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Abstract

New sediment core data from a unique slow-sedimentation rate site in Lake Tanganyika contain a much longer and continuous record of limnological response to climate change than have been previously observed in equatorial regions of central Africa. The new core site was first located through an extensive seismic reflection survey over the Kavala Island Ridge (KIR), a sedimented basement high that separates the Kigoma and Kalemie Basins in Lake Tanganyika.

Proxy analyses of paleoclimate response carried out on core T97-52V include paleomagnetic and index properties, TOC and isotopic analyses of organic carbon, and diatom and biogenic silica analyses. A robust age model based on 11 radiocarbon (AMS) dates indicates a linear, continuous sedimentation rate nearly an order of magnitude slower here compared to other core sites around the lake. This age model indicates continuous sedimentation over the past 79 k yr, and a basal age in excess of 100 k yr.

The results of the proxy analyses for the past ~ 20 k yr are comparable to previous studies focused on that interval in Lake Tanganyika, and show that the lake was about 350 m lower than present at the Last Glacial Maximum (LGM). Repetitive peaks in TOC and corresponding drops in $\delta^{13}C$ over the past 79 k yr indicate periods of high productivity and mixing above the T97-52V core site, probably due to cooler and perhaps windier conditions. From ~ 80 through ~ 58 k yr the $\delta^{13}C$ values are relatively negative (–26 to –28‰) suggesting predominance of algal contributions to bottom sediments at this site during this time. Following this interval there is a shift to higher values of $\delta^{13}C$, indicating a possible shift to C-4 pathway-dominated grassland-type vegetation in the catchment, and indicating cooler, dryer conditions from ~ 55 k yr through the LGM. Two seismic sequence boundaries are observed at shallow stratigraphic levels in the seismic reflection data, and the upper boundary correlates to a major discontinuity near the base of T97-52V. We interpret these discontinuities to reflect major, prolonged drops in lake level below the core site (393 m), with the lower boundary correlating to marine oxygen isotope Stage 6. This suggests that the previous glacial period was considerably cooler and more arid in the equatorial tropics than was the last glacial period.

*This is the third in a series of four papers published in this issue collected from the 2000 GSA Technical Session 'Lake basins as archives of continental tectonics and paleoclimate' in Reno, Nevada. This collection is dedicated to Dr. Kerry R. Kelts; Drs. Elizabeth Gierlowski-Kordesch and H. Paul Buchheim were the guest editors of this collection.

Introduction

The continental tropics play a critical role in modulating the earth's climate, yet the paleoclimate history of this area is only sparsely recorded, compared to the great abundance of data sets now available from high latitude ice sheets and from marine sediment cores (e.g., Shackleton, 1983; Petit et al., 1999). Africa is the continent with the largest tropical landmass, but the spatial and temporal details of its paleoclimate history are well-known only from the late-Pleistocene and Holocene (e.g., Street-Perrott et al., 1997). This brief record shows that cool and dry conditions prevailed across equatorial Africa at about 18 k yr BP, coinciding with full glacial conditions in the higher latitudes (e.g., Butzer et al., 1972; Talbot and Delibrias, 1980; Johnson, 1996). Marine records from the Arabian Sea (~ 25° N) contain signatures of climate instability over the past 100 k yr that are nearly identical to features observed in the $\delta^{18}O$ record of the Greenland ice cores (Schulz et al., 1998), but until now no comparable-length continuous records from the interior of equatorial Africa have been available for direct comparisons. Far-field records of north African paleoclimate from the Indian Ocean imply a change since the late Miocene from precession-dominated orbital forcing to one in-phase and presumably controlled by the fluctuations of northern hemisphere ice sheets (e.g., deMenocal, 1995). Results from equatorial regions of the oceans and from energy balance modeling support an alternative to high-latitude control of tropical climate, and suggest that climate change in the tropical-subtropical latitudes may be directly forced by orbital precession, or by combination tones of eccentricity and precession (e.g., Pokras and Mix, 1987; Short et al., 1993; McIntyre and Molfino, 1996). In this paper we present the first long (> 50 k yr), continuous paleolimnologic record of past paleoclimates from a near-equatorial region of East Africa, from a site in central Lake Tanganyika.

The study site

Lake Tanganyika (4°–9° S) in the East African Rift valley is renowned for its size and depth (the world's 2nd deepest lake), its endemism and biodiversity (most extreme of any lake in Africa) (Coulter and Tiercelin, 1991), its shallow oxicline and dynamic limnology, and for its geologic antiquity (8–12 million years) (Cohen et al., 1993). Geophysical records show that much of the lake is underlain by more than 5–6 km of syn-rift lacustrine sediments (Rosendahl, 1987), and its sediments have proven to be an archive of paleolimnologic and paleoclimatologic change representative of a broad region of equatorial and southern hemisphere Africa (e.g., Livingstone, 1965; Gasse et al., 1989; Cohen et al., 1997a,b). Lake levels in Lake Tanganyika and many other tropical lakes have been to shown to be amplifiers of climatic conditions (e.g., Butzer et al., 1972), and thus their water level fluctuations are important paleoclimate proxies over geological time scales. Extremely deep lakes such as Tanganyika and Malawi are especially useful in long-term climate reconstructions because they likely remained undesiccated and deep through the most arid periods of the Pleistocene.

