

**The origin, transformation and deposition of sediments in Lake Bosomtwe/Bosumtwi
(Ghana, West Africa)**

by
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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

ABSTRACT

Recent drought over West Africa (1970s-present) has been a global concern, and the ability to predict the frequency and severity of future droughts is important to mitigate the devastating socio-economic effects of drought. The Sahel region, situated at 10-20°N just south of the arid Sahara Desert and north of the forested Guinea Coast, is particularly vulnerable to drought periodicity because rainfall is already low at 400 mm yr⁻¹. The ability to predict future climate variability depends on adequate knowledge of fluctuations in the past. In West Africa, meteorological records are too sparse and too short in duration to characterize the drought frequency. Consequently, climate reconstructions from lacustrine sediment records are increasingly recognized as an important source of information on past climate variability. Lake Bosomtwe, Ghana (6°30'N and 1°25'W) was formed over one million years ago by a meteorite impact crater in the Guinea Coast region, just south of the Sahel region. Lake Bosomtwe has a closed-drainage hydrology and lake levels are known to fluctuate with the net flux in rainfall inputs relative to evaporative outputs. In 2004, the International Continental Scientific Drilling Program recovered the complete sediment record for paleoclimatic reconstructions. However, very little has been studied of the limnological conditions that lead to the formation of laminated sediments in Lake Bosomtwe. This thesis has set out to understand the influence climate has on the physical, chemical and biological in-lake processes that generate sedimenting materials, which are preserved as laminated sediment layers. Two years of water column sampling of temperature, oxygen and nutrients at a central deep-water site (78 m water depth maximum) found that this quiescent crater lake is thermally stratified during much of the year, with anoxia persisting below 35 m water depth. During the short dry season of July and August, the monsoon rains that are associated with the intertropical convergence zone (ITCZ) are displaced northwards over the Sahel region (and away from lake Bosomtwe), and cool air temperatures and clear night skies lead to the disruption of the thermocline and circulation of dissolved nutrients nitrogen (N) and phosphorus (P) in Lake Bosomtwe. Phytoplankton primary productivity, as measured by particulate carbon and chlorophyll *a* concentrations, was found to increase markedly following the nutrient upwelling event

in August. Sediment trap samplers deployed at 20 and 30 m water depth captured the pattern of organic matter deposition and a high flux of organic sediment was deposited shortly after the nutrient upwelling episode in August. The composition of these organic-rich sediments was distinguished by a marked depletion in $\delta^{13}\text{C}$ and enrichment of $\delta^{15}\text{N}$, as compared to sediments deposited before and after this event. Spatial assessment of sediment cores identified that presently, visible laminations were preserved at and below 35 m water depth, but, not at shallower depths. Water depth was also positively correlated with the organic matter content in sediment records and could be used to reconstruct pre-historic lake levels down core. The relationship between lake level and organic content in sediments predicted that water levels were likely 22 m lower than present levels during the period ~1425-1610 CE, which corresponds with a climatic periods known as the Little Ice Age (LIA). The spatial sediment trends also revealed that inorganic sedimentation rates had increased since the onset of recent land clearance and road construction in the catchment, particularly to the north, near the town of Abono. For this reason, two cores from the central deep-water region of Lake Bosomtwe were analysed for organic and carbonate content, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, nutrients (C, N, P), magnetic susceptibility, greyscale imagery of the x-radiograph and micro-X-ray analysis of elemental constituents. Paleoenvironmental reconstructions during the past 550 years found that climate-driven lake level change was a prominent factor contributing to the organic content of sediments. High inorganic content, iron concentrations and depleted $\delta^{13}\text{C}$ distinguished a low stand during the LIA (~1425-1610) when pelagic sediments were likely exposed to periodic oxygenation. High concentrations of organic matter, calcium (Ca) and strontium (Sr), enrichment of $\delta^{13}\text{C}$ and low C:N ratios were indicative of wet years that likely increased lake levels and the depth of water column mixing. However, sediments with high organic content, depleted $\delta^{13}\text{C}$ signatures and reduced Ca and Sr concentrations were suggestive of drought years that restricted the depth of seasonal water column mixing and nutrient circulation and did not necessarily result in pronounced lake-level change. During the past century, $\delta^{13}\text{C}$ of bulk matter was positively correlated with the rainfall anomalies ($r^2 = 0.45$, $P < 0.002$), indicating that droughts can result in reduced primary productivity, which may

ultimately lower fishery yields. The communities living within the crater are dependent on subsistence fishing and farming, and predicting the drought frequency and magnitude in this region is essential to protecting both the ecosystem and the human population. Long-range climate forecasts for West Africa predict greater drought and increasing air temperature. However, with a detailed long-term paleoclimatic reconstruction from Lake Bosomtwe sediment records, potentially the accuracy of these predictions can be improved and better equip policy makers to enact a viable action plan in the best interests of the people.

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1 Chapter - Introduction

Presently, our understanding of the linkages amongst climate patterns and the limnology and sedimentology of Lake Bosomtwe/Bosumtwi (hereafter referred to as Bosomtwe) are poorly understood. In this study we attempt to identify the regional climate patterns that affect the physical, chemical and biological characteristics of Lake Bosomtwe, which ultimately influence the formation and composition of lacustrine sediments. Lake Bosomtwe, Ghana (6°30N and 1°25W) is found in the Guinea Coast region, just south of the Sahel region. There has been a great deal of interest in the climate patterns over the Sahel region, West Africa because of the high susceptibility to drought in a region dominated by rain-fed subsistence farming. For this reason, we examine the climatic history, current meteorological patterns and limnological responses at Lake Bosomtwe.

REGIONAL METEOROLOGICAL PATTERNS AT LAKE BOSOMTWE

Lake Bosomtwe is geographically well-positioned to aid in the understanding of both regional climatological patterns of the Guinea Coast and Sahel regions, as well as understanding the influence that global climate drivers, such as Atlantic Sea Surface Temperatures (SST) and El Niño Southern Oscillation (ENSO), have on regional climate patterns (Druryan 1991; Nicholson 2008; Opokuankomah and Cordery 1994; Rowell 2001). The Guinea Coast and the Sahel region are situated geographically at 0-10°N and 10-20°N latitude, respectively, Figure 1-1 (Nicholson and Palao 1993). There are strong teleconnections between these adjacent regions (Nicholson 1980; Nicholson 1986), but they vary markedly in their pattern of annual rainfall delivery with 1,200-1,600 mm for the Guinea Coast and 100-400 mm for the Sahel (Nicholson 1980; Nicholson and Palao 1993). The resultant vegetation of the Guinea Coast is semi-deciduous forest cover while the Sahel is arid-tolerant scrubland and grasslands (Hall and Swaine 1976; Swaine et al. 1990). Due to low amounts of precipitation and high rates of evaporation, the Sahel region is particularly vulnerable to persistent drought.

The frequency of extreme drought in the Sahel region is high and can threaten the region's food security, where much of the population is dependent on subsistence farming and ranching with minimal access to irrigation or soil amendments. The word Sahel means 'shoreline' in Arabic and forms the transition zone between southern forested Guinea Coast and the northern, barren Sahara Desert. The Sahel region is susceptible to the migrating southern boundary of the Sahara Desert, which varies widely from year to year. For example, it covered 9,980,000 km² in 1984, but had shrunk to 8,600,000 km² by 1994 (Tucker and Nicholson 1999). Encroachment of the desert can be the result of either climatically driven reduction in precipitation or anthropogenically driven soil erosion. Efforts to understand drought and desertification of the Sahel and the greater sub-Saharan West Africa have revealed some clear regional meteorological linkages with the Atlantic sea surface temperatures and continental air currents (Xue and Shukla 1993).

Patterns of annual precipitation in sub-Saharan Africa are strongly influenced by the trade winds and the African Easterly Jet (AEJ). Naturally, the annual pattern of precipitation divides West Africa into these distinct ecotones, the Sahara Desert, Sahel, and Guinea Coast regions (Nicholson and Palao 1993). The delivery of rainfall to these regions comes through the northward displacement of the moisture laden intertropical convergence zone (ITCZ), a low pressure convergence of the southeast and northeast trade winds (Figure 1-1). The seasonal variability over West Africa is dictated by the migration of the ITCZ, which produces dry condition at the Sahel region when the ITCZ is displaced southward over the Guinea Coast in January and wetter conditions when the ITCZ is displaced further northward over the Sahel to the interior of West Africa in August. The monsoon rainfall can experience interannual displacement by the AEJ between the Sahel and the Guinea Coast (Nicholson and Webster 2008; Nicholson, 1980). Wet years are often distinguished in the Guinea Coast by the bimodal pattern of precipitation (Figure 1-1a), and drought years by the unimodal pattern (Figure 1-1b). The strength of the AEJ is a direct result of the baroclinic instability between continental Africa

and the Atlantic Ocean. The continental air pressure over Africa is influenced by the surface albedo and land cover that, in turn, can produce greater evapotranspiration rates and soil moisture during wet years (Lare and Nicholson 1994). The increased evapotranspiration results in latent heat transfer to the troposphere, altering the strength of the AEJ.

Interannual rainfall variability over West Africa is believed to be strongly driven by the interaction of these continental air pressures and the global climate patterns. In years when warmer North Atlantic SST meet colder South Atlantic SST at the Gulf of Guinea, a strong pressure gradient is established that produces greater monsoon winds, which transports greater moisture from the Atlantic Ocean to West Africa's interior. Global climate patterns like the North Atlantic Oscillation and the South Atlantic El Niño, which reduce the inter-hemispheric temperature differences or displace the point of convergence of these waters, result in drought years throughout the Sahel region (Nicholson and Kim 1997; Nicholson and Webster 2008). ENSO events have been documented over West Africa for some time, as they are linked to drought years over the Sahel region (Xue and Shukla 1998). Only recently, long-term paleoclimate information obtained from Lake Bosomtwe's sediment record has revealed the ENSO events have been a climate driver over the Guinea Coast region (Shanahan et al. 2009; Whyte 1975). There is a great need for long-term paleoclimatic records over West Africa and information from sediment records from Lake Bosomtwe may provide an alternative source of long-term meteorological data where instrumental data, ice cores and tree rings are not available.

LAKE BOSOMTWE

Lake Bosomtwe is situated at 6 °N latitude in the northern region of the Guinea Coast (Figure 1-1) comprised of both semi-deciduous forest and agriculture. Lake Bosomtwe is the only naturally occurring lake in this region of West Africa and it lies within the Bosumtwi meteorite impact crater, a circular depression 11 km in diameter that was formed over one million years ago (Figure 1-2b). Lake

Bosomtwe is large, measuring 8 km in diameter and 78 m in depth, and is a hydrologically closed basin (Whyte 1975). The surrounding crater rim reaches a minimum height of 110 m above present water level which measures 99 m amsl, isolating the hydrology from the surrounding Pra River Basin, as well as creating conditions of reduced wind stress. The crater impact breccia prevents groundwater exchange. As a result, the lake receives all hydrological inputs from precipitation with an estimated 80% from direct precipitation to the lake surface area, 48.6 km² (Turner et al. 1996a; Turner et al. 1996b). Consequently, the lake level fluctuates in close correspondence with changes in the ratio of precipitation to evaporation (Turner et al. 1996a).

Paleolimnological reconstructions of water-level change at Lake Bosomtwe have been shown to track changes in precipitation over West Africa that is correlated with drivers of the global climate system. Short-term drought caused by either the Pacific El Niño events or Atlantic variations in SST were found to result in periodic (3-5 year) increases in $\delta^{18}\text{O}$ of carbonate in Lake Bosomtwe sediment records (Shanahan et al. 2009). Linked to northern hemispheric climate patterns, such as the Little Ice Age (550-200 yr BP), drought has resulted in lower lake levels (by 25-31 m based on evidence from seismic unconformities) that were evident in sediment records as increased silica concentrations and increased $\delta^{18}\text{O}$ signature of carbonate at Lake Bosomtwe. During the African Humid Period (6,000 yr BP), a prolonged wet climate resulted in the water levels rising over Lake Bosomtwe's walls, based on evidence from fossil fish and beach deposits along the crater walls and an outflow channel cut in the eastern sill (Shanahan et al. 2006). A major decline in water level occurred during the Younger Dryas (over 12,000 yr BP) as implied by the formation of dolomite and enriched $\delta^{13}\text{C}$ signatures of bulk matter from Lake Bosomtwe (Talbot and Johannessen 1992). Prolonged drought from 15,000 to 6,000 yr BP transported fine Saharan Desert particulates across West Africa and ferrous mineral deposits (Peck et al. 2004) over Lake Bosomtwe, as well as deposition of fine clays over Chad and Cameroon (Maley 1982). More often, large-scale water level changes were discernible in the

information preserved in Lake Bosomtwe's sediment records, but a better understanding of the effects of present day, short-term drought frequencies such as ENSO needs to be generated.

Finely laminated sediment records from Lake Bosomtwe are believed to hold high-resolution paleoenvironmental records during most of the past one million years for sub-Saharan West Africa. Laminations are composed of dark and light couplets that are believed to be seasonally produced and represent an annual cycle (Shanahan et al. 2008). Shanahan and colleagues found that local rainfall measures corresponded ($r = 0.54$) with the thickness of the dark laminae. Dark laminae are composed of inorganic clastics washed in from the catchment and are formed during rainfall events. Conversely, light laminae consist of organic- and carbonate-rich materials likely formed during September to December when algal productivity is high (Shanahan et al. 2008). However, more needs to be understood about the connections between the regional meteorology and the in-lake processes.

This thesis will improve knowledge of how present-day meteorological patterns affect complex in-lake processes, like seasonal patterns of inorganic delivery and organic matter preservation, and how sediments are transformed and deposited within crater Lake Bosomtwe. The generation, deposition and preservation of sediment records in Lake Bosomtwe are influenced by the limnological conditions of this crater lake. The physical, chemical and biological conditions are assessed so that the effects of in-lake processes may be understood in the formation of laminated sediments.

PHYSICAL LIMNOLOGY

Crater lakes, whether formed by volcanic eruptions or meteorite impacts, have a morphometry such that a thermocline typically develops which restricts mixing of the hypolimnion (Melack 1976). In Lake Bosomtwe, the coolest water temperature is found in the hypolimnion and remains relatively constant at 26.81°C year-round. Prolonged thermal stratification can result in the development of an

oxycline that restricts oxygenation to the deep waters. Anoxia at depth can be estimated by the ratio between maximum lake diameter (D) to minimum height (H) of the crater rim (Melack 1976). For Lake Bosomtwe, the D/H is 8000 m diameter relative to 210 m crater rim (minimum elevation from lake bottom), resulting in a 38 m depth of anoxia predicted, and on average the lake is currently anoxic below 30-35 m water depth.

Crater lakes are commonly well sheltered from winds, though this depends on the height of the crater rim. Low wind speeds have limited capacity to mix the entire water column. Thus, the water column can remain unmixed for prolonged periods of time, which allows density gradients to increase over time. Crater lakes often have high concentrations of deep-water solutes below the thermocline that can form a chemical gradient. Deep-water solutes can concentrate from either enriched hydrothermal vent inputs of volcanic craters like Crater Lake, USA (McManus et al. 1992; McManus et al. 1993; McManus et al. 1996), Bishoftu, Ethiopia (Wood et al. 1976), Cameroon, West Africa (Kling 1987; Kling et al. 1987), the island of Bioko, Gulf of Guinea (Schabetsberger et al. 2004); or accelerated deep-water organic matter degradation like Lake Bosomtwe (Turner et al. 1996b). Currently, Lake Bosomtwe has elevated concentrations of dihydrogen sulphide and dissolved nutrients below 30 m water depth.

