-98M and LT-98-82M) for the late 19th and 20th centuries mirror

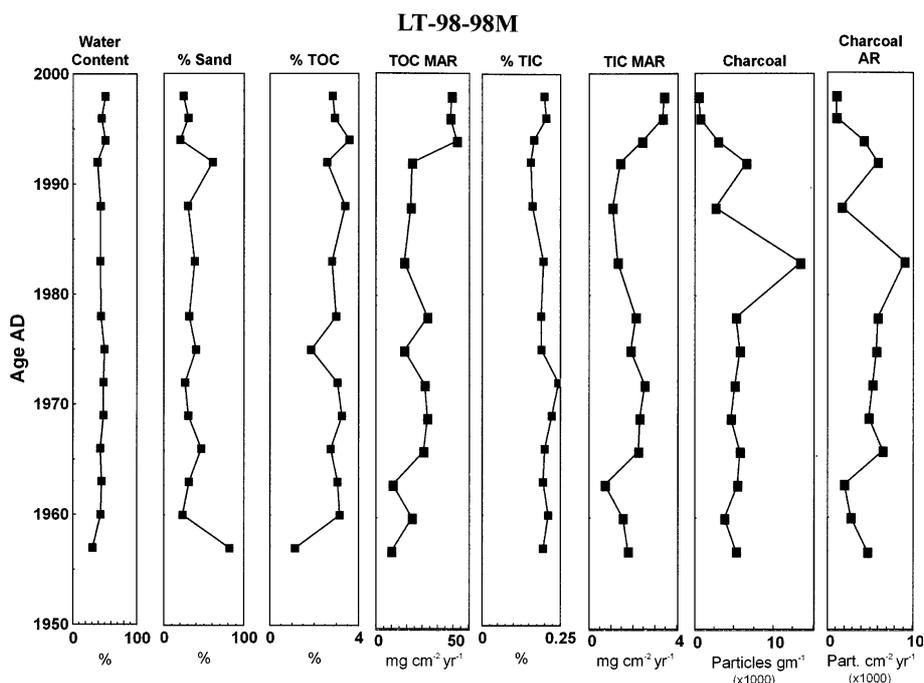


Figure 12. Sedimentologic and charcoal profiles for core LT-98-98M.

the patterns described above for TOC. At these sites, TIC accumulation rates may be tracking benthic invertebrate productivity, since most of this carbonate is shell material. However, the complicated patterns of TIC MAR at other sites argue that other factors are probably involved in this record. An interval of elevated TIC accumulation in the early 19th century is recorded at one of the Burundi disturbed sites (LT-98-82M) and one of the northern Tanzanian disturbed sites (LT-98-58M) but not the other nearby sites (LT-98-98M and LT-98-37M). These changes in carbonate production are quite localized and were probably driven by a wide variety of factors (e.g., intensity of deforestation, land use, erosion, nutrients in water, local changes in alkalinity and salinity at the mouth of the river) besides simply local benthic productivity. Abundant terrestrial plant debris throughout the upper part of LT-98-98M suggests the TOC increase is primarily driven by allochthonous organic matter coming from terrestrial sources. The increase in TIC flux, by contrast, is almost certainly autochthonous, because there is no source of particulate calcium carbonate in the watershed, and given the extremely low abundance of both molluscs and ostracodes, this rise cannot represent an increase in benthic consumers.

Charcoal fragment abundances are very high ($\sim 10^3$ – 10^4 g m^{-1}) throughout most of the cores (except LT-98-18M and, surprisingly, LT-98-82M), consistent with the common uncontrolled dry season fire activity, the use of fire in land clearance and the ubiquitous usage of fire for cooking and charcoal production. Wildfires are commonly observed in the Tanzanian coastal woodlands and grasslands today, although in the more heavily settled regions of Burundi they are now much less common. In most cases, charcoal abundance and accumulation rates cannot be directly or simply correlated with patterns of land use in the immediate adjacent watersheds. This is undoubtedly a consequence of the interactive effects of climate and changing land use. The role of climate as an important influence on fire frequency (and therefore charcoal abundance) is evidenced by the high abundances and accumulation rates of charcoal deposition during the relatively arid Little Ice Age period. The major increase in charcoal accumulation rates starting in the 12–13th centuries and reaching a maximum in the 15–16th centuries in LT-98-2M is particularly noteworthy in this regard. High charcoal abundances and fluxes at the base of LT-98-12M, and again in the mid-late 18th century, probably also