Sedimentation rates observed at deep water sites in the large African lakes are usually on the order of 1 mm/yr, and thus 5–15 m long soft sediment cores recovered from these lakes commonly yield core-bottom ages of about 10–20 k yr (e.g., Tiercelin et al., 1988; Johnson 1996). The Kavala Island Ridge (KIR) is a unique structural and depositional setting in Lake Tanganyika, and is formed by a NW-SE striking, fault-controlled basement horst that rises up from water depths of ~ 1200 m in the Kigoma Basin (Figure 1) to within 40 m of the lake surface near the ridge crest. The KIR is located far from major river inflows, and thus present-day sedimentation on the ridge consists principally of suspension deposits from dilute waters of the open lake, and from autochthonous sources. A short, 1 m long core previously recovered from the area reported sedimentation rates of about 0.1 mm/yr, or an order of magnitude slower than what is observed in most sites in Lake Tanganyika (Hecky and Degens, 1973). In 1997, an extensive suite of seismic reflection profiles was acquired, and these data were used to constrain optimal coring sites during a new study on the ridge (Figure 1). Whereas traditional hemipelagic sites in Lake Tanganyika are useful for studies over the past 10–20 k yr (e.g., Tiercelin et al., 1988), we focused on the slow sedimentation rate KIR sites in anticipation of recovering a much older suite of samples within the 10–15 m coring range of our sampling system.

Data sets and results

Several different types of data were used to constrain the history of Lake Tanganyika over the past 100 k yr.

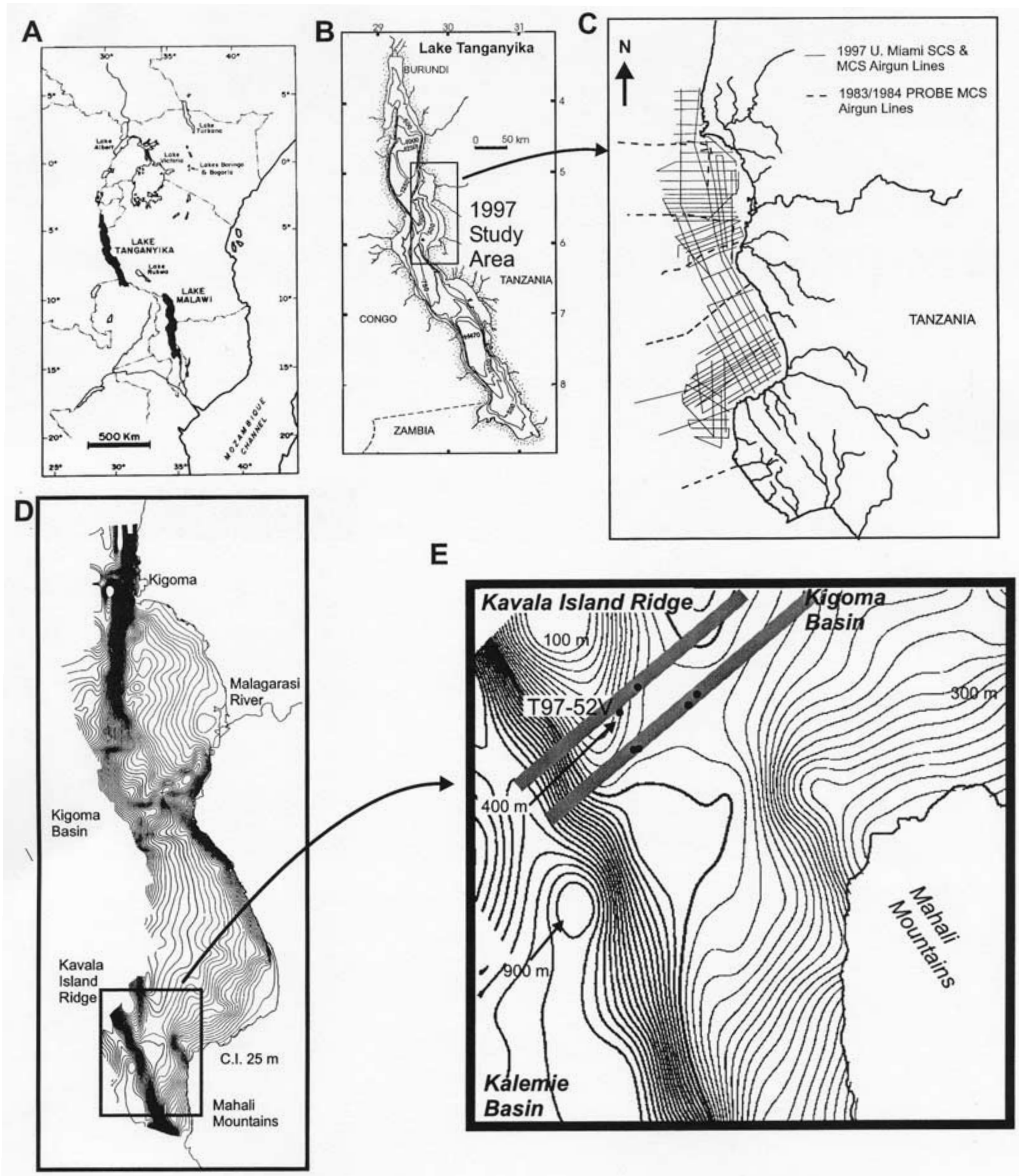

Figure 1. Lake Tanganyika location map (A), general bathymetry (B), study area seismic trackline locations (C), Kigoma Basin (Tanzania) bathymetry (D), and detailed bathymetry with core locations (E). Contour interval is 25 m. Seismic profiles presented in Figure 2 are shown shaded on E.

The initial seismic survey was critical for identifying the best possible coring sites on this structurally and stratigraphically complex sedimented basement high. Once the geomorphology and sediment cover on the ridge were constrained, we then undertook a coring program using a modified Rossfelder deep-water electric vibrocoring system (6 and 12 m barrels), and augmented with a Benthos 2 m gravity corer. Six sediment cores (1–10.4 m long) were recovered inside plastic liners, and cut into sections on deck. Standard oceanographic and limnologic handling procedures were employed throughout the coring program.