In tropical crater lakes like Lake Bosomtwe, the mixing regime is rarely controlled by the fetch and wind energy, but rather by convective heat loss during episodic cooling events that are often due to diurnal evaporative heat losses (MacIntyre et al. 2002). The mixing patterns of tropical crater lakes can be variable, with polymictic shallow craters mixing daily, moderately deep-water craters mixing completely with oxygenation to the lake bottom, and deep-water craters mixing infrequently with prolonged anoxia at depth (Wood et al. 1984). Ugandan crater lakes are known to overturn annually during the cool, dry season (November to February) when conditions of low humidity, moderate

winds and limited cloudiness prevail (Melack 1976). The Cameroon crater lakes were found to mix infrequently during the short dry period in August when air temperatures are at an annual minimum (Kling 1987; Kling et al. 1987). Diurnal studies reported rates of evaporation during the evening that greatly exceeded daytime evaporation rates, leading to daily mixing (Wood et al. 1984). In smaller crater lakes, these nocturnal mixing patterns substantially changed dissolved oxygen concentrations in the water column, with deoxygenation in the evening followed by a photosynthetic re-oxygenation during the day time (Wood et al. 1984).

In Cameroon, steep sided, volcanic crater lakes like Lake Monoun and Nyos, accumulate trapped gases under deep-water pressures that lead to supersaturation of carbon dioxide and other noxious gases that can be released upon mixing. In Lake Monoun (August 15, 1984) and Lake Nyos (August, 21 1986) the water columns became isothermal due to cooling events, which caused the carbon dioxide gas to be released explosively, asphyxiating those within a 10 km radius of the lake (Kling 1987; Kling et al. 1987). These eruptions released a characteristic sulphurous odour, which has also been reported at Lake Pawlo (Wood et al. 1984) and Lake Bosomtwe when the water column becomes isothermal. However, in these latter crater lakes, the source of deep-water sulphides is not volcanic gases, but decomposition of organic matter. The mixing of these crater lakes frequently causes anoxic events in the surface waters that result in a fish kill, as reported from Ethiopian crater lakes Pawlo, Bishoftu and Aranguai (Wood et al. 1976), Ugandan crater Lake Nkugute (Beadle 1966), and Ghanian crater Lake Bosomtwe (Puchniak et al. 2009; Rattray 1923).

The thermal stratification, deep-water anoxia and infrequent mixing make the quiescent waters of Lake Bosomtwe ideal for the preservation of laminated sediments. High sulphide concentrations in the hypolimnion contribute to the preservation of organic matter by inhibiting decomposition and bioturbation of organic deposits (Hedges et al. 1999).

CHEMICAL LIMNOLOGY

Water chemistry of tropical crater lakes is strongly influenced by their restricted hydrological budget. In African crater lakes, net evaporation results in high solute concentrations, particularly sodium carbonate and bicarbonate (Prosser et al. 1968; Talling 2001). Generally, lake-water pH rises with increasing carbonate or bicarbonate alkalinity. In Lake Bosomtwe, the pH is high (average = 8.9; Puchniak et al. 2009)) and results in a concentration of dissolved inorganic carbon (DIC) predominantly in the form of bicarbonate. The relative proportions of CO_2 , HCO_3^- and CO_3^{2-} are 0.003, 0.966 and 0.031, respectively at pH of 8.9 (Hutchinson 1957). However, the primary source of carbon for fixation during photosynthesis is carbon dioxide (CO_2), which is readily dissolved in water but temperature dependent. In warmer tropical waters, solubility of CO_2 declines from 1.1 mg L^{-1} at 0°C to only 0.4 mg L^{-1} at 30°C (Wetzel 2001). Once dissolved, carbon dioxide hydrates and dissociates into equilibrium with bicarbonate and carbonate. Tropical saline lakes are typically dominated by bicarbonate, as hydroxyl ions are readily generated. In alkaline lakes, CO_2 dissolution from the atmosphere is enhanced during photosynthetic draw down of CO_2 (Wetzel 2001). Most African lakes are older than the temperate lakes because Pleistocene glaciation did not take place over much of Africa. Over time calcium cations have been readily leached from the lake catchment area and sedimented as calcite, leaving sodium as the primary cation and reducing the overall buffering capacity.

Aside from carbon fixation, lake primary productivity is often regulated by availability of growth-limiting nutrients, such as phosphorus, nitrogen and silica. Phosphorus (P) in lake water is found as dissolved inorganic orthophosphate (PO_4^{3-}), monophosphate (HPO_4^{2-}), and dihydrogen phosphate (H_2PO_4^-). Total phosphorus concentration in the uppermost meter of Lake Bosomtwe is $2.3 \text{ } \mu\text{mol P L}^{-1}$, whereas below the oxycline, concentrations are more than double this amount ($5.8 \text{ } \mu\text{mol P L}^{-1}$).

These concentrations are well above the critical threshold of $0.1 \mu\text{mol P L}^{-1}$, known to be the condition of P famine for phytoplankton growth (Reynolds 1984).

Like phosphorus, nitrogen is an essential nutrient for phytoplankton growth. The most abundant form of nitrogen in the world is N_2 gas, which is readily dissolved in the water column but is unavailable to most biota for uptake. The pool of available dissolved inorganic nitrogen (DIN) is divided into nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3) and ammonium (NH_4^+ ; Kalff 2002). In Lake Bosomtwe, DIN is predominantly in the form of ammonium sequestered deep in the anoxic hypolimnion. Total nitrogen concentrations range from $20 \mu\text{mol N L}^{-1}$ at 1 m depth to $2,000 \mu\text{mol N L}^{-1}$ below the oxycline, and all concentrations are well above the level of insufficient nitrogen concentrations of $0.2 \mu\text{mol N L}^{-1}$ (Reynolds 1984).

Silica is the second most abundant element in the Earth's crust and is leached from terrestrial soils. Silica does not have a gaseous phase, but is found in the aquatic environment as non-ionic silicon dioxide (SiO_2) or silica (Wetzel 2001). Silica goes into solution as silicic acid (H_4SiO_4) and can react in solution with aluminum hydroxides to form aluminum silicate or 'feldspars' or can be taken up biologically and transformed to silica in diatom cells (Exley, 2009). In Lake Bosomtwe, the concentration of suspended silica is only 0.28 to $1.6 \mu\text{g L}^{-1}$, while the concentration of dissolved silica is 630 - $770 \mu\text{g L}^{-1}$ below the oxycline. The suspended silica is most likely composed of diatomaceous opal; however preservation of diatom silica frustules in the sediment record is poor because of dissolution of suspended silica in the hypolimnion.

The water chemistry and physical environment in a freshwater system often dictate the phytoplankton community composition and ultimately the autochthonous primary production. Nutrients taken up by primary producers can be preserved in organic matter and used as an indicator of the source of nutrients and the biological pathway of that nutrient uptake. The quality and quantity of

phytoplankton available is important to the generation of bulk organic matter and the deposition of organic matter preserved in the lacustrine sediments.

AQUATIC ECOLOGY

In Lake Bosomtwe, as in many other crater lakes, phytoplankton are typically spherical and small, allowing for the greatest surface area to volume ratio (SA/V). Small sized phytoplankton have greater drag and resistance to sinking (according to Stokes Law) and possess the greatest area with which to transport nutrients into the cell. Algae under 10 μm in diameter do not require continuous motion to have effective uptake of nutrients from the surrounding medium because the unstirred boundary layer that develops around a cell is too small to accumulate metabolic wastes and reduce nutrient uptake (Fogg 1991). Since Lake Bosomtwe is a sheltered crater lake with little turbulent mixing, it is likely advantageous for most algae to be of a smaller size range for both the uptake of nutrients and suspension in the water column. Other phytoplankton regulate their buoyancy by changing their ionic content and lipid storage in the cell (Reynolds 1984).

The vertical distribution of phytoplankton in tranquil crater lakes is often controlled by thermocline depth and light penetration (Talling 1957; Talling 2001). Light that penetrates the water column is attenuated (scattered and absorbed) with depth (Wetzel 2001). The exponential decline of light energy with depth is the result of photons of light being dissipated into heat (Beer-Lambert's Law).

Transmission of light through the water column is preferentially absorbed by wavelength, with red light (650 nm) having the highest extinction coefficient and hence the lowest transmission. Blue light (460 nm) has the lowest absorbance and can reach great depths in pure water (Wetzel 2001). Red picoplankton use phycoerythrin pigments to absorb green light (530 nm), while green picoplankton absorb red light (650 nm) using phycocyanin pigments (Stomp et al. 2007a; Stomp et al. 2007b). In Lake Bosomtwe, low irradiance below 15 m depth restricts phytoplankton to those that contain

phycoerythrin (i.e. cryptophytes and cyanophytes within the deep chlorophyll maxima; Gervais and Behrendt 2003) or alternative pigment like isorenieratene, β -isorenieratene and okenone found in green and purple sulphur bacteria.

Cyanophytes in particular have a low tolerance for turbulent mixing and utilize their gas vacuoles to regulate their vertical position in the water column, and, as a result, are better adapted to life in a crater lake. During periods of high thermal stability and increasing water temperatures in Lake Bosomtwe, the upper five metres of the water column are dominated by filamentous and colonial cyanophytes (Awortwi, 2010). In Lake Bosomtwe, 80% of phytoplankton cells are cyanophytes and the most common species found are *Anabaenopsis*, *Aphanizomenon*, *Aphanocapsa*, *Cylindrospermopsis*, *Pseudanabaena* and *Pelonema* (aka *Planktolyngbya*) (Hedy Kling, pers comm., F. Awortwi 2010). Heterocyst formation was found to be abundant in *Cylindrospermopsis raciborskii* and *Aphanizomenon cf bergii*. These heterocysts are used for nitrogen fixation, a characteristic unique to cyanophytes (Stucken et al. 2010; Walve and Larsson 2007). Cyanophytes play a key role in the production of dissolved inorganic nitrogen upon their decomposition through the release ammonia that becomes available for other eukaryotic phytoplankton. In Lake Bosomtwe, it appears that nitrogen-fixing cyanophytes are an important component within the nitrogen cycle, which upon degradation is capable of supplying DIN for other photoautotrophs.

Diatoms are in low abundance in Lake Bosomtwe and were only found in water samples during the summer months of July and August. Diatoms are composed of a hard siliceous outer cell wall, known as a frustule. While some species of periphytic diatoms can move along a substrate, there is no mode of motility for planktonic diatoms suspended in the water column. As a result, diatoms require turbulent energy to maintain their position in the photic zone. Species like *Nitzschia gracilis* and *Fragilaria cf. pinnata* were predominant in the diatom community in Lake Bosomtwe. *Nitzschia gracilis* is a thinly silicified, elongate species known to be a good competitor for silica, with a high

affinity for Si at low concentrations (Kilham et al. 1986). *Fragilaria pinnata* is meroplanktonic diatom inhabiting the nearshore benthic environment in Lake Bosomtwe and known to be a good competitor at low light flux. The low diatom abundance likely is due to low silica availability ($680 \mu\text{g L}^{-1}$ which is only 0.6% of concentration of silica at saturation or 2.5% of diatom culture medium), the low wind intensity, strong thermal stratification and high pH. High alkalinity results in high silica dissolution rates that can weaken diatom frustules.

During May of the long rainy season in Lake Bosomtwe (Pete Verburg personal communications), light penetration extends further into the water column and Secchi disk depth deepens to a maximum depth of nearly 3 m. A deep chlorophyll maxima (DCM) occurs at 15 m water depth in Lake Bosomtwe, where photosynthetic bacteria proliferate below the thermocline (Puchniak et al. 2009). This DCM has been identified as a species of Chlorobiaceae, or green sulfur bacteria, known as *Pelodictyon clathratiforme*, in association with species of Chromatiaceae, or purple sulphur bacteria known as *Achronema* and *Lamprocystis hyaline* (identified by Hedy Kling, personal communications). Both of these latter species are able to photosynthesize using bacteriochlorophylls. These sulphur bacteria thrive in meromictic lakes rich in H_2S because they use the oxidation of H_2S as an electron donor during anaerobic photosynthesis in anoxic, deep waters (Overmann and Tilzer 1989). The deep chlorophyll maximum consists not only of bacteria, but also includes the cryptophyte *Cryptomonas marssonii*, the chlorophytes *Chlorella* and *Chlamydomonas* and the cyanophyte *Chroococcus* (Hedy Kling, personal communications).

These primary producers form the basis of the food web in Lake Bosomtwe, supporting zooplankton and planktivorous fishes, and contributing to the organic matter sedimentation of Lake Bosomtwe. Sanful (2010) found that the cyclopoid copepod (*Mesocyclops*), the cladoceran (*Moina*), many rotifers (*Brachionus*, *Keratella* and *Hexarthra*) and chaoborids fed on the phytoplankton, potentially altering the recycling of nutrients and the nature of the sediment composition. The majority of the

zooplankton species in Lake Bosomtwe selectively feed on phytoplankton. The edible phytoplankton are consumed and packaged into fecal pellets, affecting the sedimentation of organic matter to the surface sediments. Overall, how the biological in-lake processes for Lake Bosomtwe effect the formation of sedimentary records is poorly understood.

SEDIMENTATION

Solutes are concentrated in the deep, anoxic waters because suspended organic matter precipitates through the water column to the sediment surface at the bottom of Lake Bosomtwe. As materials settle through the water column from oxygenated to anoxic deep-waters, bacterial degradation releases by-products such as ammonia, methane, dihydrogen sulphide, carbon dioxide etc. at depth. Upon sedimentation in productive, aerobic deep-water conditions, bacterial decomposition consumes oxygen and can deplete oxygen from the pore spaces and sediment-water interface generating anoxic sediments. There is little physical disturbance of these anoxic sediments because there are minimal riverine inputs to Lake Bosomtwe (no deltaic formations are evident in the bathymetry), little winnowing of the deep-water sediment facies occurs (low external wind energy minimizes the depth of mixing), and anoxia and sulphur-rich deep-waters inhibit biota from feeding on detritus. It would appear that ultimately most organic matter is either sequestered in the sediment layers or returned to the upper euphotic zone through dissolution or ebullition rather than direct resuspension.

The Bosomtwe impact crater contains a basement layer of 294 m of post-impact sediment (Koeberl et al. 2007), most of which is finely laminated. Finely laminated sediments from Lake Bosomtwe have the potential to reveal changing limnological and climatological records during the past one million years. However, more needs to be understood about the connections amongst the local and regional meteorology and in-lake processes.

OVERVIEW OF THE PRESENT STUDY

This thesis is organized into four subsequent data chapters (chapters 2 to 5) and a concluding chapter (chapter 6) to develop an improved understanding of the origin, transformation and preservation of sediments in Lake Bosomtwe, Ghana. The objective of this thesis is to present the relationships among the meteorology, limnology, sedimentology and accumulated sediment record during the past ~550 years to better understand the current factors affecting Lake Bosomtwe and to help inform interpretations based on physical and geochemical analyses of the deeper and older lacustrine sediment records from the lake.

