Lake Tanganyika paleoclimate and deforestation impacts inferred from sediment core data

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Introduction

The great lakes of East Africa's Rift Valley system contain a long sedimentary record, which can be analyzed and interpreted to reconstruct the lake's paleoenvironment. Lake Tanganyika (located at 3°18'- 8°47'S, 29°05' - 31°18') is the largest and deepest of these great lakes (maximum depth 1470 m), and formed in three alternating half-grabens striking roughly north-south. Local bedrock is composed of metasediments and metavolcanic rocks and includes Precambrian quartzite, conglomerate, and iron-rich Manyovu Red beds (Cohen et al., 2005). The maximum basin age is estimated at ~12 Ma (Cohen et al., 1993). Lake Tanganyika resides in a zone of tropical climate, with a rainy season from October to April and a dry and windy season from May to September, with mean annual rainfall of 1302 mm/yr. (Nicholson and Yin, 2001). The lake is meromictic, with some upwelling during the windy season, that is strongest in the southern basin (O'Reilly, 2003). Lake waters are anoxic below 100 – 200 m, concentrating biodiversity in the littoral zone. There are four major influent rivers, and one major outflow (Lukuga River) to the Congo basin (Cohen et al, 2005).

Lake Tanganyika has an extensive sedimentary record that is useful for understanding lake dynamics, regional and global paleoclimate, and recent human impacts on sedimentation and lake ecology. Tanganyika's fisheries are particularly important to local economy and food supply, currently meeting almost half of the protein needs of local populations in all four bordering countries (Tanzania, Democratic Republic of Congo, Burundi, and Zambia) (Molsa et al., 1999). Recent studies have indicated that deforestation of the lake's watersheds increases sediment input and decreases ostracode diversity in the adjacent littoral zone (Alin et al., 2002; Cohen et al., 2005). Understanding human impacts on the lake's ecosystem is important to both reconstructing paleoclimate and to aiding current land management efforts.

This study uses data collected from a gravity core (NP06-GC04, hereafter "GC04") retrieved just south of Gombe Stream National Park, off the Ngelwa Stream watershed. The region is a largely deforested area (1.6 km^2) that supports a small town and several agricultural plots of cassava. Erosional features such as gullies can be seen from several hundred meters offshore, cutting into the steeply sloping hills that line the lakeshore. Sediment properties of GC04 will be compared with sediment grab samples collected by fellow 2006 Nyanza students. These comparisons will provide further insight into past climate changes, differences in deposition between watersheds, and perhaps even recent human impacts.

To reconstruct past environmental changes, this study will analyze several sediment properties (also called indicators) that vary in response to changing environmental conditions. These indicators can help answer important questions such as: How did lake level change in the past, and why? How did mixing and nutrient availability vary? What causes anoxia in Lake Tanganyika? Indicators used in this study include lithology, magnetic susceptibility, organic matter, and grain size, among others. Lithology is influenced by relative influxes of clastic, organic, and carbonaceous material; magnetic susceptibility is influenced by sediment composition and compaction; organic matter is influenced by productivity (which is influenced by nutrient availability and temperature, among other factors); grain size is influenced by erosion, energy of depositional environment, and other factors.

Methods

Several different sediment properties of gravity core GC04 were analyzed: lithology, magnetic susceptibility, % water, % organic matter, % total organic carbon (TOC), % total inorganic carbon (TIC), and grain size.

Core Collection

The gravity core, NP06-GC04, was collected in July 2006 from the *M/V Maman Benita* (S04°45.594, E029°36.096) at a water depth of 106 m. It was capped and stored vertically until it was returned to shore, where it was later split lengthwise. The total core length was 86 cm and all intervals described throughout this report are cm below top of core.

Lithology

When the core was split, a visual lithologic description was made. Color was determined using a Munsell color chart; laminations, layer thickness, texture, and major features were noted with respect to depth.

For a more detailed look at sediment composition, smear slides were made at 2 cm intervals. A small amount of sediment from each interval was dabbed onto a clean glass slide, followed by a drop of water to disperse the particles. Once the slide was dry, a drop of Norland optical adhesive was used to mount a cover slip on the sample. Smear slides were analyzed using a biologic microscope to find relative abundances of charcoal, aragonite, diatoms, and mineral grains. Type and abundance of each characteristic particle was noted and used in conjunction with the visual description to make the schematic diagram shown in Figure 1.

Magnetic Susceptibility

Magnetic susceptibility was measured twice: once through the plastic core casing and once directly on the sediment after the core was split. A Bartington MS2 Instrument was used to take two measurements (which were later averaged) every centimeter.

Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC)

The core was sampled at 1 cm intervals for TOC and TIC analysis. Each sample (~5 g.) was placed in an individual crucible and weighed on an electronic mass balance, dried overnight at 110°C, and weighed again to calculate the mass of water lost. The samples were then burned in a muffle furnace at 550°C for one hour. After combustion, the samples were weighed again and their % organic matter and % TOC values were calculated using the following formulas (after Lewis, 2005; Zilifi and Eagle, 2000):

$$\%\ \text{Organic matter} = \frac{(\text{dry sample weight} - \text{post-550°C sample weight})}{\text{dry sample weight}} * 100 \qquad (1)$$

$$\%\ \text{TOC} = \frac{(\text{dry sample weight} - \text{post-550°C sample weight})}{\text{dry sample weight}} * 100 * 0.4 \qquad (2)$$

To find TIC, samples were returned to the furnace, burned at 900°C for one hour, and re-weighed.

$$\%\text{TIC} = \frac{(\text{post-550°C sample weight} - \text{post-900°C sample weight})}{\text{dry sample weight}} * 100 * 0.12 \qquad (3)$$