Seismic reflection data

Approximately 400 line-km of 'intermediate-resolution' single-channel seismic reflection records were collected in the vicinity of the KIR in a 2 × 2 km grid pattern, in order to constrain the structure, morphology, and sediment cover on this unique high-relief feature (Figure 1). Seismic signals were generated using a small airgun source (10 in^3 or 0.16 L) and signals were received by a solid-towed ITI streamer. This source-receiver configuration produced data with a bandwidth of 50–500 Hz, and a vertical resolution of ~ 1–2 m. The data were digitally acquired and recorded using an Elics Delph2 seismic acquisition system and positioning was controlled by a G.P.S. system operating in autonomous mode.

The ~ 400 line-km of intermediate-resolution seismic reflection profiles from the KIR reveal that the shallowest part of the ridge consists of exposed crystalline basement rocks, but much of the ridge is draped with a condensed interval of hemipelagic lacustrine sediments up to 450 m thick (Figure 2). Several angular unconformities that were previously interpreted as major low-lake stages (Scholz and Rosendahl, 1988; Lezzar et al., 1996) are observed to coalesce near the ridge crest (Figure 2). Seismic profiles 56 and 58X reveal that a ~ 10 m thick depositional sequence characterized by low seismic amplitudes overlies two high amplitude reflections and an angular unconformity (Figure 2). This unconformity was a principal coring target of the 1997 expedition. Sediment core T97-52V penetrates the upper high-amplitude reflection and thus helps us constrain the age of the upper seismic sequence boundary. The new core suite acquired at this unique ridge site within the context of an extensive set of seismic data allows us to dramatically extend the age-bounds of the Tanganyika paleolimnologic record and to constrain the ages of the major lake-level lowerings

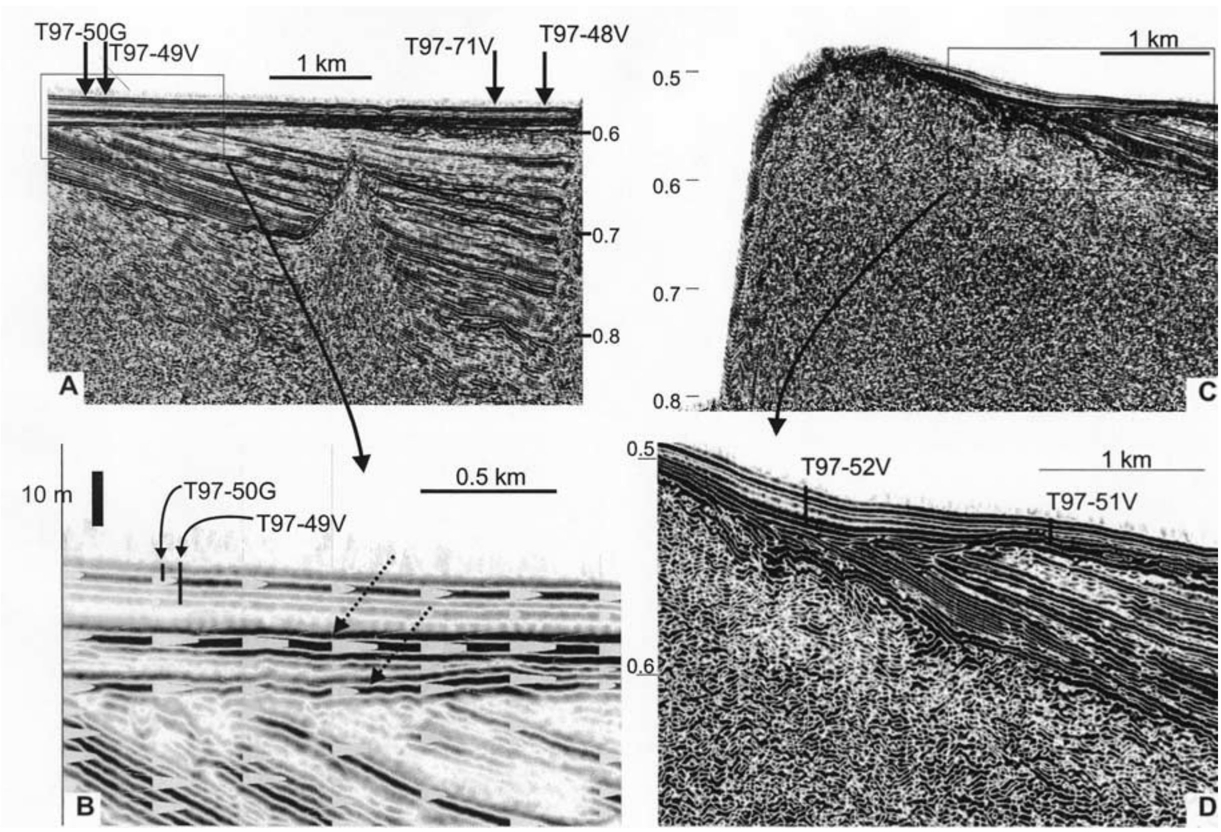

Figure 2. Seismic images and core locations across the Kavala Island Ridge. See Figure 1 for exact profile locations. Note vertical scale is two-way travel time, in seconds (except B, where vertical scale is meters). Dotted arrows indicate position of sequence boundaries. Note pronounced angular unconformity near the base, or just below each core. These unconformities are interpreted to be produced by a combination of lake level drops and tectonic tilting of the Kavala Island ridge. See text for discussion.

that could previously only be estimated from inspection of low-resolution multichannel seismic records (Scholz and Rosendahl, 1988). Core T97-52V is located in 393 m of water just above the base of the saddle that forms between the Kavala Island Ridge and the Mahali peninsula (Figure 1). It is situated about 15 km from the nearest land, and about 10 km from the crest of the ridge.

