Paleoclimatic reconstruction based upon a sediment core from the Kalya region, Lake Tanganyika, East Africa.

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Introduction

Lacustrine sediments from piston cores are used to reconstruct past climate variability (Talbot and Allen, 1996). For the present study, a sediment core was analyzed from Lake Tanganyika, located in western Tanzania, East Africa (Figure 1). East Africa is an important place to study paleoclimatology due to its equatorial position, its relationship with the El Niño Southern Oscillation (ENSO), and the interaction between the regional precipitation of the area and the Intertropical Convergence Zone (Nicholson, 1996). Lake Tanganyika is of particular interest due to its old age and excellent sedimentation record. In addition, the study of well-laminated sediments from Lake Tanganyika is useful for the display of compositional changes and the development of chronologies (Cohen et al., submitted; Schnurrenberger et al., 2003).

Long-term climate change in a lake system can be characterized by diverse analyses of cores. We chose to focus on five separate methods – Loss-on-ignition analysis of organic matter, water content, smear slide studies, detailed visual description and logging, and grain-size analysis. Separately, each data set can tell very little about the climate record, as each record can be influenced by numerous factors other than climate. However, when considered together, one can use cross-record validation and comparison to narrow the range of possible climatic forcings on a given sedimentary record, thereby developing a more detailed history or paleolimnologic and paleoclimatic variations.

Nyanza Projects in 2000 and 2001 obtained sediment cores and bathymetric data from the Kalya horst and slope region, south of the Mahale Mountains in central Lake Tanganyika (Figure 1). These studies showed that some areas of this region have slow sedimentation rates, while other sites have high sedimentation rates and annually laminated sediments (Cohen et al., submitted; Zilifi and Eagle, 2000). Such regions are ideal for paleoclimatic investigations because of the exceptional preservation of sediments and the opportunities to study climate change at a variety of different time-scales. During the 2004 field season, the Nyanza Project cored on the Kalya slope in part to study this area of varying sedimentation rates, but also because previous studies showed that the site contained annually-laminated sediments ideal for paleoclimatic investigations. The laminations consist of light/dark couplets composed of diatomaceous and terrigenous material. Cohen et al. (submitted) interpreted the laminated beds of terrigenous material as wet season indicators and the alternating diatomaceous oozes as the dry season with lower amounts of terrigenous deposition (Cohen et al., submitted). The 2004 study utilized a longer sediment record in order to study whether trends that Cohen et al. (submitted) observed continue with depth. Does a record of annual climate variability occur at greater depths in the Kalya slope record? Will coarse grain size correlate to light bands of diatomaceous ooze indicating windy dry upwelling events? Can large-scale climate events recorded in the Kalya region cores be correlated to global climatic fluctuations?

Methods

Field Methods

In July of 2004, an eight-day cruise that included both seismic acquisition and coring operations was conducted aboard the M/V Maman Benita in the Kalya region of Lake Tanganyika. During this study, four Kullenburg piston cores were recovered from the lake, as well as three gravity cores. The piston core that is the focus of this study (NP04-KH1-1K) was taken from the Kalya Slope at S06º33.147’ E29º58.480’ (Figure 2).

The recovered sediment core is 534 cm long, and was taken from a water depth of 303 m. The core tube was cut in the field into four ~1.5 m sections and remained horizontal during transport. Upon returning to TAFIRI in Kigoma, these sections were split evenly down the middle with a cast saw to create working and archive halves.

Lab Methods

The sampling scale varied for the different analyses, but the authors sampled at the same depths, every four centimeters, to allow for later data cross-correlation.
Lithostratigraphy

Upon opening, the working half was scraped to examine sedimentary structures, and color was immediately determined with the use of the Munsell color chart. The core was then digitally photographed for later reference. The core was described for its macroscopic structure and color, noting bedding planes, lamination thickness, and other structural features.

Smear slides were prepared every 1-4 cm to examine compositional changes associated with bedding noted during the visual descriptions. Over 150 smear slides were made by taking a small amount (a pin prick) of sediment from the core, placing it onto a microscope slide, and gently mixing it with ethanol to thin out the sediment. Norland™ optical adhesive was used to mount the cover slip onto a microscope slide. Each slide was then optically analyzed using a Zeiss petrographic microscope for the abundance of diatoms, clastic material and organic matter, as well as the presence or absence and the mineralogy of authigenic carbonate minerals. The data from the visual core logs and smear slide analysis were combined to create a stratigraphic column in Adobe Illustrator. Smear slides are useful to obtain abundance and grain size of clastic material (Russell et al., 2003; Schnurrenberger et al., 2003).

