

Lacustrine Micro-Fossil Assemblage from Core NP04-KH3, a Kullenberg Piston core from the Moba-Kalya Horst Region of Lake Tanganyika, East Africa, as a Biogeochemical Proxy for Late Pleistocene and Early Holocene Climate and Lake Level Changes.

Introduction:

Lake Tanganyika is the second deepest lake in the world and the largest lake in the East African Rift Zone (Figure 1). Because of its size, depth and age, it is considered to be an unparalleled archive of climate change in the African Tropics (Hayberyan and Hecky 1987). Lacustrine sediments within the basin of the lake archive decadal to millennial scale climate and lake level variations by recording changes in microfossil assemblages. Changes in diatom taxa occur in response to changes in wind intensity, precipitation, lake level, upwelling, water column stratification and nutrient influx. Deep-water anoxic sediments accumulate and preserve planktonic and benthic diatom frustules that slowly rain down and thus record the lake conditions at the time of deposition. Other pelagic silicic microfossils, such as grass phytoliths that may be wind or stream-derived, or sponge spicules derived from littoral zones also give clues to lake level changes and lake margin streamflow intensity (Hecky et al., 1991).

Diatoms are a major component of lacustrine phytoplankton and have been used extensively as a proxy for water chemistry, water quality, and changes in lake levels (Hayberyan and Hecky, 1987). Analyses of fossil diatom populations in lacustrine sediment cores also have been used to develop decadal to millennial scale climate histories (Gasse, 1986). Research on present-day diatom populations has shown that specific diatom species dominate in specific ranges of

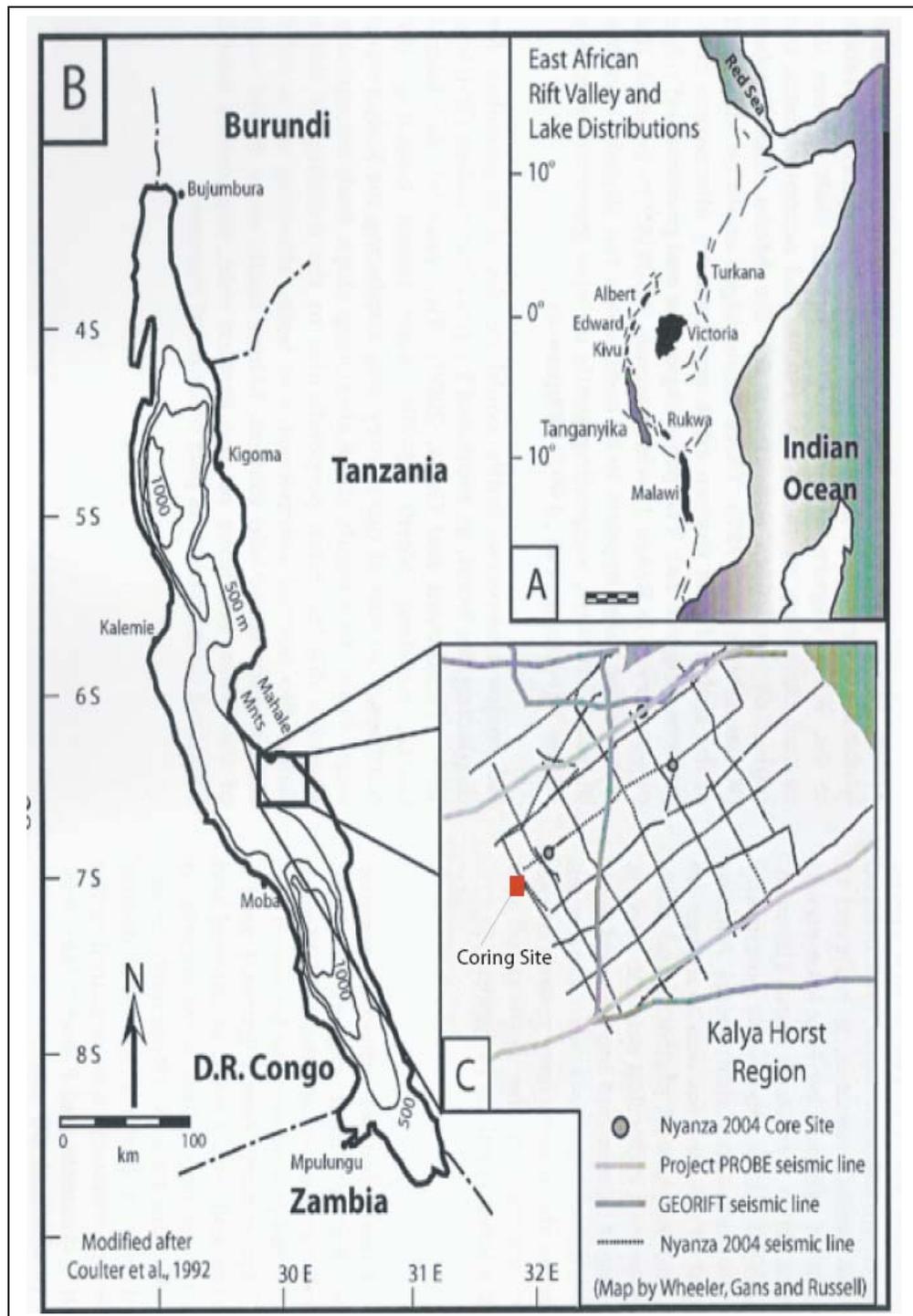


Figure 1. A) Planview of East Africa with the East African Rift Zone, west and east arm. B) Planview of Lake Tanganyika with inset box delineating coring and seismic survey area. C) Seismic survey lines and Coring Site at Kalya Horst region.

ecological conditions, and thereby record the changes in biology, chemistry and water levels of lakes as lakes adjust to shifts in climate. Thus, from analysis of fossil diatom populations one can infer past limnologic changes and paleoclimatic information (Gasse, 1986).

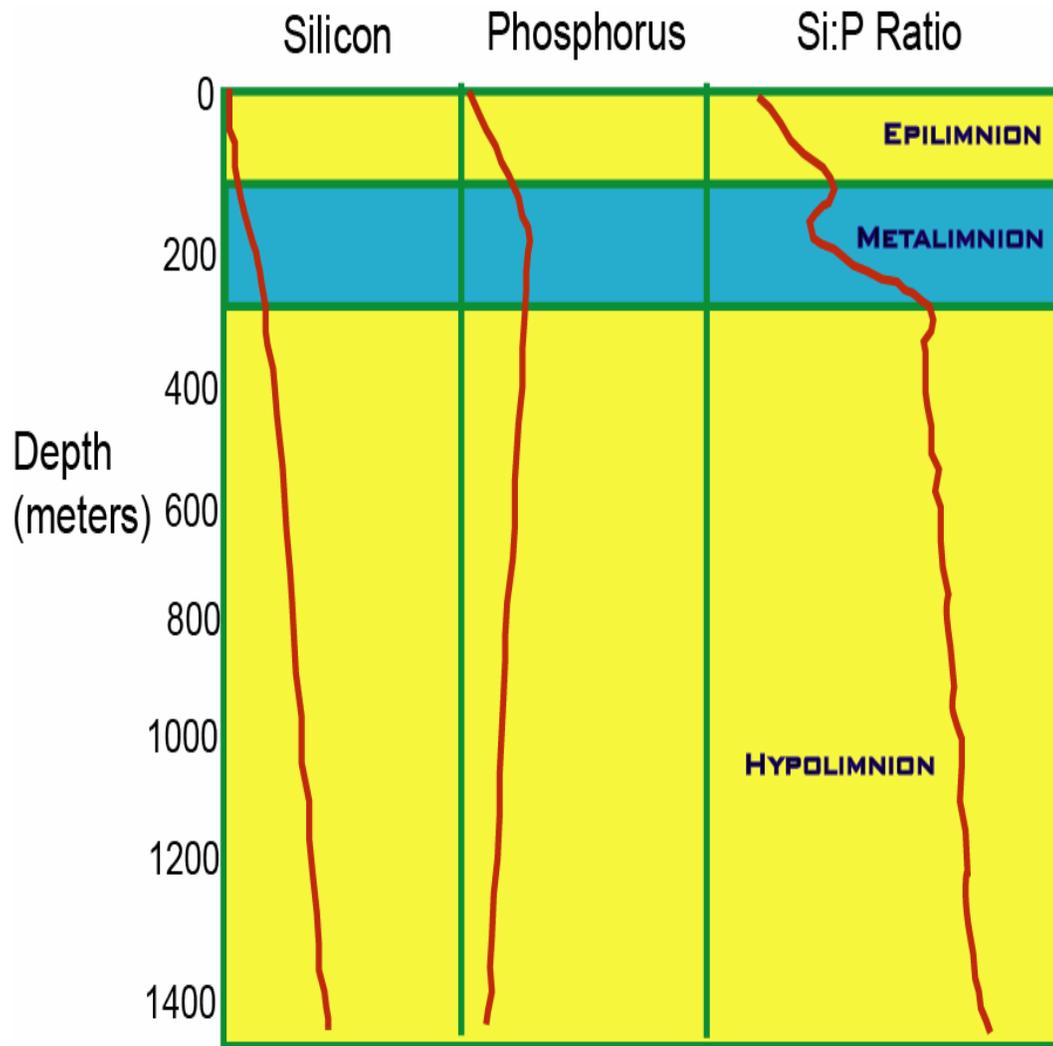
In Lake Tanganyika, changes in diatom genera over time have been interpreted to be controlled by Si:P ratios, which are controlled by depth of seasonal water-column mixing (Russell 2005, Kilham et al., 1986). The depth of mixing is correlated to the degree of seasonal cooling and wind strength (Hayberyan and Hecky, 1987). As seasonal cooling and wind strength increases, evaporation also increases which cools the surface of the lake and forces the thermocline to move higher in the water column. An increase in wind intensity then forces the thermocline to tilt to the north, which allows increased depth of mixing in the southern basin, near the Kalya Horst. Nutrients from the hypolimnion are then able to be mixed with the surface waters of the epilimnion, which increases the Si:P ratio at the surface. Thus, increases in seasonal cooling and wind strength are interpreted to correlate with deeper mixing and higher Si:P supply ratios in surface waters (epilimnion).

The distribution of planktonic diatoms in Lake Tanganyika has been shown to vary over time and is ultimately controlled by changes in Si:P ratios, which are controlled by limnological (seasonal mixing and stratification), and climatic (precipitation:evaporation (P:E) ratios and vegetation) factors. Climate affects the Si:P ratios by changing the rate of nutrient influx to the surface waters of the lake from surrounding watersheds and from deep waters of the lake. The

precipitation:evaporation ratio determines water surface cooling and vegetation cover, which controls the Si:P ratio in surrounding watersheds (Hayberyan and Hecky 1987). Wind strength and intensity controls degree of upwelling. Seasonal variations in depth of mixing thus determine the distribution of the micro-fossil assemblage. These variations are climate controlled by the degree of seasonal cooling and wind strength. Increased wind strength forces increased tilting of the thermocline, increased upwelling and increased depth of mixing. Therefore, the greater the wind strength, the greater the depth of mixing and increase of Si:P ratio in the photic zone (Hayberyan and Hecky 1987; Hecky et al., 1991).

The Si:P ratio in Lake Tanganyika increases with water depth, thus the intermediate water of Lake Tanganyika has lower Si:P ratios than the deep water (Figure 2). During periods of stratification, when intermediate water is entrained in the photic zone, the Si:P ratio remains low. Thus, when the lake is stratified, the epilimnion is enriched in phosphorous and deprived in silica (low Si:P). During periods of increased deep mixing and upwelling, the increase in Si:P is proportional to depth of mixing. The hypolimnion is enriched in silica, therefore the depth of mixing controls the Si:P ratio in the epilimnion during upwelling events and is thus the ultimate control on the diatom flora of the lake.

Long-term climate changes in East Africa have been postulated from lacustrine deposits from other lakes in the region. At Lake Naivasha, climate change data that represents the last 175 kyr has been accumulated using diatom data, authigenic mineral assemblages and sediment patterns. The data indicates



Redrawn From Haybryan and Hecky 1987

Figure 2. The Nutrient dynamics of Lake Tanganyika. Nutrients are shown as unitless.

that a chronology of lake high-stands at 10-11 kyr intervals possibly correlates with orbitally induced solar radiation in equatorial Africa (Trauth et al 2003). At Lake Malawi, researchers developed a climate history covering the past 25 kyr for East Africa using biogenic silica (from diatoms) mass accumulation rates (Johnson et al 2002). Their data suggests that the climate of the Lake Malawi basin was linked closely with the Northern Hemisphere until 11 kyr BP (Johnson et al 2002). Diatom data and geochemistry were used in Lake Magadi of East Africa to show that abrupt climate change such as the Younger Dryas was synchronous at both high and low latitudes, and that lake level changes and humidity changes coincided well with the rapid ice melting phases of the Northern Hemisphere (Roberts et al 1993). At Lake Tanganyika, Scholz (et al 2003) developed a paleolimnology chronology for the Lake Tanganyika basin for the past 100 kyr. Their results showed that cooler and windier conditions prevailed over the last 79 kyr, and that data for the last 20 kyr coincides well with other data, such as Hayberyan and Hecky (1987) and Gasse (1989) (Scholz et al 2003).

During the Late Pleistocene and Early Holocene, stratified lake conditions positively correlate with a cool, arid climate regime, whereas warm, moist climate regimes are correlated with upwelling and increased mixing caused by increased wind intensity that forces tilting of the thermocline (Hayberyan and Hecky, 1987).

Diatom genera such as *Cyclotella* spp. and *Stephanodiscus* spp. are considered to inhabit low-Si:P, stratified lake environments with a shallow annual range of mixing, which occur during periods of decreased runoff and cool, arid

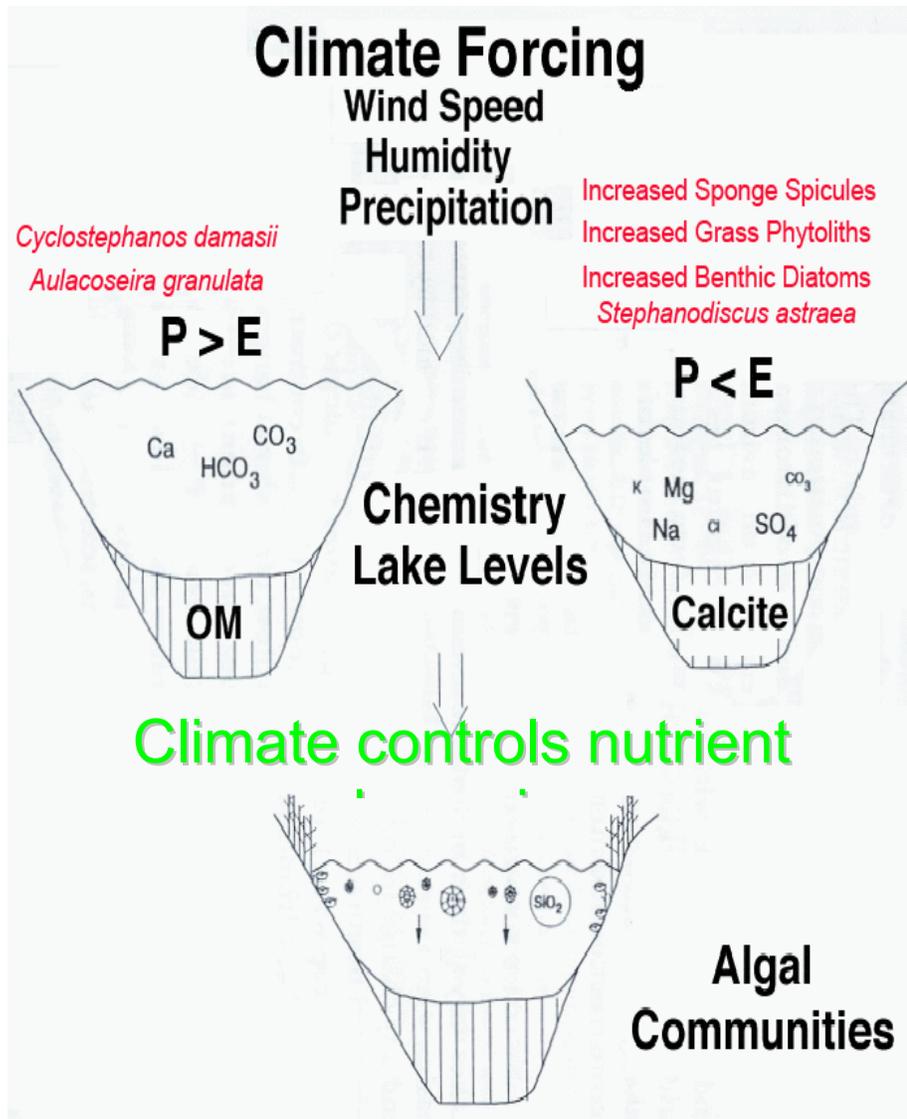


Figure 3. Climate forcing on Lake Tanganyika that controls phytoplankton (diatom) assemblage changes. Enhanced from Gasse 1989.

climate regimes (Hayberyan and Hecky, 1987; Kilham 1986). An inverse correlation occurs with the diatom genus *Aulacoseira*, which is thought to thrive and outcompete *Cyclostephanos* and *Stephanodiscus spp.* during warm, wet, and windy periods of greater mixing, water turbulence and upwelling (Kilham 1986). Upwelling increases the supply of silicon (Si) and other nutrients to the epilimnion by internal loading from the hypolimnion and aid in the suspension of its heavily silicified filaments. Additional loading of Si and other nutrients to the epilimnion of the lake are also derived from surrounding watersheds. As wetter conditions of high P:E (precipitation:evaporation) occur, increased vegetation in surrounding watersheds retains phosphorous, while silica is leached by low pH water (Figure 3). *Aulacoseira* is considered an indicator of eutrophic conditions in lakes, thus thrive in low-light, turbulent water conditions when the Si:P ratio is high. Due to the large filamentous forms of the *Aulacoseira*'s heavy body, the need for water turbulence to keep them suspended in the water column, low scattered light conditions and high silicon levels, their abundance is directly correlated to depth of mixing associated with upwelling in Lake Tanganyika (Kilham 1986).

