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# Paleolimnological investigations of anthropogenic environmental change in Lake Tanganyika: I. An introduction to the project

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## Abstract

We investigated paleolimnological records from a series of river deltas around the northeastern rim of Lake Tanganyika, East Africa (Tanzania and Burundi) in order to understand the history of anthropogenic activity in the lake's catchment over the last several centuries, and to determine the impact of these activities on the biodiversity of littoral and sublittoral lake communities. Sediment pollution caused by increased rates of soil erosion in deforested watersheds has caused significant changes in aquatic communities along much of the lake's shoreline. We analyzed the effects of sediment discharge on biodiversity around six deltas or delta complexes on the east coast of Lake Tanganyika: the Lubulungu River delta, Kabesi River delta, Nyasanga/Kahama River deltas, and Mwamgongo River delta in Tanzania; and the Nyamuseni River delta and Karonge/Kirasa River deltas in Burundi. Collectively, these deltas and their associated rivers were chosen to represent a spectrum of drainage-basin sizes and disturbance levels. By comparing deltas that are similar in watershed attributes (other than disturbance levels), our goal was to explore a series of historical "experiments" at the watershed scale, with which we could more clearly evaluate hypotheses of land use or other effects on nearshore ecosystems. Here we discuss these deltas, their geologic and physiographic characteristics, and the field procedures used for coring and sampling the deltas, and various indicators of anthropogenic impact.

## Introduction

Understanding the history and timing of disturbances caused by anthropogenic alteration of watersheds is an essential element in lake management. This task is difficult even in small, closely monitored lakes; but in large lakes with poor historical documentation, the task is particularly daunting. Under these circumstances, a paleolimnological approach may be the only means of reconstructing the cause and effect relations between human activities and lake-ecosystem change.

In this introductory paper and companion papers (McKee et al. 2005; Palacios-Fest et al. 2005a, b; Msaky et al. 2005; O'Reilly et al. 2005; Dettman et al. 2005; Nkotagu 2005; Cohen et al. 2005), we document the first detailed and well-dated records of paleolimnologic change linked to human activity for Lake Tanganyika, the largest of the African rift lakes. Lake Tanganyika houses an extraordinarily rich and complex ecosystem, which may be under threat from a variety of human activities, particularly those related to rapid deforestation in the lake's surrounding catchment (Coulter 1991; Cohen et al. 1995). Lake Tanganyika supports one of the most species-rich lacustrine biotas on the planet, with over 1500 species of organisms, at least 600 of which are endemic to the lake.

Our principal objective was to determine the timing and magnitude of changes in impacted watersheds and probable linkages between these changes and ecosystem changes in the lake. Paleolimnology provides a powerful approach for investigating ecosystem dynamics and anthropogenic impacts at Lake Tanganyika and its catchment, where only limited historical data are available to assess the timing of human impacts to lake watersheds and their relations to ecological changes in the lake. Most ecological investigations of sedimentation impacts on the lake to date have been of short duration and of limited regional scope. This impedes our ability to draw conclusions about the probable causes of observed differences in ecosystems between regions of the lake that are highly disturbed by human activities today, vs. those showing lesser or no signs of watershed disturbance, since chronologies linking the putative causes and effects cannot be obtained from modern data alone.

To conduct this research we identified, mapped, and cored a series of representative river deltas around the northeastern and east-central margins of the lake, a region that includes both some of the most highly impacted watersheds surrounding Lake Tanganyika, and some areas that have experienced very limited human impacts over the past few hundred years. Using $^{210}Pb$ and $^{14}C$ dating techniques (McKee et al. 2005), we determined changes in sediment accumulation rates, as well as changes in sedimentological (Palacios-Fest et al. 2005a), palynological (Msaky et al. 2005), lacustrine paleoecological (ostracodes, mollusks, fish sponges) (Palacios-Fest et al. 2005b), and geochemical archives (O'Reilly et al. 2005; Dettman et al. 2005) in the study areas over the last several hundred years. We further assessed the ecological impact of excess sedimentation on the benthic environment of Lake Tanganyika by comparing the species diversity and distribution of chironomid larvae (non-biting midges) adjacent to pristine and disturbed tributary drainages (Eggermont and Verschuren 2003a). In this particular study, spatial patterns in the modern fauna were surveyed using recently buried chironomid remains (Eggermont and Verschuren 2003b and c) rather than live larvae, to avoid the logistic difficulties associated with live monitoring of aquatic invertebrate populations in large lakes and more easily obtain the sample sizes needed for robust statistical analysis. Recently deposited death assemblages reflect the general distribution of suitable habitat, rather than local microhabitat conditions at (a statistically small number of) sampling sites (Frey 1988). They thus permit investigation of the ecological impacts of excess sedimentation at the appropriate spatial scale, and in a study design that controls for influences of natural habitat diversity and gradients on the distribution of benthic biota. All studies were conducted as a subcomponent of the Special Study on Sedimentation of the Lake Tanganyika Biodiversity Project, a Global Environmental Facility (UNDP-GEF) program (www.ltbp.org) designed to develop conservation and resource management strategies for Lake Tanganyika and its watersheds, in cooperation with the NSF-GEF funded Nyanza Project research training program on tropical lakes.

## Purpose and general approach of the study

The main purpose of this study was to identify the timing and magnitude of ecological and environmental changes along the eastern shore of Lake Tanganyika over the last several hundred years. The conceptual approach we have taken is to compare the historical records of offshore delta environments adjacent to watersheds representing a spectrum of modern disturbance levels, from comparatively undisturbed or slightly disturbed watersheds to highly disturbed areas. Our goal was to compare deltas of similar watershed size in such a way as to provide records from watersheds that differed primarily in their degree of disturbance, keeping other variables that are known to affect sediment discharge, such as slope and bedrock composition, relatively constant. We examined six deltas on the east coast of Lake Tanganyika as representing slightly to highly disturbed drainages: the Lubulungu, Kabesi, Kahama/Nyasanga and Mwamgongo River deltas in Tanzania, and the Nyamuseni and Karonge/Kirasa River deltas in Burundi (Tables 1 and 2).

In any paleolimnological analysis, it is important to bear in mind that a variety of environmental processes can cause changes in the variables we seek to interpret, of which human disturbance of the landscape is but one. In addition, climatic change (affecting vegetation cover and fire activity in particular), hydroclimatic changes involving changes in the depth of wind-driven mixing and productivity, and the autocyclic processes that generate changes in deltaic sedimentation patterns over time, are all known or suspected to have varied at the core sites over the last millennium, and all will have conspired to generate the record that we seek to interpret.

It is also important to recognize that human impacts have been an important factor shaping the landscape of the northern Lake Tanganyika catchment for at least the last few millennia (Schoenbrun 1998). Locally high population densities have probably existed throughout the intra-lacustrine region of Africa at least since the early Iron Age, and iron smelting itself clearly resulted in deforestation in many areas as early as the last millennium B.C. (e.g., Schmidt 2003). Furthermore, human occupation of rural landscapes in Africa have not uniformly resulted in a reduction in tree density, and some regions of East Africa have clearly undergone afforestation since the 19th century (e.g., Fairhead and Leach 1996, 1998; McCann 1997). It would be mistaken to automatically interpret what are currently "undisturbed" watersheds as regions that have not been thoroughly transformed as a result of human activity. In fact, mature *miombo* woodlands (discussed in detail below), which characterize much of the "undisturbed" watersheds at low to mid elevations around Lake Tanganyika today, are

*Table 1.* Lake Tanganyika deltas investigated in this study.