Grain size

Samples (3-5 g.) were taken every 2 cm and initially wet sieved through < 63µm sieve. To analyze the clastic < 63 µm fraction, all inorganic carbonate, organic matter, and biogenic silica was removed from a representative 10 mL subsample of the sample-water slurry. To remove organic material, samples were treated with 50% H_2O_2 in a hot water bath, and then rinsed with distilled water in a centrifuge twice for twenty minutes each time. To remove biogenic silica, samples were heated in 0.5 M NaOH. To remove carbonate particles, samples were treated with concentrated HCl in a hot water bath for ten minutes, followed by two treatments of distilled water rinse and centrifugation. One mL of this clastic solution was diluted in 100 mL of distilled water for analysis on the Spectrex Laser Particle Counter PC-2000.

Results

Water content

Throughout most of the core, water content varied between 60 and 80% (by weight) (Figure 2). From 0 – 10 cm, water content varied between 65 to 72%, with two anomalously low values: 27 and 30% at 1 and 7 cm, respectively. From 10 – 19 cm, water content increased from 66 to 84%, and between 20 – 34 cm, it decreased from 83 to 34%. Values increased at 34 – 43 cm, from 62 to 86% (the highest water content values in the core). From 43 cm downwards, values decreased. There are three minor peaks at 53, 57, and 67-69 cm, and a sharp decrease between 70 and 86 cm.

Lithology

GC04 contains three major lithologic units (Figure 1). Unit I is Brownish Black, relatively coarse-grained (predominantly fine sand), and mostly massive. Unit II is Olive Gray, finer-grained (silty), and contains thickly laminated diatomaceous material. Unit III is Brownish Black, relatively coarse-grained (predominantly fine sand, as in Unit I), and contains some clumpy diatomaceous zones.

Unit I

Unit I is brownish black (5 YR 2/1), mostly massive, relatively coarse-grained, and punctuated with clastic and diatomaceous layers. From 6 to 6.5 cm there is a layer of coarse, light-colored sand (dusky yellowish brown 10 YR 2/2). From 17 to 17.5 cm and 18.5 - 18.8 cm, there are layers of gelatinous, diatomaceous material (grayish olive 10Y 4/2). At 20 cm and 22.5 cm there are very thin, light-colored layers (grayish yellow 5Y 8/4), which have high aragonite and diatom concentrations. *Nitzschia* is the dominant genus in these layers, primarily the species classified by Haberyan and Hecky (1987) as "long *Nitzschia*." This classification is a general term for several long, thin *Nitzschia* species that are almost indistinguishable from each other. Long *Nitzschia* dominate the diatom flora throughout Unit I, with *Navicula*, *Amphora*, and *Surirella* appearing in variable, minor concentrations. The boundary between Unit I and Unit II is diffuse and gradational, primarily distinguishable by the color change from brownish black to olive gray.

Unit II

Unit II is olive gray (5Y3/2), thickly laminated, relatively fine-grained, and contains a zone of thin light-colored layers as well as several areas of clumpy diatomaceous material. The light-colored layers (~1 mm thick) occur between 29 and 33.5 cm, interrupting the unit's dominantly olive gray fine-grained character. The layers are grayish yellow 5Y 8/4, and high in aragonite, which appear as crystalline rosettes in smear slides. The intervals 41.5 to 45 cm and 49.5 to 53 cm are thick zones of lumpy, lighter-colored diatomaceous material (grayish olive 10Y 4/2). Aragonite does not appear in any smear slides below 34 cm depth. Diatoms are moderately to highly abundant throughout Unit II, and continue to be dominated by long *Nitzschia*. Some areas contain a high diversity of genera (including *Amphora* and *Navicula*), particularly between 44 and 47 cm depth. The bottom of the unit alternates between lighter- and darker-colored layers until 58.5 cm depth, where there is a sharp, planar boundary separating olive gray and brownish black sediments.

Unit III

Unit III is brownish black (5 YR 2/1), massive, and relatively coarse-grained. It contains two major diatomaceous layers (grayish olive 10Y 4/2), which occur between 64 to 67 cm and 79 to 81 cm. At 56 cm, long *Nitzschia* decrease dramatically, and *Stephanodiscus* becomes the dominant diatom genus. Then at 78 cm, *Stephanodiscus* becomes rarer and Aulacoseira dominates the diatom flora.