In Chapter 2, entitled “Effects of seasonal climatic patterns on the water column structure, nutrient dynamics and primary production of Lake Bosomtwe, Ghana (West Africa),” two years (2004-06) of nearshore meteorological data from Lake Bosomtwe are related to water column profiles of temperature, and concentrations of dissolved oxygen, dissolved nutrients (total nitrogen and total phosphorus) and chlorophyll *a* concentrations at a central sampling station. The seasonal climate patterns over Lake Bosomtwe were found to influence the water column mixing regime and nutrient circulation that stimulated seasonal primary productivity.

In Chapter 3, entitled “Seasonal sedimentation in Lake Bosomtwe (Ghana, West Africa): assessing the role of water column mixing and nutrient regeneration on physical and geochemical characteristics of sedimenting materials”, sediment trap samples were collected monthly to bimonthly at two water depths (20 and 30 m) for 18 months during 2005-2006. Trap samples and water column samples were analyzed for particulate nutrient concentrations (carbon, nitrogen and phosphorus), stoichiometric nutrient ratios, chlorophyll *a* concentrations, stable isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), loss-on-ignition and elemental fluorescence with ITRAX scanning. Bulk organic sedimentation rates followed

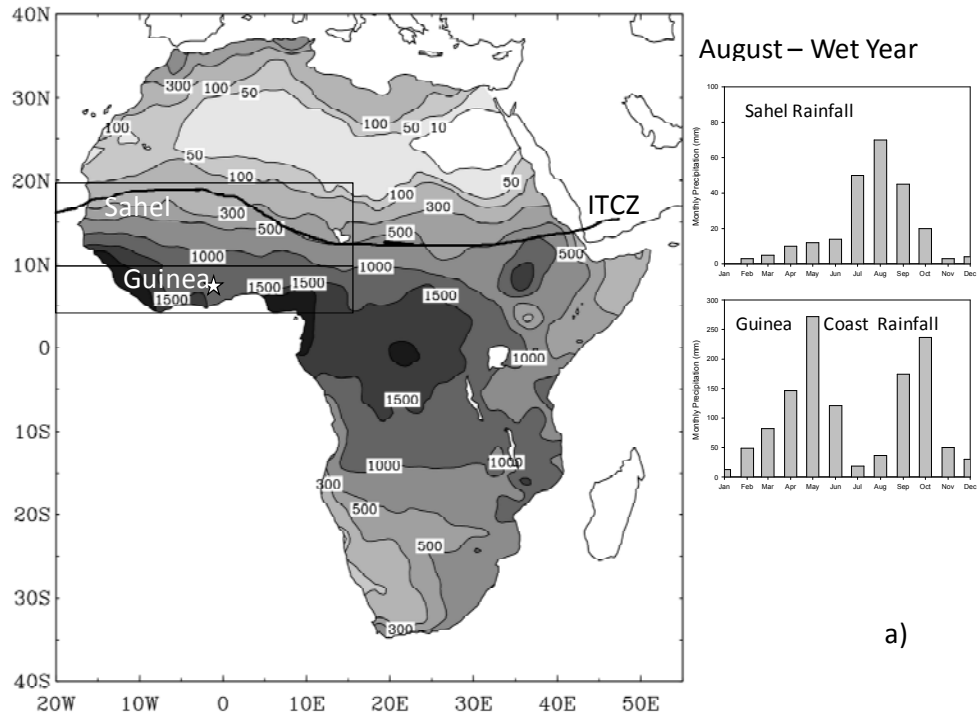
the seasonal pattern of water column productivity and biogeochemical composition of organic matter was strongly influenced by nutrient availability.

In Chapter 4, entitled “The role of water depth on spatial patterns of sediment composition and preservation of laminations in a sub-Saharan crater lake, Lake Bosomtwe (Ghana, West Africa),” ten short sediment cores (30-55 cm long) were collected along gradients of water depth at two transects that differed in the amount of anthropogenic activity. Cores were analyzed for loss-on-ignition, nutrient concentrations (C, N, P), stoichiometric nutrient ratios, stable isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and gamma ray spectrometry to characterize relationships with water depth. Nearshore sediments were affected by recent anthropogenic catchment disturbances through inorganic sedimentation.

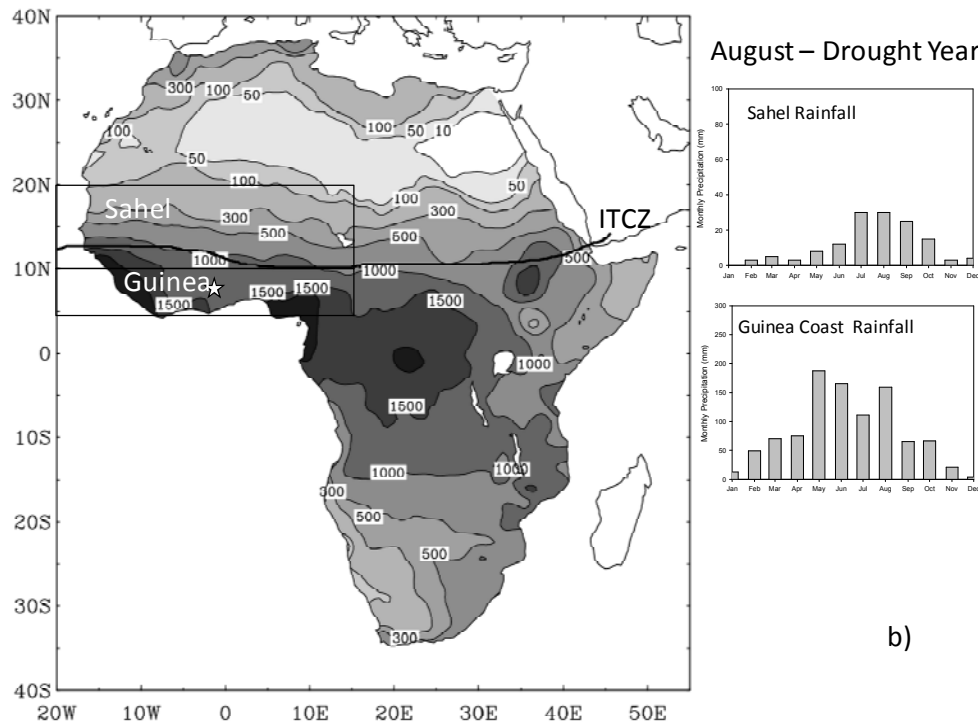
Laminations were found to be preserved below 35 m water depth and correspond with the depth at which anoxia persists in Lake Bosomtwe today. The quantity and constituents of organic matter were found to strongly correlate with water depth, as organic matter content increased with increasing water depth.

In Chapter 5, entitled “Paleolimnological reconstruction of sub-Saharan climate and human activities during the past 550 years at Lake Bosomtwe (Ghana, West Africa): how lake levels, mixing regimes and land-use practices affect the sediment record”, two dated short gravity cores were analyzed for loss-on-ignition, stable isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), nutrient concentrations (C, N, P), stoichiometric nutrient ratios, radiography and micro-scale elemental analyses using an ITRAX x-ray fluorescence core scanner (XRF). The sediment record was found to respond to drought in two ways. Long-term drought reduced water levels and reduced organic matter generation and preservation. Short-term drought reduced water column mixing regimes that altered the geochemistry of sediments with depleted $\delta^{13}\text{C}$ signatures of bulk matter. In sediments deposited since the late 1950s, the combined effects of land-use change and climate change appear to increase the inorganic matter delivery to the sediment layers, potentially dampening the effects of cultural eutrophication.

In conclusion, climate variability over and in-lake processes in Lake Bosomtwe were profoundly affected by Sahel drought patterns. Sahel drought appears to be linked to reduced nutrient delivery to the aquatic ecosystem, which reduced primary productivity, phytoplankton diversity, and organic matter sedimentation, which altered the biogeochemical composition of the sediment records. Sediments deposited during drought-induced low-water stands were low in organic content, $\delta^{13}\text{C}$ signatures and C:N ratios and high in inorganic content, magnetic susceptibility, density, and iron and titanium concentrations. In contrast, sediments deposited during wet periods were high in organic content, C, N, P, Ca and Sr concentrations and C:N ratios. Understanding these dynamic connections between sediment composition and meteorological events will improve the paleoenvironmental reconstructions from Lake Bosomtwe. Improving the ability to predict drought periodicity and severity over the region will also enable local governments to develop a planned response.



a)



b)

Figure 1-1 The position of the intertropical convergence zone (ITCZ – denoted by the black line) over the Sahel region (upper box) and Guinea Coast region (lower box) of West Africa in the month of August during a) wet years and b) drought years, presented over the map of the mean annual rainfall over Africa (modified from Nicholson 2001). Lake Bosomtwe, Ghana is denoted by a star.

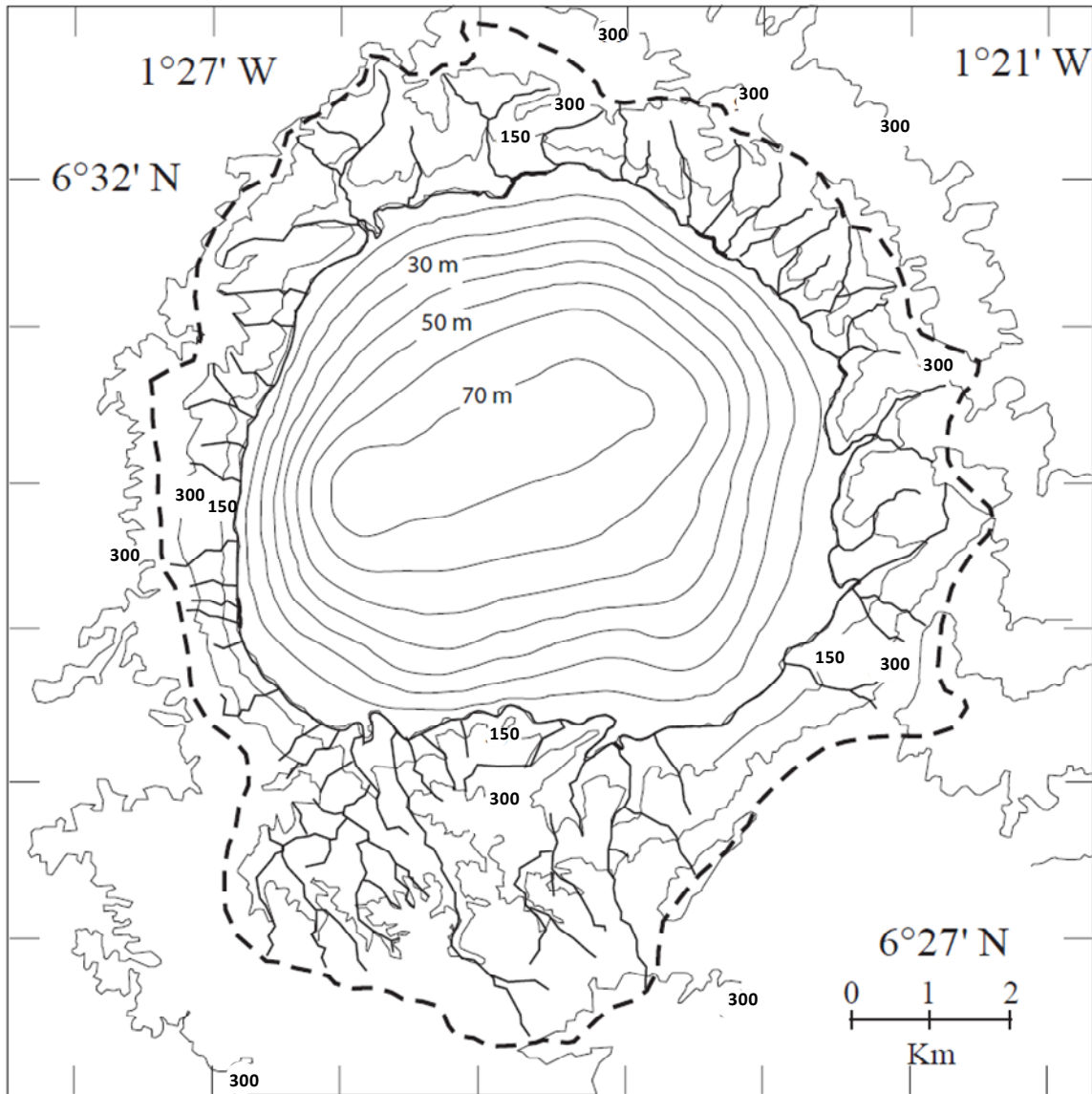


Figure 1-2 Basin map of Lake Bosomtwe showing the catchment topography (150 m increments) and the lake bathymetry (10 m increments). The dashed line denotes the extent of the catchment area (modified from Brooks et al. 2005)

2 Chapter - Effects of seasonal climatic patterns on the water column structure, nutrient dynamics and primary production of Lake Bosomtwe (Ghana, West Africa)

OVERVIEW

Understanding the role of seasonal climate patterns on the physical, chemical and biological properties of Lake Bosomtwe, Ghana will better inform paleoclimatological reconstructions from the lake's sediment deposits. Lake Bosomtwe is a site of high scientific interest because the International Continental Scientific Drilling Program coordinated collection in 2004 of a one-million-year climate reconstruction based. Our objective is to characterize the role of seasonal meteorological conditions on the physical structure, mixing dynamics, water chemistry and primary production of Lake Bosomtwe. We present the in-crater meteorological data and the water column profiles of temperature and concentrations of oxygen, chlorophyll *a* and nutrients (phosphorus, nitrogen, carbon) at a central deep-water location in Lake Bosomtwe from September 2004 to December 2006. Meteorological data indicate that the annual cycle consists of four seasons based on differences in precipitation, a sequence which includes the dry Harmattan (December and January), the long rains (February-June), the short dry period (July and August) and the short rains (September-November). The seasonal pattern of limnological variability largely coincided with the seasonal climate periodicity. The annual cycle of limnological conditions included primary production dominated by cyanophytes and strong thermal stratification during the long rain and short rain seasons. Deep-water chlorophyll *a* maxima was produced by green sulphur bacteria, which developed at the end of the long rains and extended into the short dry period. At the transition from the short dry to the short rain season, thermal destratification was observed that led to the entrainment of deep-water nutrients into the photic zone and stimulated primary productivity with up to 30 μg chlorophyll *a* L^{-1} and increased algal diversity. Finally, during the transition from the short rain to the Harmattan, the thermal stratification returned and primary productivity declined ($10.3 \pm 5.7 \mu\text{g chl a L}^{-1}$) and nutrient availability declined

gradually. The seasonal climate patterns over Lake Bosomtwe directly affected seasonal internal nutrient loading and primary productivity in the lake, which likely generates the production and preservation of laminated sediments. Based on evidence provided in this chapter, years with high amounts of rainfall over the Sahel Region that generate a bimodal pattern of precipitation over Lake Bosomtwe will likely result in greater effective cooling during the short dry season and produce more complete mixing of the water column and lead to greater nutrient regeneration and primary productivity. Climate changes that result in prolonged drought over the Sahel region and inhibit mixing of Lake Bosomtwe affect the biogeochemical cycling of nutrients, annual primary production and fisheries yields, which have profound implications for management of the local fishery. Reliable predictions of future climate trends over the Sahel region, West Africa not only better enable local governments to enact a drought management plan, but will serve to better inform the Lake Bosomtwe management of climate-induced thermal stratification.