| Drainage size category | River name | Drainage basin area | Disturbance | | | Human population density #/km$^2$ |
|---|---|---|---|---|---|---|
| | | | Low | Medium | High | |
| Small | Lubulungu (Mahale Mtns. Natl. Park, central Tanzania coast) | 50 km$^2$ | X | | | < 5 |
| Medium | Kabesi (central Tanzania coast) | 120 km$^2$ | | X | | 10–20 |
| Very Small | Nyasanga/Kahama-Gombe Natl. Park, northern Tanzania coast) | ~3.8 km$^2$ combined area | X | | | < 5 |
| Very Small | Mwamgongo (Gombe area, northern Tanzania coast) | 7.7 km$^2$ | | | X | ~800 (concentrated in lowland village area) |
| Small | Nyamusenyi (Gitaza Area, northern Burundi coast) | 30 km$^2$ | | | X (extremely high) | ~475 (dispersed) |
| Medium | Karonge/Kirasa (Gitaza Area, northern Burundi coast) | 42 km$^2$/120 km$^2$ | | | X (extremely high) | ~475 (dispersed) |

*Table 2.* List of investigated deltas and coring stations in this study.

| Delta | Station # | Date | Lat. (decimal) °S. | Long. (decimal) °E | Water depth (m) |
|---|---|---|---|---|---|
| Lubulungu | LT-98-2 | 1/7/98 | 6.1653 | 29.7060 | 110 |
| Lubulungu | LT-98-12 | 1/8/98 | 6.1655 | 29.7178 | 126 |
| Kabesi | LT-98-18 | 1/10/98 | 5.9768 | 29.8167 | 75 |
| Nyasanga/Kahama | LT-98-58 | 1/15/98 | 4.6883 | 29.6167 | 76 |
| Mwamgongo | LT-98-37 | 1/13/98 | 4.6227 | 29.6332 | 95 |
| Nyamuseni | LT-98-98 | 1/26/98 | 3.6193 | 29.3402 | 60 |
| Karonge/Kirasa | LT-98-82 | 1/25/98 | 3.5835 | 29.3252 | 96 |
| Malagarasi | LT-97-14 | 2/15/97 | 5.1400 | 29.7328 | 73.1 |

themselves arguably the product of interactions of intentional human burning with a seasonally dry climate (Lawton 1978). Watershed disturbance and its ecological consequences in a region where the human footprint is ancient can only be evaluated relative to current levels of soil erosion and lacustrine impacts, as there are probably no watersheds surrounding Lake Tanganyika that have been truly devoid of human impacts in the late Holocene.

## Review of previous work

In the late-1980s and early-1990s, several studies by our University of Arizona research group identified probable linkages between ongoing watershed deforestation within the Lake Tanganyika drainage basin and ecological changes in the lake's nearshore communities (Cohen et al. 1993a, 1995; Alin et al. 1999; Wells et al. 1999). This work was stimulated by reports from agronomic investigations of accelerated landscape degradation in the Burundian watersheds of the lake (e.g., Bizimana and Duchafour 1991). Satellite imagery and ground observations have shown that many watersheds in the northern region of the lake basin are almost completely deforested, with conversion of "*miombo*" woodland, dominated by *Brachystegia*, *Isoberlinia* and *Julbernardia*, and Afromontane or riparian forests, to a mixture of agricultural, pastoral, and village land use. Soil erosion modeling has shown the probable effects of such deforestation throughout the Lake Tanganyika catchment (Drake et al. 1999). Much of this conversion has occurred on steeply sloping land, with small-holding farm plots of cassava on unterraced hillsides, and bananas, sorghum, finger millet, beans, and oil palm grown on valley floors. Agronomic studies of various land-use types in Burundi have shown that this land-use conversion produces a 10 to 100-fold increase in soil erosion rates (Bizimana and Duchafour, 1991).

Remote sensing studies, conducted by the Lake Tanganyika Biodiversity Project have further quantified the magnitude and distribution of watershed soil erosion and discharge into Lake Tanganyika on a regional basis (Drake et al. 1999; Bryant 1999; Donohue et al. 2003a). Much of this sediment is discharged into Lake Tanganyika, where it has the potential to affect lacustrine ecosystems in various ways. Declining species richness and changing trophic structure observed in fish, ostracode and diatom communities were interpreted to have resulted from sediment inundation, declining light availability and loss of habitat heterogeneity (Cohen et al. 1993a). Alin et al. (1999) provided additional support for this interpretation based on SCUBA diver and remotely operated vehicle (ROV) transects of molluscs, fish, and ostracodes at three sites in the northern portion of the lake. In addition, O'Reilly (1998) conducted *in situ* measurements of benthic primary productivity using the clear/dark chamber method, and found that oxygen concentration, light penetration, and biomass-specific net productivity all decreased in highly disturbed areas. Recent ecological experiments and paired catchment studies on the impacts of increased sedimentation rates in Lake Tanganyika are consistent with the idea that such sedimentation increases would result in deleterious effects on the littoral ecosystem (Donohue et al. 2003b; Donohue and Irvine 2004).

Collectively, these studies strongly suggest that human impacts related to watershed deforestation are affecting nearshore lake ecosystems in Lake Tanganyika. However, all of these investigations were of short duration and could not pinpoint the timing of ecological changes required to verify the hypothesis that such severe impacts are largely a 20th century phenomenon. Indeed, historical accounts by early European visitors to what is now Burundi suggest that rising human population density and deforestation were already underway at least in the Burundi highlands (Congo/Nile watershed divide) by the late-19th century, if not much earlier (Gahama 1983). This shortcoming highlighted the need for a paleolimnological approach to study this problem, since instrumental and observational records did not exist for studying this question over the time interval in question (the last few centuries). Although numerous expeditions had investigated the paleoenvironmental history of the Lake Tanganyika region through coring prior to this work (e.g., Livingstone 1965; Haberyan and Hecky 1987; Gasse et al. 1989; Vincens 1989, 1991, 1993), these studies have generally been of insufficient temporal resolution to address questions about the timing of anthropogenic impacts over the last few centuries. Furthermore, earlier coring efforts have largely been directed toward deep-water, distal targets, which provide clearly interpretable stratigraphies, but which are distant from terrestrial inputs (thus obscuring those signals) and lack benthic invertebrate fossils. Coring studies were undertaken by our University of Arizona group to rectify this problem. Wells et al. (1999) generated the first data documenting a historic (20th century) increase in sedimentation rates in the northern portion of Lake Tanganyika (Burundi coastline, near the Karonge/Kirasa River delta), in an area with extremely low benthic biodiversity today. However, a direct relationship between increasing sedimentation rates and declining diversity could not be established in that study. Some subsequent work showed that, although the northern Burundi coastline has much lower benthic biodiversity today than do similar areas farther south, that difference may have already been established as much as 1000 years ago or more (Cohen 2000). If sedimentation rate differences were responsible for the differences seen in diversity between northerly and southerly sites, then the watershed factors responsible for those differences must at least in part predate 20th century human population increases. These could have resulted from a much earlier development of deforested conditions in the northern part of the lake's catchment, a greater susceptibility of northern catchment soils to erosion, or some combination of the two factors.

Relatively little information exists on human population densities prior to the early 20th century. Early European explorers encountered relatively low population densities in what is now the Tanzanian coastal region of Lake Tanganyika, and it is likely that the region experienced significant depopulation during the mid-19th century, as a consequence of the combined effects of the slave trade and both human and livestock epidemics (Koponen 1988). In contrast, the northern portion of the lake's catchment, in Burundi, was effectively isolated from both the effects of caravan-borne disease and the slave trade. Burundi had existed as a kingdom since the late-17th century, culminating in a region close to the nation's modern borders by the mid-19th century. Significantly, the northernmost Tanzanian areas discussed in this study (north of Kigoma) were under effective Burundian royal control by the mid-19th century as well, precluding any effective slave capture or Arab/European contact from this region up to the north end of Lake Tanganyika until the end of the 19th century (Lemarchand 1970; Gahama 1983). The Burundian king (mwami) exerted either direct control (in the highland region of the Nile/Congo watershed divide) or indirect control (through allied chiefs in the coastal plain of Lake Tanganyika) throughout the mid to late-19th century. This entire region of the lake's catchment north of the modern-day Ujiji/Kigoma urban area appears to have had much higher (and more stable) population densities throughout this period than the Tanzanian coast south of modern Kigoma and Ujiji. These human demographic changes must be factored into any assessment of the long-term effects of land-use change on lake ecosystems.