^{14}C Results and age model

Core T97-52V is composed of fine-grained hemipelagic sediments throughout its length, and a robust radiocarbon age model is presented for this core based on 11 ^{14}C-AMS radiocarbon dates that produced a near-linear sedimentation rate for this site (Figure 3). Initially, three samples were split and tested for determining the best radiocarbon dating approach; one subsample from each pair was processed for pollen extracts and then dated, whereas bulk mud was dated from the other part of the split sample. The subsample pairs each yielded similar dates, suggesting that further ^{14}C AMS dates could be accurately obtained from analyses of bulk mud alone. Samples with ages younger then 20 k yr were corrected for variations in radiogenic carbon flux, using calib4 software, based on corrections of Stuiver and Reimer (1993). Age dates younger than 45 k yr were used to construct a least-squares best-fit age-depth relationship. This equation was then applied to samples in the lower part of the core (deeper than 350 cm). Dates older than 45 k yr were assumed to represent infinite ages and were not incorporated into the linear best-fit model. The final age model (Figure 3) incorporates linearly interpolated ages between discrete ^{14}C ages in the upper (younger) part of the core and then applies the least-squares best-fit model to the lower part of the section (Figure 3). Assuming no discontinuities, this yields a basal age of ~ 89 k yr.

Sediment core observations and analyses

Lithology

The lithostratigraphy of core T97-52V is presented in Figure 4, and consists primarily of alternating zones of laminated and homogenous brown, or grey-green mud. The laminated zones are a maximum of about 75 cm in thickness, each representing about 5 k yr of hemipelagic sedimentation on the crest of the ridge. Other than the fine mm-scale laminae, the core is devoid of macroscopic sedimentary structures. Near the base of the core (950 cm) there is an abrupt transition from laminated muds to grey homogenous mud. The homog-

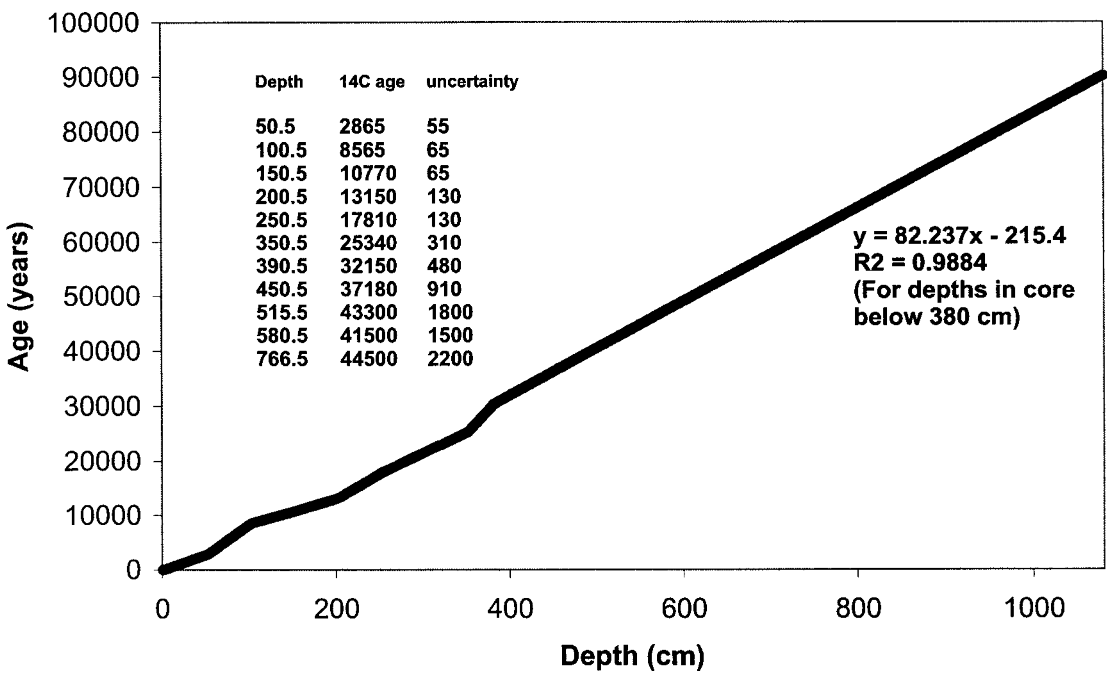

Figure 3. ^{14}C age results, regression with both calibrated (0–20 k yr), and uncalibrated (>20 k yr) ages, and final age model for entire core.