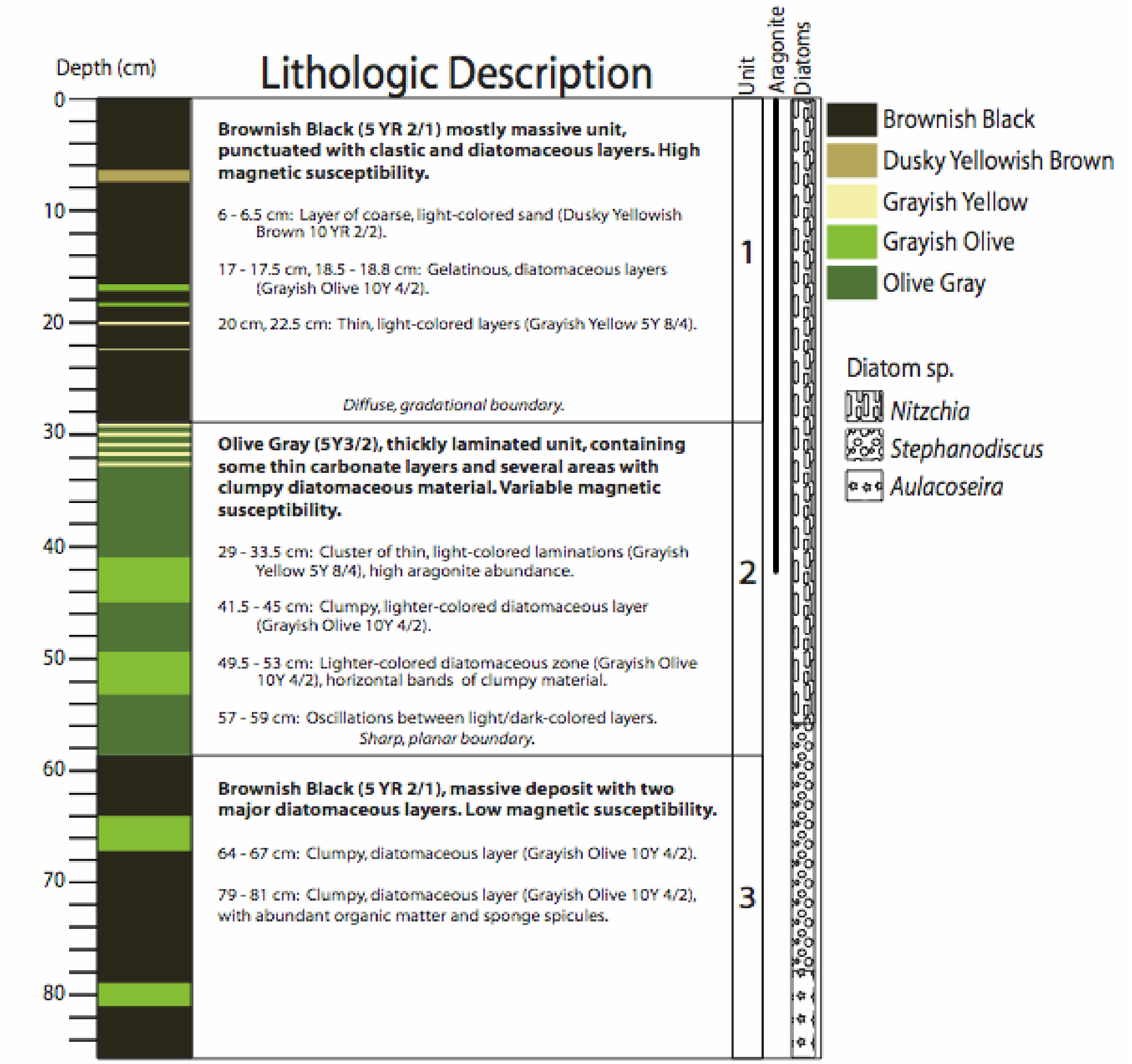

Figure 1. Lithostratigraphic diagram of core GC04.

Magnetic Susceptibility

Values measured using the MS2 Instrument were recorded as volume susceptibility, or κ (Greek letter kappa). κ is the ratio of the induced magnetism of sediments to the strength of the inducing magnetic field; since these two values have the same units, κ is dimensionless (to convert to SI scale, multiply κ by 10^{-5}). Average magnetic susceptibility values for Units I, II, and III are 19.3, 16.2, and 2.7 CGS, respectively. Values fluctuate sharply throughout Units I and II, but are much more uniform and low in Unit III (shifts in I and II are generally an order of magnitude greater than in III). In the upper, variable units, low points occur at 5, 17, 29, and 51 cm depth; highs occur at 11, 26, and 53 cm depth.

Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC)

Total organic carbon (TOC) content varies throughout the core from 1.3 to 6.1%. From 0-10 cm, regular-interval fluctuations can be observed, and there are two sharp troughs marked by one point each, 1.5 and 1.3%, at 1 and 7 cm, respectively. From 10-20 cm, TOC values fluctuate only slightly and consistently remain between 4.0 and 5.8%. From 20-40 cm, we see two sets of large, broad fluctuations marked by higher TOC values of 5.4 to 5.7%

from 21-23 cm and lower values of 3.8 to 4.1% from 24-27 cm. TOC increases again to about 5.0% from 28-29 cm, then decreases to 3.4 to 3.8% at 34-37 cm. TOC values become relatively stable from 38-46 cm, ranging only from 4.9 to 5.5%. After 46 cm, there is a series of sharp troughs and peaks marked only by 1-2 cm at each point. These values range from 3.2 to 6.1% throughout the section. Below 57 cm depth, the sharp peaks decrease in intensity and TOC values become stable. From 59-73 cm, TOC varies only between 4.2 to 4.6%. From 73-74 cm to bottom of the core, the TOC values decrease, with the exception of one spike from 80-83 cm.

Total inorganic carbon (TIC) content varies in three distinct sections. From 1-27 cm, TIC values range from 0.0-0.6% with only three peaked values at 7, 12 and 23 cm. From 28-57 cm, TIC values are much more variable. There are two sharp peaks at 31 and 39 cm, each followed by a broad decrease in values that extends for at least 5 cm. From 47-57 cm, the peaks are much sharper, but gradually decrease in intensity toward a mean value of 0.7%. From 57-86 cm, TIC values are very low and increase only slightly from 0.2 to 0.3% before decreasing to a final value of 0.05%.