INTRODUCTION

Understanding the manner in which local meteorological conditions and seasonal climate variations regulate the thermal structure and mixing regimes of deep tropical lakes better enables us to understand their influence on in-lake biogeochemical dynamics (Vollmer et al. 2002, Verburg et al. 2003). In productive tropical freshwaters, anoxia frequently develops in deep waters and enhances the dissolution of gases and nutrients in the hypolimnion to produce a sharp vertical water density gradient despite the small difference in water temperature. Lake Bosomtwe is one such tropical lake that is permanently hypoxic below 30 m and strongly influenced by regional meteorology. Lake Bosomtwe has accrued a million years of sediment at the lake bottom and contains an excellent sediment record for the reconstruction of paleoclimatic patterns over the Sahel region of West Africa. The 78-m-deep lake is located within a meteorite impact crater south of the Sahel region of Ghana, West Africa (Koeberl et al. 1997, 2007). The minimum height of the crater rim is 210 m amsl

surrounding the lake at 99 m amsl surface water level. The crater creates conditions of reduced wind stress and isolated hydrology from the surrounding Pra River Basin. The basement impact breccia formed during the initial meteoritic impact and overlying sediment layers inhibit groundwater exchange (Turner et al. 1996a). As a result, the hydrological balance and water-level fluctuations of this closed basin are driven by long-term fluctuations in precipitation relative to rates of evaporation (Turner et al. 1996a). Regional precipitation events in the Sahel are the result of the northward displacement of the intertropical convergence zone (ITCZ), a low-pressure belt formed at the confluence of the north-eastern and south-eastern trade winds (Janicot 1992). Interannual climate variability is most closely linked to the latitudinal variations in position and the intensity of the convection within the ITCZ (Mamoudou et al. 1995, Nicholson 1980). Seasonally, the Sahel region is driest when northeast trade winds, known as the Harmattan, transport dust from the Sahara Desert during the months of December and January (Beadle 1981). The northward migration of the ITCZ ushers in the rainy season over the Sahel and creates a brief dry period over Lake Bosomtwe to the south in July and August. Presently, little is known about the effect this seasonal climate forcing has on physical, chemical and biological dynamics of Lake Bosomtwe. This knowledge gap continues to hamper paleoclimatic inferences that are based on the information stored in the over 1-million-year sediment records collected from Lake Bosomtwe in 2004 (Koeberl et al. 2007).

Intra-annual variations between wet and dry seasons, and the interannual variability of these seasons have been known to influence the limnological succession of algal biomass, algal community composition and nutrient availability in tropical freshwater lakes, but are poorly understood in Lake Bosomtwe. In the equatorial tropics, it is unlikely that variations in solar radiation alone can directly induce seasonal changes in algal productivity, but the indirect effects of hydrological periodicity are often profound (Talling, 1986). For example, closed-drainage Lake Turkana (Kenya) receives nutrient-rich riverine inputs from the northern headwaters through flooding during the rainy season in August. These flood waters lead to a seasonal increase in total algal biomass, especially *Microcystis*

aeruginosa that can dominate annual primary production (Harbott, 1982). Historically, in the rift basin Lake Malawi (East Africa), a seasonal seiche event occurs during July and August that induces cool, nutrient-rich hypolimnetic waters to upwell in the southern basin. This provides an inoculum of dissolved silica that stimulates production of diatoms and causes seasonal silica delivery to the sediment layers (Patterson and Kachinjika 1998, Puchniak et al. 2010).

In deep, stratified African lakes with long water retention times like Lake Bosomtwe, internal nutrient loading to the pelagic zone often controls annual productivity. The amplitude of this primary production often varies in accordance with the magnitude of climatic variability. Talling (1969) recognized the same pattern of annual water column mixing during July and August in lakes Kariba, Malawi, N'Zilo, Victoria and Tanganyika, but the biogeochemical consequences of vertical mixing was markedly different amongst lakes. For example, mixing in holomictic lakes Victoria and Kariba circulated oxygenated waters to the lake bottom, as opposed to meromictic Lake Pawlo where mixing displaced anaerobic hypolimnetic waters to the surface and commonly resulted in a fish kill event through surface water hypoxia (Talling, 1969). The inter-annual variability of these mixing regimes directly affects the amplitude of the biomass, productivity and community composition of primary producers. Internal seiches in Lake Malawi are dependent on the timing and duration of the south-east *Mwera*. For instance, stronger winds in 1993, as compared to 1992, led to an overall increase in algal biovolume during 1993 (Patterson and Kachinjika, 1998). Although, mixing regimes for Lake Bosomtwe are not well understood, the lake is known to be anoxic within the deep-water hypolimnion and fishermen tell of fish-kill events that were believed to occur annually, but have reportedly become less frequent in recent decades.

Commonly, large, stratified African lakes are nitrogen-deficient because high rates of denitrification occur in anoxic deep-waters that lead to low nitrogen to phosphorus ratios (N:P) (Hecky et al. 1996, Patterson and Kachinjika, 1998). Dissolved forms of growth-limiting nutrients nitrogen and

phosphorus can often be found in abundance below the oxycline of these lakes, since microbial decomposition of detrital material releases labile nutrients. The ratio between total nitrogen and total phosphorus, however, can decline through the loss of nitrogen through denitrification in the anoxic zone. In nearshore Lake Victoria, nitrogen availability is limited and favours the prevalence of heterocystous cyanobacteria with greater rates of nitrogen fixation (Hecky, 1993, Ramlal, 2002). Low N:P ratios can also be found when primary production accelerates. In Lake Malawi, N:P ratios declined in algal cells during upwelling events because phosphorus was assimilated more efficiently than nitrogen (Patterson and Kachinjika, 1998). In Lake Bosomtwe, for instance, little is known of the supply of nitrogen and phosphorus to the lake or how seasonal availability influences the total biomass and productivity of primary producers. Improved knowledge of these nutrient dynamics is important because the algal growth is needed to support the fish populations and the fishery yields are a critical source of nutrition and income for the economically-disadvantaged human population of the Bosomtwe basin.

Currently, the effects of seasonal climate variability on the thermal stratification and limnological dynamics of Lake Bosomtwe are poorly documented and the objectives of this study are to characterize the seasonal changes in meteorological conditions within the crater walls and identify their influences on the physical structure, mixing dynamics, water chemistry and primary producers of the lake. This study presents the meteorological conditions, the water column profiles of the temperature and concentrations of dissolved oxygen, and the concentrations of total phosphorus (TP) and nitrogen (TN), chlorophyll *a* (chl *a*) and particulate carbon (PC), nitrogen (PN) and phosphorus (PP) and nutrient stoichiometry at a central deep-water station in Lake Bosomtwe during September 2004 to December 2006. We anticipate that improved knowledge of the linkages between climatic variations and limnological conditions will help guide paleoclimatologists to examine the most climate-sensitive proxies in the sediment matrix and enhance their interpretations.

MATERIALS & METHODS

Study Site

Lake Bosomtwe is located within a one million year old meteorite impact crater in south-central Ghana (6°30N and 1°25W). Lake surface area is 48.6 km² and centred within the 103.1-km² catchment area of semi-deciduous forest and agriculture (Figure 2-1). Maximum water depth is 78 m, but has fluctuated markedly in prehistoric times, including a high-water stand during the early Holocene that formed a terrace at 110 m above current lake level (Talbot & Delibrias 1977, 1980). Seismic evidence indicates it has been at least 35 m shallower (Brooks et al. 2005; Shanahan et al. 2009). Lake chemistry from the deep water is more dilute than expected for its age due to past overflow events (Turner 1996), with an average specific conductivity of 1150 $\mu\text{S cm}^{-1}$, alkalinity of 10320 $\mu\text{mol L}^{-1}$, salinity of 0.32 g L^{-1} , pH of 8.9 and carbon dioxide concentration of 59 $\mu\text{mol L}^{-1}$ (Puchniak et al. 2009).

Meteorological Data

A recording meteorological station, ONSET Computer Corporation part H21-001 with HOBO software, was installed in September 2004 on the north shore, near the village of Abono. This station captured rainfall, wind speed, wind direction, solar radiation, humidity and dew point every ten minutes, while lake level data were recorded biweekly to the nearest 1 cm using a staff gauge located near the shore.

Wedderburn numbers, which quantify the degree of stability of the water column stratification between the epilimnion and hypolimnion, were calculated as the ratio of the density differences relative to the wind forcing. Hydrolab profiles of temperature and conductivity were used to establish the water depth and density of the epilimnion, metalimnion and hypolimnion. Wedderburn numbers (W) were calculated following the equation $W = (Q \cdot H_i^2) / (U^2 \cdot L_i)$. Where $Q = g' \cdot (\rho_{\text{hypo}} -$

$\rho_{\text{epi}})^{1/2} \cdot (\rho_{\text{hyp}} + \rho_{\text{epi}})$, Q is defined by the force of gravity g' (9.8 m s^{-2}) on water density difference between the hypolimnion (ρ_{hyp}) and the epilimnion (ρ_{epi}), as determined through the temperature and salinity differences (Chen and Millero 1977, 1986). H_1 is the mixed layer depth, L_1 is the maximum breadth of Lake Bosomtwe (8.1 km) and U is the friction velocity in water where $U = (\rho_{\text{air}}/\rho_{\text{water}}C_d u^2)^{1/2}$ where C_d is the drag coefficient modified for winds measured at approximately 3 m height above the water surface and u^2 is the maximum wind speed (m s^{-1}), as in Imberger and Patterson (1990).

Limnological Sampling

Water column temperature, oxygen, conductivity and pH were profiled biweekly using a Hydrolab H₂O Multiprobe 6SBP, alongside Secchi disk measurements. Oxygen probe measurements were validated with surface water Winkler titrations to correct for possible erroneous measures when the probe was exposed to sulphide-rich waters. Water samples were collected with either a Niskin sampler or 6-L Van Dorn sampler at discrete depths (0.3, 1, 2, 5, 8, 10, 12.5, 15, 20, 25, 30 m). Whole water samples for total nitrogen and total phosphorus analyses were pre-screened through a 63- μm mesh into scintillation vials. All other subsamples for each depth interval were taken from a carboy of pre-screened water (63 μm), placed in a dark cooler and transported to shore. Sampling for TN, TP, chl *a*, PC, PN and PP was performed every two weeks during September 2004 to December 2006 at each of the depths. Intensive sampling of multiple chemical constituents in excess of the routine water chemistry was conducted in May 2004, September 2004, June 2005 and August 2006 providing concentrations of sulphate, chloride ions, nitrate, nitrite, ammonia, isotopic concentrations $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of particulate organic matter, and $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of water through a greater range of water depth (0, 5, 10, 15, 20, 25, 30, 40, 50, 60 and 70 m).

Chemical Analyses

Chlorophyll *a* concentrations were determined by filtering a measured volume (0.5–1.0 L) of lake

water through a Whatman GF/F filter (0.7 µm pore size), and extracting pigments into acetone solvent. Fluorescence was measured by a Turner Designs Field Fluorometer 10-AU-005 (Sunnyvale, CA) set to deliver excitation of blue light (430-450 nm) and sense the emission of red light (650-675 nm). After the excitation was obtained, the sample was acidified with 3 drops of 1N HCl to denature the chlorophyll *a* porphyrin ring and re-measured. The difference was used to calculate the undegraded chlorophyll *a* concentrations removed from humic impurities and phaeophytin (Stainton et al. 1977).

Concentrations of total phosphorus (TP), dissolved phosphorus (DP) and particulate phosphorus (PP) were analyzed at the University of Waterloo, Waterloo, ON. Samples for measuring TP concentration were collected in scintillation vials, acidified with 0.15 ml of 4N H₂SO₄ and stored at 4°C until transport to Waterloo. TP was measured from unfiltered lake water by a potassium persulfate digestion and analyses of orthophosphate measured with molybdate, ascorbic acid and trivalent antimony to produce blue coloured phosphomolybdic acids that can be quantified at 885 nm on the spectrophotometer (Stanton, 1977). Concentrations of DP were measured from the filtrate that passed through Whatman GF/F filters, and was transferred into scintillation vials and acidified with 0.15 ml 4N H₂SO₄ and stored at 4°C until analysed with the ascorbic acid method. Concentration of PP was measured by filtering a known volume (0.5-1.0 L) of lake water onto a pre-ashed Whatman GF/F filter, wrapping the filter in aluminum foil, sealing it in a Ziploc® bag and storing it frozen until analysis at the University of Waterloo.

Concentrations of total nitrogen (TN), nitrite (NO₂), nitrate (NO₃) and particulate nitrogen (PN) were analyzed at the University of Waterloo or the Freshwater Institute, Winnipeg. Samples for analysis of TN were collected in scintillation vials, acidified with 0.15 ml of 4N H₂SO₄ and stored at 4°C until analysis at the University of Waterloo. TN was analyzed by L. Pinnell using a reduction column of cadmium filings exposed to copper and the addition of a buffer solution (ammonium chloride, sodium

tetraborate and disodium dihydrate EDTA). The resultant nitrite fraction was reacted with a solution of sulfanilamide, hydrochloric acid and N-(1-naphthyl) ethylene diamine dihydrochloride to produce a pink azo dye that was quantified by measuring absorption at 543 nm. Concentrations of NO₂ and NO₃ were measured from filtrate of Whatman GF/F (0.7µm pore size), transferred to scintillation vials, acidified with 0.4 ml of 4N H₂SO₄ and stored at 4°C until transport to the Freshwater Institute, Winnipeg.

Carbon species measured included dissolved inorganic carbon (DIC), carbon dioxide (CO₂), methane (CH₄), bicarbonate (HCO₃⁻) and particulate carbon (PC). Sampling for DIC, CO₂, CH₄ and HCO₃⁻ followed protocols of P. Ramlal (2002). Water samples from the Niskin sampler were transferred to evacuated glass serum bottles containing KCl (10% by volume). The Niskin sampler was fitted with surgical latex tubing, a duct clamp and syringe to allow the bottles to be filled until pressure equalized within the bottle and the rubber stopper maintained the seal. The water volume was determined by weighing samples and subtracting the weight of the bottle and stopper. Subsequent analyses were performed by P. Ramlal at the Freshwater Institute in Winnipeg, MB. Particulate carbon and particulate nitrogen were collected from 0.5-1.0 L of lake water filtered onto pre-ashed, Whatman GF/F filters that were wrapped in aluminum foil, sealed in a Ziploc® bag and stored frozen until analysis. Filters for analysis of PC and PN were dried overnight at 60°C, cut into half and packed into a nickel sleeve for combustion. Samples were processed with elemental analyzer Exeter CEC Model 440 (Zimmermann & Keefe 1997). Carbon and nitrogen peaks were used to calculate molar units (µmol g⁻¹ dry sediment weight) to determine the molar ratio between carbon and nitrogen.