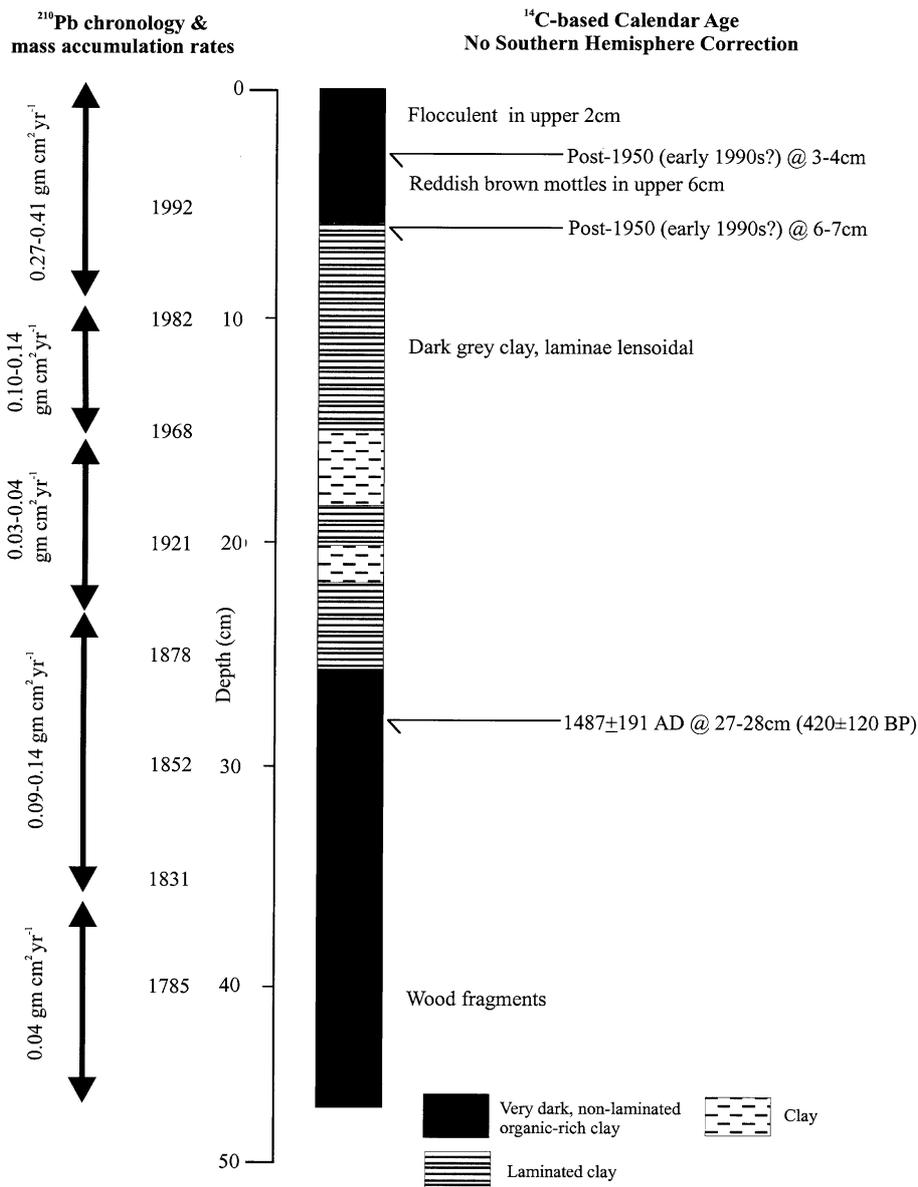


Figure 13. Lithostratigraphy of core LT-98-82M, Karonge/Kirasa River delta, 96 m water depth. Total core length 46 cm. See Cohen et al. (2005a, Figure 5) for location and bathymetric map.

correlate with intervals of abundant fires related to aridity, and are contemporaneous with the interval of maximal aridity inferred from the palynological portion of this study (Msaky et al. 2005). Msaky et al. (2005) indicate that aridity of the region began ~500 A.D. (~1450 B.P.) with the gradual replacement of forest by open grassland vegetation. These high charcoal abundances mimic the more clearly anthropogenic effects of the late 20th

century. In an earlier study of late Holocene paleoclimates in the Lake Tanganyika region, Alin and Cohen (2003) suggested that arid conditions and low lake stands occurred in the mid-late 16th century and again in the mid-18th century. By contrast, these results place the arid events slightly earlier, discrepancies that are likely the result of remaining uncertainty in our radiometric dating and age models.