Grain Size

The grain size trends observed in GC04 can be roughly correlated to the three lithostratigraphic units initially described upon splitting the core. Grain size, here described as the percentage of particles by dry weight which are >63µm and those <63µm, is divided into three prominent sections in the GC04 (Figure 3). In the first section, from the top of the core to ~13 cm depth, the majority of grains (>50%) are larger than 63µm with one anomalous interval at 3 cm, in which only 41% of grains are larger than 63µm. The second interval, between 15 cm and 69 cm depth, contains a majority of grains finer than 63 µm. This section generally contains less than 40% of the >63 µm fraction, although 49-67 cm depth shows a gradual increase in percentage of grains >63 µm, from 31 to 48%. The lower section of the core, between 55 cm and the bottom of the core, shows an increase in grain size, with all depths containing >41% of the >63 µm.

<u><63 µm Fraction Results</u>

The mean grain size of those particles in the <63 µm fraction (silt+clay, those measured by the laser particle analyzer) vary between 10-30 µm, with the only exception at 81 cm depth (~8 µm) (Figure 3). Generally, the means of the silt+clay fraction for Unit I and III are smaller than for Unit II. From the top of the core to ~35 cm, there is a gradual increase in grain size within this fraction, from 10 to 29 microns. From 35 cm to the bottom of the core, there is a general trend towards smaller grain sizes, ranging between 29-8 µm.

<u>>63 µm Fraction Results</u>

Although samples were not dry sieved, the >63 µm fraction was observed macroscopically. It showed two distinct shifts in grain size that generally correspond to the units described previously. From the top of the core to 13 cm depth, the sediment is composed of the coarsest fraction of very fine sand to fine sand. Microscopically, this fraction contains abundant angular quartz and opaque mineral fragments, with common charcoal grains. Ostracodes and sponge spicules, while present, were rare. Carbonate crystals were completely absent at these depths.

From 15 cm-75 cm, the grains appear to be the more fine-grained fraction of the >63 µm. From 15-30 cm there is a minor increase in ostracodes, charcoal, and fine acicular crystals of a precipitated mineral, that are thought to be carbonates, and that are found both in mats and acting as a cementing agent to aggregate other grains. From ~39-65 cm, this carbonate mineral is a predominate feature of this interval, and sponge spicules continue to increase in percentage throughout this interval. At 31 cm, there is a large increase in the number of ostracodes found.

From 75 cm to the bottom of the core, there is a pronounced change to coarser grains. This section also corresponds to a pronounced increase in sponge spicules, accounting for nearly 50% of the >63 µm fraction of each of these depths. The remainder of this fraction is composed of quartz and opaque mineral fragments.

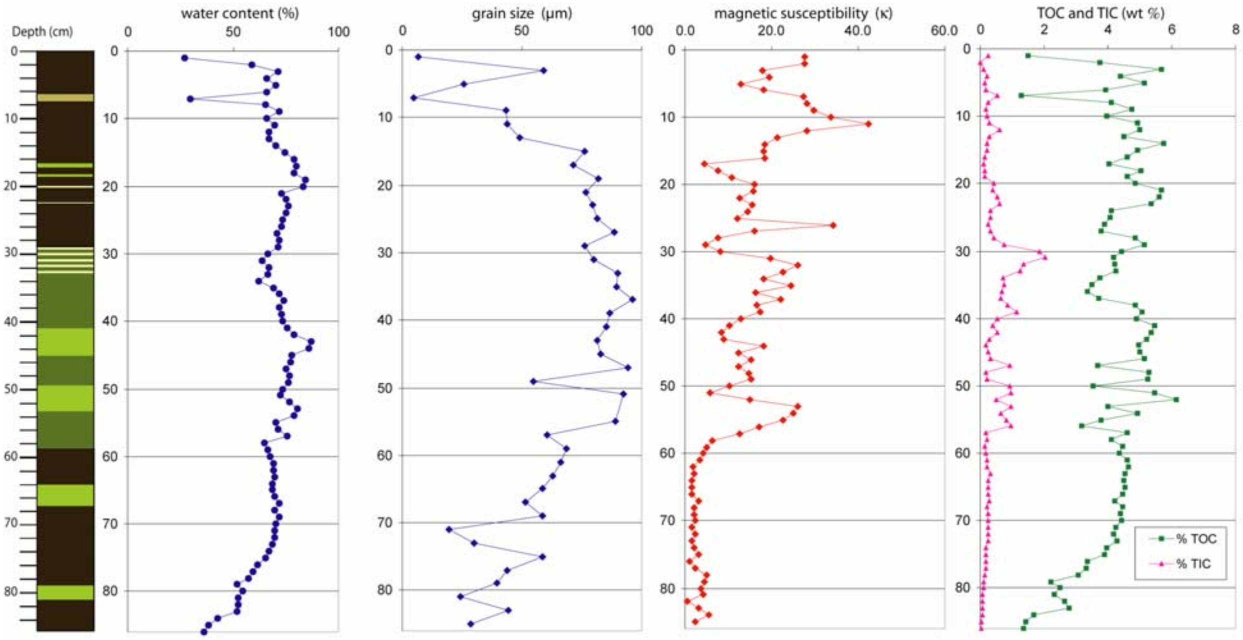

Figure 2. Multi-indicator graph: lithostratigraphy, water content, grain size, magnetic susceptibility, total inorganic carbon, and total organic carbon.

Interpretation

A single paleoclimate indicator is influenced by multiple environmental factors – for example, TOC production depends on water temperature, salinity, CO_2 concentration, and the presence or absence of nucleation sites. A study using only TOC could suggest several interpretations. Only when indicators are combined for analysis can we start to narrow down possible interpretations and make strong hypotheses about past environmental conditions. In this section, individual indicators and their various interpretations are described separately; in the discussion, they will be integrated to enable stronger hypotheses about Lake Tanganyika's past conditions and regional climate, specifically regarding lake-level changes.