RESULTS

More than two full annual cycles of meteorological data, water temperature and oxygen concentrations were captured between September 2004 and December 2006 (Figure 2-2 & 2-3). The

four annual seasons at Lake Bosomtwe were characterized as: 1) the dry northeast winds of the Harmattan during December and January; 2) the long rains during February to June; 3) the short dry period during July and August; and 4) the short rains during September to November. Annual precipitation during 2005-2006 was on average $1,250 \text{ mm yr}^{-1}$, yet both years were considerably lower than the basin average from 1969 to 1992 ($1,380 \text{ mm yr}^{-1}$) reported by Turner et al. (1996b). Monthly rainfall maxima were measured in May during the long rain season in 2005 and 2006, while monthly rainfall minima occurred in December during the Harmattan season (Figure 2-2). The distribution of precipitation was bimodal in 2005 with a short dry season evident as a marked decline in monthly rainfall during July and August, whereas the distribution of precipitation was unimodal in 2006 because the short dry period had greater rainfall.

The warmest daily air temperatures occurred in March at the onset of the long rain season, whereas the coldest air temperatures occurred in January during the Harmattan and August during the short dry season (Figure 2-2). The lowest maximum daily air temperature (24.8°C) was recorded on 12 August 2005, which coincided with high daily average relative humidity (95.1 %), high daily precipitation (31.6 mm), elevated wind speeds (0.93 m s^{-1}) and a documented fish-kill event (P.O. Sanful, personal observation). Overall, the average monthly minimum air temperature was 1.8°C colder and the wind speed was higher in 2005 than in 2006.

Low Wedderburn numbers (values approaching 1) indicated that the probability of water column destratification during both the arid Harmattan and the short dry period was high during both 2005 and 2006. Conversely, during the long rains, destratification was very unlikely (Figure 2-2) and was characterized by a deepening and strengthening of the density stratification (Imberger & Patterson 1990). After January 2006, the overall pattern of thermal stratification was characterized by increasing Wedderburn numbers, low wind intensities and relatively high precipitation during the short dry period, which indicated low probability of water column mixing (Wetzel 2001).

The water column of Lake Bosomtwe was stratified throughout most of each year, but was weakly stratified during the dry seasons. The long rain season from February to June was characterized by a deepening of the thermocline and increased Secchi disk depth, as water transparency increased (Figure 2-3). The increased water transparency was associated with a rise in chlorophyll *a* concentrations at 12.5 m water depth during May and June, which measured $99 \mu\text{g L}^{-1}$ as per the chl *a* fluorescence technique. This deep chlorophyll *a* maxima (DCM) was found to consist primarily of green sulfur bacteria, c.f. *Pelodictyon clathratiforme* and purple sulphur bacteria *Lamprocystis sp.* (Hedy Kling, personal communication). The period of high water column transparency and the DCM was later disrupted by an abrupt cooling event on August 12th, 2005 (Figure 2-3), which altered the phytoplankton community composition (F. Awortwi, personal communication). This cooling event resulted in isothermal water temperatures measuring $26.81 \text{ }^\circ\text{C}$ that included hypolimnetic water temperatures. This cooling event also caused the upwelling of anoxic deep-waters, which led to hypoxic surface waters that asphyxiated fishes (Figure 2-3). In 2006, oxygen concentrations declined during the month of August, but surface water hypoxia did not occur. Throughout the duration of this study, oxygen profiles remained anoxic below 30-35 m water depth.

Seasonal variability of the phytoplankton biomass was estimated by the chl *a* concentrations (Figure 2-4a), which corresponded with the seasonal pattern of water column mixing. There was only one peak in surface water chlorophyll *a* concentrations annually, during the transition between the short dry and the short rain seasons in August (excluding the effects of the DCM). When water column thermal stability was disrupted in August, chlorophyll *a* concentrations tripled. In 2005, these concentrations were found throughout 30 m water depth, but in 2006 concentrations were restricted to the surface 15 m. Chlorophyll *a* concentrations during the year were on average, $10.3 \pm 5.7 \mu\text{g L}^{-1}$ for the euphotic depths, and only 2.7 ± 4.8 below 30 m depth. Using a light meter during 2004-2005 (after which the light meter was broken), light penetration in the euphotic zone of Lake Bosomtwe

was only 4.75 ± 1.57 m (Awortwi 2010).

Nutrients phosphorus and nitrogen are essential to algal growth and were found in abundance below the thermocline (Figure 2-4b, c). The concentrations of phosphorus were one order of magnitude greater in the deep water (> 20 m) than in the surface waters (Figure 2-4b), likely because phosphorus was released from degrading sedimenting particulates into dissolved form and accumulated with time in the anoxic deep waters, whereas TP was rapidly consumed in upper waters. In August and September 2005, TP concentrations were moderately high at mid-water depths (5-20 m), however, TN concentrations were relatively low throughout the water column (Figure 2-4c). Only during much deeper mixing in July 2005 of the short dry, and in January 2006 of the Harmattan, did TN concentration increase to $\geq 2,000 \mu\text{mol L}^{-1}$. The low TN availability implies that internal N loading is more restricted than P loading. Reduced TN concentrations may be caused by the process of denitrification in the anoxic zone, which converts nitrates into N_2 gas and degasses to the atmosphere (Hecky et al. 1996). The TN concentration during February 9, 2006 was high at $1,075 \mu\text{mol L}^{-1}$ compared to the average of $305 \mu\text{mol L}^{-1}$ and may be evidence of the start of a deep-water nutrient upwelling during the Harmattan in February 2006, although it was not complete mixing. The lake has been known to mix and result in a fish-kill event during both the short dry period in August and potentially the Harmattan in January (James Addai, personal communications).

The distribution and form of growth limiting nutrients P, N, and C in the water column of Lake Bosomtwe appear to be constrained by the depth of the thermocline (Figure 2-5a, b, c). There was an abundance of dissolved nutrients in the anoxic deep-water hypolimnion. The majority of TP was found to be in the dissolved phosphorus form sequestered deep in the hypolimnion, while particulate phosphorus remained near $0.2 \mu\text{mol L}^{-1}$. TN was largely made up of ammonia and was in extremely high abundance near the sediment-water interface from the deamination of decomposing particulates accumulating at the lake bottom. Total dissolved nitrogen also included a small fraction of nitrite and

nitrate (one tenth) at 10-20 m near the oxycline, where high rates of nitrification and denitrification occur. Dissolved inorganic carbon was highly abundant throughout the water column, even in the surface waters, and ranged from 8,500 – 10,500 $\mu\text{mol L}^{-1}$. However, pH varied from 8.4 to 9.8 and DIC was comprised mostly of bicarbonate. Deep-water methanogenesis during decomposition of surface sediments and sedimenting particulates evolved a small fraction of methane $< 500 \mu\text{mol L}^{-1}$, but did not provide an appreciable contribution to the total dissolved inorganic carbon concentrations (Figure 2-5c). Particulate C, N and P concentrations showed a comparable distribution of autochthonous production within the surface 10 m water depth, each measuring maxima within the upper 2-10 m water depth, while their concentrations were uniformly low within the hypolimnion.

The highest PC, PN and PP concentrations for Lake Bosomtwe (Figure 2-6) were measured after the Harmattan and short dry seasons. The complete mixing event in 2005 was accompanied by a larger vertical distribution of PC and PN in the water column, while the limited number of sampling episodes prevented a clear characterization of the distribution of PC and PN during 2006. The PP concentrations were relatively constant year-round until the short rains during August to November, when it doubled and was distributed throughout the entire water column. The duration of the elevated PP concentrations in 2005 was longer than in 2006.

The stoichiometric ratios of particulate C, N and P in Lake Bosomtwe (Figure 2-7) highlight the dissimilar rate of nutrient assimilation within algal cells. The ratio of C:N:P indicated severe phosphorus limitation in Lake Bosomtwe for nearly all sampling dates (Guildford and Hecky 2000), except on 12 August 2005 when the water column mixing supplied readily assimilated dissolved phosphorus from the deep hypolimnetic waters. The carbon to nitrogen nutrient ratio was nearly static at 7.9 ± 0.9 from 2004-2006. There was a brief rise in deep-water C:N ratios during the deepening of the thermocline in July 2005 to 25.8 that rapidly returned to 8.9. The slight rise by one unit C:N in October and November may be due to accelerated primary production, as indicated by the elevated

chl *a*, PC and PN concentrations in the water column after the mixing event.

DISCUSSION

The air temperature and wind speeds, as well as in-lake thermodynamics were strongly influenced by annual patterns of precipitation over Lake Bosomtwe, which can be unimodal or bimodal. Periods of reduced rainfall during the dry seasons at Lake Bosomtwe were associated with reduced thermal stability of the water column due to effects of evaporative cooling and increased turbidity (Figure 2-8). In contrast, periods of elevated rainfall and cloud cover were associated with warming surface waters, greater thermal stability and water clarity. Like many thermally-stratified African tropical lakes, annual variations of primary production in the pelagic zone of Lake Bosomtwe were influenced by the water-column mixing patterns because of internal loading of growth-limiting nutrients nitrogen and phosphorus that far outweighed nutrient loading via seasonal wet or dry deposition to the lake surface or riverine inputs from the catchment (Bootsma et al. 2003, Hamblin et al. 2003, Pasche et al. 2009).

The seasonal climate patterns observed during 2004-2006 affected the physical structure, chemical composition and biological diversity in Lake Bosomtwe, shaping the four periods of limnological conditions: 1) a period of low nutrient availability when a cyanophyte community composition dominated during the long rain season; 2) a period of high thermal stratification and light penetration when a deep-water chlorophyll *a* maximum was produced by a bacteriochlorophyll *a* layer from green sulphur bacteria in May; 3) a period of increased nutrient availability supplied internally when a rise in algal productivity and diversity occurred during August of the short dry season; 4) and finally, a period of declining nutrient availability through the loss of nutrients to sedimenting particulates when primary productivity declined during the short rain and Harmattan seasons. Deep-water mixing events, driven by evaporative cooling, affected the quantity and quality of autochthonous organic

matter production (Figure 2-8), and likely increased the amount of organic matter delivered to the sediment layers seasonally.

Local meteorological conditions within the Lake Bosomtwe crater differed during 2005 and 2006 due to the interannual variability of the position of the ITCZ. During 2005, precipitation exhibited a bimodal pattern that was indicative of more northward displacement of the ITCZ over the Sahel during the short dry period in July and August (Figure 2-8). The lower air temperatures in August 2005 relative to 2006 produced a cooling event in the water column. In 2005, maximum daily air temperatures (24.8°C) fell below water temperatures (26.96°C) and caused vertical mixing of the water column. The convective heat loss from the lake's surface area increased surface water densities, which then displaced a mass of deeper water upwards during periods of increased wind intensity (Talling & Lemoalle 1998). As a result, vertical mixing of anoxic deep waters that were rich in reduced sulphides contributed to the chemical oxygen demand and depleted surface water oxygen concentrations (Whitmore et al. 1991, Escobar et al. 2009). This surface-water hypoxia produced a fish-kill event. The local Ashanti oral history tells of cyclic fish kills at Lake Bosomtwe in association with the smell of sulphur released from the deep water (Rohleder 1936). Local residents believe that the frequency of these fish kills has declined in recent times, which is a concern for the fishermen who benefit from harvesting the asphyxiated fishes. There may be reason to believe that fish kills have declined due to increased thermal stratification in Lake Bosomtwe during the past 40 years. Thermal water column profiles have found that small temperature and density differences between surface and deep waters were strong enough to resist complete mixing during annual climate variability.

A deep-water chlorophyll *a* peak during the long rain season in April and May coincided with strong thermal stratification and increased water clarity in Lake Bosomtwe. Seasonally, there was a deep chlorophyll *a* maximum at 12.5-20 m water depth, which greatly exceeded values in the surface

waters. These DCM were positioned in the water column at the thermal density difference between the metalimnion and the hypolimnion. Here, primary producers in the water column have access to an abundance of dissolved phosphorus and readily-assimilated ammonia. Whole water samples examined by H. Kling found that the autotrophic community consisted of both purple sulphur bacteria (*Lamprocystis sp.*) and green sulphur bacteria (*Pelodictyon sp.*). These sulphur bacteria were poised to take advantage of increased light penetration in May and higher nutrient availability that exists below the oxycline. Sulphur bacteria can emit high chlorophyll *a* fluorescence due to the nature of their low-light adapted, bacteriochlorophyll *a* pigment concentrations (Vila et. al, 2002, Vila and Abella 2001). For this reason, PC and PN concentrations were not found to increase at this deep-water chl *a* peak, rather, the analytical measure of chlorophyll *a* fluorescence had captured and over-quantified bacteriochlorophyll *a* concentrations. The detection of this deep-water autotrophy was a seasonal phenomenon in Lake Bosomtwe that was able to form when high water temperatures increased the depth of thermal stratification and algal biomass declined in the epilimnion, allowing sufficient light to penetrate to nutrient-rich deeper waters.

Chlorophyll *a* concentration and phytoplankton biomass in Lake Bosomtwe were found by F. Awortwi (2010) to be weakly correlated. A surrogate for chlorophyll *a* could be Secchi disk depth, which is easily and independently measured. Secchi disk depth is a measure of water column transparency that is inversely related to algal biomass and is removed from the effects of changing chlorophyll *a* concentrations both within algal cells and amongst algal species. The Secchi disk depth measures for Lake Bosomtwe exhibited two periods of declining water transparency annually. The first period, during the short rain season, has been discussed previously because of the large-scale changes in particulates associated with accelerated primary production. The second period occurred early during the long rain season when concentrations of particulate carbon and nitrogen increased in the water column. The long rain season, however, showed lower primary production in the form of low chlorophyll *a* concentrations. During the long rain season, cyanophytes were known to dominate

the algal community of Lake Bosomtwe (Awortwi 2010), which included *Anabaenopsis* spp., *Aphanocapsa* spp., *Lemmermaniella palida*, *Pseudoanabaena limnetica* and *Cylindrospermopsis* spp. Many of these species have the competitive advantage of producing heterocysts (frequently counted in abundance for *Anabaenopsis*) that are used in nitrogen fixation (Hedy Kling personal communications). The onset of the dry rains could be providing valuable trace elements from accumulated dusts, such as iron, molybdenum and manganese that critical in nitrogen fixation (Vitousek et al. 1991). The distinguishing difference between accelerated productivity during the short rain mixing event and long rain was that nutrient availability during the mixing event allowed for the succession of new algal taxa, such as diatoms, which had been less abundant in the water column of Lake Bosomtwe. A similar pattern of algal community composition was found in nitrogen-limited freshwater systems in the East African Rift lakes, Malawi and Tanganyika (Patterson and Kachinjika 1993, Hecky et al. 1996). The supply of dissolved nitrogen and phosphorus from the deep waters allowed new autotrophic species to out-compete cyanophytes in assimilating the nutrients. The high concentration of suspended particulate carbon and nitrogen during the long rains was confined to the upper 5 m water depth potentially due to wet deposition of nutrients. Increased concentrations of algae in the surface waters reduced the water transparency, as measured by Secchi disk depth, and likely caused self-shading within the algal community. The depth of the epilimnion increased during the long rains, but primary productivity decreased with increasing P limitation. The long rains appear to stimulate algal productivity with little evidence of changing water chemistry or nutrient stoichiometry, likely because the season is cyanophyte dominated and cyanophytes can fix nitrogen.