Loss-on-Ignition

Sediments were subsampled for loss-on-ignition analyses on a one-centimeter scale and placed into pre-weighted crucibles. The crucibles were then placed in a drying oven at 110°C overnight. The dried samples were weighed at room temperature prior to burning at 550°C for one hour the following day. The loss-on-ignition procedure followed the procedure conducted in past Nyanza studies and determined by Dean (1967).

The % organic matter for each sample was calculated from the difference between the weight of the dried sample and the burnt sample divided by the difference between the dried sample and the empty crucible, all multiplied by one hundred.

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\frac{(\text{Dried sample weight} - \text{Beginning sample weight}) \times 100}{\text{Beginning sample weight}} = \% \text{ Organic Matter}
\]

Sediment samples that did not have % organic matter or % water content values consistent with the surroundings sediment were resampled in order to ascertain validity of anomalous data points. The % water content values were examined for down core trends.

Grain size

0.3 to 0.5 g sediment samples were extracted from the core at 4 cm increments for clastic mineral grain size analysis. Samples were pretreated with 50% hydrogen peroxide in a boiling hot water bath to remove organic material, followed by two distilled water rinses with high-speed centrifugation at 20 minutes each. After the second water rinse, the samples were heated in 0.5 M NaOH to remove biogenic silica (diatoms). After treatment (NaOH digestion), each sample was diluted with distilled water, and analyzed using a Spectrex Laser Particle Counter PC-2000. This system operates by use of a laser beam that is shot through the container holding the diluted sediment, which, assuming each grain is a perfect sphere, produces a size distribution based on the calculated angle of refraction off of each grain (Spectrex instruction manual).

Results

Lithostratigraphy

The NP04-KH1-1K core has two major units (Figure 3). Unit I, from 0-300 cm, is composed of alternating beds of thickly laminated clayey diatomaceous ooze, medium laminated diatomaceous clay and thinly laminated sapropelic clay. The uppermost ~65 cm of unit I have very thickly laminated diatomaceous beds, while the lower part of unit I from ~65 cm to the contact zone around 300 cm is devoid of these very thickly laminated beds and changes to medium and thinly laminated beds (Figure 4). Overall, the dark laminations are olive gray in color whereas the light diatomaceous laminations are of a moderately greenish yellow color.

Both aragonite and calcite can be found in unit I in low but varying percentages from the surface down to about 86 and 160 cm, respectively. Aragonite is found at frequent levels (<15%) in the top 1.5 cm of the core. After this, rare amounts (<5%) are found sporadically down core at 14.5 cm and between 37.5 and 39.5 cm. There is a noticeable absence of aragonite from 21 to 26 cm (Figure 3). Calcite is found in trace amounts (<1%) until it noticeably rises to frequent amounts at 65.5-73.5 cm, again at 85.5-133.5 cm and finally at 151.5-155.5 cm. Calcite disappears between 159.5-163.5 cm.
Unit II is 234 cm in length, from 300 to 534 cm depth, and contains beds of massive silty clay alternating with both diffuse (indistinct) laminations and medium laminated diatomaceous ooze (Figure 3). The contact zone between unit II and unit I is gradational. There are three dominant colors in unit II. The massive silty clay is greenish black in color, while diffuse and medium laminated beds are dark yellowish green and yellow green, respectively. Indistinctly or diffusely laminated beds occur at 375, 380, between 390-398, and 402 cm. Beds of medium laminated diatomaceous ooze are present between 445-450 and 460 to 480 cm. The intervening beds are massive silty clays, and the contact between the laminations and the massive silty clay is sharp.

**Loss-on-Ignition**

Loss-on-ignition analyses of organic matter from the NP04-KH1-1K core show a distinct shift between the two lithostratigraphic units in the core. There is an ~5% decrease in organic matter between 300 and 400 cm depth prior to the transition at 300 cm depth (Figure 5). This change across the Unit I/II transition is apparent in the percent water content of the sediment samples as well. The average percent organic matter for the upper 300 cm is 16.2% with a standard deviation of 2%, whereas the lower 230 cm has an average percent organic matter of 13.6% with a standard deviation of 3.2%.