Water Content

Water content of lake sediment can be influenced by dominant grain size and/or compaction. Grain size strongly influences pore space volume, which determines how much water sediment can hold. In addition, sediments often become increasingly compacted over time due to the increased weight of sediments above them. In GC04, it appears that neither of these factors dominate – rather, water content increases in areas of high organic matter, suggesting that a significant amount of water is being stored in biologic material rather than in pore spaces.

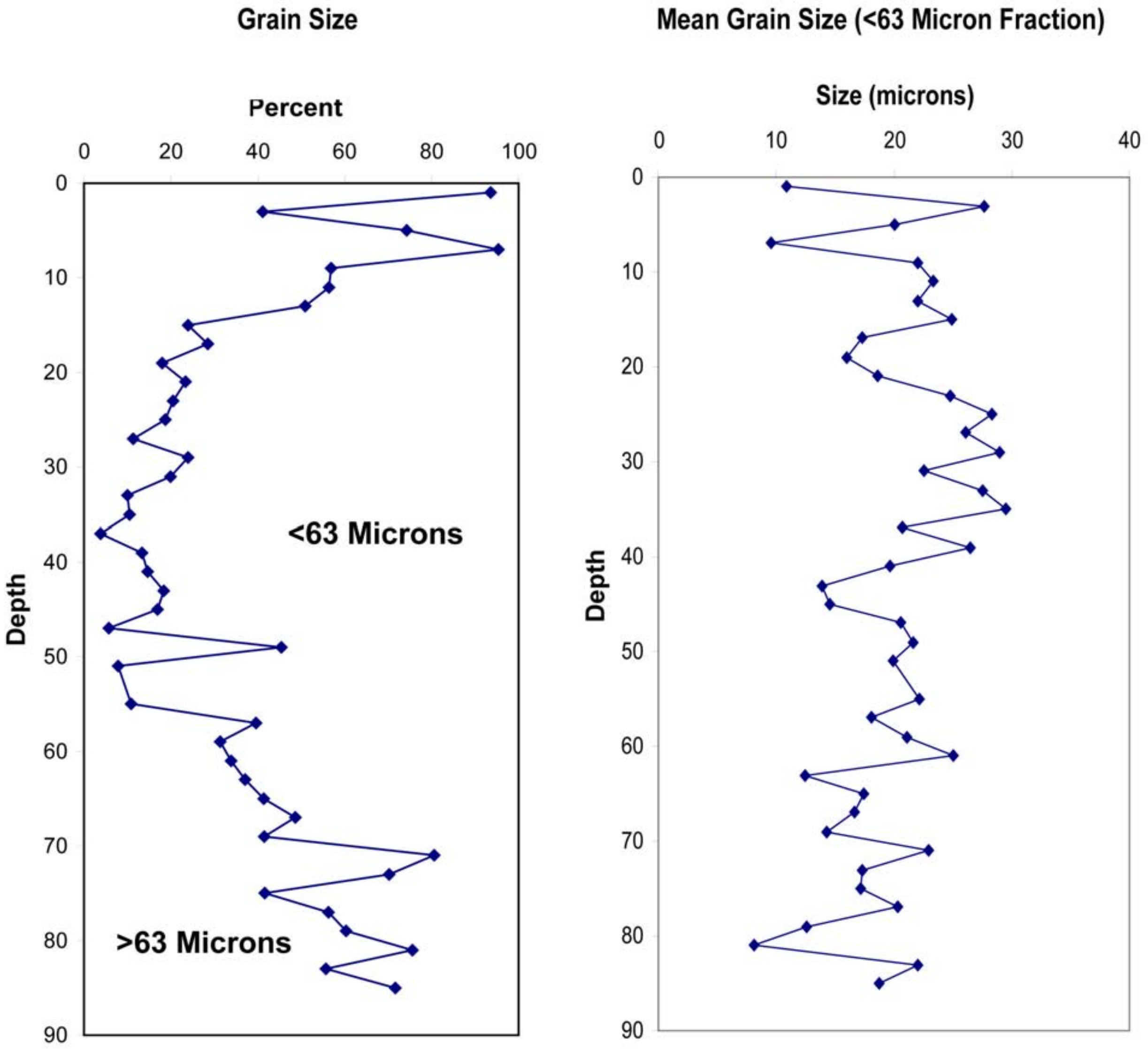

Figure 3. Grain size data. Graph on left indicates percentage of grain size for each sampled depth (as grouped into % >63 microns and % <63 microns. Graph on the right indicates the mean grain size of the <63 micron fraction (as measured by the laser particle analyzer.

Magnetic Susceptibility
Magnetic susceptibility is a measure of a substance's response to a magnetic field, or in other words, how 'magnetizable' it is (Dearing, 1994). The major controls on magnetic susceptibility in sediments are: material type, concentration, and grain size (Sandgren and Snowball, 2001).

Material type is important because different substances respond differently to a magnetic field, depending on the electron configurations of their atoms. Some minerals, such as magnetite and hematite, are strongly magnetic, yielding high magnetic susceptibility values, while other minerals, such as biotite, pyrite, and Fe/Mn carbonates, are only weakly magnetic. Some materials like quartz, calcium carbonate, organic matter, and water are "diamagnetic," meaning they will yield extremely low magnetic susceptibility values. Concentration is also important because magnetic susceptibility is measured over a certain volume: if there is a greater density of (para or ferri)magnetic material in that volume, measured values will be higher.

Post-depositional processes further complicate interpretation, because they can create or destroy magnetic material in sediments during diagenesis. Thus the original magnetic signal can be increased or decreased depending on redox conditions and trace element supply below the sediment-water interface, among other factors.