The prominent Late Glacial Maximum to Early Holocene planktonic diatom taxa previously recorded for Lake Tanganyika are *Stephanodiscus spp.*, *Cyclostephanos spp.*, and *Aulacoseira spp.*, which thrive in varying Si:P supply ratios (Hayberyan and Hecky 1987). *Stephanodiscus spp.* and *Cyclostephanos spp.* have been determined to thrive in low Si:P supply ratios and extreme Si-limitation, whereas *Aulacoseira spp.* outcompete the other prominent taxa when

nutrients such as Si are abundant, and turbulent, windy conditions and deep mixing prevail (Hayberyan and Hecky 1987).

Changes in the relative abundance of benthic and other littoral diatom taxa in deep water lacustrine sediments have been determined to be an indicator of lake level regression and influx of allochthonous material from marginal watersheds. An increase in benthic and littoral taxa may indicate a littoral zone regression during decreased lake levels (Gasse et al., 1989), although it may also indicate increased fluvial discharge from marginal watersheds that redistribute littoral taxa into the pelagic zone of the lake (Barker and Gasse, 2003). However, due to the short, steep longitudinal profile of marginal streams, and transgression of littoral zones during wetter climate regimes, the increase in littoral taxa in areas protected from the effects of marginal watersheds would indicate a source of littoral species that is close to the coring site (Batterbee et al 2001). Also, research on diatom distribution using near-shore tows and sediment traps show that benthic diatom percentages in deep water rarely exceed 1%, although they increase toward shore (Hayberyan and Hecky, 1987).

Mass Accumulation Rates (MAR) of biogenic silica (BSi) also change according to climate shifts (Johnson et al 2002). The abundance of diatoms in lacustrine sediments is reflected by the percent biogenic silica in cores. Cool, arid conditions are indicated by low BSi MAR, which may be directly associated with a low river influx of silica. An increase in periphytic diatoms, sponge spicules and phytoliths associated with low BSi MAR are indicative of dry climate and low lake-level conditions (Johnson et al 2002).

Changes in sediment grain size and amounts of organic matter also have been used to interpret climate fluctuations (Bosworth et al., 2004; Tiercelin et al., 1991). An increase in grain size of lacustrine sediments correlated with a decrease in organic matter is interpreted to be indicative of arid climate conditions whereas wet climate conditions are indicated by a decrease in grain size and increase in organic matter (Bosworth et al., 2004; Tiercelin et al., 1991).

Due to the complex structural geometry of Lake Tanganyika, some areas are protected from the influx of marginal watersheds and have been found to be accumulating autochthonous pelagic sediment at a very slow rate. One such area is the Moba-Kalya Horst, a sub-aqueous structural platform at the center of the lake, at the base of the Mahale Mountains. Previous coring on the platform has determined sediment accumulation rates of 0.1 to 1.0 mm/yr. (Zalifi and Eagle, 2001), with laminated sediments ideal for paleoclimate studies (Zalifi and Eagle, 2001). Other regions of the lake have similar sediment accumulation rates or higher rates, yet those sites are located in areas of erosion and bioturbation (Tiercelin et al., 1991). In 2004, a new suite of piston cores was collected to test the vertical extent of fossil diatom preservation and to compare core data to other studies in the area and region. This study addressed the following questions: Are climate shifts and Late Glacial Maximum to Holocene trends that are evident at a mid-lake site in the Kalya region similar to the changes recorded at the southern and central region of the lake? Is there evidence from changes in fossil diatom populations from Kalya for lake-level changes during the Late Pleistocene and Early Holocene? Does the data signal rapid climate changes that are synchronous

with the Northern Hemisphere? Is the Moba-Kalya Horst a good target area for a long-term drilling project? To answer these questions, micro-fossil data from Core NP04-KH3 was analyzed and compared to previous coring records of Late-Pleistocene/Early-Holocene climate variability recorded by changes in micro-fossil assemblages in Lake Tanganyika lacustrine sediments.

Previous Work

In 1987, Hayberyan and Hecky used fossil diatom evidence, along with chemistry and sedimentology from two Kullenberg piston cores from 440 meters water depth at the southern end of the lake to determine that Lake Tanganyika experienced late Pleistocene low stands and shifts in climate and lake level during the Holocene. The authors developed a sequence of biozones from the diatom data that indicate shifts in lake conditions, and thus climate. This climate history includes low lake levels of -350m below present during the Last Glacial Maximum, as estimated by the increase of periphytic diatoms and sponge spicules at the coring site, a wet and turbulent early Holocene, and a drier late Holocene with less stable water column and more turbulent mixing.

In core T2, 10.60 meters of lacustrine sediment was recovered, which Hayberyan and Hecky (1987) divided into 4 separate bio-zones (Zones A-D) according to the changes in diatom taxonomic dominance. Zone A was further subdivided into sub-zones A1-A4. Sub-zone A1, which begins at the base and was radiocarbon dated to 15,900 +/- 600 B.P., showed a dominance of *R.gibberula*, considered an epilithic benthic diatom, and *S.astraea*, a planktonic diatom, which continued up-core into sub-zone A2 in which the significant

appearance of *S.fullebornii*, an epipelagic benthic diatom, began at around 8.90 meters down-core. The authors correlated Zone A with cool, arid climate conditions previously recorded for Tropical Africa at that time. In sub-zone A3, *Surirella fullebornii* is scarce, and the dominance continues of *Rhopalodia gibberula* and *Stephanodiscus astraea*. The base of sub-zone A3, at around 7.50 meters down-core is radiocarbon dated to 14,030 +/- 180 yr B.P. and ends 6.80 meters down-core (Haberyan and Hecky, 1987).

S.astraea overwhelmingly dominated sub-zone A4, from 6.80-4.60 down-core, yet was intermittently replaced by the planktonic diatoms *Aulacoseira spp.* and *Nitzschia spp.*, indicative of a change in mixing. *S.astraea* is indicative of a very stable water column, shallow mixing and low Si:P supply ratios, whereas *A.granulata* outcompetes other diatoms, such as *S.astraea*, when there is abundant silica and high turbulent surface water conditions and deep mixing (Kilham 1986). The top of sub-zone A4 is radiocarbon dated to 9900 yr B.P. and represents a change to complete dominance of *Aulacoseira granulata* in Zone B, from 4.60-2.40 meters down-core. The transition of Zone A to Zone B is correlated with a climate transition from cool, arid to warm, moist conditions. The upper extent of Zone B was estimated to date to around 5200 yr B.P., the mid-Holocene, when a transition from a wetter to more arid climate regime occurs (Hayberyan and Hecky, 1987).

Fluctuations in the water level of Lake Tanganyika during the late Pleistocene and early Holocene were studied by Gasse et al (1989), using diatom assemblages from two diatomaceous cores, also from the southern end of the lake.

They concluded that lake level fluctuations were correlated with changes in global sea level variations and ice volume, and were in phase with African lakes north of the equator that are linked to the Milankovitch cycles. Core MPU XII, a 10.13 meter core from 422 meters water depth contained a total of nine diatom biozones in three main stages, that were linked to changes in lake levels from the past 40 kyr B.P. (Gasse et al 1989). Stage II (21,700-12,700 ^{14}C yr B.P.) biozones indicated very shallow water conditions due to the abundant appearance of periphytic diatoms such as *Rhopalodia spp*, *Surirella fullebornii* and *Gomphonema clevei* in association with sponge spicules and phytoliths. The authors also indicate that a positive water balance oscillation ($P > E$) occurred around 14,500 ^{14}C yrs B.P. with the sudden appearance and overall dominance of planktonic diatoms.

Stage III in Core MPU XII indicates deep water conditions from 12,700 ^{14}C yrs B.P. to the present, with a perennial stratification from 12,700-10,600 ^{14}C yrs B.P. as evidenced by the increased presence and dominance of the planktonic diatom *Cyclotella*. From 10,600 to ~5000 ^{14}C yrs BP, the dominance of the planktonic diatom *Aulacoseira* indicates deep mixing possibly due to increased upwelling.

In 2003, a 9.5 meter lacustrine sediment core was collected from the Kavala Island Ridge at the north end of the Mahale Mountains, a subaqueous structural platform at the center of Lake Tanganyika (Scholz et al 2003). Core T97-52K contained approximately 100K years of sediment, of which the first 28k years recorded the presence of diatoms. The author's diatom analysis indicated

similar findings to those made by Hayberyan and Hecky (1987) in core T-2 from the southern end of the lake.

Scholz et al (2003) observed transitions in diatom assemblages in which a shift in genera dominance was recorded. The genus *Rhopalodia* was dominant at ~14.5 ky, whereas the genus *Stephanodiscus* dominated at ~13 ky, followed by *Aulacoseira* at ~10 k yr. The genus *Aulacoseira* continued dominance until ~3 ky when it was dominated by the genus *Nitzschia*. The authors also noted two peaks in the dominance of benthic diatoms at 14.5 ky and 22 ky. Furthermore, an abundance of benthic diatoms, sponge spicules and phytoliths, indicative of shallow water levels, was recorded for the time between the two benthic diatom peaks of 14.5 and 22 ky in which lake levels may have been 350 meters lower than present (Scholz et al 2003).

In 2004, core NP04-KH-1K, a 5.34 m Kullenberg piston core, was extracted from the Kalya Horst region of Lake Tanganyika at 303 meters water depth (Steinkamp and Russell 2004). Results of the diatom analysis were very similar to the findings of Hayberyan and Hecky (1987), and Scholz et al (2003), and the results of this study. An overall dominance of the genera *Stephanodiscus* was recorded prior to ~11 k yr yet shifted to alternating dominance of *Stephanodiscus* and *Aulacoseira* following that time period until an overall dominance of *Aulacoseira* occurred ~10 ky B.P.

Methods:

Study Site:

Lake Tanganyika is the second deepest lake in the world and the largest lake in the East African Rift Zone. Because of its size, depth and age, it is considered to be an unparalleled terrestrial archive of climate change in the African Tropics (Hayberyan and Hecky 1987). The lake trough is coupled to the western arm of the East African Rift Zone, which extends from Afar to Mozambique. The lake is approximately 700 km long from north to south and 50 km wide from east to west and is bordered by tilted and metamorphosed Precambrian crystalline blocks (Tiercelin et al 1988) (Figure 4).

The existing structural geometry of Lake Tanganyika consists of a basin bounded by high relief as the result of long-term extensional faulting (Ebinger, 1989). Large, subaqueous horsts bounded by half-grabens are the dominant structures within the basin and are of high enough relief and distance from terrestrial stream inputs that only fine grained autochthonous sediments accumulate on their subaqueous surface. Streams that drain into the lake along the border faults exhibit longitudinally short, but vertically steep profile gradients that carry coarse clastic sediments to the littoral zone of the lake (Figures 4) (Sander and Rosendahl, 1989). These sediments are seasonally displaced laterally by channeled trade winds that produce long-shore currents, yet may be gravitationally forced down- slope into the basin by turbidity currents (Cohen et al 1993). The large overall size and steep sided geometry of the lake basin confines coarse

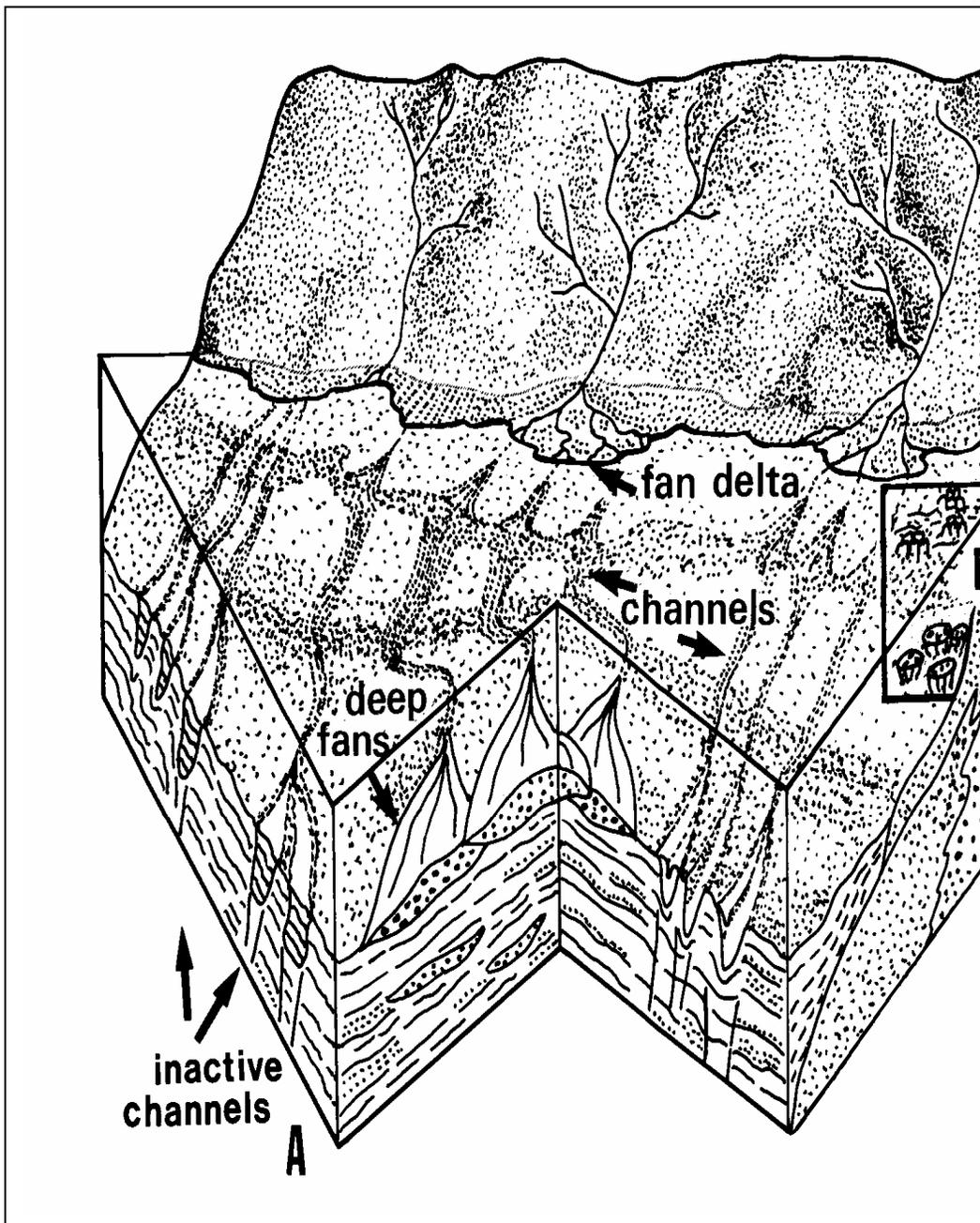


Figure 4. Tiercelin clastic model for Lake Tanganyika. Steep, short longitudinal streams flow into the lake and drop heavy clastics at the littoral zone, which are carried laterally by wind-driven currents. Fine sediments may move by interflow, and heavy clasts may move by turbidity flows. From Tiercelin, (1988).

sediments to the margins of the lake. Fine-grained pelagic sediments, in the form of clay-sized particles may reach the center of the lake and accumulate with very slow sedimentation rates. Biogenic oozes formed from the accumulation of planktonic and benthic diatom frustules and other biological sources may be integrated with the pelagic clays that slowly rain down on the lake bottom portions isolated from terrestrial inputs. These fine grained sediments have been shown to reach the sub-aqueous horsts in the center of the basin that accumulate sediments at rates as low as 0.1mm/yr., which contrast with much higher sedimentation rates (>1 mm/yr) that occur throughout a greater portion of the lake (Cohen et al 1993).

Changes in sedimentation rates, erosion and bioturbation, as the result of lake level changes, have been determined through piston and gravity coring of various subaqueous sites throughout the lake that are targeted by seismic reflection profiles (Hayberyan and Hecky 1987). Geochemistry, provenance and diatom analysis from these cores have been used to determine paleo-lake levels induced by climate and tectonic forcing on the basin. Researcher have encountered difficulties in geochronology and integration of structural/sedimentary processes due to limits in radiocarbon dating, as well as techniques of dating available, and location of coring sites in dynamic sedimentary environments (Cohen et. al. 1993). Coring of undisturbed sites in 1993, within the lake basin, have revealed clues to a more complete and accurate portrayal of the tectonic history and control on sedimentary regimes (Cohen et al 1993).

Extensional faulting of the western rift arm is estimated to have begun some time in the mid to late Miocene based on extrapolation of modern sedimentation rates within the lake basin, as well as seismic reflection profiles, although faulting may have initiated in the early Miocene (Sander and Rosendahl, 1989; Ebinger 1989). Some researchers have combined the methods mentioned above by using RSRM (reflection seismic-radiocarbon method), in which radiocarbon dates are taken from short cores and correlated to seismic reflection data to basement levels (Cohen et. al. 1993). This method has produced estimates of the initial formation of Lake Tanganyika beginning between 9-12 my BP, and the center of the lake is older than the northern and southern basins (Cohen et. al. 1993). According to this data, and previously addressed by Sander and Rosendahl (1989), the geometry of the lake consists of a crescent-shaped planview of the rift showing the center of the crescent as the zone of maximum subsidence, which would produce greater age, higher vertical displacement, and varying sedimentation rates compared to the northern and southern ends. According to Sander and Rosendahl (1989), the border faults at the center of the crescent may endure over 8 km of throw, while the ends of the crescent would exhibit horizontal motion in the form of strike-slip. The authors also note that there seems to be a correlation between the amount of subsidence and the height of rift mountains at the border fault areas. At the center of the lake basin, the rift mountain rises abruptly over 2 km above lake level, thus the highest uplift coincides with the highest subsidence. Further, this location enhances the productivity of drainage basins to deliver sediments into Lake Tanganyika (Sander and Rosendahl 1989).

Over time the geometry of the basin has shifted with the formation of half-grabens and shifting of syn-rift blocks that have re-oriented sediment deposition zones and rates. Some basins that were directly influenced by border fault drainage patterns may have become isolated from those faults and/or affected more by intra-basinal blocks that redirected sediment placement (Sander and Rosendahl 1989; Masse 1988).