The organic matter concentration in unit I is relatively constant throughout the unit with a few slight variations. Between 75 and 125 cm depths there is more variance in the organic matter content than in the rest of the unit, where samples with values from ~10% to over 20% occur.

Unit II is characterized by two sections of differing organic content. The sediments that lie between 300 and 400 cm have significantly lower organic matter content than the underlying portion of unit II and the overlying unit I. The average organic matter content of the 300-400 cm depth zone is 11.7% with a standard deviation of 2.3%. The decrease in organic matter corresponds with a decrease in water content in the same section of the sediment core. The lower portion of unit II has more variable % organic matter values than the upper 100 centimeters of unit II. There is a decrease in organic matter content located between 470 and 480 cm, and a considerable increase between 470 and 534 cm depth.

The water content of the sediment samples differ noticeable between two different sections of the core. The upper 300 cm of the core have values greater than 80%, whereas the lower portion of the core has water content values that range between approximately 70 and 80 percent. The average water content for unit I is 86% with a standard deviation of 5.3, whereas unit II has an average % value of 71 with a standard deviation of 3.8%.

**Grain size**

Throughout unit I, the mean grain size remains relatively constant, averaging at 26.57 microns with slight variations (Figure 5). There is, however, a noticeable peak above the average at about 130 cm depth, which shows a marked difference from the more constant background data. This peak, as well as numerous smaller variations, appears to correlate with fluctuations in lamination thickness and composition. In general, coarser grain sizes correspond to the darker, thinly laminated sapropelic clays, while finer grain sizes appear in the more thickly laminated diatomaceous beds.

Beneath the transition to unit II from unit I, average grain size increases between 300 and 400 cm depth from 33.81 to 72.72 microns. The bottom 130 cm of the core shows greater variation than unit I, with grain size averaging 41.46 microns. When looking solely at general trends, unit II is, on average, coarser than unit I. Taking 300 cm depth as the dividing line between the two, the average mean grain sizes for the upper
and lower units are 28.9 and 49.41 microns, respectively. Within unit II, coarser grain sizes occur in darker beds, and finer sizes in lighter ones, just as in unit I.

**Discussion**

The lithostratigraphy and the mean grain size can be interpreted to reflect paleoclimatic changes in the Lake Tanganyika basin. Organic matter preserved in the sediments can correspond to periods of high and low productivity under constant sedimentation.

In 2000, Zilifi and Eagle utilized four gravity cores and analyzed the lithostratigraphy and the % organic and inorganic carbon at five centimeter intervals of these cores. The total organic carbon for the four cores averaged between 5 and 10%. LT00-01 and LT00-02 were obtained from the horst shelf and slope, respectively, whereas LT00-03 and LT00-04 were recovered from the horst. The authors interpreted the organic and diatom-rich sections in these cores as a wet, productive period, whereas the dry periods of lower lake levels were represented by the basal and gray clays from the horst (Zilifi and Eagle, 2000).

Variations in grain size down core, and therefore going backwards through time, reflect fluctuations in lake level as well as general trends of warming versus cooling periods. Larger grain sizes are generally interpreted to indicate periods of warmer and drier climate, whereas smaller grain sizes generally indicate cooler and wetter periods (e.g. Zilifi and Eagle, 2000). However, this is not always the case. It is also possible that a greater influx of clastic material from the rivers feeding the lake would occur during wet conditions, and that decreased inflow would occur during dry conditions. This would lead to larger grain sizes during wetter periods, and smaller grain sizes during drier periods. Such a relationship between grain size and river discharge occurs in Lake Tanganyika today near the mouths of some of the large rivers that debouch into the lake (Tiercelin et al., 1991).

We suggest that our data favor the latter idea rather than the former. The significant shift that occurs at the transition between unit I and unit II in our core corresponds to a dramatic climate change determined by Haberyan and Hecky (1987). Those authors conducted an analysis of relative diatom abundance from a sediment core recovered from the southern basin of Lake Tanganyika. A similar study was conducted by Steinkamp (2004) on core NP04-KH1-1K. Steinkamp concluded that the transition noted by Haberyan and Hecky was reproduced in

![Figure 4: Unit I (0-300 cm) composite (Lithostratigraphic symbols are the same as figure 3)](image-url)
the core at ~300 cm, which is the same location as the contact between our unit I and unit II. Haberyan and Hecky dated this transition to about 5,500 years BP, and concluded that it represented a transition from wet to dry conditions. Under this assumption, we can conclude that the length of time represented by unit II was, in general, much wetter than that represented by unit I.