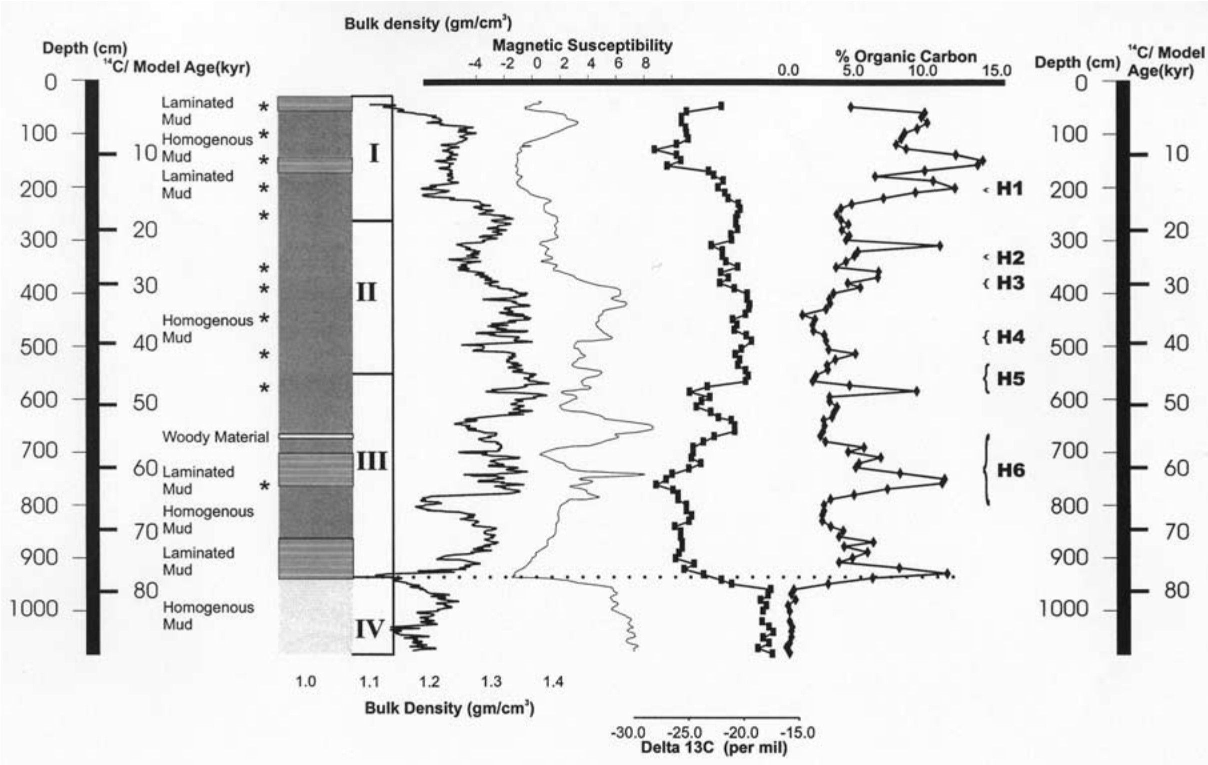

Figure 4. Lithology, index properties, and geochemical results for core T97-52V. Position of radiocarbon dated samples shown by *. Lithology key: striped pattern = laminated mud; grey pattern = dark grey-green/brown homogenous mud; light grey pattern = light grey, desiccated mud; white pattern = woody material. Roman numerals refer to core sections discussed in text. H1–H6 = possible correlation with North Atlantic Heinrich events; age estimates follow Schulz et al., 1998). Brackets indicate uncertainties; see text for discussion.

enous mud at the base of the core has noticeably lower water contents (45% for the core base vs. 75% at mid-depth levels in the core), and is characterized by a grey color, in contrast to the homogenous dark brown-green muds observed in the upper sections of the core. Whereas most of the core is composed of fine-grained sediments, there is a distinctive 5 cm thick zone of fibrous woody material at about 665 cm.

Index properties and paleomagnetic results

Index properties for core T97-52V were measured at the University of Rhode Island using a GEOTEK multi-sensor track data logging system. The following parameters were measure at 1 cm intervals: magnetic susceptibility, sediment wet-bulk density (using the gamma ray attenuation porosity estimation method or GRAPE), and P-wave velocity (Figure 4). Discrete magnetic susceptibility measurements were also carried out on the core using a Bartington magnetic sensor loop, and as were discrete measurements of water content.

Magnetic Susceptibility (MS) is a routine down-core measure of change of sedimentary conditions that is commonly used in paleoceanographic and paleolimnologic studies. The MS signal is in a practical sense an indicator of the concentration of ferromagnetic grains in a sample, and is also used under certain conditions to indicate the relative fraction of lithogenic vs. biogenic material in sediments. Sediments from meromictic lakes such as Lake Tanganyika are also commonly altered by exposure to anoxic bottom waters through processes of reduction diagenesis (e.g., Karlin and Levi, 1983). In this process, fine-grained magnetite is altered to pyrite through Fe and S reduction, and thus the magnetic susceptibility signal can under certain circumstances be used to record exposure to anoxic bottom waters, and thus approximate lake depth.

The magnetic susceptibility records from core T97-52V show marked downcore fluctuations, which can also be correlated with adjacent sediment cores from the Kavala Island Ridge. Whereas low levels of magnetic susceptibility coincide with laminated intervals, notable excursions are observed at 665 cm, near the woody horizon. Some of the highest MS values are observed near the base of the core, coincident with the interval of grey, homogenous, low water-content mud.

Saturated Bulk Density, measured using the Gamma Ray Attenuation Porosity Evaluator (GRAPE) usually varies with lithology and water content. In core T97-52V GRAPE wet bulk density values were measured every 1 cm, with results ranging in value between 1.1 and 1.4 gm/cm^3. GRAPE is commonly used to discriminate zones of increased terrestrial components versus biogenic components, and other subtle textural variability not routinely detectable through standard visual core inspections. Seven distinct cycles are observed in the GRAPE data from the top to bottom of the core, although there are no clear parallels or correlations with either magnetic susceptibility, or laminated and unlaminated intervals.

Total organic carbon and isotopic analyses of bulk organic matter

Total organic carbon measurements (TOC) reflect deposition at the core site of both allochthonous (terrestrial) sources of carbon and autochthonous carbon derived through primary production in the water column. Preservation and diagenesis also play an important role in determining the final quantity and character of organic carbon in the sediment. Discrete samples were taken at 10 cm intervals down core T97-52V, and analyzed for $CaCO_3$, total organic carbon, and C isotopes of organic matter. $CaCO_3$ analyses were completed at the University of Miami using the gasometric bomb technique (Jones and Kaiteris, 1983). Determination of the $\delta^{13}C$ and TOC content was accomplished using an ANCA Elemental Analyzer interfaced with a Europa 20–20 mass spectrometer with a continuous flow device, and measured on a carbonate-free basis.