Finally, tectonics set the foundation for changes in lake level and sedimentation rates, but changes in climate control rates and magnitude of sedimentation and lake level changes within the basin. Warm, wet climate regimes raise lake levels, which change sediment deposition patterns and sedimentation rates, as well as grain size, nutrient influx, and location of littoral zones. Transgression of littoral zones occurs during lake level rise which may be indicated in sediment cores as an increase in planktonic diatom species and decrease in littoral or benthic diatom species. Dry, cool climates have an inverse affect. Lake levels drop, evaporation and salinity increase, sediment and nutrient influx decreases production decreases and littoral zones regress towards the basin center (Cohen 2003). Windy conditions force tilting of the lake thermocline, which induces upwelling and increased phosphorous influx from the hypolimnion to the epilimnion (Figure 5). Further, changes in the Inter-Tropical Convergence Zone (ITCZ) location force shifts and strength in wind speed, direction and intensity, which control upwelling (Trauth et al 2003). A shift of the ITCZ to the north of Lake Tanganyika causes winds to move from south to north

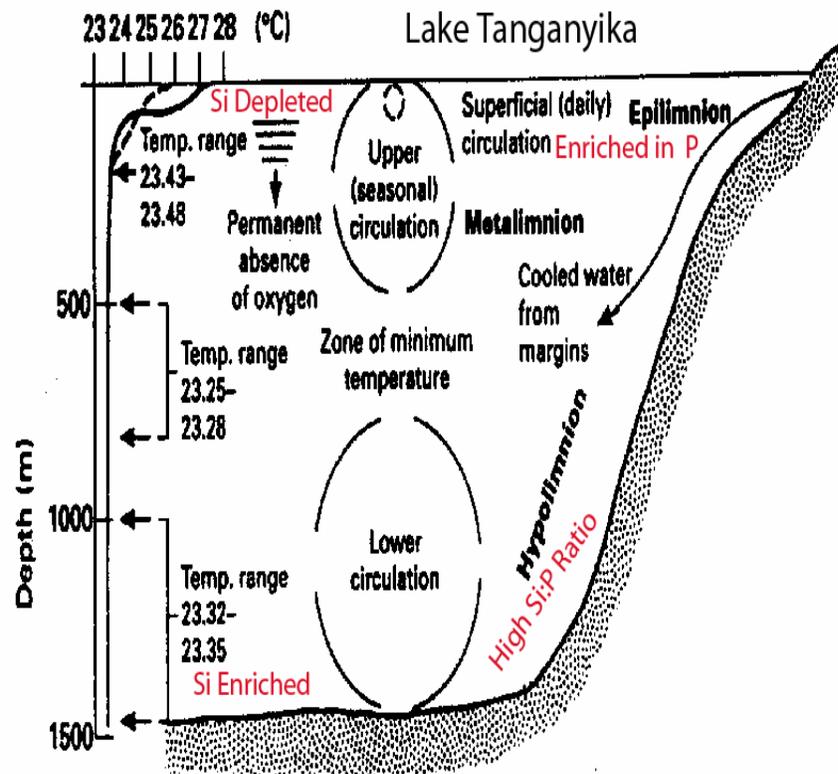


Figure 5. Idealized cross-section of Lake Tanganyika showing vertical temperature profile through epilimnion, metalimnion and hypolimnion. During upwelling events, the hypolimnion is mixed with the metalimnion and epilimnion by deep mixing and tilting of the thermocline. In a stratified lake setting, the epilimnion is enriched in phosphorous and depleted in silica (low Si:P ratio). The hypolimnion is enriched in silica and depleted in phosphorous, thus during deep mixing/upwelling, the epilimnion has a high Si:P ratio. (Modified from Gasse 1989).

longitudinally across the lake surface, which forces a tilting of the thermocline to the north and upwelling in the south and central portion of the lake.

In summary, Lake Tanganyika, as the result of long term extensional forces, is the second deepest lake in the world-the southern basin is 1470m deep. Various models have been developed for the tectonic history of the lake basin. These models are summarized by Masse (1988) in which three stages of development for the lake is established. The first stage consists of initial extension followed by the development of low subsidence basins with fluvial sedimentation. The second stage involves the disruption of fluvial systems by tilted blocks and the formation of noticeable topographic features. Today, Lake Tanganyika falls into the third stage of tectonic development in which large blocks are substantially subsided and border faults exhibit high relief. During this stage, vertical movement dominates horizontal displacement (Masse 1988).

Changes in sedimentation within the basin are thus established by changes in the formational stages of the rift. In the first two stages, fine sediments of sand, silt and clay predominate, yet in the third stage coarse sediments are introduced into the basin due to the formation of steep-angled, longitudinally short stream channels that carry large bed-loads to the basin and produce relatively large deltas (Masse 1988). Changes in lake levels due to climate forcing may pro-grade deltas deeper into the basin, or aggrade deltas during lake level rise (Ebinger 1989). During aggradation and pro-gradation of deltaic sediments, the angle of repose for the sediments may be breached, resulting in avalanches or turbidity currents that carry coarse sediments into the basin (Cohen et. al. 1993).

According to Ebinger (1989), the Western rift has undergone less than 10 km of horizontal extension and roughly 3 km of vertical motion. Fault geometry of the border faults consists of normal faults that probably cut through the crust and end as listrics. As discussed above, stage three of Masse's (1988) tectonic evolution would involve initial large vertical movement along the high angle of the footwall followed by decreasing vertical and increasing horizontal motion as the down-thrown block reached the listric portion of the fault. Further tilting of the blocks and subsequent synthetic and antithetic faulting results in a horst and graben morphology (Ebinger 1989). Sedimentation rates would change in graben basins, yet remain the same over long periods of time on subaqueous horsts, as long as lake levels remained above horst platforms (Cohen et. al. 1993). These characteristics make isolated horsts promising locations for coring, because long term sedimentation patterns and tectonic histories could be archived on these isolated horsts, which could be located using seismic reflection profiles (Cohen et. al. 1993; Haybryan and Hecky 1987).

The Coring Site:

The Moba-Kalya Horst is a sub-aqueous structural platform at the center of the lake at the base of the Mahale Mountains (Figure 6). The horst is a topographic high relief accommodation zone separating two opposite-polarity half grabens (Helfrich et al 2004). The distance from shore and depth as well as vertical relief have isolated and protected the Moba-Kalya Horst from low lake

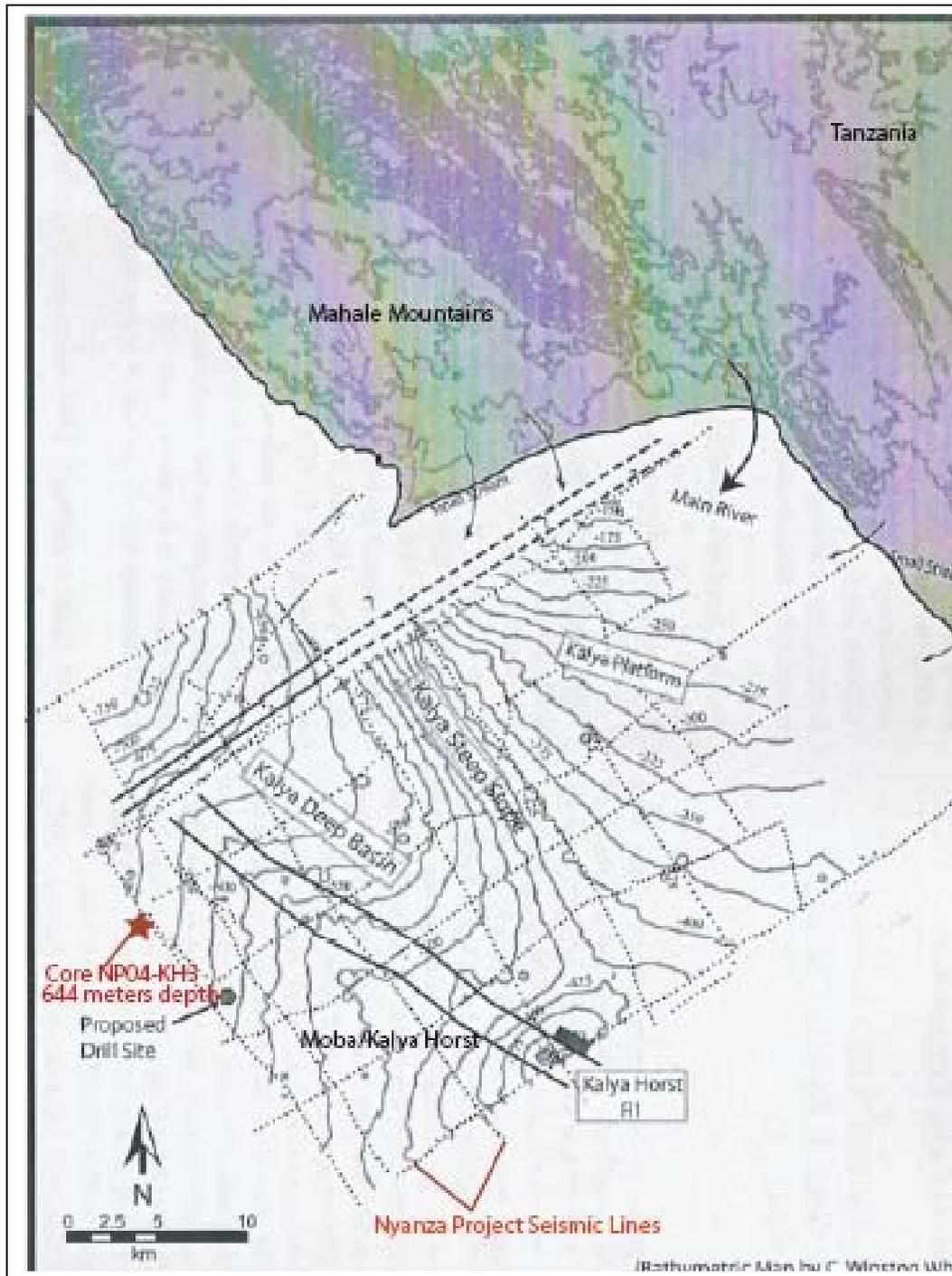


Figure 6. Bathymetric map of Moba-Kalya Horst region with overlying seismic reflection survey lines and coring site. Note that the core site is protected from the influx of allochthonous sediments by Kalya Deep Basin and half-graben. Proposed deep drilling site lies just southeast of the coring site in stable sediments. From Helfrich et al 2004.

stands and terrestrial sediment inputs, such as fluvial and turbidite deposits (Steinkamp and Russell 2004). The coring site is located on the west aspect of the Kalya Horst at 644 meters water depth at the terminus of seismic line NP04-06. At the present lake level, the closest shoreline, the southwestern base of the Mahale Mountains, is approximately 30 km from the coring site. The location of the coring site is protected from the influx of allochthonous material from marginal watersheds of the Mahale Mountains by the ridge of the Kalya Horst, the Kalya Deep Basis and Kalya Steep Slope. Sedimentation rates for the coring site have been estimated to be between .1-.6mm/yr, or 30-60 cm/kyr. Lacustrine sediments at the site consist of alternating biogenic oozes and sapropelic clays.

Field Methods: *Seismic Survey*

Prior to conducting piston and gravity coring of the Kalya horst, a total of thirty lines of multi-channel reflection seismic data were acquired to map the bathymetric features of the area and to pinpoint target areas for coring (Figure 7). Seismic reflection data were collected in a seven by seven line N/S and E/W grid approximately 4 to 7 km spacing (Figure 6 and 7).

Speed, position and bearing were recorded using a Garmin GPS II+ system, which was correlated to probe lines P83.84 and P83.78 (Rosendahl et al. 1987). Seismic data was acquired using an S.I.G. built streamer with 6 channels and 8-meter takeouts (lines with attached hydrophones). The first hydrophone was positioned 60 meters astern of the boat, and 70 meters behind the GPS antenna. The source used was a fish type sparker redesigned for use in fresh water, built by S.I.G. operating with 1000 joules and delivering 4000 volts.

Arrivals were recorded on a DELPH computer between 0 and 1500 hz frequency. Data from channel 3 were then scaled and printed by an Oyio 612 printer on 12 inch thermal paper. Interpretation of the data focused on locating terminating and crossing reflectors, as well as changes in reflector characteristics (Helfrich et al 2004).

Core NP04-KH3 site is located at the western terminus of Seismic Line NP04-06 (See Figures 6 and 7).

Field Methods: *Coring*

During an eight-day cruise in July 2004, aboard the 30-meter Congolese freighter ship “Maman Benita”, core NPO4-KH3 was extracted from the lacustrine sediments of the Moba-Kalya Horst in Lake Tanganyika using the Kullenberg piston coring method (Figure 8). The location of the core was recorded as 29.83^o Longitude, 6.71^o South Latitude, at 644 meters water depth. Utilizing an electric winch attached to the deck of the ship, the 9-meter long, 6 cm diameter Kullenberg piston core, equipped with a roughly 220 kg lead head weight, was deployed and returned on a 1000-meter steel cable guided by pulley systems attached to a steel crane (Figure 9). The Kullenberg piston core shafts were lined with 3-meter clear plastic core liners secured together and held in core by an aluminum core-catcher. Once the piston cores were returned from deployment and sediment extraction, they were laid to rest on the deck of the ship. Core liners were then systematically removed (following removal of the core-catcher) beginning with the distal end of the core (distal from the core head weights and sediment/water interface), cut into roughly 1.5-meter sections,

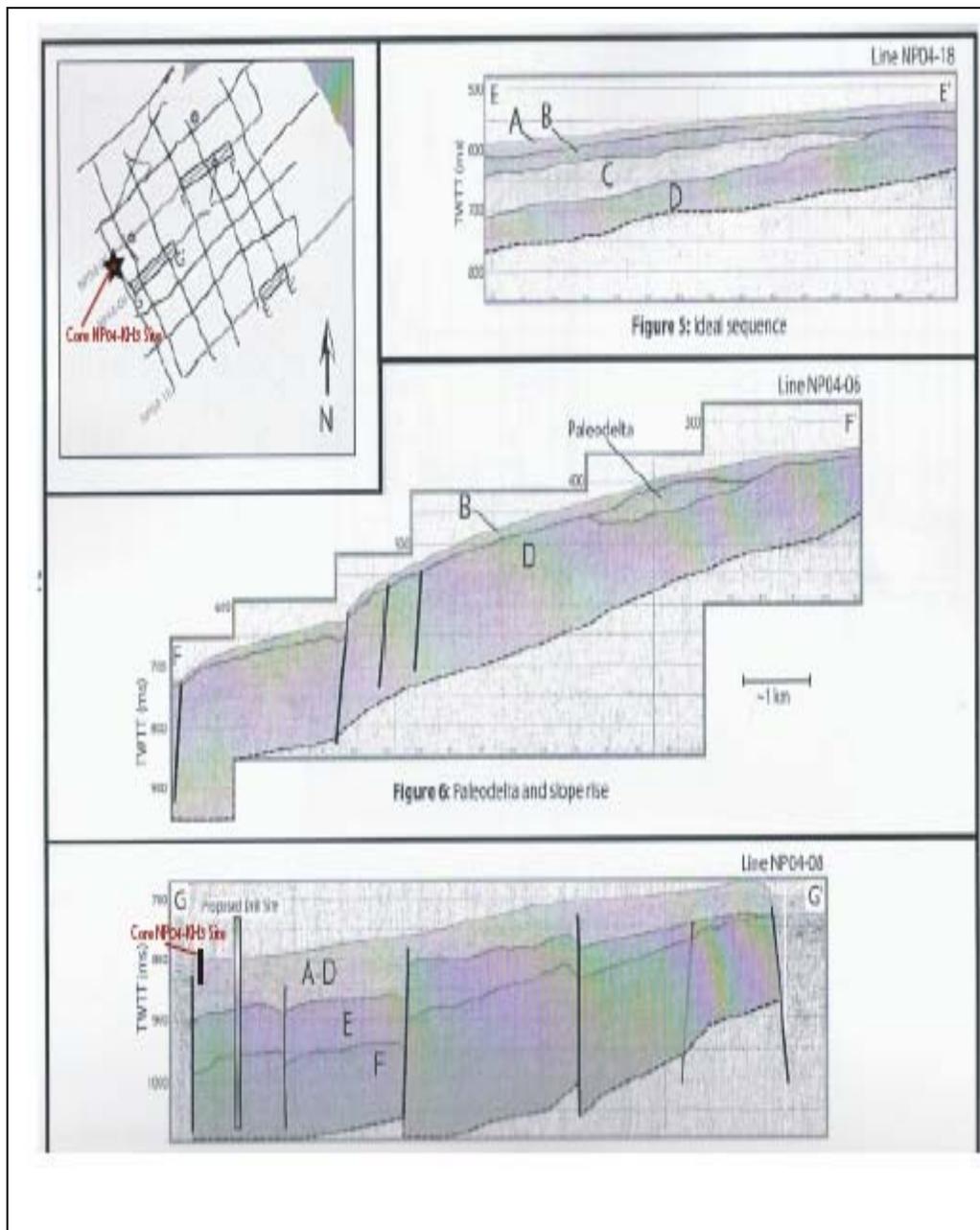


Figure 7. Seismic Reflection profiles for the Kalya Horst region. Core NP04-KH3 was extracted from the terminus of Survey Line NP04-06 which is displayed in profile G-G'. Actual length of core is exaggerated for visual purposes. See Figure 8 for a planview map of seismic lines and bathymetric map of the Kalya Horst. (Revised from Helfrich et al, 2004).