Understanding sediment magnetism is helpful to paleoclimate studies because it is strongly influenced by environmental conditions. Most magnetic minerals in lake sediments usually come from catchment erosion, although dust and volcanic aerosols transported by wind are sometimes significant (Sandgren and Snowball, 2001). The large amounts of dust transported by wind in East Africa (especially during the dry season) suggest this source could be important in Lake Tanganyika. Catchment erosion is influenced by climate: arid conditions cause decreased vegetation cover, and increased erosion, but wet conditions could have the same effect by enabling greater transport of eroded material to the lake basin. Also, the presence or absence of an oxycline can influence the solubility of Fe and Mn, which changes the preservation rates of magnetic minerals in sediment.

There are two major scales of magnetic susceptibility fluctuation in core GC04: small-scale, sharp variations throughout Units I and II, and a large-scale difference between the average values of the upper two units and Unit III.

Magnetic susceptibility κ values for Units I and II of core GC04 fluctuate sharply, ranging from 5 to 40. These shifts are probably not due to diagenetic compaction, as those effects would probably increase uniformly down-core. Rather, a compositional change is likely responsible. A change in any one or any combination of the following could cause such sharp changes: 1) relative abundance of organic and carbonaceous material, 2) volume of clastic influx, 3) composition of clastic material. Clastic influx depends on catchment weathering and transport, which in turn depend on climate. Arid conditions lead to less vegetation cover, which can lead to more soil erosion. Conversely, arid conditions can also slow sediment transport due to decreased precipitation and runoff. Major climate and vegetation fluctuations on such a small timescale (10 to 20 years, assuming a 1 mm/yr sediment accumulation rate) are relatively unlikely, but may be very important in explaining the major differences between units, discussed below. Storm events are also capable of moving large amounts of sediment from alluvial deposits to the lake bed in a short time span, and could significantly contribute to the κ values seen in Units I and II (Cohen, 2003). Even if the total volume of magnetic minerals being deposited did not change, a shift in magnetic mineral type could cause large variation in magnetic susceptibility values. For example, magnetite is about 1,000 times more magnetic than the strongest paramagnetic minerals, and 10,000 times stronger than the weaker clay minerals (Dearing, 1994). In GC04, productivity may have played an important role in the accumulation of magnetic minerals: high productivity causes large amounts of organic matter to fall to the lake bottom, where it decomposes and removes oxygen from bottom waters. Anoxic conditions severely limit Fe accumulation, because Fe often enters lakes as a particulate oxide, but will dissolve under reducing (i.e., anoxic) conditions. To investigate this possibility, magnetic susceptibility should be compared with productivity indicators such as diatom abundance/diversity, and TOC.

The large difference between the average magnetic susceptibility values in Units I and II and III (19.3, 16.2, and 2.7, respectively) likely reflects a major environmental change between units. Unit III may have been deposited in shallower water than Units I and II, which would make the core site closer to the Ngelwa stream outlet (increasing the probability that larger, more abundant clastic grains could be transported there). Shallow water at the core site also means that shallower-water organisms, such as sponges, would probably dominate biologic sediments. An increase in sponge spicules (made of silica) could have diluted the overall magnetic sediment signal, causing the drop in magnetism seen in Unit III. A decrease in water column mixing would also contribute to the occurrence of anoxic bottom waters, which would tend to dissolve any magnetic minerals that managed to accumulate. To test this hypothesis, paleo-indicators of lake level, mixing, and anoxia in the three units should be compared (i.e. relative abundances of different diatom species, grain size, and organic matter accumulation).

Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC)

Because of its potential as a paleoclimate proxy, carbon is an important component of the sedimentary record. Both inorganic and organic carbon can be indicators of the rates of carbon fixation in the water column and can provide insight into the biological processes within Lake Tanganyika. Changes in atmospheric CO_2 level due to climate change may also affect the amount of carbon consumed by the lake and therefore and sediment archives may reflect those changes (Cohen 2003).

TOC is a good paleoenvironment indicator because of its sensitivity to changing environmental conditions. TOC is a measure of the relative abundance of organic matter that remains in the sedimentary record. Values obtained reflect both the initial production and deposition of organic matter, and the subsequent preservation or degradation of that matter (Last and Smol, 2001).

Organic matter observed in the core GC04 is of both autochthonous and allochthonous origin, but autochthonous matter is more abundant throughout the length of the core. Autochthonous organic matter is produced through the dissolution of CO_2 and uptake through photosynthesis during primary production. Because phytoplankton production takes place primarily in the epilimnion, the residence time of aqueous organic matter in the epilimnion has a large affect on organic matter accumulation rates. In deep, meromictic lakes such as Lake Tanganyika, TOC values often do not directly reflect the rate of primary production because mixing is minimal and much of the organic matter decomposes before it reaches the lake bottom (Cohen, 2003).

Allochthonous organic matter forms from the physical and chemical decay of terrestrial organic matter in the catchment (Cohen, 2003). The rate of accumulation of allochthonous matter can vary due to changes in stream runoff, as a result of either seasonal variation or climatic changes. Variation in the vegetative cover of the region can also affect both the type and amount of allochthonous matter that is deposited.

The precipitation and dissolution of inorganic carbonate minerals often reflects the chemistry of the lake, and changes in that chemistry over time. Inorganic carbon can be formed in one of four primary ways: precipitated in the water column in the epilimnion, in the pore water as overgrowths on other grains, as part of the detritus fraction, or diagenetically (Last and Smol, 2001). Through smear slide observation, we determined that most of the inorganic carbon in GC04 was formed either from precipitation in the water column or as overgrowths in the pore water after deposition.