The coring and paleolimnological studies described in this paper, and companion papers published in this issue, were undertaken to provide a more comprehensive analysis of ecosystem change for a variety of watersheds along the Lake Tanganyika coastline than was available from previous studies. They allow us to frame our understanding of the relationship between deforestation and lake-ecosystem change in an historical context, thereby improving our understanding of the timing and probable causes and consequences of changing sedimentation rates in Lake Tanganyika.

## Geologic and physiographic setting

Lake Tanganyika (3°18′–8°47′ S, 29°05′–31°18′ E, 772 masl), in the western branch of the East African Rift System, is the largest of the African rift lakes and the second deepest lake in the world (Figure 1). The lake occupies a series of interconnected half-graben basins, the oldest of which are probably between 9 and 12 Ma (Cohen et al. 1993b). Bedrock within the lake's catchment includes early-middle Proterozoic metasediments and metavolcanic rocks, upper Proterozoic and Karoo (upper Paleozoic-lower Mesozoic) non-marine sedimentary rocks, and, at the north end of the basin, upper Tertiary volcanic rocks in the Ruzizi River valley.

The Lake Tanganyika region experiences a semi-humid (900–1500 mm year$^{-1}$) tropical climate, with distinct rainy (October–April) and dry/windy seasons (May–September). The lake is hydrologically open, although most water loss is through evaporation. Four major influent rivers (the Ruzizi, Malagarasi, Lugufu, and Lufubu Rivers) and numerous smaller rivers drain into the lake, and its outflow, the Lukuga River, drains into the Congo River basin. Lake Tanganyika covers an area of 32,600 km$^2$ and has a volume of 18,880 km$^3$. The average depth is 570 m with a

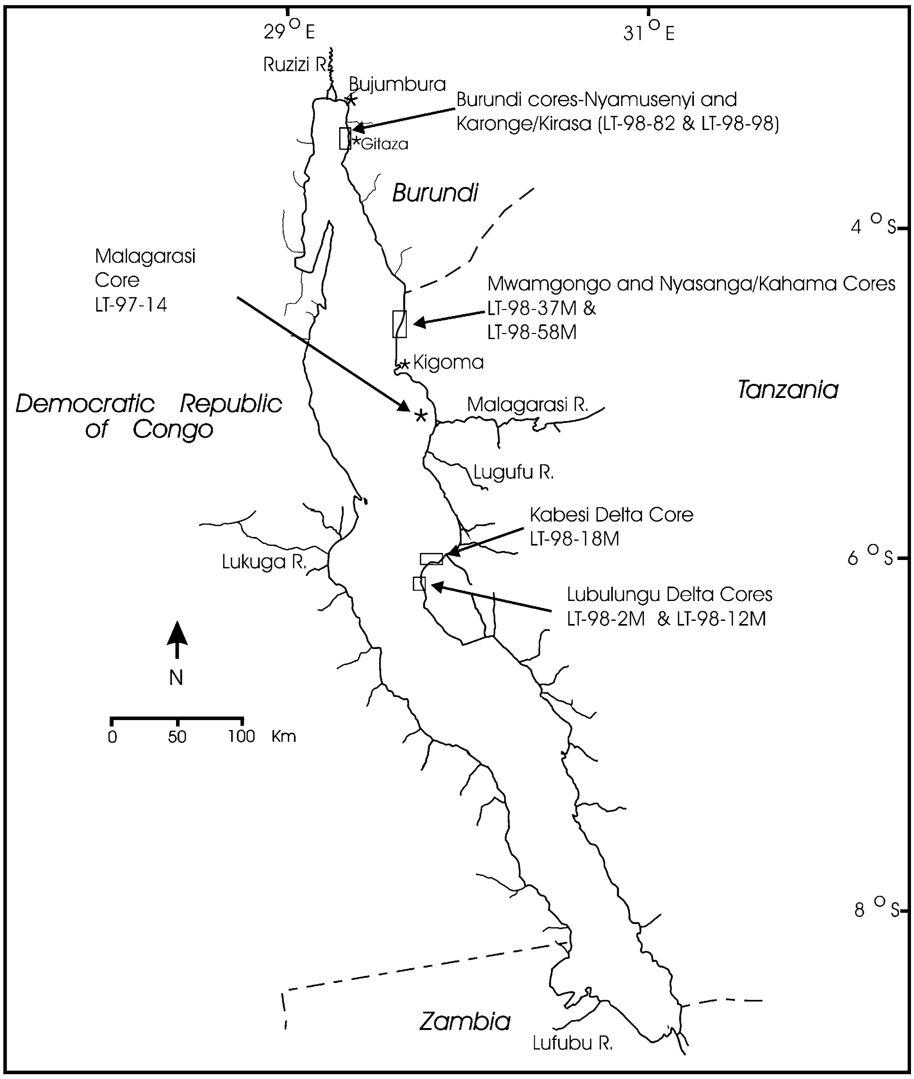


*Figure 1.* Lake Tanganyika, showing areas investigated in this study.

maximum depth of 1470 m in the southern basin. The lake is characterized by moderately low salinity and alkalinity (specific conductivity = 670 $\mu$S cm$^{-1}$, Alk. = 6.6 meq l$^{-1}$; Cohen et al. 1997). Lake Tanganyika is meromictic, with anoxia occurring at depths below 100–200 m, limiting benthic animal life to a "bathtub ring" around the lake.

## Methods

### *Watershed selection and characterization*

Data collection and sampling for this study were organized around a strategy of collecting information about sedimentation impacts and rates for a variety of river deltas of different sizes. To select appropriate study localities, an array of relatively undisturbed, moderately disturbed and highly to very highly disturbed drainage basins were grouped on the basis of similarities in drainage basin area and bedrock geology, and, to the extent possible, geomorphology (Table 1). All catchments described in this study lie on Precambrian metasedimentary bedrock, and drain rift escarpments.

Watersheds were characterized as currently experiencing low, medium, or high levels of disturbance based on assessments of the degree of forest/woodland cover existing in the watershed. *Low disturbance* areas are those in which both the delta plain and upland portions of the watershed retain their vegetative cover, and where extremely limited or no agricultural/grazing activity or tree felling are evident. *Medium disturbance* watersheds are those in which extensive agricultural development exists in the lowland and/or delta-plain regions of the watershed, but where the upper reaches of the watershed are forest, woodland, or mixed woodland/grassland, all without significant agricultural development or tree felling. Such watersheds retain between ~25–75% of forest/woodland cover. This category follows the general pattern of disturbance characteristic of most Lake Tanganyika drainages, which is that lowland portions of the delta-plain (the areas that today are most accessible to immigrants, who almost invariably arrive by boat) are developed/cut first, exposing alluvium to erosion but not the upland reaches of the catchment. Development of the steeper hillslopes only proceeds when the lowland areas have been largely or fully exploited. *High disturbance* areas are regions where land clearing has proceeded to the point of very extensive agricultural conversion and tree removal on both lowland and upland areas, with generally > 75% of forest/woodland cover removed. The two deltas in Burundi are additionally characterized as "extremely highly" disturbed because these watersheds show extensive evidence of surface slope failure.

Study localities incorporating two drainages (the Nyasanga/Kahama and Karonge/Kirasa drainages) are those where two river deltas coalesce offshore because the rivers discharge in close proximity along the lakeshore. In such cases, it is unlikely that deposits of the two systems could be differentiated without much more extensive work. Therefore, those localities can be treated as single "deltas" for the purposes of this study. An additional vibracore, LT-97-14 V, was collected from the Malagarasi River delta by an earlier University of Arizona/University of Miami/Global Environmental Facility cruise in 1997 and was analyzed as part of the current study for $^{210}$Pb analysis of sedimentation-rate changes. This site represents our sole datum for an extremely large watershed feeding the lake, but was not a central focus for this study because of the lack of another comparably sized river entering Lake Tanganyika.