CONCLUSION

The climate-induced seasonal patterns of water column mixing and primary production in Lake Bosomtwe show one pronounced mixing period in August of the short dry period that is associated with the northward excursion of the ITCZ over the Sahel region. The transition from the short dry

period to the short rain period brought about a cooling event that disrupted the thermal stratification of the water column and stimulated primary production. The extent of water column mixing affects the amount of internal nutrient loading to the euphotic zone and the extent of primary production in August. Two years of limnological sampling of this sheltered crater lake show that small-scale climate variability result in dramatic ecological changes within the water column. The period of increased primary productivity in August resulted in greater organic matter generation that most likely resulted in greater organic matter deposition.

Inter-annual variability in the amount and timing of rainfall over Lake Bosomtwe has a pronounced effect on the extent of vertical water column mixing and primary productivity. The pattern of rainfall over West Africa is such that during wet years the northward displacement of the ITCZ to the Sahel region typically results in high rainfall delivery over the Sahel and a pronounced short dry season during July and August over Lake Bosomtwe and the Guinea Coast. Years with a cooler, more pronounced short dry season result in greater thermal destratification and more complete mixing of the deep waters that circulate nutrients into the euphotic zone. Thus, drought years over the Sahel region result in a unimodal pattern of precipitation and greater cloudiness over Lake Bosomtwe that create limnological conditions that inhibit or restrict complete mixing and reduce internal nutrient loading, primary productivity and likely also fisheries yields. The link between climatic and limnological conditions enables Lake Bosomtwe sediment records to preserve past drought events in both the Guinea Coast and the Sahel region.

Periods of prolonged drought would then restrict cooling and deep-water circulation, resulting in increased water temperatures and greater thermal stratification (Verburg et al. 2003, Verburg and Hecky 2009). Surface water heating would gradually decrease dissolved oxygen concentrations, aerobic water volume, nutrient recirculation, algal species diversity, and promote more persistent N₂-fixing cyanophyte dominance. The effects of such long-term climatic changes may be evident in deep

water temperatures that have increased from 26.38°C in 1935 (McGregor 1937) to 26.81°C in 2006. Meteorological drought conditions over the terrestrial Sahel region of West Africa likely result in limnological ‘drought’ conditions in Lake Bosomtwe, characterized by reduced primary productivity that likely supports lower fish yields.

The strong influence of water column mixing in Lake Bosomtwe makes the lake incredibly vulnerable to eutrophication because internal nutrient loading can greatly exceed external nutrient loading during mixing events. Lake Bosomtwe has a long water residence time, allowing for continual accumulation of nutrients in the deep waters. Presently, hypolimnetic waters are rich in growth-limiting nutrients. However, accelerated transport of nutrients by human activities would likely result in greater nutrient concentrations sequestered in the deep-waters. Pollution should be avoided, as the effects may be irreversible or slow to be amended in this closed-basin lake.

Anthropogenic activities in the catchment will affect the present limnological conditions of the lake’s productivity and likely its ability to preserve sediment records of recent climatic conditions. For this reason, paleoclimatic reconstructions must be cautious of the effects of long-term anthropogenic activities within the Lake Bosomtwe crater, West Africa.

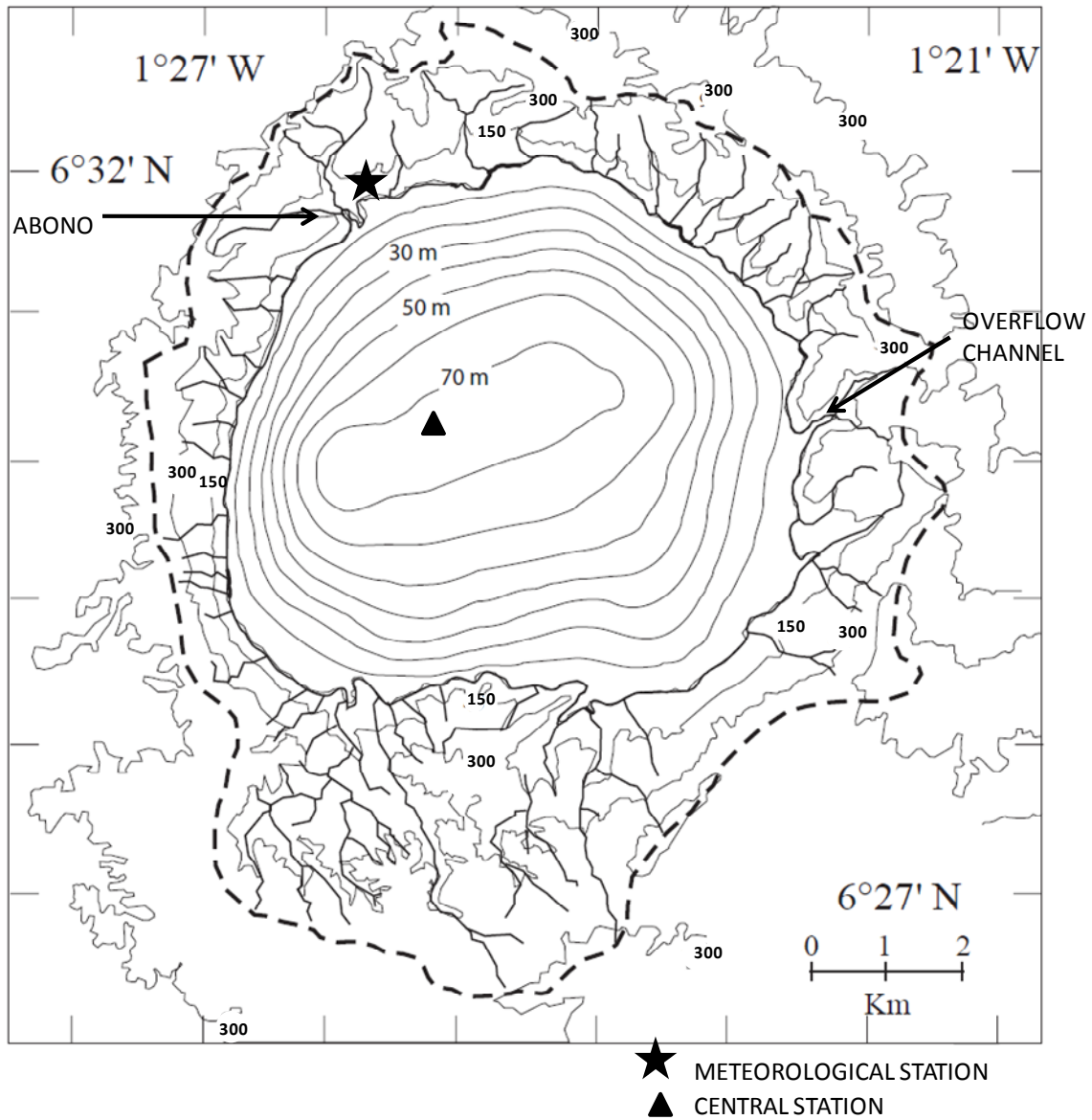


Figure 2-1 Basin map of Lake Bosomtwe showing the bathymetry in 10 m increments and catchment topography in 150 m increments. The dashed line denotes the extent of the catchment area. Maximum water depth is 78 m. (modified from Brooks et al. 2005)

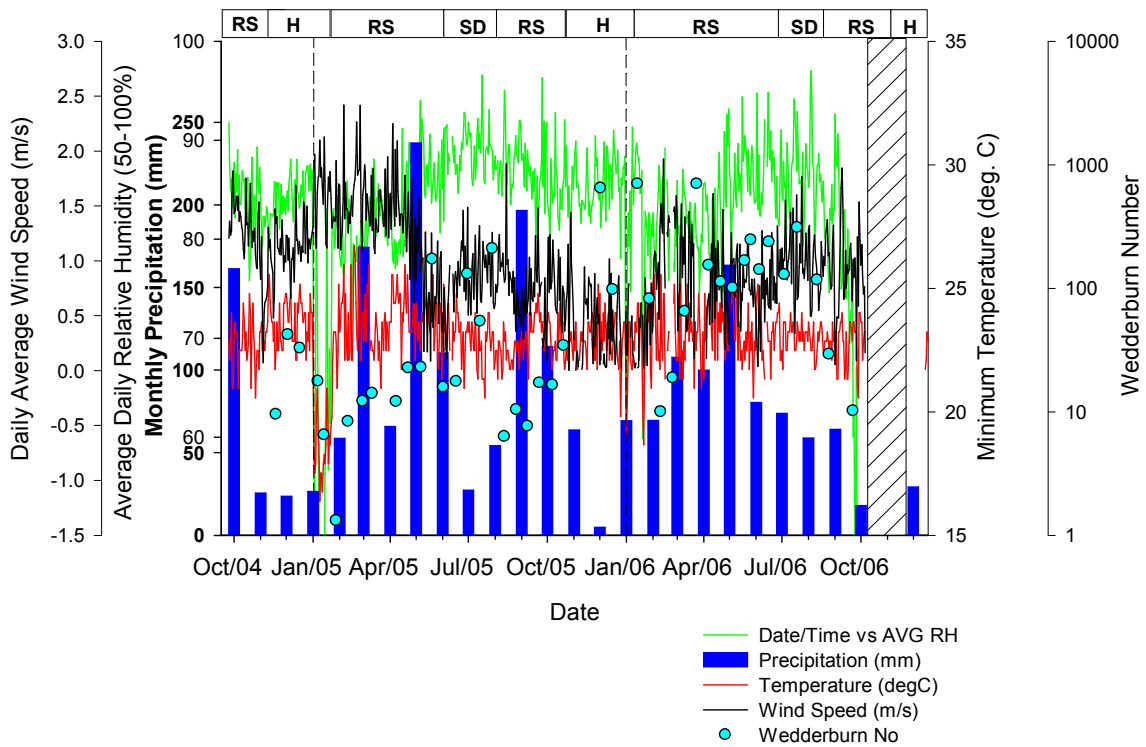


Figure 2-2 Distribution of monthly precipitation (mm, blue vertical bars), minimum daily air temperature ($^{\circ}\text{C}$; red line), average monthly wind speed (m s^{-1} ; black line) and average daily relative humidity (%; green line), as recorded at the nearshore meteorological station at Lake Bosomtwe during September 2005 to December 2006. Calculated Wedderburn values for the water column are indicated as light blue circles. Dashed vertical line denotes January 1, 2005 and 2006. Seasonal periods are denoted along the top axis with the Harmattan (H), the long rain (LR), the short dry (SD) and the short rain period (SR). The hatched box identifies a period when data were not collected due to malfunction of the meteorological station.

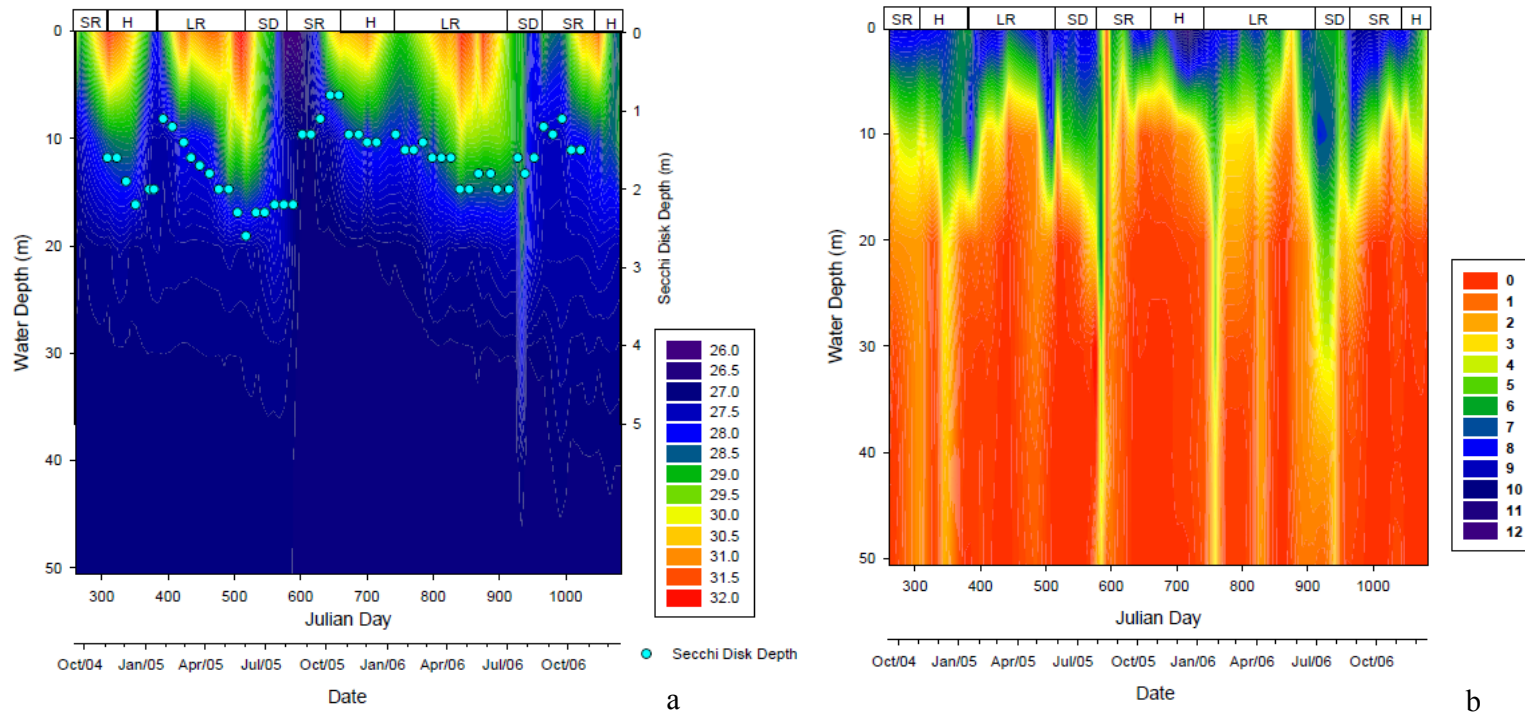


Figure 2-3 Isobaths of a) water temperature (with Secchi depth (m) reading as light blue dots) and b) dissolved oxygen concentrations (mg L^{-1}) in 0-50 m water depth for Lake Bosomtwe from September 2004 to December 2006 with seasonal periods known as the Harmattan (H), the long rains (LR), the short dry (SD) and the short rains (SR) denoted along the top axis.