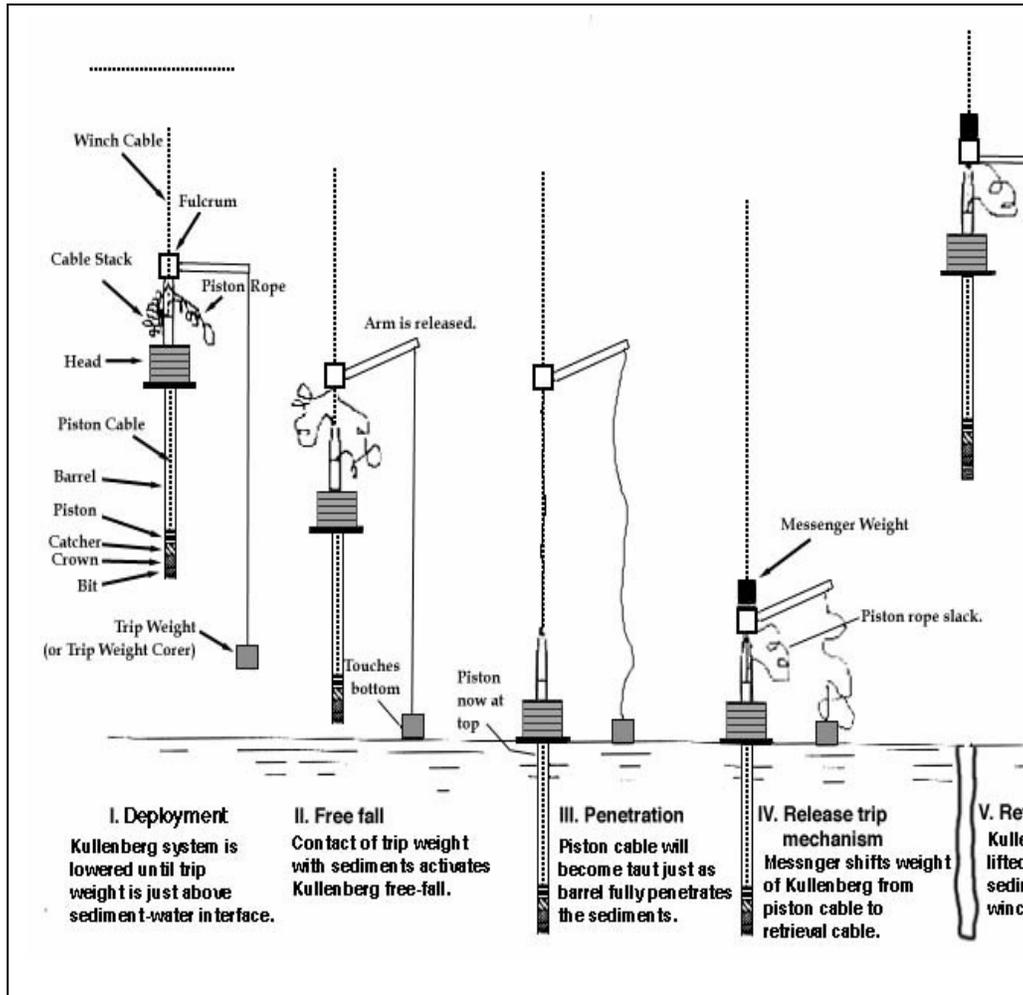


Figure 8. Cartoon depicting the Kullenberg Piston coring method as used to obtain Core NP04-KH3 on the Kalya Horst. (Copied from Kullenberg.com web page).

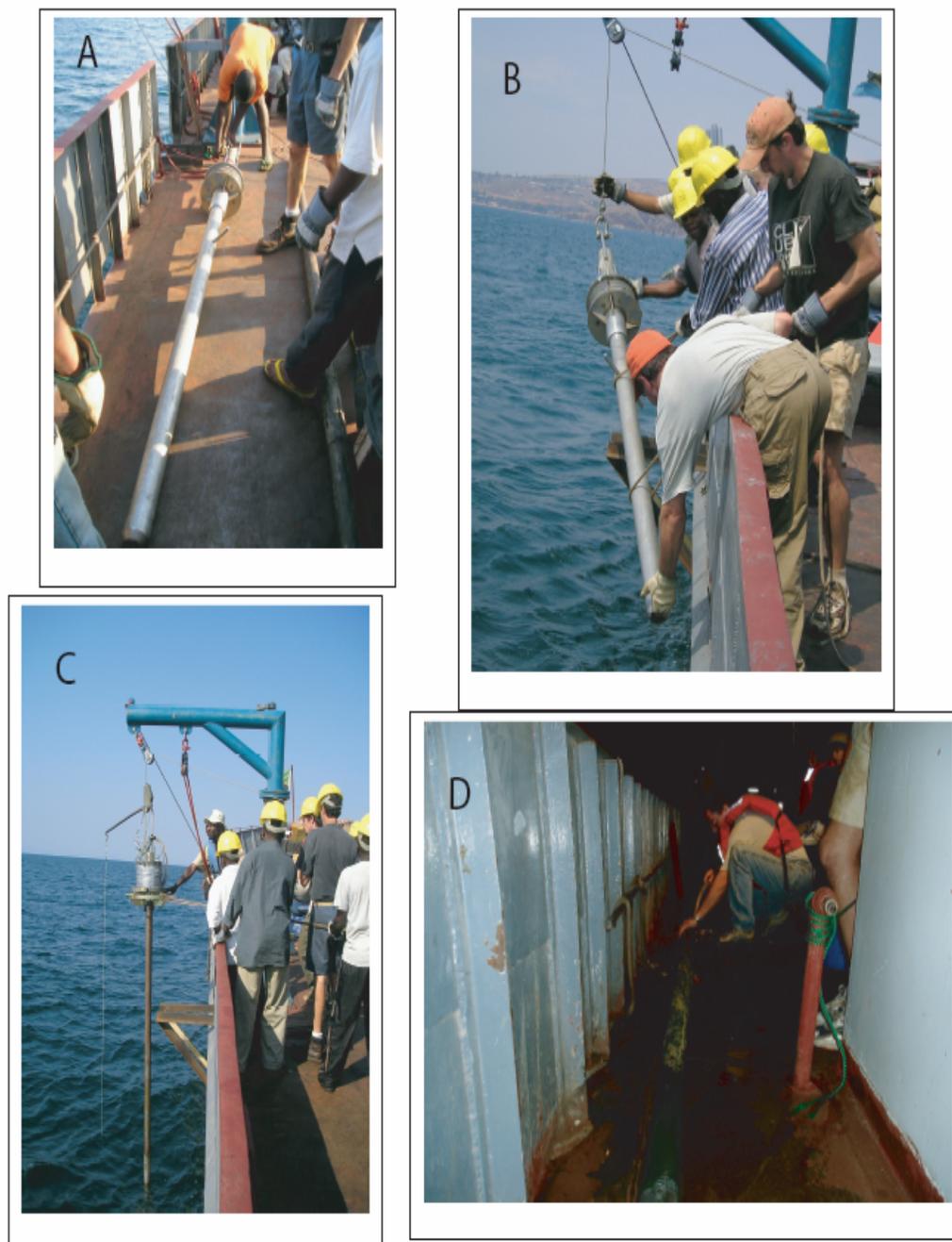


Figure 9. Kullenberg piston coring and recovery of Core NP04 -KH3, from 644 meters water depth at the west aspect of the Kalya Ridge. A)Kullenberg core fitted with 220 kg head weight. B) Core lifted by hand and lowered to crane. C) Kullenberg ready for deployment with trip weight.D) Core recovered and placed on deck for cleaning and core-liner removal. Steinkamp 04

plugged with floral foam and capped with plastic core liner caps. The core sections were then labeled with the appropriate project name, number and year, location, core number and type, section number and arrows marking direction to top of core (the sediment/water interface). The cores were then safely stored for shipment to the United States.

Laboratory Methods: *Sampling*

Sampling of the Kullenberg piston core NP04-KH3 was systematically conducted initially at 8 cm intervals throughout the length of the core. Following analysis of diatoms from samples at 8 cm intervals, higher resolution sampling at 1 cm intervals was conducted for a section of the core (from 199 to 351 cm down-core). Glass slides were made for samples from each centimeter, though initial diatom counts were made at 2 cm intervals for the entire section from 199 to 351 cm down-core. Higher resolution diatom counts were then made at 1 cm intervals from section 221 to 271 cm down-core. All samples consisted of approximately 20 mg of lacustrine sediment from the cores extracted using a 1cm wide metal spatula for each sample. Each sample was placed directly into a 15 ml plastic centrifuge test tube for storage until slide preparation. A total of 184 samples were removed for analysis, of which 116 were used for analysis.

Laboratory Methods: *Slide Preparation*

For slide preparation, 5-10 ml of (30%) H₂O₂ (hydrogen peroxide) was added to the sediment sample in the 50 ml centrifuge test tube and allowed to react for 5 minutes. Next, test tubes were placed in a glass beaker and allowed to boil and further react for 60 minutes on a medium heat hot plate, then neutralized with

5-10 ml of distilled H₂O. Samples were allowed to settle for 8 hours, then H₂O₂/H₂O solution was pipetted off, and 12 ml of distilled H₂O was added and the sample was again allowed to settle for 8 hours. No centrifuging was conducted. Final pipetting was then conducted at the end of this cycle.

Next, the sample was placed in a glass beaker and diluted with distilled H₂O to a volume visually desired for optimal diatom population counts on slides (usually a slightly cloudy solution is desired). The solution was pipetted off after mixing, and a 1 mL sample was placed by pipette onto a 22x22 mm glass cover slip and allowed to dry overnight. Coverslips were mounted onto glass slides with Permount mounting medium heated on a hotplate. Slides were left to cool, extra Permount was removed, and the slides were cleaned and filed until identification.

Laboratory Methods: *Micro-Fossil Counts*

Diatoms, grass phytoliths and sponge spicule counts were conducted on a Zeiss binocular microscope with 1000x (10x100) magnification in oil immersion. Counts were made in top to bottom transects across each slide until a minimum count of 500 diatom frustules was recorded for each slide. Counts were conducted at the species level based on taxonomic literature by Cocquyt (1998), Gasse (1986), and Barber and Haworth (1981) recorded as quantity and percentages. Additionally, counts were conducted on all slides for the presence and number of grass phytoliths (Figure 10) and sponge spicules.

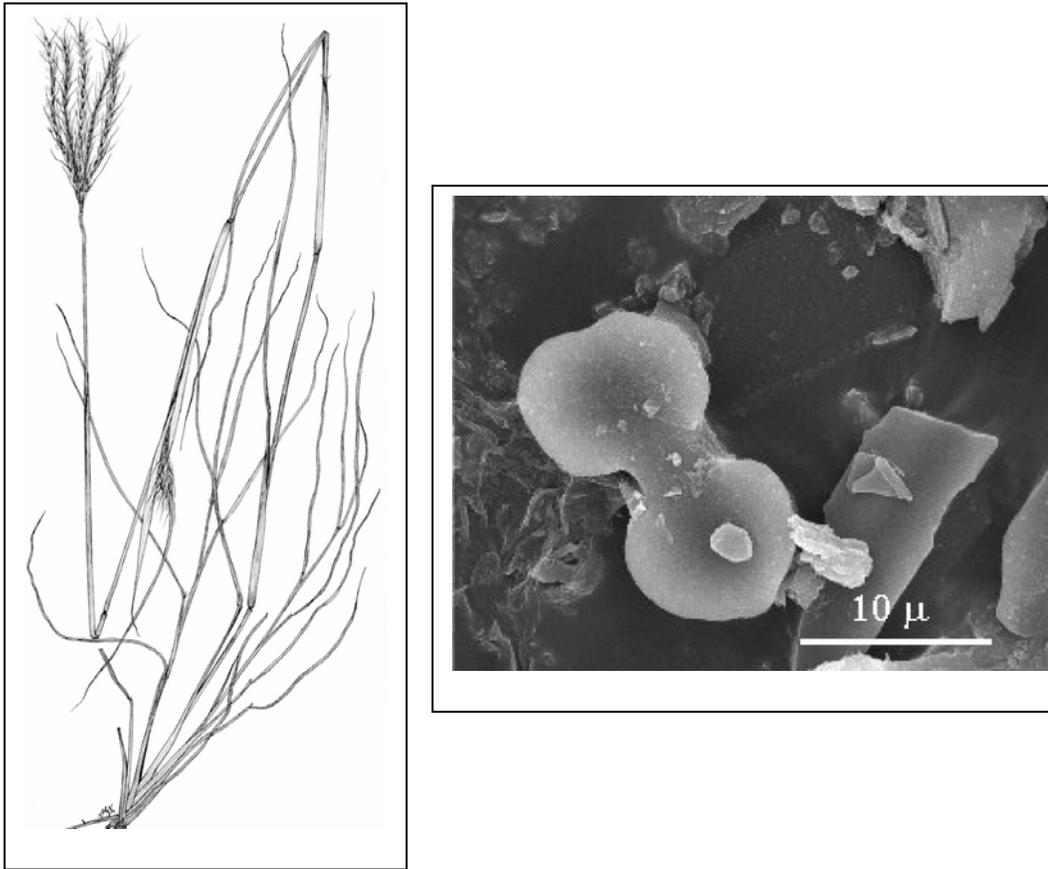


Figure 10. From left to right. Example of the species *Bothriochloa edwardsiana*, a native grass of East Africa. SEM of a “dumbbell” shaped grass phytolith associated with *Bothriochloa edwardsiana*, the dominant grass phytoliths in the micro-fossil assemblage of Core NP04-KH3. From Annals of Botany Company 2006.

Statistical Method: PCA

The results of the micro-fossil data analysis was further interpreted by conducting principal component analysis (PCA) on the diatom percentages calculated from the raw diatom counts, using SPSS version 13.0 software. Ordination was utilized on the correlation matrix in an attempt to standardize the species percentage abundances. The results of the analysis using raw diatom counts did not differ significantly from that of the results using percentages, and the method using raw counts indicated less variability, thus was not utilized.

Results:

Seismic Survey:

A total of thirty lines of multi-channel reflection seismic were acquired over an eight-day period to map the bathymetric features of the Moba-Kalya Horst region (Helfrich et al 2004). The results of the survey are shown in Figures 6 and 7.

Lithology and Chronology:

The stratigraphy of Core NP04-KH3 consists of massive silty clay bundles that change into zones of alternating diatom ooze and massive clay (Figure 11). A total of nine samples were recovered from Core NP04-KH3 for Radiocarbon Dating and age model development (Figure 12, Table 1). Results are shown in the age model for Core NP04-KH3 in which the sediment accumulation rate is 45 cm/kyr or 0.45 mm/yr in the post Last Glacial Maximum (LGM) linear regression (Russell 2005).

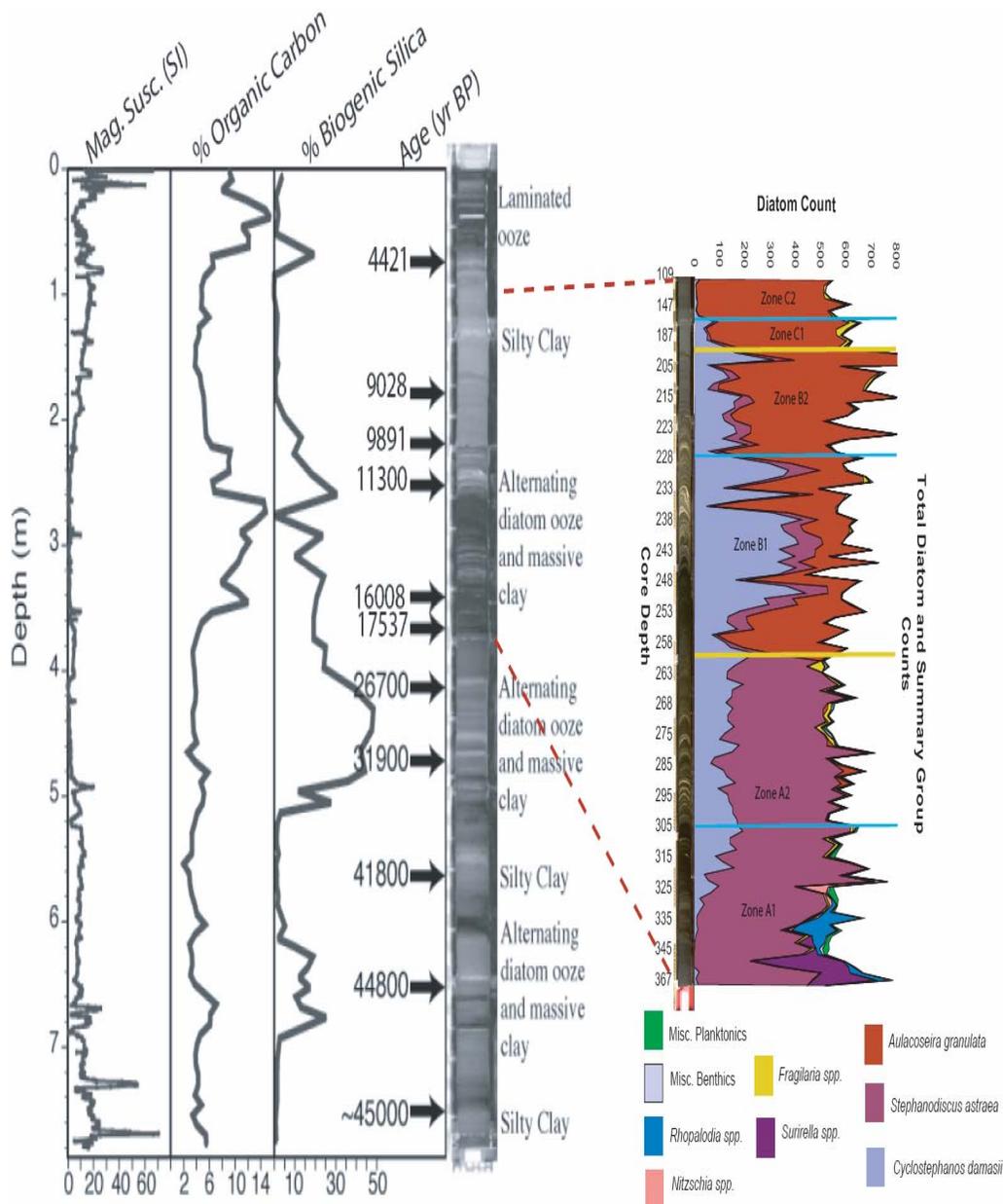


Figure 11. General Lithology of Core NP04-KH3 with low-resolution magnetic susceptibility, % organic carbon and % biogenic silica. The section of core analyzed for this study is shown as colored window offset to right, which depicts diatom counts within biozones attributed to core depth. Note the peaks in biogenic silica and % organic carbon and drop in magnetic susceptibility that correlate with arid periods in East Africa (i.e. Last Glacial Maximum at 16,000 calendar years BP, Younger Dryas prior to 11,300 calendar years BP, and Mid-Holocene at 4200 years BP). Left Graph by Russell 2004.