### *Bathymetric surveys*

Prior to coring, detailed bathymetric surveys were conducted at all study localities. Mapping was conducted using a combination of ship's echosounder and non-differential global positioning system data. Generally, these surveys were performed on a half-kilometer spacing grid, with depth and location data collected every 0.05 or 0.02 nautical miles along a transect line. Preliminary bathymetric maps were constructed by hand in the field to identify promising coring sites (i.e., sites which were both relatively flat and at an appropriate range of depths and distances from the river mouth). Detailed bathymetric maps were produced with Surfer© for Windows software, using approximately 2000 grid points per map. Gridding was done using the kriging method, with a linear variogram model. Bathymetric grids were overlain onto shoreline maps from the relevant 1:50,000 topographic sheets for Burundi and Tanzania.

*Coring operations and core handling*

Once sufficient bathymetric data had been collected to reconstruct the general geomorphology of target deltas, coring operations began. Short cores with intact sediment–water interface were recovered from 36 localities in proximal, distal, and lateral delta areas between 53 and 189 m water depth. Most coring work in this survey was undertaken using a Hedrick–Marrs© MC-400 Multicorer (www.oceaninstruments.com/products/multicorers/mc_400.html). Under optimal conditions, this device will collect four cores up to 57 cm in length, each with a 10-cm inner diameter and arrayed in a square grid that separates the center of each core from its neighbors by about 30 cm. This arrangement allows the investigator to sample the same stratigraphic horizon from multiple core barrels (the device does not use a separate core barrel and liner). This coring device functioned extremely well, despite the frequently suboptimal coring conditions (high slope angle and coarse sediments), and almost every successful cast produced cores that had undisturbed tops (frequently, live snails, copepods, and ostracodes could be observed trapped in the surface waters of the core).

Between one and seven multicores were collected from each study delta (Table 2). An attempt was made to collect cores across a range of depths and distances from the river mouth, because optimal conditions for geochronology and determination of sediment accumulation rates (extremely fine-grained sediment, no bioturbation) do not occur in the same samples as those that optimally preserve benthic faunal signals of sedimentation disturbance. Cores analyzed in this study necessarily involved a compromise between the above factors, but ultimately we decided that it was critical to study sites within the oxic layer (based on modern oxygen penetration depths) in order to obtain a meaningful lake faunal-ecology signal.

Multicores were extruded immediately upon retrieval. Generally, two of the four retrieved multicores were sectioned, one being reserved for geochronological work (primarily $^{210}$Pb and AMS $^{14}$C), and a second for paleobiological, stable isotope, sedimentological, and additional AMS $^{14}$C studies. At recovery, visual inspection allowed us to determine the two most appropriate cores to be processed for geochronological work ($^{210}$Pb and $^{14}$C) and micropaleontological, sedimentological, and stable-isotope analysis. Cores used for micropaleontological and sedimentologic study are labelled with an "M" suffix, whereas cores used for radiometric geochronology are labelled "R", but it is important to bear in mind that in all cases the two cores are from identical multicore casts (i.e., they are separated from each other by only ~30 cm, and sample the same stratigraphy. Cores were extruded at 1 cm intervals, with the entire interval being retained (double-bagged) for sampling purposes. Normally, core lithostratigraphy was logged during extrusion, although this step was accidentally skipped during extrusion of core LT-98-18M. X-radiography of numerous gravity and vibracores from sites adjacent to our multicoring localities revealed that the typical depth of active bioturbation is ~3 cm, normal for the relatively shallow (60–120 m) water depths of these delta areas in Lake Tanganyika. Thus, we adopted a sample analysis strategy for most studies discussed in these papers of analyzing samples at 3-cm intervals, the maximum potential level of analytical resolution. In practice, this resulted in an average sampling time interval of $18 \pm 10$ years for all cores except LT-98-2M throughout their length, and $13 \pm 6$ years for the same cores during the 20th century only. Core LT-98-2M had extremely low and erratic sedimentation rates, and for this core the mean sampling interval was approximately 300 years.

All extruded and intact cores were shipped to the University of Arizona and Tulane University for paleobiological, sedimentological, geochemical, and geochronological analyses following the cruise. Core samples have been maintained continuously at 4 °C in the University of Arizona Laboratory of Paleolimnology core locker.

## Descriptions of study watersheds

Study watersheds and core sites are described sequentially from south to north (Figure 1). The geographic scope of this study (central Tanzania to northern Burundi) reflects the time available to complete the field work (approximately one month total cruise time) and the feasibility of operations from our support base (Kigoma, Tanzania). All study areas have similar patterns of rainfall seasonality (i.e., rains concentrated between October and April, and very dry, windy conditions from June to early September) (Nicholson 1996), although considerable variation exists in total rainfall among sites and years.

*Lubulungu River and Delta, Mahale Mountains National Park, Tanzania (Core Sites 2 and 12)*

This 50-km$^2$ watershed is located on the western side of the Mahale Peninsula that juts out into the lake about 120 km south of Kigoma (Figure 2). The watershed lies entirely within the Mahale Mountains National Park, at elevations between lake level and ~2000 masl. Local climate is strongly influenced by orographic effects related to the Mahale Mountains. Rainfall at Kansyana, 4 km north of the Lubulungu River delta, averages 1870 mm/year, whereas at Bilenge, only 9 km farther north, but less directly adjacent to the Mahale Mountain front, rainfall averages 1400 mm/year (Bygott 1992).

Bedrock lithology within the Lubulungu watershed comprises lower Proterozoic (Ubendian) metasedimentary rocks (dominantly gneisses, with secondary amphibolites and schists), and in the upper portion of the watershed, some metabasites, intermediate granulites and quartzites (Schluter 1997). The physiography of the Lubulungu River Valley comprises a deeply incised valley with considerable relief and several areas of rapids. The watershed itself is relatively small (50 km$^2$). Major rift-related border fault structures and orthogonal joint systems traverse the western margin of the watershed and strongly influence the rectilinear pattern of tributaries feeding the Lubulungu. Inspection of the map and satellite photographs suggests that the upper portion of the adjacent watershed has been involved in relatively recent episodes of drainage capture, reducing the Lubulungu drainage basin from a formerly larger size.

Vegetation cover within the watershed is stratified by elevation, consisting of relatively dense lowland forest up to about 1300 masl, and then a mixture of bamboo bushland and montane