$CaCO_3$ values were less than 3% throughout all of T97-52V, and show no clear trends. Throughout most of the core, total organic carbon varies from background values of 3–4% to a maximum value of 14% (Figure 4). Several abrupt increases in TOC values are observed occurring every ~ 10–17 k yr. The marked increases tend to be relatively short-lived, with a duration of about 2–7 k yr. Additionally there are some broad shifts over the length of the core. Lowest values are observed below about 950 cm, and correlate with the zone of low water content homogeneous muds, and high magnetic susceptibility values. Highest values were observed between 100 and 250 cm from the top of the core (~ 8–18 k cal. yrs). Peaks in TOC were observed at 12–15, 23, 29, 42, 48, 62, and 78 k yr.

High-frequency spikes in organic carbon are inversely correlated with decreases in $\delta^{13}C$ for the organic carbon (Figure 4). Consistent 1–3‰ decreases from background values are observed coinciding with the TOC spikes. Additionally, several long-term trends are observed throughout the core. Below the marked discontinuity at 940 cm (~ 79 k yr), $\delta^{13}C$ values reach their maximum of –17‰, coincident with the lowest TOC values in the core. Immediately above the discontinuity, $\delta^{13}C$ values are low (–26 to –28‰). They gradually increase between ~ 79 and 40 k yr BP to about –19‰ at about 40 k yr BP. The $\delta^{13}C$ values then decrease to somewhat lower values around the time of the last glacial maximum (e.g., Figure 4).

Preliminary biomarker analyses have been completed on the lipid fraction of four sediment samples from high- and low-TOC intervals. The ratios of short- to long-chain carbon fractions in all samples indicate a predominance of algal material in the T97-52V sediments, with only minor terrestrial contribution.

Diatoms and biogenic silica

Diatom assemblages were examined on 33 samples from core T97-52V at 1000× under oil immersion. In most instances the diatom preservation was poor, and abundances dropped to negligible levels below 370 cm. Given the age model described above, the oldest sample with identifiable diatom remains is about 28 k yr in age.

The results of these analyses are similar to previous investigations of Lake Tanganyika diatom assemblages over the interval from 0–370 cm down core T97-52V (e.g., Haberyan and Hecky, 1987; Tiercelin, et al., 1988; Gasse et al., 1989). We observe a similar sequence of transitions of diatom assemblages which are dominated by *Rhopalodia* at ~ 14.5 k yr, followed by *Stephanodiscus* (~ 13 k yr), then *Aulacoseira* (10 k yr), then *Nitzchia* (3 k yr). Two prominent peaks in benthic diatoms are observed at 185 cm (14.5 k yr) and at 275 cm (22 k yr). In between these two peaks benthic diatoms are high, as are other siliceous microfossils such as sponge spicules, phytoliths and amoeba plates, all indicative of shallow water conditions.

Paleolimnologic interpretations

The well-constrained geochronology of core T97-52V, the marked variability in several paleoclimate proxy measurements, and the well-constrained seismic stratigraphy of the study region allow us to reconstruct the lake level and productivity history of Lake Tanganyika over the past 90+ k yr. The proxy records measured, analyzed and discussed above allow us to break the core T97-52V record into four main intervals: Section I: 0–270 cm (0–19 k yr BP), Section II: 270–550 cm (~ 19–45 k yr BP), Section III: 550–950 cm (45–79 k yr BP), and Section IV: 950– 1040 cm (base of core) (more than 89 k yr at the base) (Figure 4).

Section I

Section I (Figure 4) extends from the present to 19 k yr (modeled C-14 years), and covers the same age interval considered in several other studies (Haberyan and Hecky, 1987; Tiercelin et al., 1988; Gasse et al., 1989). In our current study however, the dense grid of seismic reflection data over the study area allowed us to precisely locate the best possible coring site for a sampling of the condensed stratigraphic interval of the Kavala Island Ridge. In particular, the seismic data recovered over the study area indicate that this region and the sedimentary section in this area have remained undisturbed, unlike other study sites such as the locality of core T2 in southern Lake Tanganyika which is a zone of mud waves and possible sediment reworking. (e.g., Gasse et al., 1989; Tiercelin et al., 1989; Johnson, 1996). However the results of analyses of the uppermost part of core T97-52V bear strong similarity to other cores from southern Lake Tanganyika, notably core MPU-XII (e.g., Tiercelin et al., 1988).

The uppermost 35 cm of the core is composed of finely laminated brown-green muds and reflects the recent lake highstand, relatively high-productivity conditions, and anoxic bottom waters bathing this 393 m deep site. The diatom assemblages observed suggest that over the past ~ 14 k yr lake levels were at least close to the modern spillway height. Planktonic diatoms dominate the record from the present back through about 14.5 k yr. At 14–18 k yr we interpret water levels as low as –350 m below modern water levels, based on peaks in the benthic diatom assemblages. The TOC values are high throughout the upper part of the sediment core, and peak near 14% at the transition from high to low lake level, between 10 and 14 k yr. The dramatic decrease in $\delta^{13}C$ during the interval 170–130 cm probably indicates increased productivity due to nutrient mobilization during a lake level rise (Talbot and Laerdal, 2000). This decrease in $\delta^{13}C$ after ~ 12 k yr is very similar to that observed in core MPU-12 (Tiercelin et al., 1988; Hillaire-Marcel et al., 1989).

Section II

Section II covers the core interval 270–550 cm, corresponding to an age of ~ 19–45 k yr. We interpret the paleolimnologic record as characterized by periods of fluctuating lake level, with water probably markedly higher than during the Last Glacial Maximum. The entire interval is represented by homogenous muds, suggesting a lake level somewhat lower than present, yet not so deep as to extend to the T97-52V core site (393 m). TOC values are mostly in the range of ~ 3–5%, and $\delta^{13}C$ values of –20 to –22‰ indicate mixed sources of organic matter. Magnetic susceptibility and GRAPE bulk density are in general higher during this time interval than during section I (Holocene and LGM). Diatoms and biogenic silica are at negligible levels below a depth of 360 cm (~ 29 k yr).