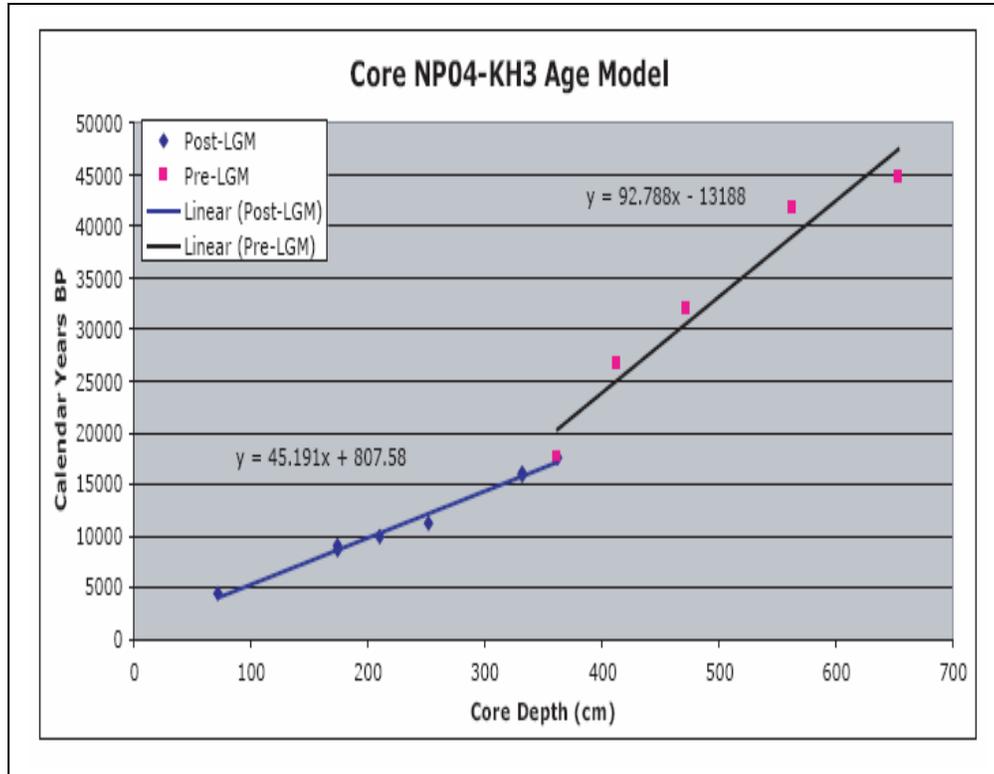


Figure 12. Age model for Core NP04-KH3 developed from 9 radiocarbon dates acquired from lacustrine sediments. A 50% reduction in the sediment accumulation rate or mass accumulation rate (MAR) occurs (from 93 to 45 cm/kyr) after the Last Glacial Maximum as lake levels rose during the African Humid Period from 15-5 kyr B.P. (From Russell 2004 pers. comm.).

Submitter Identification	Material	Age	Age Error	Res. corrected 14C age	KH3 Depth	calib Age	1-sig range	2-sig upper	2-sig lower	Ties
Lake Tanganyika NP04-KH3-I-93 cm Bulk OM	Bulk OM	4380	40	3980	72.5	4421	4514-4413	4565	4301	
NP04-KH1-III-91.0cm (wood)	wood	7838	51	8598	174	8598	8643-8545	8930	8458	KH3 II 84, KH4 IV 140
NP04-KH1-III-91.0cm (sed.)	bulk sediment	8135	51		174	9028	9237-9012	9267	9001	KH3 II 84, KH4 IV 140
NP04-KH3 Sect II dep 80	bulk sediment	9113	60	8813	210	9891	10146-9703	10154	9602	
NP04-KH3 Sect III dep 30	bulk sediment	10268	62	9968	252	11300	11552-11236	11913	11205	
NP04-KH1-IV-98.0cm (wood)	wood	13250	69	15925	332	15925	16161-15695	16405	14903	KH3 III 120, KH4 III 110
NP04-KH1-IV-98.0cm (sed.)	bulk sediment	13321	71	16008	332	16008	16245-15776	16491	15097	KH3 III 120, KH4 III 110
Lake Tanganyika NP04-KH3-III 140cm Bulk OM	Bulk OM	14650	70	14650	362	17537	17809-17281	18095	17036	
Lake Tanganyika NP04-KH3-IV-40 cm Bulk OM	Bulk OM	24600	170	24600	413	26700				
Lake Tanganyika NP04-KH3-IV-100cm Bulk OM	Bulk OM	28300	290	28300	473	31900				
Lake Tanganyika NP04-KH3-V-70 cm Bulk OM	Bulk OM	39400	500	39400	563.5	41800				
Lake Tanganyika NP04-KH3-VI-8 cm Bulk OM	Bulk OM	44500	760	44500	653	44800				
NP04-KH3-VI-25.0cm	bulk sediment	43200	1800	43200	770	43100				

Table 1. Kalya Radiocarbon dates and corrected ages used to construct the Kalya Age Model. From Russell 2004.

Micro-Fossil Counts:

A total of 71,234 diatom frustules, 2186 grass phytoliths, and 800 sponge spicules were counted from 116 glass slides from the 109 to 370 cm down-core section of Core NP04-KH3 (See Data Compact Disc attached to back cover).

From the total diatom frustules counted, a total of 23 genera and 90 species of diatoms was recorded. Of the 23 diatom genera, *Cyclostephanos spp.*, *Stephanodiscus spp.*, and *Aulacoseira spp.* dominated the fossil assemblage.

Total diatom counts for each slide ranged from a minimum of 507 to a maximum of 1870. Biozones were established by diatom species dominance.

Zone (Biozone) (i.e. Zone A) boundaries were determined by the dominant species, and subzones (i.e. Zone A1) were based on sub-dominant taxa.

Variations in the abundant (>33% of total diatom assemblage) planktonic genera *Cyclostephanos spp.*, *Stephanodiscus spp.*, and *Aulacoseira spp.* allow a division of the core into 3 biozones; Zone A, B and C from bottom to top of the core (Figures 13, 14, 15).

Biozones

Zone A is located at the basal end of the studied section of core NP04-KH3, from 370-256 cm. *Stephanodiscus astraea* dominates this zone, and indicates a general increasing trend down-core from the top to the bottom of the zone (Figure 16). Brief spikes in population increases by *R.gibberula*, *Nitzschia spp.*, and *S.fuellebornii* are noted, as is an increase in miscellaneous benthics, as well as an increase in the number of grass phytoliths and sponge spicules. The

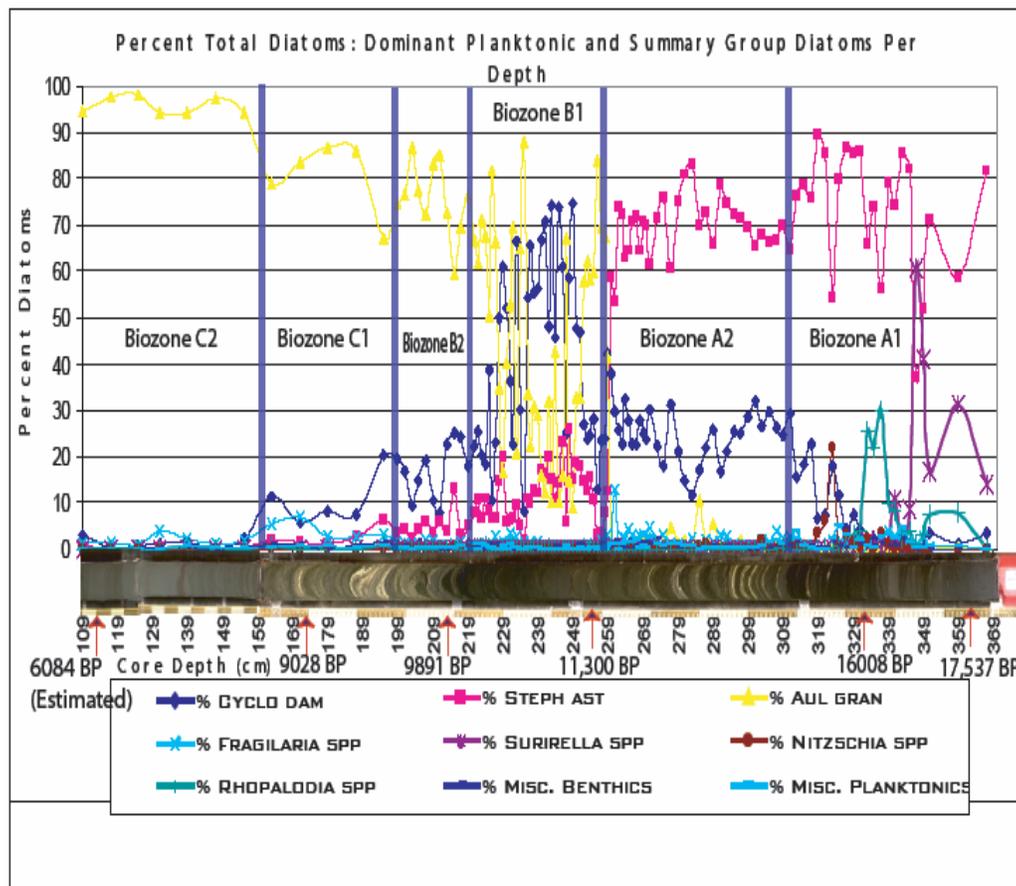


Figure 13. Percent Total Diatoms consisting of the dominant planktonic diatoms such as *S. astraea*, *C. damasii*, and *A. granulata*, and summary groups of all other diatom species. At the base of the graph is a photo of Core NP04-KH3 for visual comparison. Note the visual changes in sediment that correlate with changes in diatom species dominance. Dates below graph are calendar ages BP from corrected Radiocarbon ages. Age of 6084 BP is estimated from sediment accumulation rates. (Photo by Russell, 2004).

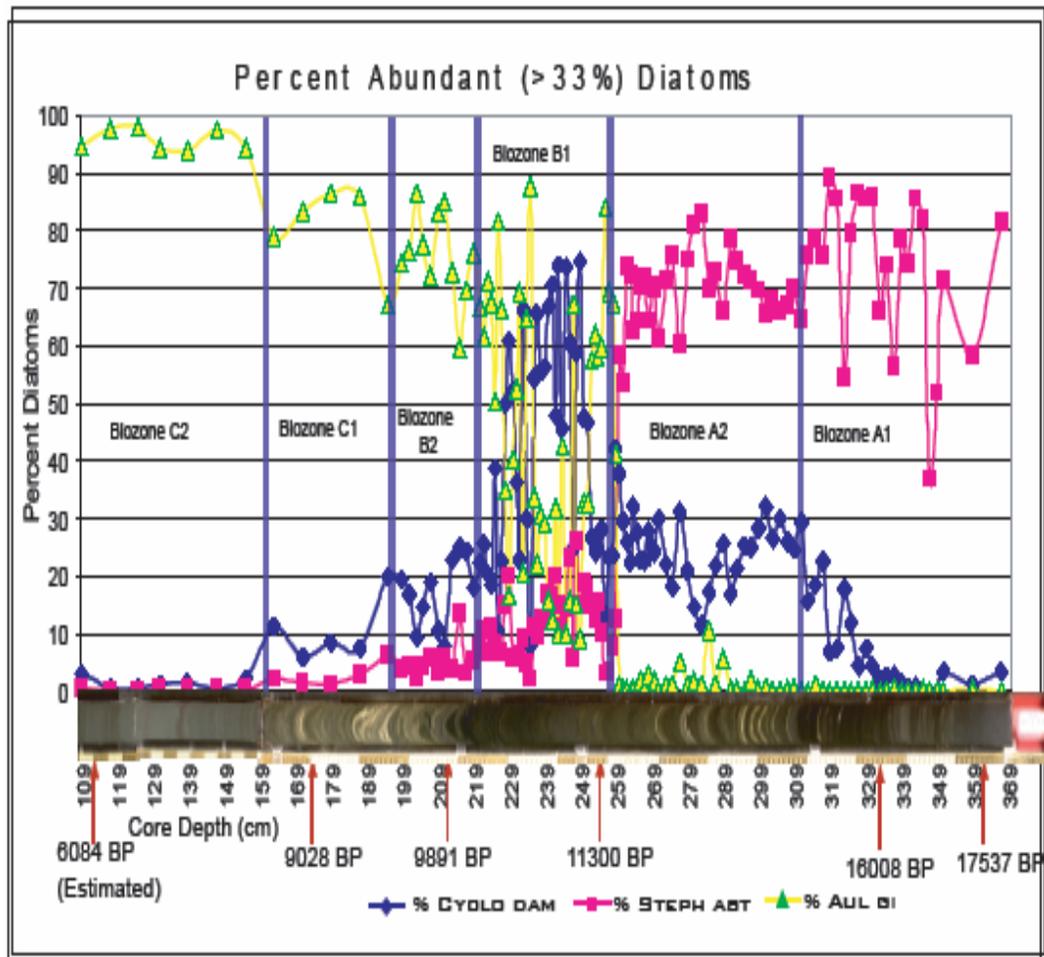


Figure 14. Graph of Percent Abundant Diatoms (>33%) of total diatom assemblage using Gasse 1986 population distribution method. Red arrows indicate location of radiocarbon samples collected (except age 6084 BP which is estimated using sediment accumulation rate of 45 cm/kyr).

Percent Rare (<1%), Uncommon (1-<5%) and Common (5-<33%) Diatoms

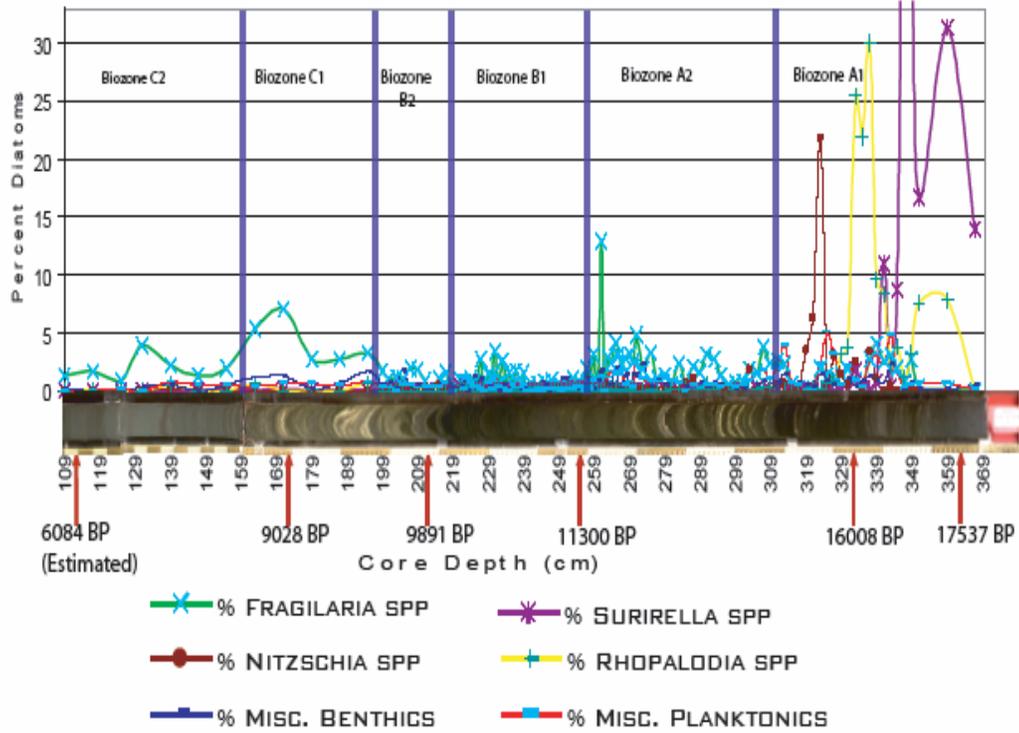


Figure 15. Graph of Percent Rare (<1%), Uncommon (1-<5%) and Common (5-<33%) diatoms using Gasse 1986 percent population classification method.