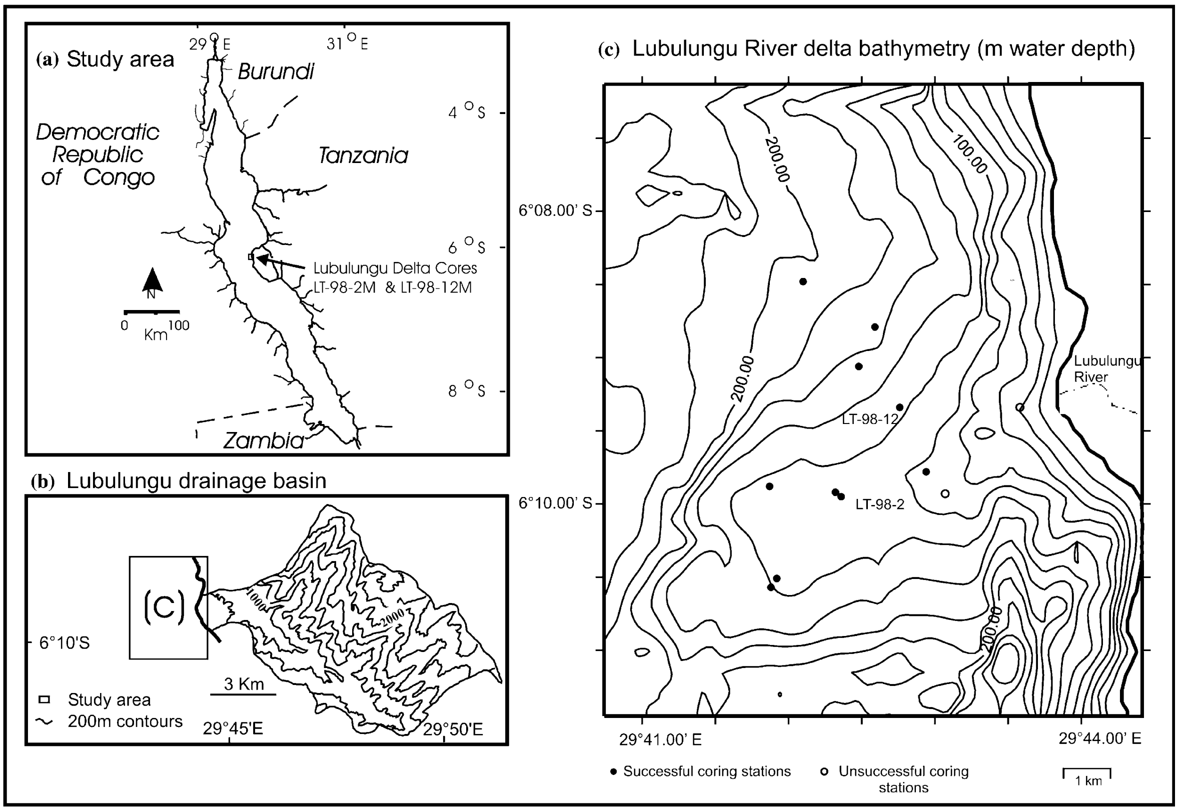


*Figure 2.* Lubulungu River delta. (a) areas of study, (b) drainage basin, and (c) coring sites.

forest above 1800 masl, dominated by the latter (*Podocarpus*, *Bersama*, *Macaranga*, and *Croton*) at the highest elevations (Bygott 1992).

The Lubulungu River delta forms a prominent fan-delta on land where the river discharges from its deep canyon front. Offshore, the delta occupies a prominent ESE-trending topographic high, which, based on its size and sediment accumulation rate data obtained in this study, is probably fault bounded. This bench slopes gently into deeper water, merging with the surrounding border fault-controlled slope break at about 150-m water depth. Coring activities were concentrated on the bench and adjacent gently sloping areas to the north, to avoid problems with secondary resuspension on steep slopes.

Mahale Mountains National Park, which completely encompasses the Lubulungu watershed, appears to have been protected since the early-1960s, but the National Park was not officially established until 1980. The park has an area of 1613 $km^2$, located between 6° and 6°30′ S and 29°40′ and 30°10′ E. Human population density within the Lubulungu drainage is low ($<5$ people/$km^2$: team's observation 1998), and there are no roads. The watershed's small size further limits sediment discharge.

### *Kabesi River and Delta, Mahale Mountains, Tanzania (Core Site 18)*

The Kabesi River delta lies on the northern end of the Mahale Mountains peninsula (Figure 3). The watershed is considerably larger (120 $km^2$) than the Lubulungu drainage basin. It drains much of the northeast flank of the Mahale Mountains, over part of its course lying adjacent to the Lubulungu watershed. The Kabesi drains the highest portions of the Mahale Mountains (up to about 2500 masl) and flows northwest toward the northern side of the Mahale Peninsula. The watershed straddles the current National Park boundary. Rainfall data are not available from the watershed but are probably comparable to the range of values observed near Lubulungu, with perhaps somewhat higher levels of precipitation than Kansyana at the highest elevations and somewhat lower values than Bilenge on the river's northern coastal plain.

The Kabesi River traverses similar bedrock to the Lubulungu, although the proportion of meta-igneous rocks (especially metabasites) is higher in the Kabesi watershed. Also, like the Lubulungu, the river's morphology is strongly controlled by NNW-trending rift-related structures (themselves overprinted on the major Proterozoic structural grain of the region). In its upper reaches, the Kabesi runs through a deep (~1000 m) canyon, with most tributaries rising off the high Mahales to the southwest and entering the Kabesi at near 90° angles. The Kabesi exits this valley over its last ~5 km, traversing low hilly terrain, and, over its last 2–3 km, a lowland delta.

Vegetation patterns of the Kabesi differ from the Lubulungu as a result of the greater range of relief and rainfall found in the basin. Lowland areas are partially cultivated (primarily bananas, cassava, and oil palm) and cleared by brush fire, particularly within the coastal plain, and irrigation works have locally diverted part of the modern river flow. Extensive miombo woodland (*Brachystegia*, *Isoberlinia*, and *Julbernardia*) occupies the lowland foothills. Higher-elevation areas are similar to those of the Lubulungu, but at the highest elevations ($>2300$ masl), forests give way to montane grasslands.

The Kabesi delta forms a ~5 km-wide lobe of sediment, including both subaerial and subaqueous regions of sedimentation. The delta is partitioned by two prominent (~N–S) sublacustrine canyons up to 30 m deep, which increase in relief below 100 m depth and probably serve as major distributary channels to focus sediment off the coastal Mahale Platform.

Human population density is relatively low on the Kabesi delta Plain (10–20 people/$km^2$: team's observation, 1998, consistent with the most recent census data during the study period, Tanzania Bureau of Statistics 1991). However, fishing encampments and localized agricultural activity concentrated in the lowlands of the watershed, outside of the Mahale Mountains National Park boundary, contribute to modifications in the watershed environment, and the watershed is considerably more impacted by human activity than the Lubulungu River basin.

### *Nyasanga/Kahama Deltas (Gombe National Park), Tanzania (Core Site 58)*

The Nyasanga and Kahama river valleys lie entirely within the Gombe Stream National Park