The section located prior to the wet-to-dry transition (300 cm) has significantly lower amounts of organic matter and increased grain size than unit I. Since the core under observation represents a minimum 8,000 years of sediment deposition, it is likely that the two units correspond to the transition between the Early and Late Holocene, which is reported to have occurred about 5,500 years ago (Russell et al., 2003; Barker et al., 2002). This would explain both the sharp rise in grain size at 300 cm, as well as the large difference between average mean grain size before and after this point. Based on these studies (Steinkamp, 2004; Tiercelin et al., 1991), it is inferred that coarse grain sizes indicate wetter periods, and that finer grain sizes indicate periods that are more arid. Taking this into account, a description of grain-size variation down the core can be correlated with known periods of warm versus cool climate trends, leading to a more complete and accurate description of these trends, as well as their timing throughout history.

**Unit I**

In unit I, the lower percentages of organic matter generally coincide with thick laminations in the core stratigraphy, whereas the sections of higher organic matter content correlate
to lithostratigraphic beds of thin laminations. This could reflect variations in productivity between high and low periods depicted in the lithostratigraphic changes. Alternatively productivity variations may reflect changes in productivity of diatoms versus green algal/cyanobacteria in the water column. Diatom productivity is influenced by the stratification of the water column and changes in upwelling, which may be reflected in the organic matter variations throughout the core (Cohen et al., submitted).

Both aragonite and calcite mineral grains are present in the upper half of unit I but are absent from unit II. Two contrasting scenarios exist for the presence of calcite in this core, the first being higher evaporation rates. Russell (2003) cites Lehman (2002) as suggesting that the presence of calcite in Lake Edward can be linked to aridity, because it is a sign of slightly salty waters. Applying this study to the NP04-KH1-1K core, unit I has frequent to trace amounts of calcite from the top to ~160 cm, which could be an indication of drier conditions.

Another possible explanation for the presence of calcite and aragonite could be from variations in the influx of salts from Lake Kivu to Lake Tanganyika via the Rusizi River (Haberyan and Hecky, 1987). When Lake Kivu has a high overflow it feeds the Rusizi River, which then discharges into Lake Tanganyika, carrying salty waters from Kivu. Under this scenario, the presence of these carbonates would imply wetter climatic conditions to cause the increased discharge of the Rusizi River. The second scenario seems to be more likely for the Tanganyika core based on other geochemical evidence for Rusizi River inputs becoming stronger during the late Holocene (Haberyan and Hecky, 1987). Our hypothesis should be tested with oxygen isotope analysis and trace element geochemistry from the northern part of the lake to further understand the presence of calcite and aragonite in the sediments.

As mentioned previously, there is a noticeable peak in mean grain size at ~130 cm that corresponds with a particularly large bed of thinly laminated sapropelic clays. Although unit I represents a period that is, in general, drier than that represented by unit II, there are fluctuations such as the large peak at ~130 cm that indicate shorter, wet periods within the larger-scale dry period of unit I. From the presence of calcite as noted above, this particular peak probably represents the beginning of the large increase in the amount of river discharge flooding the area, which would be shown by an increase in the amount of coarser grained sediments. However, since the peak has such significantly increased values in grain size as compared to the rest of the unit, it is probably the result of the abrupt start of increased river inflow after a long, continuous dry period, during which coarser sediments had time to accumulate in river bottoms and deltas. This would result in a large peak immediately following the beginning of the increased inflow, followed by a long interlude of more constant and decreased grain sizes.

With the exception of this large peak, grain sizes for the rest of unit I remain both relatively low and constant, indicating a long, dry period without many major climatic fluctuations. There are, however, numerous minor fluctuations between thick and thin beds that likely reflect decade- to century-scale climate variability during the deposition of this unit.

**Unit II**

The contact that separates unit I from unit II is located at approximately 300 cm depth. Although the contact appears visually gradational, this change is seen as an abrupt shift in % organic matter, % water content, and the mean average grain size values. The high mean average grain size and decrease in organic matter between 300 and 400 cm prior to the contact between unit II and unit I corresponds with a massive bed with little or no structure (Figure 6). The section of the core located between 300 and 400 cm indicates a significantly wetter period, because of the increased mean grain size.