Prior to 22 k yr, the diatoms are dominated by genus *Cyclotella* which has been interpreted as having both planktonic and benthic forms. Based on the lack of sponge spicules, amoeba plates or phytoliths at this site, as well as data from other proxy records, we interpret that water levels were relatively high during this time interval. Below 360 cm core depth, fragmented diatom remains are rarely observed suggesting that dissolution may be responsible for the limited diatom and biogenic silica record.

Narrow but pronounced spikes in TOC and $\delta^{13}C$ are observed at 23, 29, and 42 k yr during this section. We interpret these spikes to indicate cooler, drier and perhaps windier intervals, when lake levels may have been lower, but when reduced thermal stratification enabled nutrient-rich bottom waters to circulate, enhancing primary production in the surface waters. An analogous situation regularly develops on a seasonal basis in both Lake Tanganyika and Lake Malawi, when during the cool, dry months of the austral winter, strong south-to-north winds initiate algal blooms, especially at the ends of the lakes (e.g., Plisnier et al., 1999; Johnson et al., 2001).

Section III

Section III extends from 550 to 950 cm (45–79 k yr) and is characterized by a zone of mixed homogenous and laminated mud. Where finely laminated muds are observed, there are also intervals of elevated TOC, which themselves are closely correlated with lower $\delta^{13}C$ values (Figure 4). These organic carbon spikes are developed at 48, 62, and 78 k yr, and following the interpretation of the upper parts of the core, we interpret these TOC spikes to indicate cooler, drier periods that promoted enhanced primary productivity around the Kavala Island Ridge, and in Lake Tanganyika as a whole.

Another pronounced feature of Section III is a 5 cm-thick horizon of densely matted, fibrous woody material that is sandwiched between zones of homogeneous grey-green mud. There are sharp, horizontal contacts between the woody zone and the adjacent mud. This suggests that either material washed into the coring site, settled in from a floating mat of vegetation, or that the ridge experienced a brief period of drastically lower lake level during this time. We tentatively interpret this layer to indicate a lowering of lake level to more than 350 m below its current level at 55 k yr BP. This interval coincides with enhanced values of magnetic susceptibility and decreased values of GRAPE saturated bulk density, all suggestive of terrestrial conditions during this interval.

The most pronounced signatures in Section III are the generally negative values of $\delta^{13}C$. Throughout most of this interval $\delta^{13}C$ values range from –23 to –26‰, with a minima of –28‰ for this interval at 760 cm (62 k yr). This extended interval of lower $\delta^{13}C$ values implies a dominantly algal origin for the Lake Tanganyika organic matter from ~ 79–58 k yr, and then a transition interval from ~ 58–45 k yr. Following this transition we interpret the organic matter composition to be of mixed aquatic or algal and terrestrial material, based on the intermediate values of $\delta^{13}C$ that are observed from ~ 45–14 k yr BP.

Section IV

The most pronounced discontinuity in core T97-52V is observed between Sections 3 and 4 (Figure 4). Lithology changes abruptly from laminated brown mud in Section III, to a low-water content grey mud at about 940 cm down core. The transition is also interpreted to represent the first major unconformity that is observed in the seismic reflection data around the study site (Figure 2). The extreme low values of TOC, and the very high values of $\delta^{13}C$ and magnetic susceptibility are all indicators of oxidation and subaerial exposure, suggesting a drop in water level more than 400 m below modern lake level, prior to 79 k yr. If the lake level excursion was brief, and if sedimentation rates prior to the excursion were comparable to the later rates, then the base of the core is a minimum of 89 k yr in age. Given the major seismic stratigraphic, lithologic and textural changes at this discontinuity, we interpret a major time gap at this horizon and estimate a basal core age much older than 89 k yr.

Discussion

Rapid changes in TOC and correlations to high latitude events

The patterns observed in the down core proxies reflect a complex and dynamic history of fluctuating water levels, varying vegetation, and dynamic intrinsic limnologic processes. We interpret the sharp periodic increases in total organic carbon, and the corresponding decreases in the carbon isotopic record as reflecting brief periods of enhanced biologic productivity, induced by more vigorous mixing of nutrient-rich deep waters, due to cooler and perhaps windier conditions. Analogous intervals of increased productivity are observed on a seasonal basis in both Lake Tanganyika (Plisnier et al., 1999) and Lake Malawi (Johnson et al., 2001).

Our interpretation of Core 52V supports a low lake level in the range of 300–350 m during the LGM, and strong mixing and lake level excursions to ~ 200–250 m at ~ 23, ~ 29, ~ 42, ~ 48, ~ 62, and ~ 78 k yr in the past 79 k yr. In addition, a major discontinuity at the base of the core, and two major seismic stratigraphic sequence boundaries near the core base suggest two severe lake level lowerings below the site of the core, prior to 79 k yr BP.

All of these excursions are indicative of rapidly changing climatic conditions in equatorial Africa over the past 100 k yr, and the high-frequency behavior of the proxies is not dissimilar from some of the well-known paleoclimate records of the high latitudes, such as found in North Atlantic sediment cores and the Greenland and Vostok ice cores. Perhaps most intriguing is the potential match of the core 52V TOC spikes with the timing of the discharge of ice-rafted debris in the North Atlantic Region. Heinrich Events 1–6 appear to coincide with the TOC peaks observed in this core, within the error of the age model (Figure 4). Whereas these preliminary data provide no information on relative lags in the global climate system, these data suggest that the teleconnections operative between the high latitudes and the northern subtropics (e.g., Schulz et al., 1998) may also extend to the interior of tropical Africa.