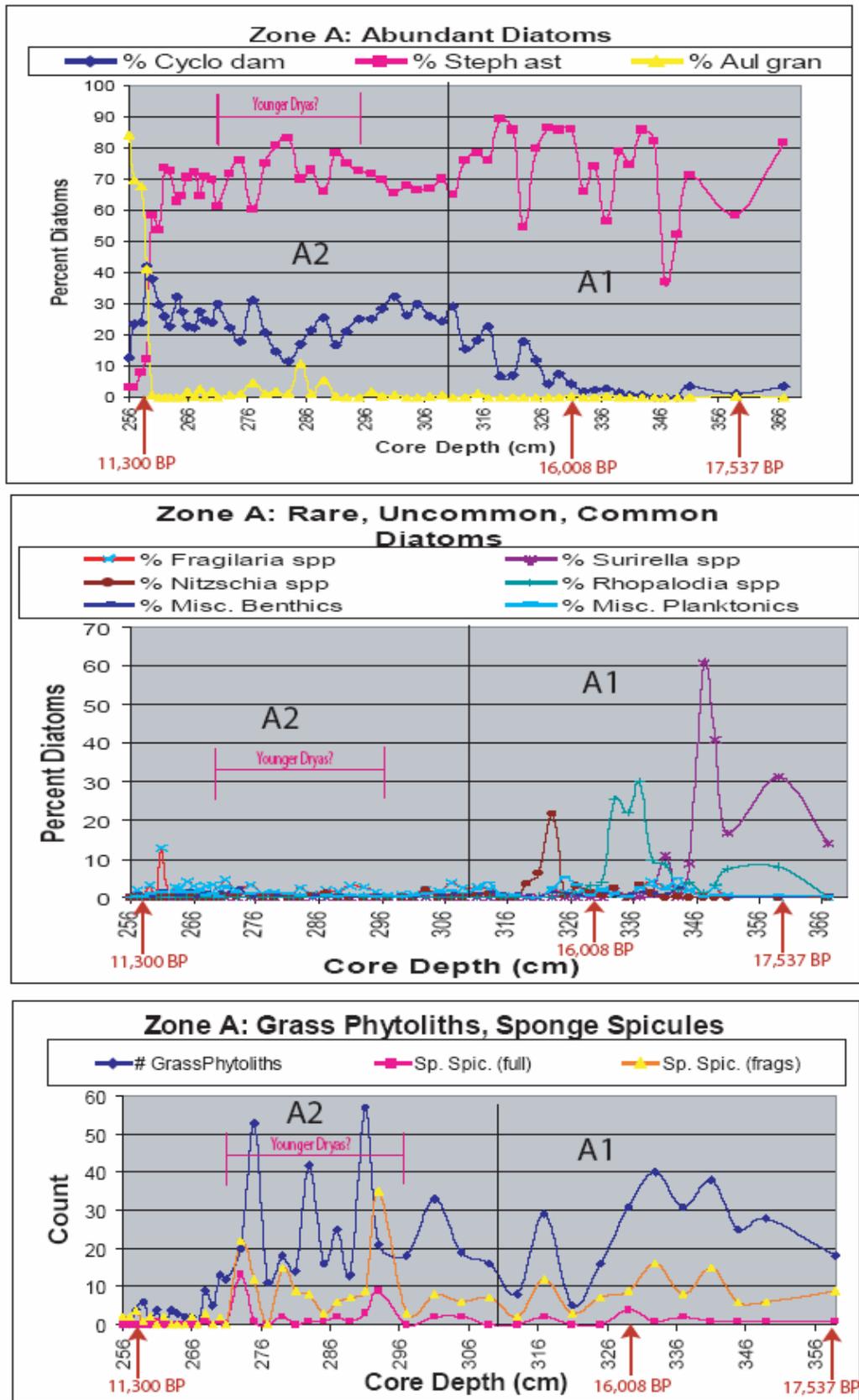


Figure 16. Zone A

highest counts for grass phytoliths and sponge spicules are found in Zone A1, with a dominant peak from 369-319 cm.

Zone A is sub-divided into Zone A1 and A2 (Figure 16). Zone A1, from 370 to 311 cm, shows a steady, though fluctuating dominance of *S.astraea*, and a sudden increase in *C.damasii* from the base of A1 to 311 cm. *S.fuellebornii* displays a local peak abundance from 370 to 343cm which correlates to an increase in miscellaneous planktonics, miscellaneous benthics and increased count in sponge spicules and grass phytoliths (Figure 16). From 343 to 330 cm (around 16,000 calendar years BP), *S.fuellebornii* is replaced by *R.gibberula* and continued high levels of sponge spicules and grass phytoliths counts. At 330 cm *R.gibberula* is replaced by *Nitzschia spp.* a well known planktonic diatom that makes an appearance only in Zone A1 and peaks only from 370 to 325 cm (17600 to around 16,000 calendar yr BP) down-core (Figure 16).

Zone A2, from 311 to 256 cm, is marked by a general increase in *S.astraea* and general decrease in *C.damasii* up-core from 311 to 280 cm (Figure 16). This trend reverses in the upper half of Zone A2 from 280 to 259 cm (from around 13,000 to 11,300 yr BP) in which there is a general decrease in *S.astraea* and an increase in *Cyclostephanos damasii*.

The lowest count for *C.damasii* in Zone A2 coincides with a sudden decrease in *S.astraea* and the highest count for *A.granulata* in this zone, occurring from 285-279 cm (around 13,000 yr BP). A notable increase in miscellaneous planktonics, miscellaneous benthics and *Fragilaria spp.* occurs from 279-256cm

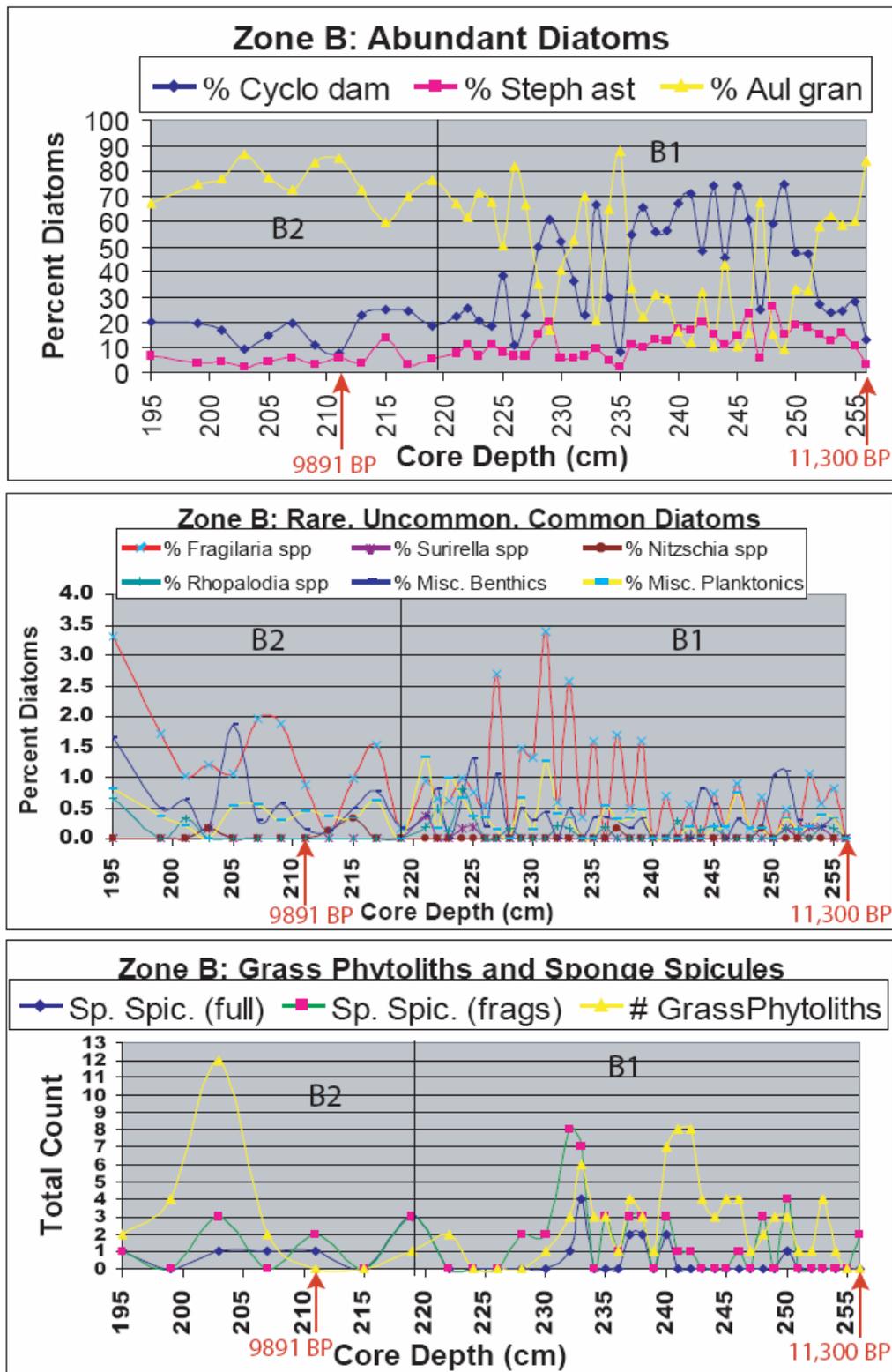


Figure 17. Zone B.

(from around 12,500 to 11,300 yr BP) which correlates to a high number of sponge spicules and grass phytoliths (Figure 16).

Zone B (Figure 17) is located near the center of the studied section of the core, from 256 to 195 cm, from 11,300 to around 9500 yr BP. The dominant feature in Zone B is the alternating dominance of *A.granulata* and *C.damasii* (Figure 17).

Zone B is sub-divided into Zone B1 and B2 according to changes in diatom flora. Zone B1 is from 256-219 cm, from 11,300 to 9900 yr BP, and is accentuated by alternating dominance of *Aulacoseira granulata* and *Stephanodiscus astraea*. In this zone, the alternating appearance of miscellaneous benthics and miscellaneous planktonics, as well as *Fragilaria spp* coincides with the alternating dominance of *A.granulata* and *S.astraea* (Figure 17). An increase in *C.damasii* correlates with an increase in miscellaneous benthics, sponge spicules and grass phytoliths (Figure 17) and a decrease in miscellaneous planktonics, and a decrease in *Fragilaria spp*. An inverse correlation occurs with an increase in *Aulacoseira granulata* in which Miscellaneous Benthics, sponge spicules and grass phytoliths decrease, Miscellaneous Planktonics increase, and *Fragilaria spp* also increase.

Zone B2, from 219 to 195 cm (9900 to 9700 yr BP), shows a continued overall dominance of *A.granulata* with a steady up-core decrease in *C.damasii* and *S.astraea*. An increase in *Fragilaria spp* and miscellaneous planktonics occurs up-core in this zone, though intermittent spikes of miscellaneous benthics, sponge

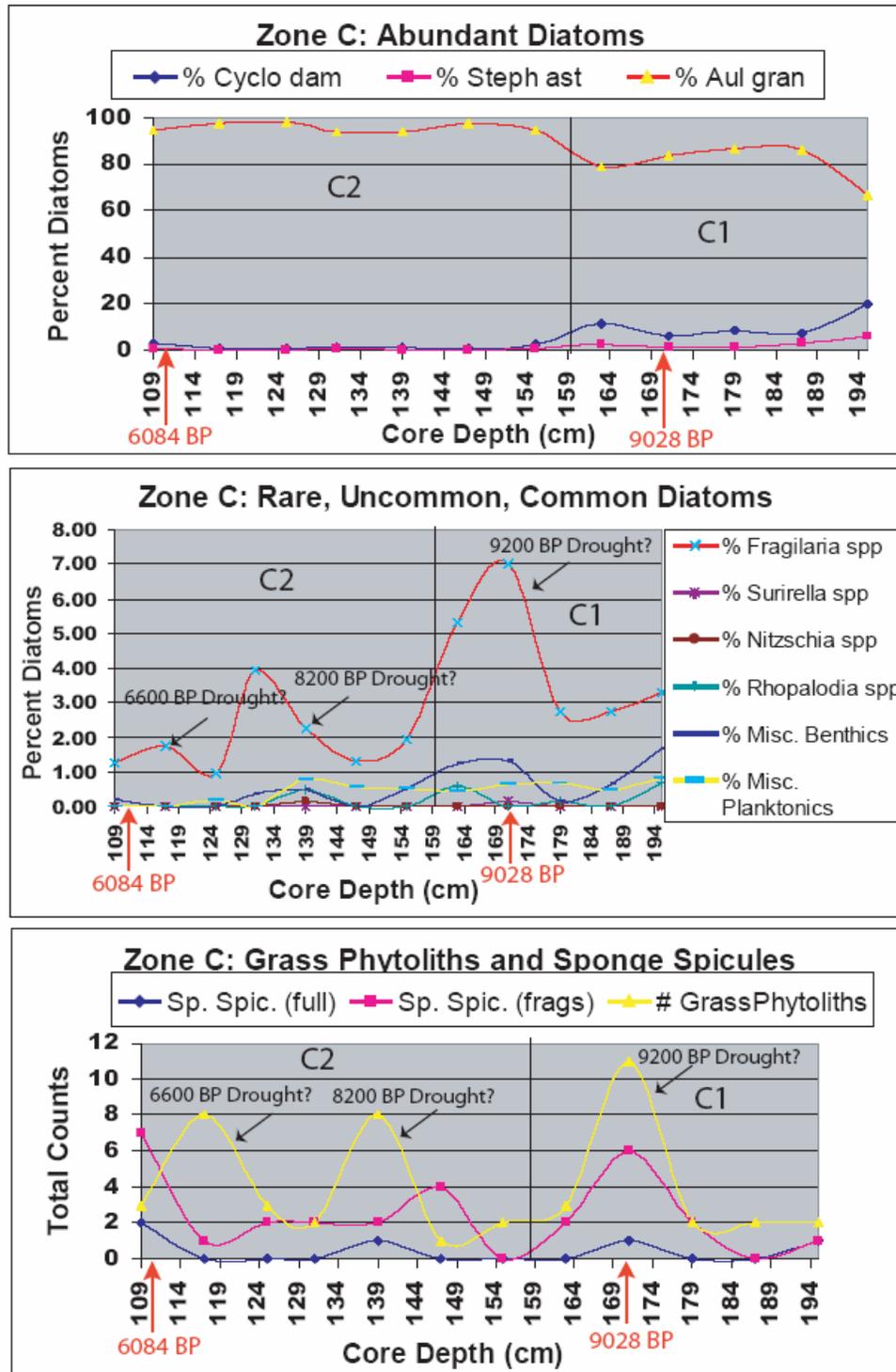


Figure 18. Zone C

spicules and grass phytoliths occur at 205 cm and 195 cm which correlate to decreases in *A.granulata* and *Fragilaria spp.*

Zone C (Figure 18) is located at the proximal end of the studied section of the core from 195 to 109 cm (9700 to 6000 yr BP). *A.granulata* dominates this zone, and increases dominance up-core. *C.damasii* shows an inverse correlation to the increased dominance of *A.granulata*, and decreases in percentage until the species is almost completely replaced by *A.granulata* by 145 cm down-core.

Zone C is sub-divided into Zones C1 and C2. Zone C1, from 195 to 159 cm, shows an increase in *A.granulata* and *Fragilaria spp.* In this zone, decreases in *Fragilaria spp* correlate with decreases in miscellaneous benthics and increases in miscellaneous planktonics. At 171 cm, a spike in *Fragilaria spp* is correlated with a spike in Miscellaneous Benthics and slight decrease in *A.granulata*. Zone C2, from 159-109 cm, is marked by an overall dominance of *A.granulata* and very low count of *C.damasii* and *S.astraea*.

Principal Component Analysis (PCA).

The results of the diatom data was further interpreted using Principal Component Analysis (PCA) utilizing SPSS version 13.0 software. The principal component analysis ordination grouped the main diatom taxa along three major axes that explain 62%, 46% and 25% of the cumulative variance in diatom taxa abundance (Figure 19). Using a scree plot, only components with an eigenvalue of >1 was used in the analysis.

The eigenvectors of the species' loadings on the three principal components indicates that component 1 is controlled by the abundances of

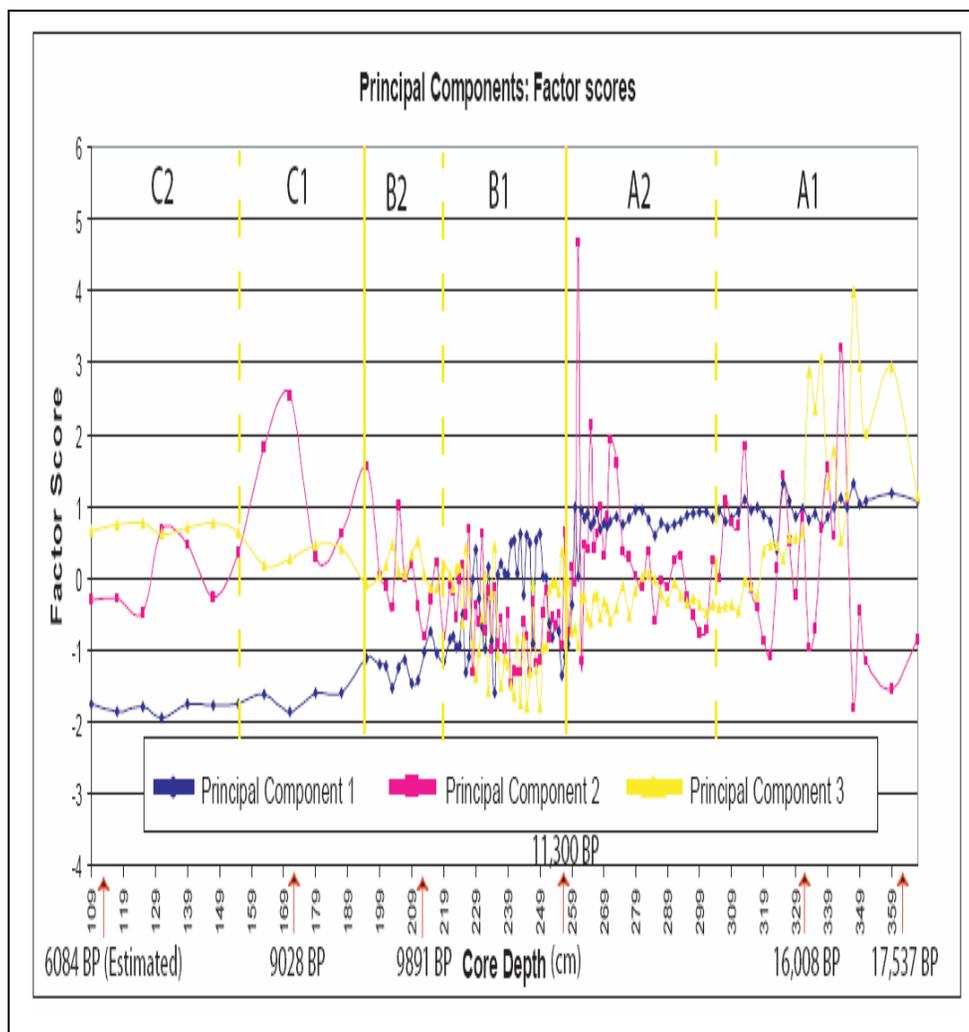


Figure 19. Principal Component Analysis for Core NP04-KH3 using SPSS software. Output of graph constructed from diatom percentages. Vertical yellow bars indicate Zone/Biozone change. Dates at base of graph are calendar years BP. Principal Component 1 (blue line) correlates to water column stratification whereas positive factor scores correlate to stratification, negative numbers suggest mixing and upwelling. Principal Component 2 (Red line) correlates with Lake levels; positive numbers correlate with higher lake levels, negative to lower lake levels. Principal Component 3 (yellow line) correlates with precipitation to evaporation ratio (P:E). Positive factor scores suggest $P < E$, whereas negative scores suggest $P > E$.