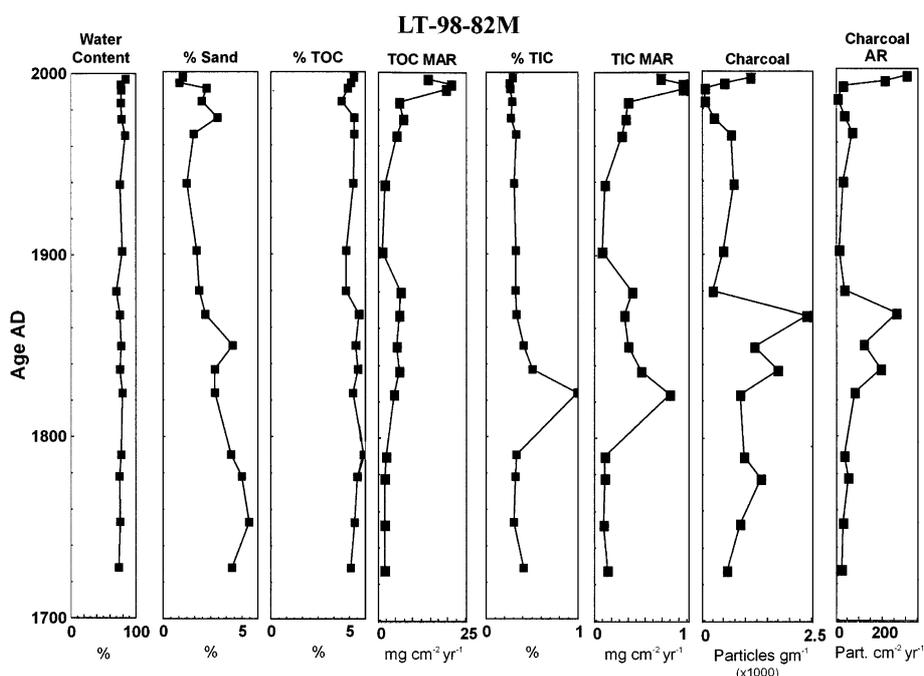


Figure 14. Sedimentologic and charcoal profiles for core LT-98-82M.

Reduced charcoal accumulation rates during the 19th century at most of our study sites may reflect a combination of two factors affecting the region at the time. First, East/Central Africa appears to have become generally wetter during that period relative to the early 19th century (Verschuren in press). Second, human population densities in much of the western rift valley region during the mid-19th century appear to have been greatly reduced, as a result of both the deprivations of slaving activity in this region and disease (Stanley 1878; Bennett 1970; Koponen 1988). It is important to note, however, that the timing of this reduction is not synchronous between sites. At Lubulungu, by far the wettest region of any of the study areas, charcoal accumulation rates were relatively high in the mid-18th century but then declined during the late 18th through the mid-19th century, and have remained low between that time and the present. It may be significant, in this regard, that forest cover in this region of west-central Tanzania appears to have been increasing during the period of caravan route incursion, when human populations are presumed to have been on the decline. At the Kabesi and Nyasanga/Kahama sites, lower charcoal accumulation rates started in

the early 19th century and persisted until the mid-20th century. Further north, at Mwamgongo, low sampling resolution in the 18th and 19th century precludes an accurate determination of the timing of rising charcoal sedimentation, other than making it clear that this occurred before the late 19th century. In northern Burundi, the decline occurred later, in the late 19th century. This geographic pattern may be related to the differences in human demographic history between the central Lake Tanganyika catchment (strongly influenced by the effects of 19th century caravan routes) and the more northerly Burundian catchments, away from the caravan trade routes, a point discussed in more detail in Cohen et al. (2005b). However, at the present time, we do not know how charcoal input into the sediments of Lake Tanganyika from cooking fires or charcoal production might differ from the pattern produced by uncontrolled wild-fires or intentionally-set fires for land clearing. Understanding such differences might help clarify the complex patterns observed in our cores. We also do not know the extent to which anomalously elevated values of charcoal in these profiles may represent single large fire events, or alternatively, integrate longer-term changes in charcoal input.

Summary

A sedimentologic analysis of cores collected from the deltas of disturbed and undisturbed watersheds of various sizes around Lake Tanganyika shows that patterns of sediment deposition and charcoal flux are complex, representing an interplay of anthropogenic, climatic, and transport phenomena. Fairly clear indications of increased mass accumulation rates and TOC accumulation rates are evident from disturbed sites, starting in the 19th century at some sites but increasing rapidly and apparently synchronously in the mid-20th century. These rate changes are in some cases accompanied by accumulation rate increases of autochthonous inorganic carbon deposition, possibly reflecting *in situ* rises in benthic productivity since most carbonate is shell material. They are also accompanied by rising charcoal fluxes at a number of sites, which are indicative of land clearing activities. However, the effect of anthropogenic land clearance is mimicked during arid intervals by higher charcoal deposition rates and/or by rising sediment accumulation rates. The mid-late 19th century was generally a period of low charcoal flux at the more southerly sites, consistent with both wetter conditions and relatively low human population densities. To the north, high charcoal accumulation rates in the mid-19th century, followed by an abrupt decline to low rates, which persisted from the late 19th to mid-20th century, indicate a different fire and human demographic history.

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