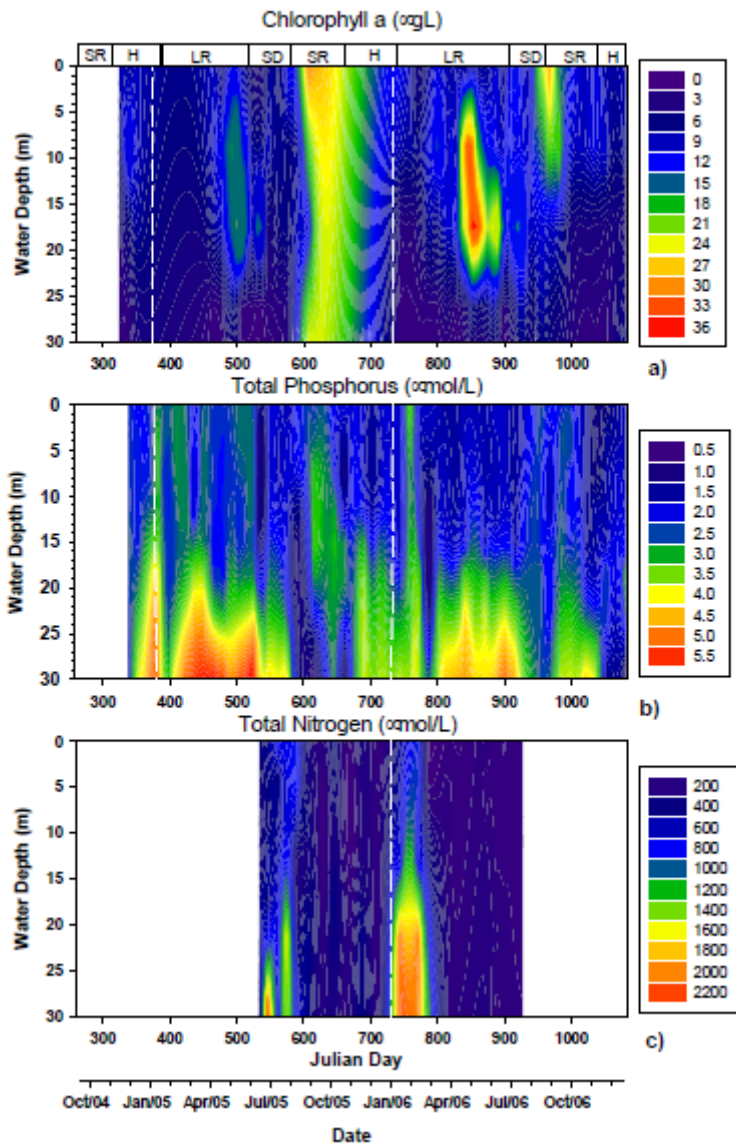


Figure 2-4 Isobaths showing surface water concentrations from 0-30 m water depth of a) chlorophyll *a* ($\mu\text{g L}^{-1}$), b) total phosphorus ($\mu\text{mol L}^{-1}$) and c) total nitrogen ($\mu\text{mol L}^{-1}$) from Lake Bosomtwe, West Africa between September 2004 and December 2006 with seasonal periods known as the Harmattan (H), the long rains (LR), the short dry (SD) and the short rains (SR) denoted along the top axis. White vertical dashed line denotes a new calendar year, 1 January 2005 and 2006. (Note: α in place of μ units)

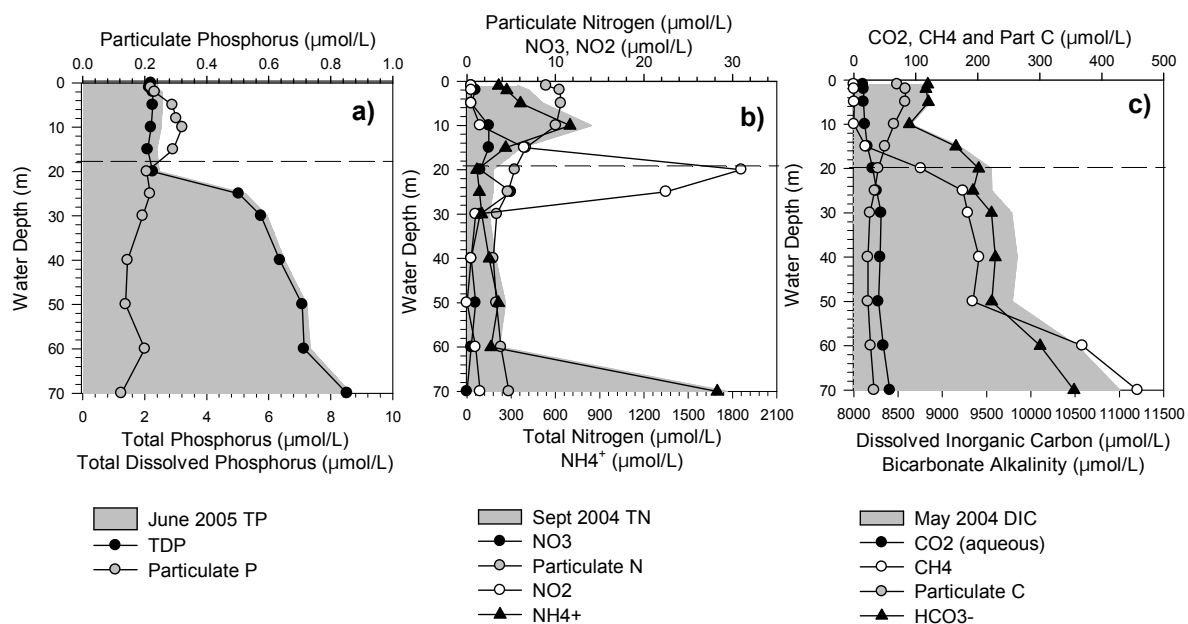


Figure 2-5 Profiles showing the depth distribution through the entire 70 m water column of concentrations ($\mu\text{g L}^{-1}$) of a) total phosphorus (TP), total dissolved phosphorus (TDP), particulate phosphorus (PP) during June 2005, b) total nitrogen (TN), ammonium (NH_4^+), particulate nitrogen (PN), dissolved nitrite (NO_3) and nitrate (NO_2) during September 2004 and c) dissolved inorganic carbon (DIC), carbon dioxide (CO_2), methane (CH_4) and particulate C (PC) and bicarbonate alkalinity (HCO_3^-) during May 2004 from Lake Bosomtwe, West Africa. The dashed line is the thermocline demarking the anoxic, deep-water hypolimnion from the metalimnion.

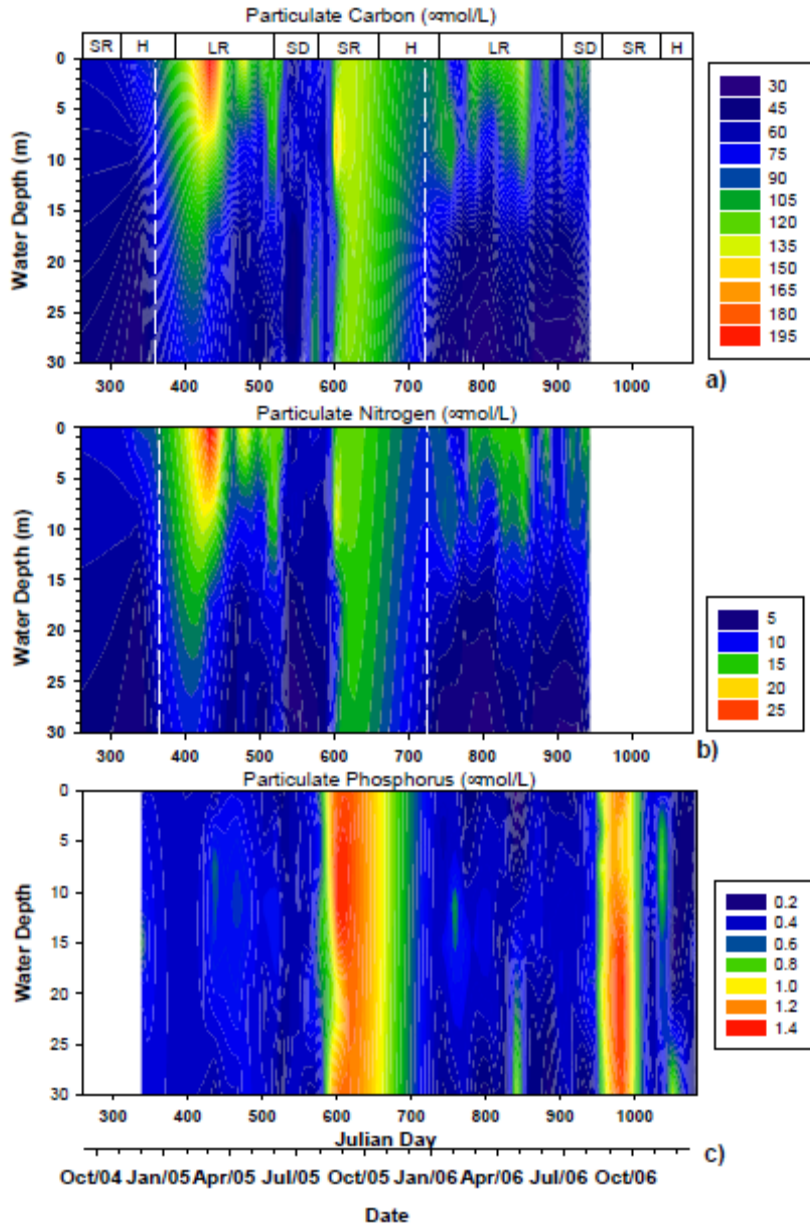


Figure 2-6 Isobaths showing the distribution of concentrations ($\mu\text{mol L}^{-1}$) of water column particulate nutrients within 0-30 m water depth a) particulate carbon, b) particulate nitrogen and c) particulate phosphorus from Lake Bosomtwe, West Africa from September 2004 to December 2006 with seasonal periods known as the Harmattan (H), the long rains (LR), the short dry (SD) and the short rains (SR) denoted along the top axis. White vertical dashed line denotes a new calendar year, 1 January 2005 and 2006. (Note: α in place of μ units)

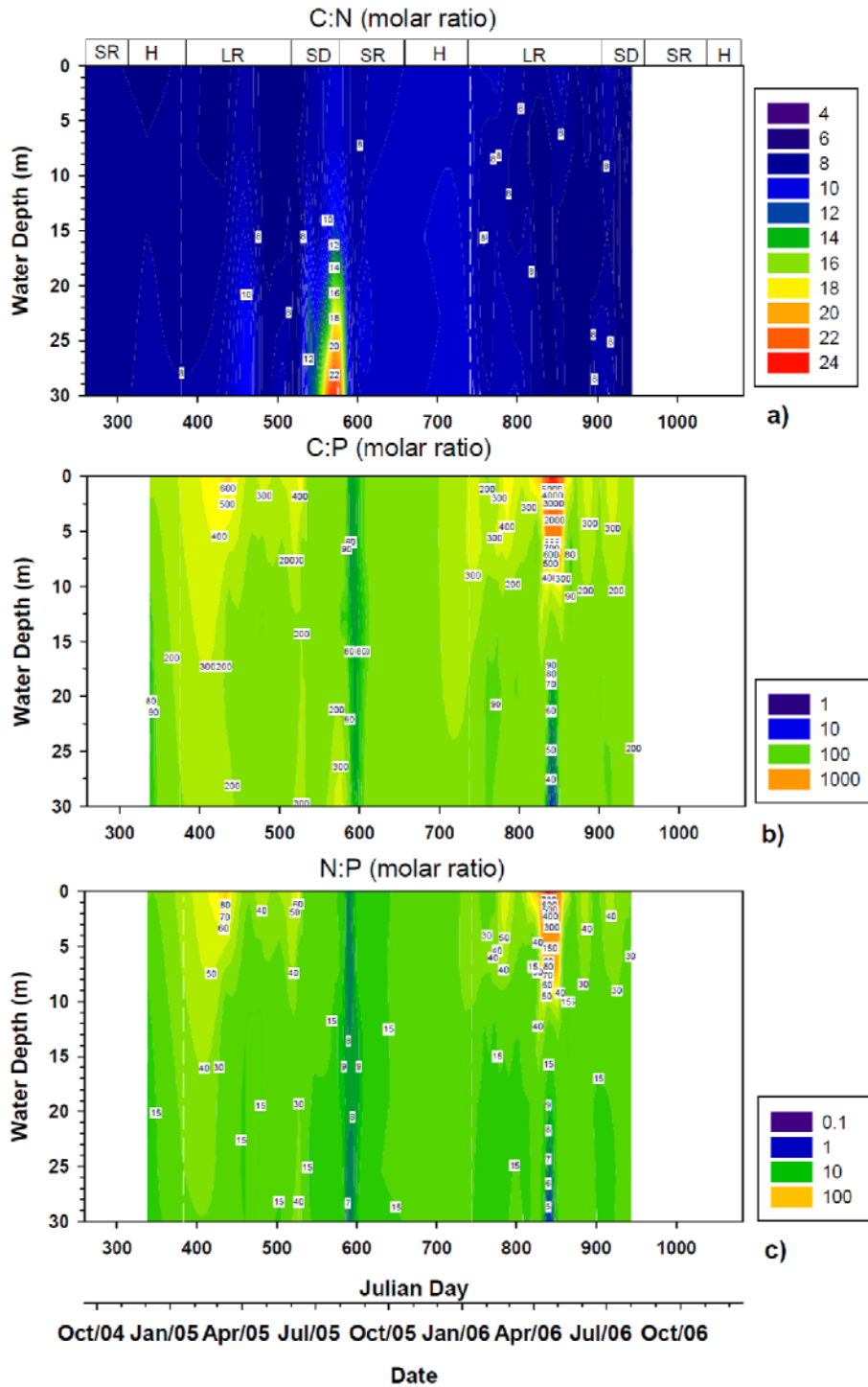


Figure 2-7 Isobaths showing the distribution of molar nutrient ratios through depth (upper 30 m) and time in Lake Bosomtwe, Ghana for a) carbon to nitrogen C:N, b) carbon to phosphorus C:P and c) nitrogen to phosphorus N:P for water column particulates between September 2004 and December 2006 with seasonal periods known as the Harmattan (H), the long rains (LR), the short dry (SD) and the short rains (SR) denoted along the top axis. White vertical dashed line denotes a new calendar year, 1 January 2005 and 2006.

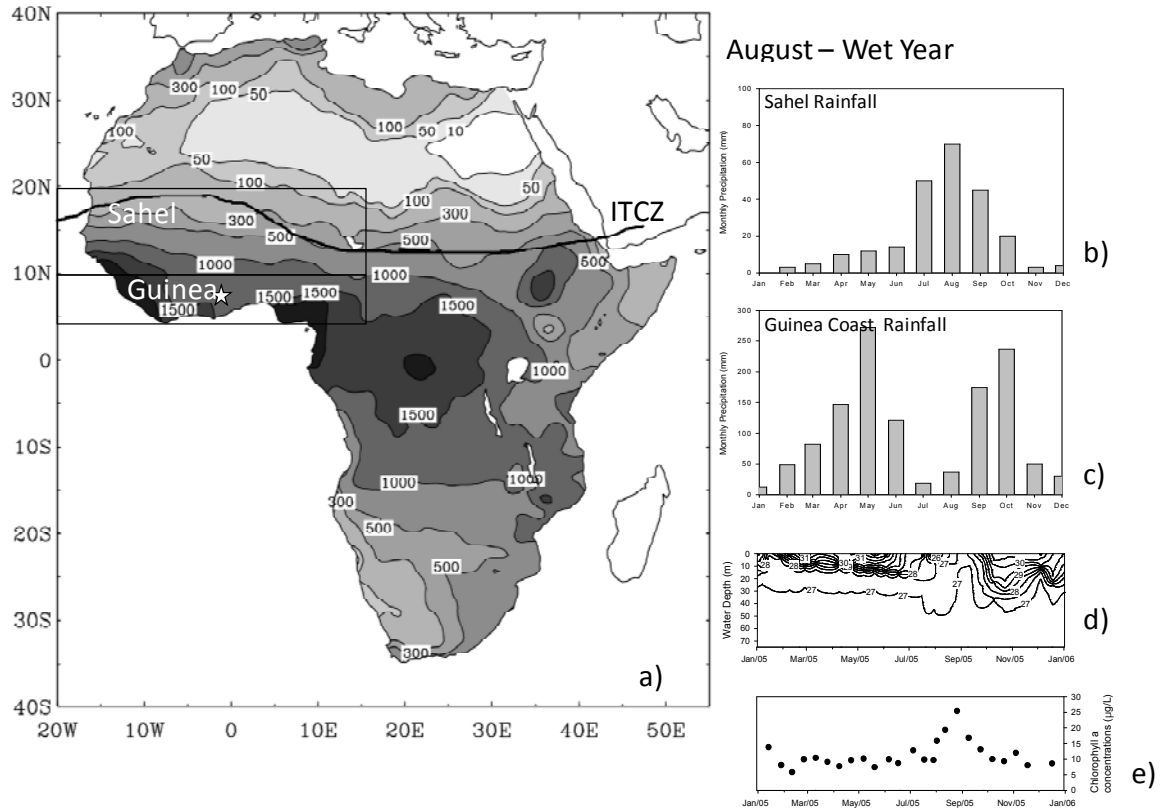


Figure 2-8 a) The displacement of the ITCZ over Africa during August presented over a map of annual rainfall. Bar charts show the pattern of rainfall over b) the northern Sahel region (10-20°N) and c) the southern Guinea Coast region of West Africa (0-10°N) during a wet year in the Sahel when a bimodal pattern of precipitation over Lake Bosomtwe (6°N denoted by a star) results in a cool short dry season and results in d) water column mixing as shown by temperature isopleths and e) stimulate increased primary production as shown by chlorophyll *a* concentrations.