Throughout the core, and particularly in the lower 134 cm of unit II, increased grain size values correspond to decreased values of organic matter. These changes likely reflect changes in climate from arid to wetter conditions. However, at around 475 cm depth there is a decrease in organic matter that corresponds to a decrease in mean grain size. This relationship is inverse to the trends in the overlying sections of the core, which makes it difficult to interpret in the same manner as the rest of the discussion. However, due to the small scale of the fluctuation in data, it can be interpreted to be a relative transition from a wet to a dry period within a phase that is, on the whole, more wet than that from unit I.

Cohen et al. (submitted) focus their study on gravity cores recovered from the Kalya region and link fluctuations in lithostratigraphy to shorter-scale fluctuations. The Kullenburg piston core lithostratigraphy shows two units, which can be linked to a major climatic shift. The smaller shifts present in unit I could cover the same timescale examined by Cohen et al. (submitted). However, it is difficult to decipher specific annual to decadal events in the organic matter and grain size, or to link the cores directly to those of Cohen et al. at the present time. Lamination counts along with radiometric ages would aid in determining the timescale and frequency of the laminated bed and cross-core correlation (i.e. seasonal, annual or decadal).

**Chronology**

Steinkamp (2004) produced two age estimates for the NP04-KH1-1K core based on pronounced diatom events in his study. Event one is located at a depth of 411 cm and corresponds to an age of 11,000 years BP, and event two is located at the transition between unit II and unit I at 300 cm with an age of 5,500 years BP. The most recent sediment of the core was assumed to have been lost during coring operation due to over-penetration of the Kullenburg piston core. Russell (pers. comm., 2004) suggests that the uppermost sediments in the recovered core are from about 750 years BP.

Assuming that sedimentation rates remain constant within units, specific events can be dated within a reasonable range of error. The sedimentation rate of unit I was determined to be 0.06 cm/year and the sedimentation rate from 411 to 300 cm in unit II was determined to be 0.02 cm/year.
Sedimentation rate = \left( \frac{\text{older depth} - \text{younger depth}}{\text{older age} - \text{younger age}} \right)

Age within unit I = \left( \frac{1}{\text{sedimentation rate}} \times \text{depth} \right) + 750 \text{ cm}.

Age within unit II = \left( \frac{1}{\text{sedimentation rate}} \times (\text{depth} - 300 \text{ cm}) \right) + 5,500 \text{ years}

These age estimates assume a wide range of error due to the age assumption of the youngest sediments in the core.

In unit I the peak of mean grain size occurs at a depth of about 130 cm, which corresponds to an age of about 2,900 years BP. The peak in mean grain size in unit II is located at 350 cm with an age of 7,900 years BP. There is a decrease in grain size located at 480 cm that corresponds with an age estimate of 14,000 years BP.

The event that occurred at 7,900 years BP is within the error range of the 8,200 years BP massive cooling event that is recorded in northern latitudes (Alley et al., 1997). The significant decrease in northern temperatures could cause the ITCZ to migrate to lower latitudes into the Lake Tanganyika region resulting in increased precipitation (Johnson et al., 2002). This change is reflected in the increased grain size and decreased organic matter indicated of this wetter period that could be reflected by the large scale cooling occurring in the Northern Atlantic. This period would be reflected in decrease wind and an increase in rainfall (Gasse, 2000), which coincides with the data from the Kalya slope core.

The second change in Unit II correlates to a dry period based upon a decrease in grain size and organic matter indicative of a cooler period. The arid period around 14,000 years BP coincides with warming events recorded in the Greenland ice core record (Gasse, 2000).

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**Figure 6: Unit II (300-534 cm)**

![Graph showing % Water, % Organic Matter, and Mean Grain size (micron) across depth (300-550 cm)].

- % Water
- % Organic Matter
- Mean Grain size (micron)

Depth (cm):
- 300
- 350
- 400
- 450
- 500
- 550

Age (years BP):
- 60 to 80
- 10 to 15
- 20
- 30
- 40
- 50

This figure illustrates the changes in water content, organic matter, and mean grain size across the depth range of Unit II (300-534 cm), reflecting the sedimentary processes and environmental changes over time.
Conclusion

There is a distinctive transition zone between units I and II that is depicted in water content, organic matter, mean grain size, and lithostratigraphy of a piston core from the Kalya horst region, central Lake Tanganyika. It is believed that this zone represents a major climatic shift between the Early and Late Holocene, when the climate of East Africa changed from wetter to drier conditions. In addition, there is evidence for shorter-term events located at depths below ~400 cm that may correlate with high latitude climate events.

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