The relative abundance of inorganic carbon precipitated in the water column is directly related to the amount of CO_2 in the system. TIC can increase either through increased photosynthesis, which removes CO_2 from the system, or from lowered solubility, which can be caused by changes in both temperature and salinity. TIC can decrease through the respiration and decomposition of organic matter, which produces CO_2 and leads to dissolution of calcium carbonate minerals.

From 0-20 cm TIC is relatively low, and exhibits just two peaks at 7 and 12 cm. TOC remains high, with a distinct low at 7 cm. There is a possible inverse pattern that suggests that this may have been a time when wetter climate prevailed. High TOC could be attributed to increased productivity, which may occur if nutrient input from rain and stream water is larger. TIC could be low in this unit as a result of a dilution factor. As more water is added to the system, the concentration of ions in solution would decrease, making carbonate precipitation less abundant. Trends in this unit may also be attributed to anthropogenic affects. If this region was burned, we may see an increase in terrestrial organic matter being deposited. This, in turn, could lead to more dissolved CO_2 and to the dissolution of carbonate material.

From 20-45 cm there is a distinct covariance between TIC and TOC, which is most likely due to climatic changes as well; these cycles could be attributed to periods that are arid and windy. In a windy climate, more mixing would occur, which could increase nutrient availability and productivity. In an arid climate, there is enhanced evaporation, which may cause an increase in ion concentration in solution and cause the precipitation of carbonate minerals.

The trends seen in 45-58 cm are much like those in 0-20 cm. TIC and TOC exhibit an even stronger inverse relationship, where the peaks of one indicator correspond well to the valleys of the other. This is most likely due to a wetter climate, where there is less evaporation and more nutrient input by rain and stream runoff. Talbot et al. (2006) suggest a several-percent rise in TOC in Lake Tanganyika reflects a lake transgression. Because TOC fluctuates from 3.2 to 6.1% in this unit, this is a viable conclusion. The inverse relationship between TOC and TIC means that TIC values are low when TOC values are high. This may be a result of a dilution effect, or of the dissolution of carbonate minerals with increased respiration and decay of organic matter.

From 59-86 cm, TIC values are very low, while TOC is low and decreases with depth. This could be a period where Tanganyika experienced a low lake stand. If the oxycline were to have changed, the lake may have experienced less mixing and decreased productivity, which is the best explanation for low TOC values. Cohen et al. (2005) conclude that diagenetic alteration may occur in sediments with high TOC values (>20-28%), and that downcore trends would be observed. Because our values are significantly lower and no downcore trends are seen, diagenetic alteration is probably not a significant factor in our low TOC values. The increase in TOC over time may be attributed to better preservation of organic matter as it accumulates in anoxic conditions. TIC could be low due because of a dilution by clastic material or silica-rich organisms.

All of these hypotheses must be matched against other factors, such as grain size, magnetic susceptibility, and smear slide description, to determine their validity.

Grain size

Sediment grain size in large-scale lacustrine environments is controlled directly by proximity to and exposure of source areas (local bedrock or soils) and energy of the transporting and reworking agents (Cohen 2003). These factors may be influenced by a variety of local and global scale phenomenon due to climatic or anthropogenic changes. These include, but are not limited to, changes in lake level or and/or changes in river discharge.

A change in lake level would alter the proximity of the sediment surface to the action of reworking waves and currents, and would also alter the transport distance for sediments traveling into the lake basin. An increase in grain size has been correlated to wetter, cooler climatic conditions, with smaller sizes indicating prolonged periods of aridity. This influence of precipitation on grain size has been shown by Tiercelin et al. (1991) for Lake Tanganyika. Modern studies in Lake Tanganyika have shown that fine-grained sediments do not accumulate in water depths <100 m except near the Ruzizi delta, which may help constrain lake levels and areas of fine-grained paleodeposition (Haberyan and Hecky, 1987). A lower lake level relating to increased aridity may also contribute to the formation of carbonate precipitation, due to increased saturation in calcium and carbonate ions caused by evaporation. With a change in lake level, one would also expect to see depth-sensitive biotic indicators, such as diatom assemblages, reflect these changes (Haberyan and Hecky, 1987). Changes in lake level may relate to global scale events including Milankovitch cycles (Cohen, 2003).

Alternatively, a change in river energy may alter the size, amount, and composition of material being brought into the lake (Sly, 1978). With increased precipitation during wet climate cycles, larger and more abundant particles could be eroded and carried downstream. This increase may also be evident in increases in terrigenous TOC or changes in nutrient-limited species of diatoms. Deforestation or natural fire cycles could also play a role, exposing more material for erosion and thus leading to an increase in fine- grained material being deposited and a decrease in TOC deposited (Strickler, 2006; Jankowski, 2006). Likewise, higher rates of erosion of bedrock erosion may provide necessary ions for precipitation of common lacustrine carbonate minerals such as aragonite and low/high-Mg calcite (Cohen, 2003). Isotopic evidence from carbonates may confirm any prolonged periods of drought/arid climate with a large positive $\delta^{18}O$ value (Russell et al., 2003). Localized flood/drought cycles or larger scale ENSO cycles may be evident in patterns of grain size associated with a change in runoff (Bosworth et al., 2004).

Discussion

Different indicator trends will be combined to construct hypotheses about Lake Tanganyika's past environmental conditions. Interpretations will be discussed by unit, beginning with the oldest sediments and working towards the present.

Unit III

Sediments in Unit III could have been deposited during an arid period, when lake levels were lower than present. The GC04 core data support this hypothesis in several ways. Sponge spicules are very abundant below 50 cm core depth, suggesting a shallower depositional environment, closer to the depths at which sponges are abundant in the Lake Tanganyika (C. O'Connell, personal communication). Unit III is also relatively coarse-grained and massive, suggesting closer proximity to clastic sediment source (the stream mouth) and a higher-energy environment.