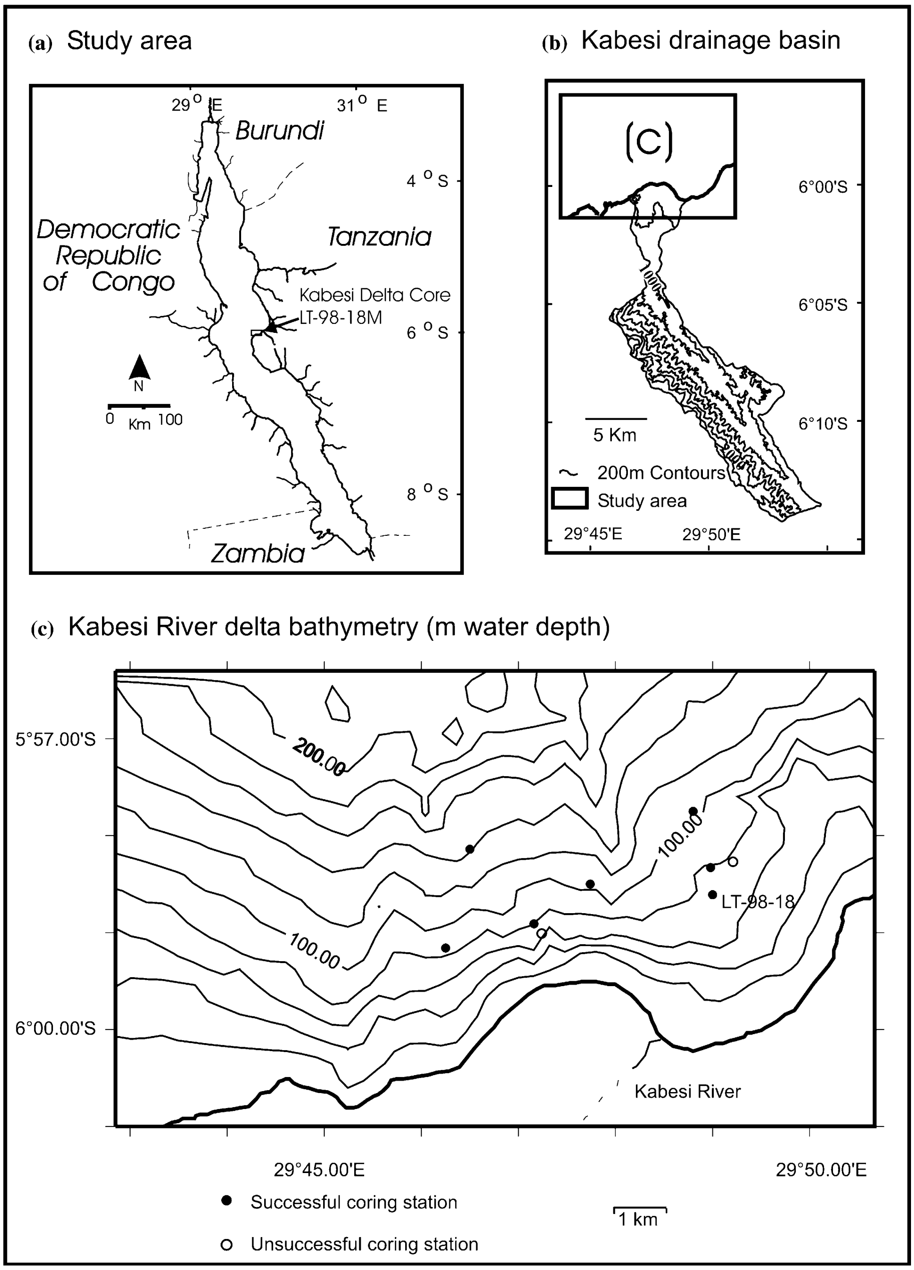


*Figure 3.* Kabesi River delta. (a) area of study, (b) drainage basin, and (c) coring sites.

(Figure 4). Both are very small drainages, arising at the crest of the local rift escarpment. Because of their close proximity and our inability to differentiate their deltas bathymetrically, we treat them here as a single watershed entity. Bedrock geology within the Nyasanga and Kahama valleys is dominated by Ubendian (2.1 Ga) metasediments, overlain by upper Precambrian quartzites and sandstones (Nkotagu 2005). Both watersheds occupy small, steeply sloping valleys draining the major rift-boundary fault surface. Rainfall is approximately 1600 mm/year, and possibly higher in the upper parts of the watersheds. The combined aerial extent of these watersheds is ~3.8 km$^2$.

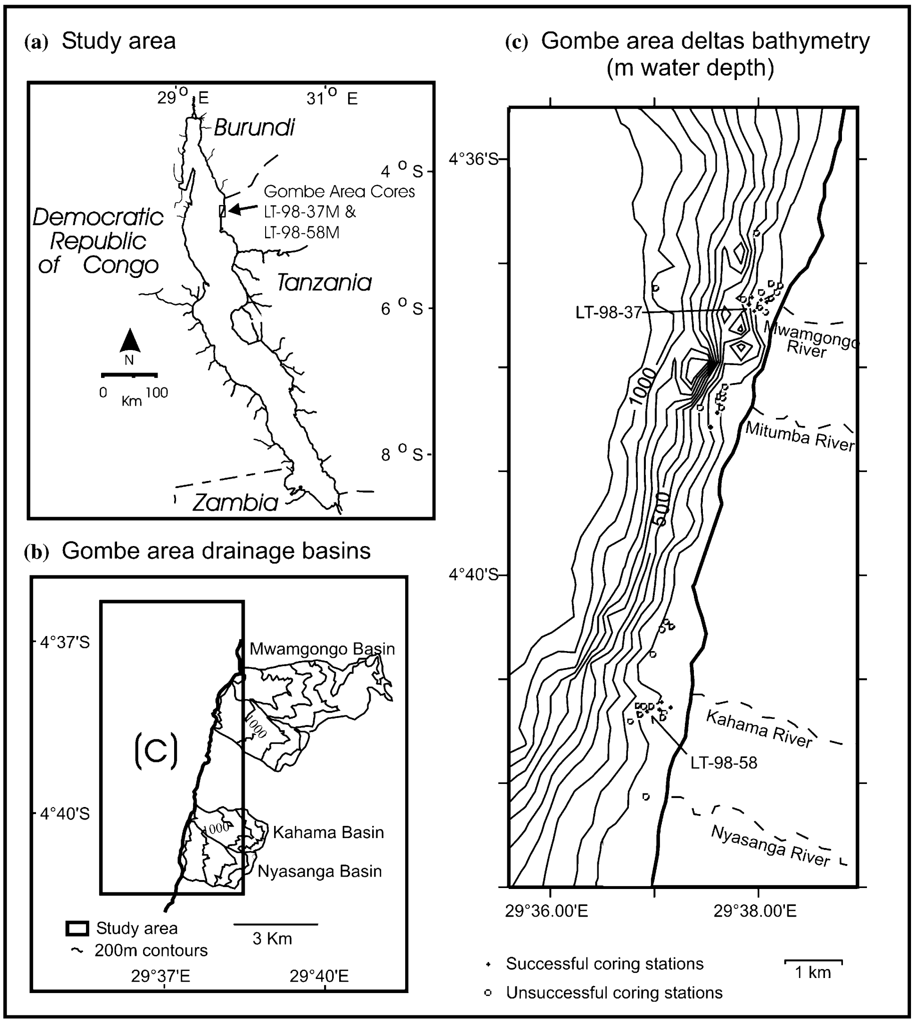


*Figure 4*. Nyasanga/Kahama and Mwamgongo River deltas (Gombe National Park area). (a) areas of study, (b) drainage basins, and (c) coring sites.

Vegetation within these watersheds consists of semi-deciduous woodland (*Combretum*, *Anisophyllea*, *Schrebera*, *Pterocarpus*), wetter canopy forests (*Albizia*, *Newtonia*, etc.), and riverine forest at lower elevations; and dry (*Brachystegia*- or *Uapaca*-dominated) forest and open grasslands at higher elevations. Along the lower-elevation stream channels, relicts of cultivated lands (particularly mango and oil palm) occur. Higher-elevation grasslands are burned on a near-annual basis, both within and outside the National Park, and the demarcation between woodlands and deforested grasslands is both sharp and (based on analysis of older aerial photographs taken in the 1950s) relatively stable.

A bench of relatively gently sloping, coalesced fan-delta fronts flanks the coastline through much of southern Gombe Stream National Park. Consequently, individual "deltas" cannot be recognized based on our bathymetry. As with the Mwamgongo delta discussed below this bench gives way to a very steeply sloping bottom about 0.5 km offshore.

Because the Nyasanga/Kahama watersheds lie entirely within the Gombe Stream National Park, their only permanent residents are park personnel and their families ($< 5$ people/km$^2$ in the Nyasanga/Kahama watersheds; park administrator personal communication 1998). Temporary fishing camps are also established along the fan deltas. Further information concerning this delta, as well as the Mwamgongo River delta discussed below, is provided in Alin et al. (2002).

*Mwamgongo River and Delta–Gombe Region, Tanzania (Core Site 37)*

The Mwamgongo River occupies a small (7.7 $km^2$) watershed at the northern edge of Gombe Stream National Park (the southern edge of the watershed approximates the northern park boundary), approximately 30 km north of Kigoma (Figure 4). The watershed runs approximately E-W, traversing the area from the upper (eastern) flank of the local rift escarpment ($\sim$1600 masl) down to Lake Tanganyika. Rainfall and relief within the Mwamgongo River watershed are nearly identical to those of the Nyasanga/Kahama watersheds. Bedrock geology is dominated by the same upper Precambrian quartzites and sandstones as occur at Nyasanga/Kahama (Nkotagu 2005). A $\sim$0.5 km diameter fan delta has formed at the discharge point into Lake Tanganyika.

The Mwamgongo River watershed vegetation is dominated by cultivated areas (particularly cassava on steep slopes and oil palm and bananas along valley bottoms) and disturbed (burned and grazed) grassland. Relict patches of miombo woodland occur in parts of the watershed, particularly at higher elevations.