Diatom Species	Lake Condition	Relevant Literature	Loading on Principal Components		
			1	2	3
<i>S. astraea</i>	P<E; stratified; low Si:P; high light	Haybervan and Hecky 1987; Gasse 1986,1989	0.88	0.18	0.20
<i>A. granulata</i>	P>E upwelling; turbulent; deep mixing high Si:P	Kilham and Kilham 1986	-0.98	0.01	0.03
<i>C. damasii</i>	P>E;stratified; medium Si:P; low light	Cocquyt, 1998; Gasse 1989	0.14	-0.36	-0.81
<i>R. gibberula</i>	P<E benthic; low lake; stratified	Haybervan and Hecky 1987; Gasse 1986,1989	0.26	0.05	0.60
<i>S. fuellebornii</i>	P<E; benthic; low lake; stratified	Haybervan and Hecky 1987; Gasse 1986,1989	0.14	-0.29	0.65
Misc. benthics	P<E; low lake; regressed littoral zone	Kilham and Kilham 1986; Gasse 1989	0.28	0.78	0.01
Misc. planktonics	P<E; low lake; regressed littoral zone	Kilham and Kilham 1986; Gasse 1989	0.47	0.62	0.14
<i>Fragilaria spp.</i>	P<E; low lake; stratified	Haybervan and Hecky 1987; Gasse 1986,1989	-0.03	0.79	-0.02

Table 2. Diatom species recorded in Core NP04-KH3 and their ecological conditions that they thrive in. Constructed from data by Haybervan and Hecky, 1987; Kilham and Kilham, 1986; Gasse, 1989 and Cocquyt, 1998.

S.astraea, *A.granulata* and miscellaneous planktonics, with *S.astraea* and miscellaneous planktonics contributing positive loadings and *A.granulata* contributing negative loading (Figure 19). *Fragilaria spp*, miscellaneous benthics and miscellaneous planktonics all contribute positive loadings to component 2, and component 3 is controlled by the abundances of *Cyclostephanos damasii*, *Surirella spp.*, and *Rhopalodia spp.*, with a negative loading by *C.damasii* and positive loading by *Surirella spp.* and *Rhopalodia spp.*.

Thus, the dominant components of variance in the diatom data are the relative abundances of *S.astraea*, *A.granulata*, *Fragilaria spp.*, *Surirella spp.*, *Rhopalodia spp.*, miscellaneous benthics and miscellaneous planktonics. The dominant environmental control on principal component axis 1 is likely to be water column stratification with negative loading reflecting increased mixing (and upwelling) and decreased light, and positive loading reflecting increased stratification and light (Table 2). For principal component axis 2, the dominant environmental control is likely to be water level, with negative loadings reflecting increased water levels (transgressive littoral zone) and positive loadings reflecting decreased water levels (regressive littoral zones). Principal component axis 3 is probably controlled by the precipitation:evaporation balance. Positive loadings of principal component 3 are theorized to correlate with precipitation evaporation, whereas negative loadings correlate with precipitation > evaporation. Thus principal components 2 and 3 are controlled by changes in lake levels.

Discussion

This study is a contribution to a large body of work conducted at Lake Tanganyika since 1987. Initially, the research concentrated on the geophysical aspects of the basin (Rosendahl, 1987; Masse, 1988; Tiercelin et al, 1988; Ebinger, 1989; Sander and Rosendahl, 1989). Since 1987, the research has shifted towards paleoclimate studies (Hayberyan and Hecky, 1987; Gasse, 1989; Scholz et al, 1988; Gasse, 2000; Johnson et al, 2001; Zalifi and Eagle, 2001; Trauth et al, 2002; Johnson et al, 2002; Gasse and Barker, 2003; Scholz et al, 2003; Steinkamp and Russell, 2004). The value of Lake Tanganyika is in its capacity to illustrate tropical continental climate patterns not discernable from marine sediments, polar ice cores, or terrestrial sediments. This unique capacity is attributable to the rift zone structural geology of the lake which allows the accumulation of a pelagic sediment record isolated from coastal (littoral) factors.

Henry Thoreau once wrote “Lakes are the eyes of the Earth” (Russell per commun 2004). He may not have been referring to geology or climate, but the fact remains that lakes adjust to changes in the earths climate and geological history. Lakes quickly respond to changes in climate and tectonic geometry by adjusting their chemistry, biology and water levels. These changes are archived in the physical, biological and chemical remains that accumulate at the bottom of the lake. Unfortunately, most lakes have formed too recently, in the past 13 ky (Tiercelin, 1991; Masse, 1988). Some lakes are quite old, yet during climate shifts such as peak glacial advances, were dried up (Cohen, 1993; Gasse, 2000). Basal sediments were then exposed and eroded. So the only lakes to archive continuous

long-term changes are the very old, very deep ones. Lake Tanganyika is the second deepest lake in the world (after Lake Baikal) and is very old, thus it is one of the best candidates to archive long-term, high resolution climate changes in Tropical Africa.

In the last paragraph of the Introduction, this study addressed the following questions: Are climate shifts and Last Glacial Maximum to Holocene trends that are evident at a mid-lake site in the Kalya region similar to the changes recorded at the southern and central region of the lake? Is there evidence from changes in fossil diatom populations from Kalya for lake-level changes during the Late Pleistocene and Early Holocene? Does the data signal rapid climate changes that are synchronous with the Northern Hemisphere? Is the Moba-Kalya Horst a good target area for a long-term drilling project?

The first two questions addresses whether climate shifts from the Last Glacial Maximum to the mid-Holocene indicated in Core NP04-KH3 are consistent with other regions of the lake and indicate lake level changes. The timing may differ somewhat between regions, but the change in diatom population over time from the Last Glacial Maximum to the Mid-Holocene are very consistent with the data of Hayberyan and Hecky, 1987, Gasse, 1989, and Scholz (et al 2003). The data consistently shows a strong presence of benthic diatoms such as *R. gibberula* and *S. fuellebornii* coinciding with a dominance of the planktonic diatom *S. astraea* and significant counts of grass phytoliths and sponge spicules from the Last Glacial Maximum to the start of the African Humid Period around 15 calendar years BP, indicative of low lake levels and a regressing littoral

zone near the coring site. Similar findings of increased periphytic/benthic diatom species were recorded by Johnson et al (2002) in Lake Malawi (Figure 20) at the same time interval, and a strong increase in more negative $\delta^{18}\text{O}$ values was recorded for the same time period in the GRIP ice cores (GRIP website). Benthic diatom populations and grass phytoliths and sponge spicule counts decrease dramatically from 15,000 calendar years BP to around 13,000 calendar years BP indicating rising lake levels, which abruptly changes at the start of the Younger Dryas. Around 13,000 calendar years BP, lake conditions revert to glacial conditions with a sudden appearance of benthic/periphytic diatom species and an increase in sponge spicules and grass phytoliths until around 11,700 calendar years BP indicating a rapid lake level decrease and regressing littoral zone. The timing of this event coincides well with an increase in periphytic diatoms in Lake Malawi (Figure 20) to the south (Johnson et al 2002), and correlates with more negative $\delta^{18}\text{O}$ values recorded in the GRIP ice cores from Greenland (GRIP 2006 website).

A rapid and dramatic shift from the post-glacial stratified lake conditions to increased upwelling, deep mixing and rapid dominance of the planktonic diatom species *A. granulata* signal the start of the Early Holocene in East Africa. A wet and windy Early Holocene with strong southerly winds, strong upwelling and tilting of the thermocline is indicated by the dominance of *A. granulata* which needs turbulent surface water, low light and deep mixing to keep it in the photic zone. These changes coincide well with climate changes in the Northern Hemisphere.

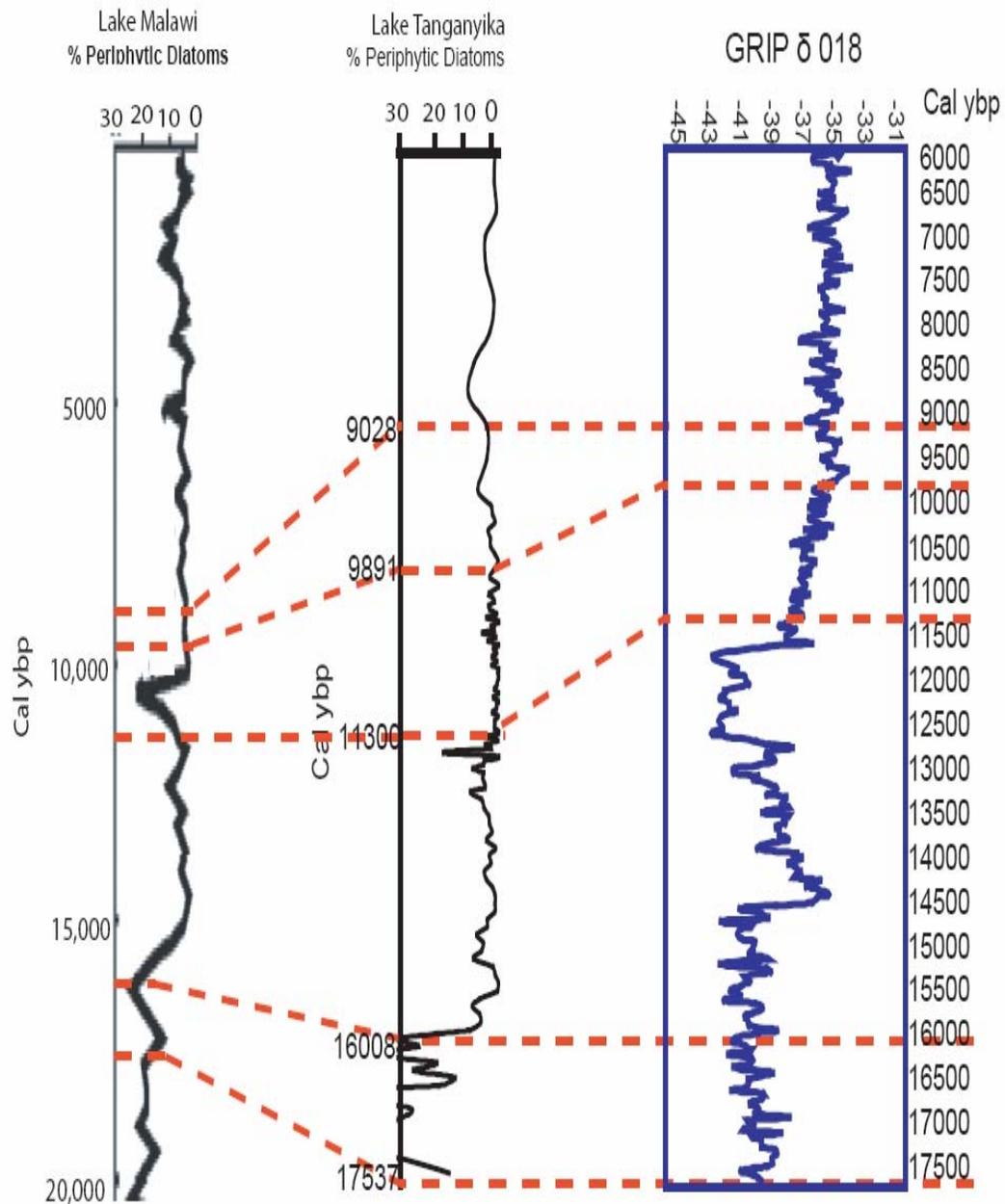


Figure 20. Percent periphytic diatoms from Lake Tanganyika from 17,537 to 6,000 calendar years BP recorded in this study, and compared to percent periphytic diatoms of Lake Malawi from Johnson et al 2002, and the $\delta 018$ values recorded in the GRIP ice core data from Greenland from the same interval (GRIP website). Dashed tie-lines correlate calendar dates from the three records.

The last question addresses whether the Kalya Horst region is a good target location for a long-term coring project, which is the main purpose of this pilot study. Other regions of the lake have very similar diatom assemblages from the Last Glacial Maximum through the Holocene, yet no other coring site has recorded complete, undisturbed sediments for the last 20 kyr or longer. Hayberyan and Hecky (1987) found erosion, bioturbation and eroded diatom frustules in the sediments of their shallow coring site at the southern end of the lake. According to the authors, diatoms disappear after around 27 kyr. Core NP04-KH3 contained complete diatom frustules throughout the continuous 42 kyr of sediment. Scholz (et al 2003) found similar conditions at the Kavala Island Ridge at the center of the lake, in which diatoms disappear around 29 kyr BP. Thus no other core has recorded complete diatom frustules prior to 29 kyr BP. The Kalya Horst thus contains complete, undisturbed sediments of at least 42 kyr. Reflection seismic data suggests that lacustrine sediments are complete for at least 600 meters from the top sub-aqueous surface of the horst, which is interrupted by an angular unconformity at that sediment depth (Helfrich et al 2004).

The results of the micro-fossil analysis from Core NP04-KH3 indicate dramatic shifts in the micro-fossil assemblage during the Late-Pleistocene and Early Holocene. These fossil shifts are indicative of climate shifts that occurred in East Africa that are evidenced in previous cores extracted from Lake Tanganyika.

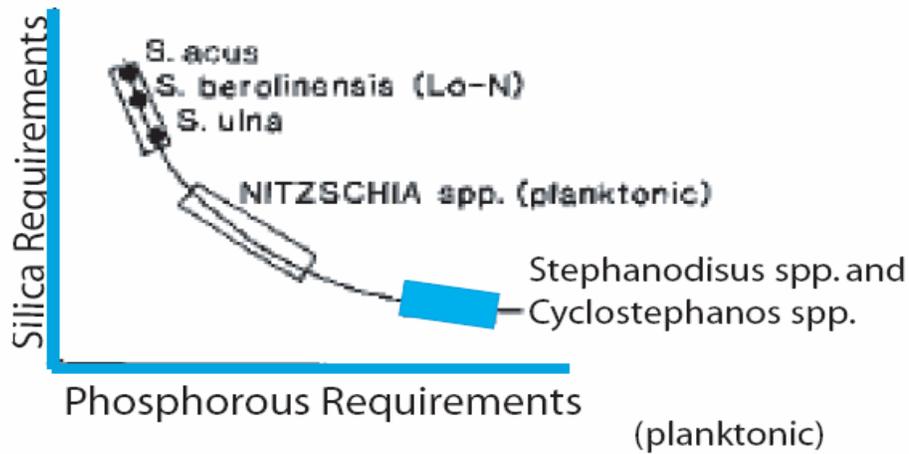
According to the micro-fossil assemblage in Core NP04-KH3, the Lake Tanganyika basin experienced dramatic climate shifts that correlate with regional

as well as hemispheric climate regimes. Near the terminus of the Last Glacial Maximum around 17ky B.P. Lake Tanganyika experienced an extreme negative water balance with lake levels estimated to be 250-350 meters lower than present.

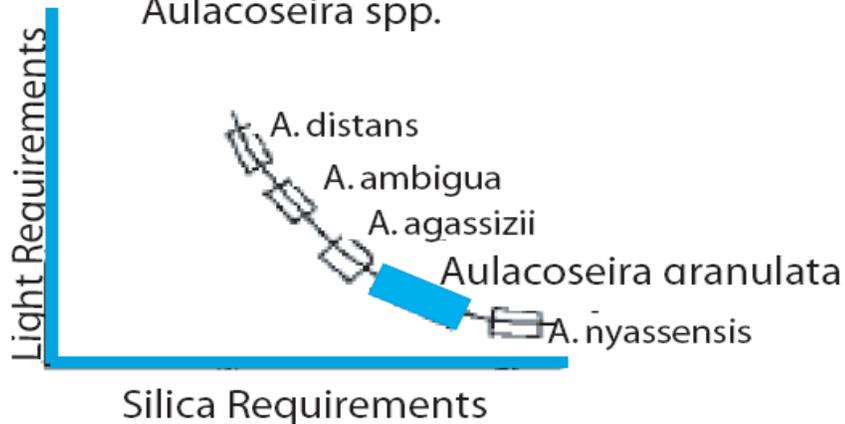
At the coring site of Core NP04-KH3, located at 644 meters present water depth, this low lake stand is signaled by the abundance of the benthic diatoms *S.fuellebornii* and *R.gibberula* (epipelagic and epilithic respectively) in Biozone A1, which correlates to the date range of 17,537 ky B.P. to ~ 15 ky B.P. Since both species are littoral benthic species, it is likely that the littoral zone was close to the coring site and above the annual thermocline during this period. The lack of laminated sediments and formation of massive clays in this zone further implies that mixing was occurring similar to that which is evident today in sediments above the 200 meter annual thermocline. The period (17.5-15 kyr BP) includes the highest abundance of grass phytoliths and sponge spicules recorded in the core (17.5-6 kyr BP). The abundance of grass phytoliths indicates a dry climate regime and low P:E ratio, implying the existence of a grass savannah surrounding the lake basin. The abundance of sponge spicules is indicative of a littoral zone that is close to the coring site. The abundance of *S.astraea* in Zone A1 indicates a stratified lake

(*S. astraea* has been determined to thrive in low Si:P (Figure 21) surface water conditions which only occur in a stratified lake environment (Kilham and Kilham 1986)), with shallow annual mixing, low Si:P supply ratios (Figure 21)

Stephanodiscus spp. and Cyclotella spp.



Aulacoseira spp.



Revised From Kilham and Kilham 1986

Figure 21. Silica, light and phosphorous requirements of *S. astraea*, *C. damasii* and *A. granulata*. The planktonic species *S. astraea* and *C. damasii* require high phosphorous, low silica (low Si:P ratio) which occurs during a stratified lake environment and limited upwelling. The planktonic species *A. granulata* on the other hand requires high silica and low light which occurs during upwelling events that force deep mixing of epilimnion waters with hypolimnion waters, resulting in turbulent surface water conditions that *A. granulata* requires to keep its heavy filamented frustules (siliceous outer shells) floating in the photic zone. (From Kilham and Kilham, 1986).

and a cool, dry climate regime with sodium-bicarbonate rich waters. Finally, the presence of abundant *Nitzschia spp.* which thrive in high phosphorous, low silica conditions also indicates that the lake was in a stratified state, and that the epilimnion is enriched in phosphorous and deprived of silica (low Si:P supply ratio).