Assuming this low lake level scenario, our depositional site was probably shallower than the oxycline. Shallow, higher energy waters tend to be better-mixed than deeper waters. The presence of benthic organisms suggests oxygen was available deep in the water column. Also, if magnetite had been dissolved in anoxic bottom waters, we would have expected to see re-mineralization of pyrite, which we did not see either in smear slides or in examination of the coarse sediment fraction.

Alternatively, sediments in Unit III might have been deposited during a wet period, when lake levels were high. The GC04 core site is located on a flat shelf at the bottom of a steep slope; it is possible that an extremely wet period caused high sediment influx and triggered slumps that transported shallow sediments en masse to the deeper platform. This could explain the presence of sponge spicules, large quartz grains, and benthic diatoms in Unit III. Slump deposits would also be consistent with the massive layers we see in this section. In this scenario, anoxia is more probable.

In both scenarios, the extremely low values of magnetic susceptibility and TIC, and the somewhat lower TOC values can likely be explained by the dilution effect, caused by the high abundance of sponge spicules.

Unit II

Unit II has two distinct sections with differing trends. From 58-45 cm, grain size decreases over time. TOC and TIC exhibit sharp peaks and inverse variation. Magnetic susceptibility increases over time. We have interpreted these analyses to indicate a predominantly wet climate. In a wet climate, nutrient input would increase through the influx of rain and stream water, which could increase productivity. Meanwhile, TIC values would decrease as a result of a higher rate of dissolution caused by increased levels of CO_2 in the water. An increase in dissolved CO_2 levels would be expected as a result of the decomposition of terrestrial and aqueous organic matter. A wetter climate could also cause enhanced erosion and clastic input, which explains the sharp increase in clastic material at 49 cm.

From 45-20 cm, grain size remains relatively constant and is dominantly fine. Magnetic susceptibility slowly increases through this section. TOC and TIC both exhibit broad peaks and valleys, and they distinctly co-vary. Our interpretation for this section is that it represents a period that was arid and windy. In an arid climate, a lack of water could result in less erosive power, which explains the increase in fine-grained clastic material in this section. Also, in an arid climate, more evaporation would occur, causing a concentration of ions in solution and the precipitation and accumulation of more carbonate minerals. Windy conditions would cause more mixing, which would increase nutrient availability and, ultimately, increase production. This explains the increased TOC values where TIC increases. Magnetic susceptibility is generally high in oxic conditions because Fe-rich minerals remain oxidized. Lithologically, this section of the core also fits with an arid and windy climate hypothesis. The section of 45-20 cm crosses the boundary from lower Unit I to upper Unit II. Throughout this region of the core, we see many laminations that are diatom-rich. The diatoms in the section are both abundant and diverse, which provides evidence supporting a high level of productivity.

Unit I

In Unit I of GC04, the sedimentary analyses performed suggest a somewhat gradual change in environmental conditions between this unit and the previous due to a more diffuse sedimentary boundary. Although gravity cores are often disturbed in their upper portion, the presence of a well-defined layer at 6cm depth suggests this unit is mostly intact. The data supports the theory that this interval may have formed during a period of wetter climate and thus potentially higher lake levels. Grain size is generally coarser than in Unit II, suggesting a greater erosive energy of rivers flowing into the lake in this area. Greater erosion of clastic material from the watershed is also supported by the high magnetic susceptibility values seen in Unit I. It is also possible that there are fewer biotic components due to deposition near the oxycline where oxygen levels are low enough to preclude many organisms.

High, but variable TOC values may suggest greater nutrient supply (for increased lacustrine carbon supply) or input of greater amounts of terrestrial carbon into the lakes from more powerful rivers.

Coarser grain size and the abundance of charcoal seen in the >63 μm fraction and in smear slides may suggest a possible anthropogenic impact from deforestation and land clearance for cultivation. Although ^{14}C dates are needed to confirm this hypothesis, an assumed sedimentation rate of 1mm/yr or less may be consistent with a land clearance date (either anthropogenically or by natural fire cycles) within the last few hundred years.

With an increase in lake level due to higher precipitation, there would be a dilution effect (enhanced by lower evaporation rates) of calcium and carbonate ions, which would lead to lower levels of carbonate formation. This is evident in the low TIC abundance in Unit I.

Conclusions

Gravity core NP06-GC04, recovered in Lake Tanganyika at 106 m depth off the Ngelwa watershed, contains three distinct units. Initially defined by color and lithology, these units were further differentiated by sedimentological properties such as grain size, magnetic susceptibility, total organic carbon, and total inorganic carbon. Differences between units and variations within those units may reflect changes in past depositional environments. Through a multi-indicator evaluation, we have determined the following:

1. Unit III was likely deposited under low lake level conditions. Levels probably rose slowly through the unit.

2. Sediments from Unit II were probably initially deposited under rapidly rising lake level conditions. The core site likely became anoxic during this time, possibly causing reduction and removal of Fe from previously deposited sediments.

3. Unit I was likely deposited during a period of higher lake levels and wetter climate.

Future Work

This study would be greatly strengthened by establishment of ages throughout the core. This would enable comparison with other climate studies in the area, and a calculation of accumulation rates. An analysis of a complementary core from a forested watershed (such as Kalende) may enable evaluation of deforestation impacts. In addition to gravity cores, collection of multi-cores would better preserve the recent/modern sedimentary record and provide insight into anthropogenic impacts in the region.

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