Because the Mwamgongo River drains a major rift escarpment, the subaqueous development of the river's fan delta is very limited. A small, relatively flat bench extends for approximately 0.4 km offshore, and almost all successful coring for this study area was accomplished here (including core LT-98–37, described in this report). West of this bench, water depths increase rapidly, and the 1000 m depth contour lies only about 1.5 km offshore.

Human settlement patterns for the Mwamgongo watershed were broadly documented by our team through interviews with the local village elders and census keepers. During the 20th century prior to the 1940s, Mwamgongo was a small village, probably with about 1000 people. In 1943 the colonial government established the Gombe Stream Reserve and relocated inhabitants north of 4°38′ S by the Mwamgongo River (Bygott 1992). The population of Mwamgongo village consequently increased greatly in the late 1940s. A second period of rapid population increase occurred in 1972, during the Tanzanian government "villagization scheme", when many individuals from small nearby villages were resettled in Mwamgongo. At present, about 7000 people live within the watershed (i.e., $\sim$900 people/$km^2$). Extensive clearing of steep slopes, particularly within the lower parts of the watershed, has resulted in rapid soil erosion in the area.

*Nyamuseni River and Delta–Gitaza Region, Burundi (Core Site 98)*

The Nyamuseni River drains a 30-$km^2$ watershed in northern Burundi, approximately 28 km south of Bujumbura, near the town of Gitaza (Buyenzi) (Figure 5). The river rises in the Burundi highlands, with maximum elevations in the watershed of about 2500 masl. Rainfall data are not available for this area, but are probably slightly higher than at Bujumbura ($\sim$850 mm/year) for the lower elevations (based on the increased rainfall gradient toward southern Burundi, e.g., Nyanza Lac = 1080 mm/year), and much higher in the upper reaches of the watershed.

Bedrock geology within the Nyamuseni River watershed consists of possibly middle Proterozoic metasediments (quartzites and amphibolites), Kibaran (middle Proterozoic) granites, and minor mafic intrusive rocks. The river rises within the rift and steeply traverses a series of $\sim$N–S-oriented rift-related normal faults in deeply incised canyons, but its course shows little obvious relation to secondary rift structures.

Both the Nyamuseni and the Karonge/Kirasa watersheds discussed below have been almost completely deforested of primary woodland/forest cover, with land primarily used for agricultural purposes (monocultures of cassava cultivation on steep slopes and banana and oil palm cultivation in river bottoms or lowlands near the lake, with little additional ground cover). Many areas of steep slopes are covered by disturbance shrubs, herbaceous plants, ferns, or grasses where croplands have been abandoned or slopes are too steep for planting, and may be barren of vegetation in some areas. *Eucalyptus* has been planted extensively in monocultures in the upland regions since the early-1930s (experimental plantings began in

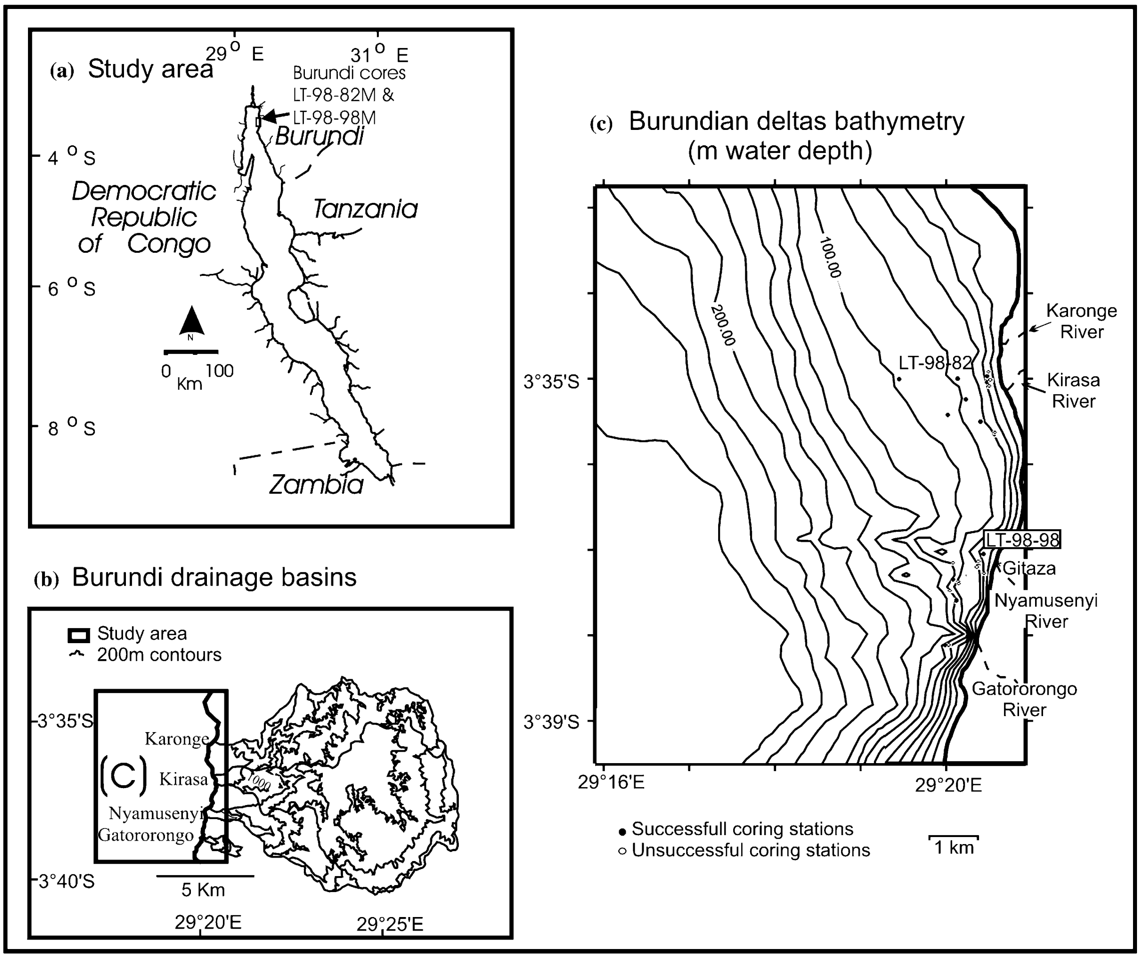


*Figure 5.* Nyamusenyi and Karonge/Kirasa River deltas (northern Burundi area). (a) areas of study, (b) drainage basins, and (c) coring sites.

the late-1920s; P. Ndabaneze and K. West personal communication 1999), mostly for fuelwood.

The Nyamuseni River has built a steep-fronted fan delta into the lake, lobes of which can be traced for up to several kilometers offshore. Water depths into which this delta is building in this northern part of the lake are considerably shallower than in either the Gombe or Mahale regions.

The Nyamuseni watershed is very heavily disturbed by human activity. This includes agriculture on steep, unterraced terrain, criss-crossed by numerous unregulated paths, which become important gulley cuts after major rains, and the existence of a major local market village (Gitaza) near the river mouth. Unlike the previously discussed sites, the Nyamuseni watershed is traversed in its lower reach by a paved road (and several smaller, unsurfaced roads), the construction and maintenance of which generates large quantities of road debris, which has been discharged directly into the adjacent parts of Lake Tanganyika. Population density is high in this region (475 people/km$^2$ in 1990 census (Republique du Burundi Ministere de l'Interieur 1990)).

### *Karonge/Kirasa Rivers and Delta–Gitaza Region, Burundi (Core Site 82)*

The Karonge/Kirasa delta is located about 20 km south of Bujumbura on the northern Burundian coast of Lake Tanganyika (Figure 5). The two rivers converge near the lakeshore to form a contiguous delta lobe. Collectively, they drain a considerably larger area than the Nyamuseni River alone (Karonge = 42 $km^2$, Kirasa = 120 $km^2$). Maximum elevations within the watershed are about 2100 masl, somewhat lower than the Nyamuseni. This fact, plus the more northerly location, suggests that average rainfall values within the watershed are probably slightly lower than for the Nyamuseni, although no precise data are available.