We conducted spectral analyses on key proxies in order to identify any patterns consistent with an astronomical forcing of the Lake Tanganyika limnologic system. The analyses were run on the saturated bulk density records (GRAPE), Total Organic Carbon, and magnetic susceptibility. Analyses were conducted using the ARAND software series that uses a Blackman-Tukey approach to generate power spectra for paleoclimate time series data.

GRAPE bulk density records are shown in Figure 4 and suggest a ~ 11 k yr cyclicity, perhaps matching the patterns of half-precessional cycles predicted by insolation and energy balance models for the equatorial latitudes. TOC records show a cyclicity of about 16 k yr. Additionally the TOC curve is far from sinusoidal, but rather shows a marked spiky signature. We postulate that this signature indicates a threshold response in water column productivity, probably brought on by mixing, and possibly rapidly rising water levels and increased nutrient availability following brief intervals of low lake level. A similar response is observed in both Lake Tanganyika at the LGM and in Lake Victoria (e.g., Talbot and Laerdal, 2000).

Long term trends in $\delta^{13}C$

The record of δ^{13}C from core T97-52V shows changes of more than 10‰ along the length of the core. The reworked interval at the core base has very high values of δ^{13}C that are possibly related to reworking and oxidation of organic matter at this site during the ~ 80 k yr lowstand. Above this interval the background values of δ^{13}C range from –24 to –26‰ that we interpret to indicate deposition of mainly aquatic organic matter, with a possible mix of aquatic and C-3-based land plant material. There is a shift in this trend at ~ 58 k yr, to significantly higher values of δ^{13}C (to about –20‰) that may indicate a contribution from grassland-type, C-4 metabolic pathway-dominated plants in the Tanganyika catchment. This suggests that cooler and drier conditions prevailed in the study area from ~ 55 k yr through the Last Glacial Maximum (e.g., Street-Perrott et al., 1997). The dominantly aquatic signal only returned to the Tanganyika catchment in early deglacial times, beginning about 12 k yr.

Major Lowstands prior to 79 k yr

The lowermost interval (from ~ 950 cm to the base of the core) is evidently older than 78 k yr. This interval is probably composed of reworked material that was subaerially exposed for an extended period, based on inspection of the seismic reflection data in the vicinity of the coring site. This discontinuity must represent a drop in water level in the Tanganyika basin of at least 400 m. Immediately beneath this reflection on seismic profiles (Figure 2) we observe another boundary defined by a high-amplitude reflection and erosional truncation of the underlying strata. In order to produce this degree of erosional truncation, this site must have experienced prolonged shallow-water conditions or subaerial exposure *and* contemporaneous tectonic tilting along one of the intrabasinal faults that are observed on the Kavala Island Ridge.

It is not possible to present absolute ages for these surfaces without completely penetrating through the two sequences and obtaining age dates independent of the radiocarbon chronology. However all the data assembled indicate that sedimentation at this site was continuous to at least 58 k yr, when the thin horizon of woody material was deposited. Given the consistency of the lithofacies and index properties above and below the woody zone, we interpret this deposit as an event of extremely limited duration, and interpret a continuous chronology for T97-52V down to a depth of 940 cm where we observed the marked contrast in proxies and lithology. Thus we interpret the upper of the two major sequence boundaries observed in the seismic data as developing prior to 79 k yr BP. The age of the lower sequence boundary observed on seismic profile 58, beneath the upper sequence boundary, is considerably more speculative. If the sedimentation rates in the intervening interval are comparable to the rates measured in the near surface sediments, then this boundary has a minimum age of about 120 k yr. If we assume that Lake Tanganyika water levels and regional P:E are closely coupled to the high latitude climate system, then it is reasonable to speculate that this lower boundary and erosional surface developed as a consequence of significant cooling and aridity during the penultimate glaciation or marine oxygen isotope stage 6 (~ 130–190 k yr BP). If this speculation is correct, it implies that the Stage 6 cooling and aridity event in the continental tropics was much more severe than that of the last glacial period.

Conclusions

The signatures of various proxy measurements reflect a complex response to climate forcing in Lake Tanganyika.

- Both GRAPE and TOC data show a periodic signature occurring at sub-Milankovitch frequencies. The GRAPE/saturated bulk density profile indicates an 11 k yr response whereas a spectral analysis of the TOC response indicates power at about 16 k yr. The decline in $\delta^{13}C$ at this interval also supports an interpretation of a pronounced water level drop, and subsequent rise during those short intervals (~ 2–7 k yr). The TOC/$\delta^{13}C$ spikes observed also appear to correlate with North Atlantic Heinrich events, within the error of our age model.
- A long-term shift in $\delta^{13}C$ suggests that contributions of organic matter to the basin were dominated by aquatic algal material from ~ 80–58 k yr. Following a brief transition period, $\delta^{13}C$ values are markedly higher, suggesting that C-4, grassland-type vegetation may have contributed organic matter to this site from ~ 55 k yr through the LGM. Values decline during the deglacial period (beginning about 13 k yr) suggesting a return to deposition of algal-dominated organic matter through the present.
- The abundant high-quality seismic reflection data over the KIR show evidence of two pronounced seismic sequence boundaries, the upper boundary corresponding to a marked discontinuity near the base of T97-52V, and a minimum age of ~ 79 k yr. The lower boundary, which occurs within 7 m or less of the upper sequence boundary over this part of the KIR, shows evidence of angular truncation of underlying reflections over much of the KIR, suggesting a long period of exposure. No data is available to assess the duration of this exposure. We interpret both sequence boundaries to represent major drops in lake level below the site of our core (393 m). Assuming that sedimentation rates between the two boundaries are comparable to those measured in T97-52V, we interpret the lower sequence boundary to have formed during the penultimate glaciation (Marine Oxygen Isotope Stage 6). If this speculation is correct, then the cool and arid tropical climate response to the penultimate glaciation was much more severe than what occurred during the recent glaciation.

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