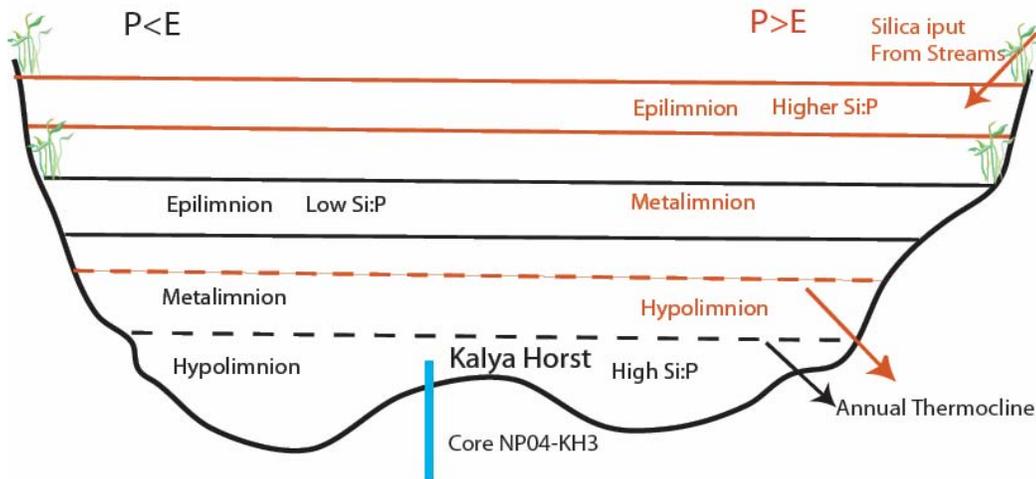
Following the Last Glacial Maximum low lake levels, Lake Tanganyika experienced a slow progression of increased lake levels and positive water balance beginning at around 16 kyB.P. as indicated at the coring site by a steady decrease in benthic/periphytic diatoms, grass phytoliths and sponge spicules. At the same time, a decrease in *S.astraea* and increase in *C.damasii* signals wetter conditions. Bundles of dark laminated sediments formed during this period indicating that the coring site was below the oxycline and was receiving a greater abundance of allochthonous sediments and organic matter from increased fluvial influx from marginal watersheds and less biogenic silica.

At around 13 ky B.P. (the Zone A1/A2 boundary), a shift in moisture balance occurred as indicated by the abrupt termination of dark bundled sediments at 311 cm down-core (Figure 22). A steady increase in the number of sponge spicules and grass phytoliths from 311-255 cm indicates drier climate conditions, similar to the Last Glacial Maximum lake conditions. Thus a shift from wetter to drier, glacial conditions occurred, which lasted from approximately 13 ky B.P. to 11.5 ky B.P.. This cold, dry event is further evidenced by an abrupt increase in benthic diatoms and development of visually distinct autochthonous biogenic silica half bundles and decreased allochthonous dark half bundles. *S.astraea*

continued dominance in Zone A2, followed by *C.damasii*, yet at around 285cm both species decreased abruptly which correlated to a sudden increase in *A.granulata*, indicating that the climate made a short, abrupt shift from cold, dry and stratified, to warmer, wetter and more mixed with an increase in upwelling. From the core data this period is estimated to have lasted for approximately 250-300 years and occurred from roughly 12,300 B.P to 12,600 B.P.. Thus Zone A2 is estimated to represent the Younger Dryas cold event.

The boundary from Zone A to Zone B represents a major and abrupt shift in diatom dominance and climate. Dated to 11,300 B.P. the shift indicates a sudden change in climate, lake levels and water column stability (Figure 23). A change in dominance from *S.astraea* to *A.granulata* and *C.damasii* highly suggests a change in the lake from cool, calm and stratified to wet, windy and turbulent with increased depth of mixing and upwelling. Sponge spicules and grass phytoliths numbers diminish to less than ten/sample suggesting possible re-deposition from surrounding watersheds. Sediments consist of strongly dark laminated bundles suggesting wetter conditions and enhanced influx of allochthonous material from marginal watersheds. Internal loading of silica from the hypolimnion due to upwelling and silica from fluvial influx allowed *A.granulata* to fill its large filamentous pores and water turbulence allowed it to stay in the photic zone. Another important feature of Zone B1 is the alternating dominance of *A.granulata* and *C.damasii*. This suggest that the lake was fluctuating from wet, windy and turbulent to simply wet with shallower mixing,

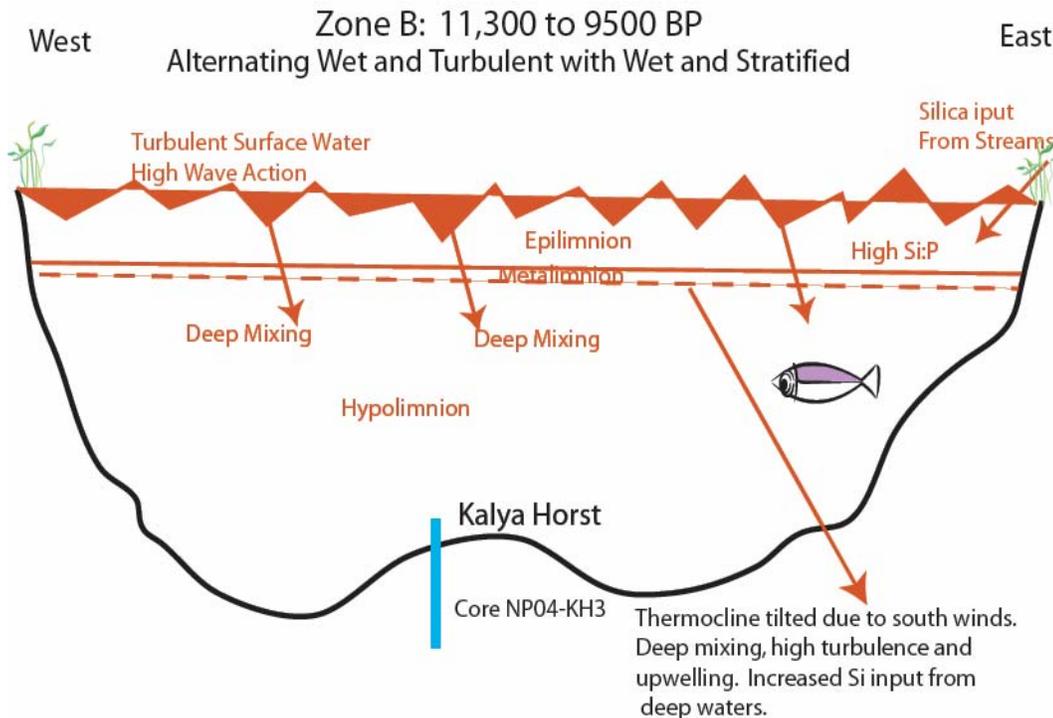
Zone A: @ 17,600 to 11,300 BP



Zone A1: @17,600-15,000 BP. Last Glacial Maximum; $P < E$. Stratified Lake, low lake levels (@ -350m), arid, shallow mixing. Low Si:P supply ratios in epilimnion due to shallow mixing and low stream discharge resulting in dominance of *S. astraea*. High percentage of periphytic/benthic diatoms at coring site, such as *R. gibberula*, *S. fuellebornii*. High grass phytolith and sponge spicule counts. Lake levels rising by end of Zone A1 at the start of the African Humid Period as periphytic/benthic diatoms decrease at coring site due to littoral zone transgression away from site (landward).

Zone A2: @15,000-11,300 BP. Start of African Humid Period. $P > E$. Increased lake levels. Stratified lake with turbulent surface water and shallow mixing. Increased silica input from margin watersheds. Decrease in *S. astraea* and increase in *C. damasii* due to decrease light. Lake level drop @ 13,500 with sudden increase in periphytic/benthic diatoms, sponge spicules and grass phytoliths. Lake reverts to Glacial conditions similar to A1 till 11,300 BP.

Figure 22. Zone A lake levels. Zone A1 lake levels are indicated by black lines and print; Zone A2 lake levels are indicated by red lines and print.



Zone B1: 11,300 to 10,000 BP. Alternating wet and turbulent with wet and stratified. *A. granulata* dominance during wet and turbulent conditions with upwelling, though alternates dominance with *S. damasii* during wet, stratified, calm, less stormy conditions. Highest lake levels recorded in Tropical Africa during this time period. Lowest grass phytolith and sponge spicule counts. Massive clays without fine laminations in core due to deep mixing. Strong southwesterly winds force tilting of the thermocline in southern and central Lake Tanganyika. Silica loading from hypolimnion of lake and from river discharge. Phosphorous retained by vegetation on land.

Zone B2: 10,000 to 9500 BP. Wet, turbulent conditions dominant with steady dominance of *A. granulata*. Continued upwelling and deep mixing, with high Si:P ratios in the epilimnion from deep waters and surrounding rivers.

Figure 23. Zone B lake levels and ecological conditions. Red lines and print indicate wet conditions that continued from Zone A2.

yet with enough water turbulence to scatter light in the photic zone and inhibit the growth and dominance of *S.astraea* (Figure 23).

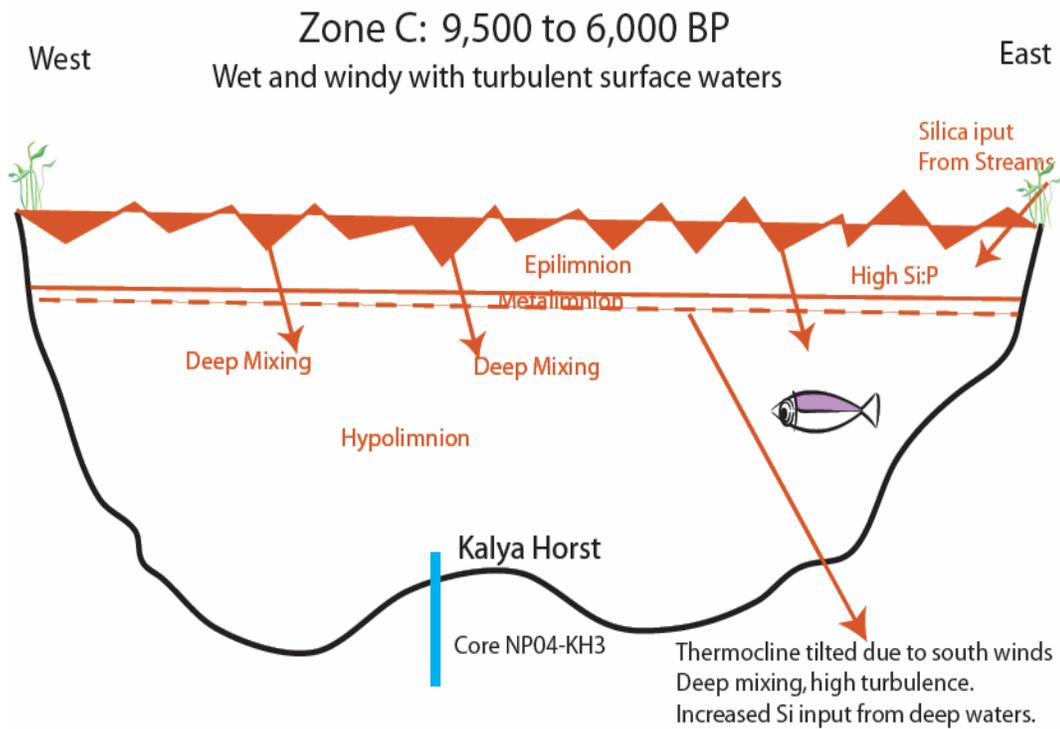
The shift in lake conditions in Zone B1 indicates another interesting point. A shift from *S.astraea* to *C.damasii* indicates that the two species thrive in very different ecological conditions, such as changes in light, suggesting that they are separate species. According to some Diatomists *Cyclostephanos spp.* could be a complex of *Stephanodiscus spp.* If this is the case then the smaller *Stephanodiscus* existing in higher light conditions that allow for its small size, whereas the *Cyclostephanos spp.* thrive in lower light conditions correlated with wetter climate conditions. Kilham (1986) suggests, that a single species such as *A.granulata* may vary in size according to light availability. Each individual may vary in frustule size, or size of areolea or punta that grow according to intensity or availability of light. Smaller species or species with smaller areolea thrive in higher light conditions, and lower light conditions correlate to larger species with larger areolea. This would suggest that *Cyclostephanos spp* thrive in lower light, wetter climate regimes and *Stephanodiscus spp* thrive in brighter light conditions of cool, dry climate regimes, yet are a complex of the same taxa (a possible mix of species).

Thus Zone B1 represents a time when the lake was experiencing fluctuating climate conditions (Figure 23) possibly tied to latitudinal migration of the ITCZ (Intertropical Convergence Zone) (Cohen et al, submitted). A shift of the ITCZ to the north increases wind intensity from the southeast which forces tilting of the thermocline and enhances upwelling in the southern and middle

portions of the lake. When the ITCZ is closer to the lake the wind shifts and upwelling decreases and precipitation increases. Zone B1 is dated from 11,300-10,000 B.P. and represents the close of the Pleistocene and start of the Early Holocene in Tropical Africa.

At the end of Zone B1, the climate surrounding the lake has stabilized. The beginning of Zone B2 represents the complete dominance of *A.granulata* and indicates that upwelling has become a dominant force in the lake's water column. The ITCZ probably shifted north of the lake and stabilized without long-term migration to the south, as evidenced in Zone B1. A steady increase in percentage of *A.granulata* continues up-core from Zone B2 through Zones C1 and C2 (Figure 24), the top of the core. Thus it is theorized that the climate of the Early Holocene at Lake Tanganyika became wet and windy, with strong annual upwelling, low scattered light in the photic zone, high Si:P supply ratios and high fluvial discharge from surrounding watersheds, which prevailed through most of the Early Holocene (Figure 24).

The results of this study indicate that the Kalya Horst is an excellent candidate for archiving long term climate records, and is the ideal setting for a deep sediment coring project. Unlike other regions of Lake Tanganyika, the Kalya Horst contains sediments that preserve diatom frustules and other microfossils longer than 29 kyr BP, which are good indicators of paleolimnological conditions for Lake Tanganyika, and paleoclimate records for tropical Africa.



Zone C: Continued wet and windy conditions with upwelling and deep mixing. Continued high river discharge and loading of Silica to epilimnion of lake. High silica loading also from hypolimnion during deep mixing/upwelling events. *A. granulata* shows highest dominance during this period.

Figure 24. Zone C lake level and ecological conditions for Lake Tanganyika according to the micro-fossil assemblage of Core NP04-KH3.

Conclusion

Lake Tanganyika is a very old and very deep lake that has been accumulating sediment continuously from the Miocene. Subaqueous portions of the lake have endured extreme climate shifts that dessicate most lakes. The tectonic structure of the lake has formed structural highs that are separated by half-grabens that act like protective moats surrounding a caste. The protection has allowed these structural highs to be protected from extreme low-stands, extreme sediment influx from marginal watersheds, turbidity currents and water column instability, yet allowed the slow deposition of pelagic mineral and biologic sediments that archive the conditions of the lake at the time of deposition.

Lacustrine sediments in Core NP04-KH3 archive a continuous record of paleoclimate and Paleolimnology for Lake Tanganyika, and demonstrate that the Moba-Kalya Horst region is a good long-term paleoclimate and paleolimnological archive for tropical Africa, and excellent location for a long-term drilling project. The preservation of lacustrine microfossils within the sediments of core NP04-KH3 allow for a detailed chronology of climate events from 42 kyr to the present, and hint to the possibility of much longer climate records. Changes in climate are recorded by the changes in micro-fossil assemblages of Core NP04-KH3, which indicate that climate changes that were recorded in cores from the southern end of the lake are similar to findings at the center of the lake (Kalya Horst), and just north of the Kalya Horst at the Kavala Island Ridge. Thus analysis of distinct fossil assemblages in sediments from the Kalya Horst allow for the deciphering of

paleo lake conditions that are controlled by climate and tectonics. The depth of the horst has kept its surface below the oxicle, as demonstrated by the microfossil preservation in Core NP04-KH3, allowing the complete preservation of siliceous micro-fossils such as diatoms, sponge spicules and grass phytoliths over long periods of time.

The Kalya Horst Ridge is an excellent candidate for long-term drilling to recover a paleo-climate record for Tropical Africa for more than the past 1Gyr. Sediments have been continuously accumulating on the surface of the horst for millions of years and have been relatively undisturbed by climate and tectonic forcing. Sediment accumulation rates range from 0.1-1.0 mm/yr and consist of predominantly pelagic sediments. Seismic reflection profiles conducted at the Moba-Kalya Horst region establish a fairly stable tectonic environment that allows long term preservation of lacustrine sediments that archive the long history of Lake Tanganyika and East African climate regimes.

Micro-fossil data from Core NPO4-KH3 indicate that Lake Tanganyika climate changes are synchronous with high latitude climate shifts, as well as changes recorded in other lakes such as Lake Malawi to the south. An increase in periphytic diatom species following the Last Glacial Maximum to around 15,000 calendar years BP correlates with a periphytic species increase in Lake Malawi at the same time, both of which correlate with more negative $\delta^{18}\text{O}$ values in Greenland GRIP ice cores, indicating colder, dryer climate conditions in the northern hemisphere. This correlation is again noted from around 13,000-11,700

calendar years BP, indicating cold, glacial conditions that influenced equatorial African lakes such as Lake Tanganyika and Lake Malawi.

Further coring of the Moba-Kalya Horst region is recommended, as well as coring of other protected subaqueous regions of the lake to establish if a better chronology of climate events. Furthermore, a higher sampling resolution should be conducted on Core NP04-KH3 to establish higher resolution climate signals at the decadal to millennial scale. Finally, micro-fossil assemblages such as diatom, sponge spicules and grass phytoliths should be compared to pollen records of the same time period to compare lacustrine and terrestrial climate signals, and more proxies such as magnetic susceptibility, grain-size analysis and paleomagnetic analysis should be conducted on Core NP04-KH3.

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