The bedrock geology of the Karonge/Kirasa watersheds is almost entirely Kibaran (middle Proterozoic granitic rocks), with minor gneissic rocks exposed only in the northern part of the Karonge watershed. Physiography is similar to the Nyamuseni, with deeply incised consequent drainages off the local rift escarpment.

Upland vegetation is also similar to the Nyamuseni, although patches of montane forest vegetation still existed within the central upper river basin at the time of coring, particularly along steep-sided river valleys in the upper Kirasa basin between ~2000–2200 masl. However, the lowland area encompassed by the Karonge/Kirasa delta is much larger and consequently lowland cultivation (especially oil palm) is much more extensive.

The Karonge/Kirasa subaerial delta forms a prominent geomorphic feature, and marks the southern edge of the Burundian coastal plain. Subaqueously, no deltaic lobe is evident, and bathymetric contours expand continuously towards the north, suggesting a major input of sediment from the north (presumably the Ruzizi River system extending as far south as this area). The idea that Ruzizi River sediments significantly inundate the Burundi coastal plain as far south as the Karonge/Kirasa area receives further support from fossil pollen analyses (Msaky et al. 2005).

Local structural control also undoubtedly plays a role in the change in bottom morphology, as the major rift-related border fault in this area extends inland to the north of these rivers, causing coastal bathymetric slopes to be more subdued. Water depths and bottom morphologies in front of the Karonge/Kirasa delta were the shallowest and most gently sloping of any encountered in our study areas (Figure 5).

High human population densities and extreme levels of land-use disturbance in the Karonge/Kirasa River valleys are similar to those observed in the Nyamuseni watershed, with the exception that the proportion of lowland population to total density is probably higher (~475 people/$km^2$ in 1990 census; Rep. Burundi Ministere de l'Interieur 1990), because of the considerably larger coastal plain. Construction debris from major road works to the lake is probably lower for the Karonge/Kirasa system given the greater distance from the surfaced road to the shoreline in this area.

## Summary of major findings discussed in companion papers in this volume

Our results are described in individual papers in this volume, including descriptions of geochronology and mass sediment accumulation rates (McKee et al. 2005), lithostratigraphy, sedimentology and charcoal analysis (Palacios-Fest et al. 2005a), lacustrine paleoecology (Palacios-Fest et al. 2005b), palynology (Msaky et al. 2005), organic matter geochemistry (O'Reilly et al. 2005), isotope geochemistry of carbonates (Dettman et al. 2005), and watershed hydrology (Nkotagu 2005). Additionally, a major synthesis of the findings of this study is presented in the summary paper of this volume, relating our results to human and climatic history in the region (Cohen et al. 2005). Here we only note our major conclusions. Differences in depositional, paleoecological and watershed indicator histories over time and between study sites can be linked to climatic change, differences in the histories of forested vs. deforested watersheds, differences in regional patterns of deforestation, and the interaction between deforestation and climatic events.

(1) *Important climate events*. Paleoecological, sedimentation rate and charcoal evidence for a major episode of late-Holocene aridification occurs after the 1st century B.C. Approximately 400–500 A.D. lacustrine paleoecological indicators show that Lake Kivu began to overflow into Lake Tanganyika from the north, consistent with other indications of wetter climate in the northern portion of the western rift valley. However, more local records of paleoclimate from the central Lake Tanganyika region show that this precipitation increase was probably more subdued towards the south. We see evidence for relatively dry conditions in the central Lake Tanganyika catchment in the early-13th century, followed by somewhat wetter conditions from the 13th to 15th centuries. During the latter part of the Little Ice Age (16th to

19th centuries) we observe evidence for at least three extremely dry periods, marked by major drops in lake level, centered around the early-16th, late-17th, early to mid-18th and late-18th to early-19th centuries.

(2) *Differences related to forested vs. deforested watersheds.* A clear difference exists between currently forested and deforested watersheds in terms of rates of sediment mass accumulation (much higher in the latter). Deforested watersheds display lower rates of groundwater infiltration and evapotranspiration than forested ones, manifest in solute geochemistry and stable isotope differences in surface waters. Deforested watersheds yield sediments that are enriched in laterized soil particles, terrestrial plant debris and are more frequently laminated than those of forested watersheds, and deforested watershed organic matter is enriched in $\delta^{15}N$. Marked differences exist in lake faunal composition (fossil invertebrates and fish), with the persistence of higher diversity communities in the deltas of undisturbed watersheds and low diversity or even extirpation of benthic communities in very highly disturbed areas. These differences appear to be linked to both direct impacts on habitat by sediment inundation and indirect, possibly top-down effects of sedimentation on community structure.

Impacts of sedimentation appear to be lessened where watersheds are very small or sublacustrine slopes are very steep. Our analysis of modern chironomid species distribution across the various river deltas (Eggermont and Verschuren 2003a) showed that local abundances of a modest 15% of common chironomid species in Lake Tanganyika differ significantly between sites adjacent to pristine and disturbed drainages, suggesting that the ecological effects of excess sedimentation so far do not override natural, mainly depth-related habitat variation within each delta. However, in all three drainage size classes ($<10$, 30–50, 50–162 $km^2$), sediment pollution due to catchment disturbance has resulted in similar shifts in chironomid species composition that are equivalent to the effects of a reduction in water depth and distance to shore. This result indicates that low-organic and coarsely textured, shallow-water substrates are expanding to greater depths and greater distances from shore, at the expense of the soft-bottom, organic muds characterizing the natural deep-water environment.

3. *Differences related to regional patterns of deforestation.* Palynological data (especially from fern spores), mass sediment accumulation rate and geochemical data all point towards a difference in the timing of deforestation events along the eastern side of Lake Tanganyika. Strong evidence for deforestation appears in the northern Burundian sites by the late-18th century, and in northernmost Tanzania by the late-19th century, but not until the mid-20th century along the central Tanzanian coast. The timing of this change is consistent with known human demographic trends and the probable relative impacts of the slave and caravan trade, which greatly impacted the Tanzanian coast during the 19th century, keeping human population densities low, while simultaneously having little impact on the heavily populated Burundian kingdom to the north. The major expansion of cassava cultivation in the Lake Tanganyika region in the late-19th to early-20th centuries may have played a major contributory role in erosion rate increases, since cassava, unlike other important local crops, can be successfully grown on very steep slopes. Palynological evidence is greatly complicated by taphonomic biases and pollen production differences between disturbed and undisturbed landscapes, given the types of land use patterns that exist in the Lake Tanganyika catchment.

4. *Differences related to interactions of deforestation and climate effects.* We observe a marked rise in sedimentation rates and linked ecosystem responses in the early-1960s at all currently disturbed watersheds, but this event is unrecorded in undisturbed watersheds. This event is recorded in both Tanzanian and Burundian watersheds, and in areas with very different prior deforestation histories. We attribute this to the triggering effects of extraordinary rainfall, which occurred in the 1961/1962 rainy season. We hypothesize that this precipitation event began a process of erosion of large quantities of previously stored alluvium in the river valleys of disturbed watersheds, a process that continues to the present in these areas. Similar interactions where climatic events exacerbate anthropogenic impacts are known from other African great lakes (e.g. Verschuren et al. 2002), and need to be incorporated into watershed impact models for management purposes.

We argue that there are predictable relationships between watershed properties and probable lacustrine ecological impacts from watershed deforestation that must be taken into consideration in the development of watershed management plans for the Lake Tanganyika catchment. Especially, given the potential for time-lagged interactions between human activity and climate change, we believe that paleolimnological techniques provide the most promising means of forecasting these impacts over the decadal to centurial time scales of interest to planners.

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