3 Chapter - Seasonal sedimentation in Lake Bosomtwe (Ghana, West Africa): assessing the role of water column mixing and nutrient regeneration on physical and geochemical characteristics of sedimenting materials

OVERVIEW

Sub-Saharan West Africa, in particular the Sahel region, is prone to devastating periods of drought. The need to better predict drought periodicity in this region has led to the use of paleoclimatic reconstructions from information preserved in Lake Bosomtwe's sediment deposits. Lake Bosomtwe, Ghana is situated in the transition zone between the moist, forested Guinea Coast and the drier, scrubland of the Sahel region. The climate over Lake Bosomtwe is dictated by migration of the intertropical convergence zone (ITCZ) which, during wet (or non-drought) years in the Sahel region, results in a bimodal distribution of monthly precipitation at Lake Bosomtwe. An assessment of the climatic conditions that control the seasonal sedimentation patterns is required to interpret climate-related information in the laminated sediment records. Eighteen months of meteorological and limnological measurements and sediment trap collections at Lake Bosomtwe have advanced our understanding of the formation of light and dark laminae. Analyses of water column and sediment trap particulate nutrients (carbon, nitrogen and phosphorus), nutrient stoichiometry (C:N, C:P, N:P) and stable isotopic signatures ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), along with analyses of sediment trap samples for loss-on-ignition and X-ray fluorescence of elemental constituents were used to characterize sedimentation in Lake Bosomtwe. Climatic conditions during the short dry period of July and August were conducive to cooling of the water column, which led to water column mixing in August. This seasonal mixing stimulated primary production and resulted in increased organic matter flux that apparently produced the light laminations of the varved sediment. The breakdown of thermal stratification circulated deep-water nutrients into the surface waters and supplied an isotopically distinct nitrogen source that resulted in rapid $\delta^{15}\text{N}$ enrichment (by 6.1 ‰ to an average of 17.5 ‰) of

sediments. The $\delta^{13}\text{C}$ signature of the sediment responded inversely, with a marked depletion (by 4.9 ‰ to an average of -31.9 ‰) that likely was due to a large supply of $\delta^{13}\text{C}$ -depleted deep-water CO_2 from respiration. After the mixing event, sediment isotopic signatures recovered to pre-upwelling values, but were associated with the deposition of calcium and carbonate, likely due to biologically-induced calcite precipitation from the stimulation of primary production that resulted in CO_2 -limitation in alkaline surface waters. In contrast, inorganic matter deposition peaked following the onset of the short rains in August and September with over $3 \text{ g m}^{-2} \text{ d}^{-1}$. Inorganic matter was likely delivered through riverine inputs from the erodible catchment area. This seasonal inorganic matter flux was abrupt and potentially enhanced by the current farming practices in the catchment, where the planting of a second crop in October results in immature vegetation that cannot hold back soils during overland flow events. Anthropogenic activities, as well as the pattern of annual precipitation, are likely the factors contributing to the thickness of dark inorganic-rich laminae in Lake Malawi, as hypothesized by Shanahan et al. (2008). Whereas, the most important seasonal climatic conditions that exert control over organic matter sedimentation in Lake Bosomtwe appear to be the short dry period of July and August, which cooled and deepened the thermocline and resulted in thermal destratification that generated suspended autochthonous organic matter and subsequent organic matter sedimentation. High-resolution paleoclimate reconstructions of drought over the Sahel region from information in Lake Bosomtwe's laminated sediments, particularly measures of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ in bulk matter, are very promising and will better enable policy makers to mitigate the effects of prolonged drought in the region.

INTRODUCTION

Understanding seasonal sedimentation patterns that produce varved lacustrine sediments is important to inform accurate paleoclimatic reconstructions in lacustrine systems, particularly in Lake Bosomtwe (Ghana), which lies south of the Sahel region of sub-Saharan West Africa, a region that is highly

vulnerable to prolonged droughts. The regional patterns of precipitation over West Africa result in three different vegetation zones: the southern forested Guinea Coast, the arid-tolerant Sahel scrub land, and the northern barren Sahara Desert (Nicholson and Palao 1993, Hall and Swaine 1981). These vegetation zones correspond to the annual patterns of precipitation and evaporation that are affected by the location of the intertropical convergence zone (ITCZ), a moist low-pressure meteorological system (Nicholson and Webster 2007). Rainfall delivery by the ITCZ commences in February over Lake Bosomtwe and the northward progression of the ITCZ latitudinally brings rainfall to the Sahel region by June. Rainfall over the Sahel region is restricted to June, July and August, after which the ITCZ migrates southward over Lake Bosomtwe and the Guinea Coast. Drought years in the Sahel region occur when northward displacement of the ITCZ is restricted and rainfall is limited to the southerly Guinea Coast region. Agricultural practices in the Sahel region depend on precipitation for crop production, and subsistence farmers are vulnerable to food and water shortages during inhospitable climatic conditions. Furthermore, expansive cultivation, bush fires and deforestation over the Sahel region are believed to alter land surface albedo (Lare and Nicholson 1994), which potentially amplifies the effects of drought. Concern for human population under conditions of reduced rainfall and rising air temperatures has spurred a multidisciplinary scientific assessment of West Africa's long-term climate trends.

Long-term instrumental records over the Sahel and Guinea Coast regions of West Africa are sparse and restricted to meteorological stations that have operated irregularly during the past century. Few alternative sources of long-term meteorological data are available. Lake Bosomtwe is the only crater lake in sub-Saharan West Africa and its lacustrine sediment deposits hold the promise of long-term climatic records. Lake Bosomtwe, Ghana (1°25 N, 6°30 W) is situated at the northern extent of the semi-deciduous forested Guinea Coast and is contained within a 11-km-diameter crater that was formed by a meteorite impact 1.07 million years ago (Koeberl 1997). Previous, paleoclimatological studies at Lake Bosomtwe reconstructed lake level changes in association with drought periodicity

over West Africa during the Holocene (Shanahan et al. 2009, Peck et al. 2004; Brooks et al. 2005). In 2004, however, the International Continental Scientific Drilling Program (ICDP) recovered the complete-million year lacustrine sediment record from the bottom of Lake Bosomtwe (Koeberl et al. 2007). The goal of the ICDP is to reconstruct a million years of past climate variability over Lake Bosomtwe to better understand the factors that regulate the climate of sub-Saharan West Africa and the impacts of climate on the landscape.

Most of the 294-m sediment record from Lake Bosomtwe are finely laminated, providing information at high temporal resolution. Tropical crater Lake Bosomtwe is ideal for the recovery of undisturbed lacustrine sediments. Warm water temperatures enhance the stability of thermal stratification in the surface waters (> 26.5 °C). The lake today is 8 km in diameter and maximum water depth is 78 m. The lake is completely contained within the impact crater walls. As a result, the crater walls buffer the effects of wind stress and mixing below 30 m water depth, resulting in an anoxic, sulphide-rich hypolimnion. The thermal stratification precludes benthic biota and deep-water oxygenation of sediments. Consequently, the sediment layers at the lake bottom consist of well-preserved laminae, believed to record seasonal sedimentation patterns (Shanahan et al. 2008).

To date, long-term climatic patterns have been inferred from information of past water-level fluctuations preserved in the laminated sediment records of Lake Bosomtwe. The hydrological regime of Lake Bosomtwe is a balance between evaporative losses and gains from direct precipitation and catchment runoff (Turner et al. 1996). The basement impact breccia and overlying sediment layers that line the Bosomtwe crater have restricted hydrological exchange between the lake and ground water. Likewise, the steep crater walls have prevented any hydrological connection to the surrounding Pra River basin. Early exploration of the exposed river beds around the Bosomtwe impact crater found that the lake levels have fluctuated substantially during millennial-scale climate variability, leaving ancient terraces 110 m above present-day lake levels (11.6-8.8 cal ka) and depositing beach

sands and fossil fish remains extensively along the crater walls (Talbot and Delibrias 1977, Shanahan et al. 2006).

Climate changes over Lake Bosomtwe during the Holocene have contributed to our understanding of global circulation patterns, providing evidence that well-documented northern hemispheric climatic events extended to the equatorial tropics. Paleoclimatological analyses of sediment cores recovered from Lake Bosomtwe revealed that the Younger Dryas (12.6-11.6 cal ka) and Heinrich 1 (17.8-16.8 cal ka) and Heinrich 2 (23.0-22.3 cal ka) events corresponded with periods of reduced lake level due to more arid climate conditions (Peck et al. 2004, Shanahan et al. 2006). These low lake levels were inferred in the sediment stratigraphy from elevated deposits of calcium carbonate minerals that progressed from calcite to Mg-calcite to aragonite and dolomite (Talbot and Kelts 1986), enriched $\delta^{13}\text{C}$ (-12 ‰) due to increased evaporative carbonate deposition and enriched $\delta^{15}\text{N}$ (15 ‰) stable isotopic signatures due to enriched deep-water nitrogenous species rather than atmospheric N_2 fixation (Talbot and Johannessen 1992), increased magnetic susceptibility from iron-sulphide-rich greigite mineral deposition (Peck et al. 2004), greater silica XRF intensity from allochthonous material and enriched $\delta^{18}\text{O}$ signatures from in-lake carbonate deposition (Shanahan et al. 2009). Conversely, the African Humid Period was characterized by moist climate conditions that are believed to have resulted in the overflow of Lake Bosomtwe (11.6–8.8 cal ka), as indicated by a deeply cut overspill on the eastern shore (Shanahan et al. 2006). Sediments deposited during the AHP contain a large sapropel layer of organic-rich deposits of blue green algae, primarily *Anabaena*, and depleted $\delta^{15}\text{N}$ signatures near 0‰ (Russell et al. 2003) with greatly reduced inorganic deposition. These lacustrine deposits have proven that Lake Bosomtwe sediments are a well-suited to gauging pre-historic lake level fluctuations.

Lake Bosomtwe has well-preserved laminated sediments that can potentially provide fine, decadal- to interannual-scale records of past climatic variability. These laminae are believed to be annual varves

driven by seasonal changes in precipitation and primary productivity in Lake Bosomtwe, based on thin sections of laminated sediments (Shanahan et al. 2008). Annual couplets consist of a light-coloured organic- and calcium-rich lamina and a dark-coloured inorganic-rich lamina, high in concentrations of aluminum, silica, titanium and potassium from minerogenic inputs (Shanahan et al. 2008). Light-coloured laminae were found to have variable thickness that does not correlate with meteorological records, possibly due to the effects of post-depositional sediment compaction (Shanahan et al. 2008). In contrast, the thickness of the dark coloured laminae was found to be strongly correlated with local rainfall anomalies ($r = 0.54$, $P < 0.05$) and thus, believed to be driven by catchment runoff during the rainy season (Shanahan et al. 2008). Shanahan et al. (2008) state that laminations point to seasonally alternating periods of higher fluvial input of terrigenous material and periods of increased productivity and deposition of organic material. These inferences were largely based on our understanding of temperate aquatic systems and very little is known about the biogeochemical cycles within Lake Bosomtwe that drive these sediment deposits. A detailed examination of the seasonal sedimentation of Lake Bosomtwe is required to better understand the pattern of varve formation and to determine whether alternating allochthonous and autochthonous inputs drive the formation of these couplets.

Here we present 18 months of sediment trap data collected in Lake Bosomtwe between June 2005 and December 2006. This study captured sediment trap samples simultaneous with meteorological measures from a nearshore station and biweekly limnological samples from a central, deep-water station of Lake Bosomtwe. Our objective was to capture the sedimenting materials at high temporal resolution to reflect seasonally alternating allochthonous and autochthonous inputs responsible for the observed pattern of laminations in deep-water sediments. Secondly, vertical water column sampling of physical, chemical and biological factors were obtained to characterize seasonal variability of the water column. Limnological sampling can serve to determine the source and timing of the seasonal sedimenting materials collected in the sediment traps that are responsible for the formation of laminae

at the lake bottom. Thirdly, meteorological data from within the crater were recorded to assess the role of climate variability on the seasonality of sedimenting materials. Sedimenting materials were examined for loss-on-ignition (water, organic, carbonate and inorganic content), nutrient content (carbon, nitrogen and phosphorus concentrations), stable isotopic signatures ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and micro X-ray fluorescence of major elements (Fe, Ti, Mn, Ca, K and Rb) to characterize our sediment trap samples with respect to previous paleoclimatological research at Lake Bosomtwe.

MATERIALS & METHODS

Study Site

Lake Bosomtwe (elevation at lake surface 99 m amsl, surface area 48.6 km²) is situated in the Bosomtwe impact crater (surface area 103.1 km²), which was formed 1.07 million years ago as a result of a meteorite impact (Figure 3-1). The crater currently forms a closed basin with the basement impact breccia sealing off the lake from ground water inputs (Turner et al. 1996). Hydrological inputs are restricted to rainfall, and consequently lake level fluctuates in response to variations in the balance between the rates of precipitation (80% direct precipitation on the lake surface area) and evaporation (Turner et al. 1996). The crater walls extend to a minimum height of 210 m amsl, creating conditions of reduced wind stress over the lake's surface. The bathymetry of the lake is a simple bowl-shaped depression and riverine inputs largely come from small ephemeral streams that deliver runoff during precipitation events. A dense human population resides within the crater, with a total of 22 townships around the lake and the human population exceeds ~20,000. Residents subsist on fishing and farming practices within the crater.

Meteorological and Lake Level Data

A recording meteorological station, ONSET Computer Corporation part H21-001 with HOBO software, was installed in September 2004 on the north shore, near the village of Abono. This station

measured rainfall, wind speed, wind direction, solar radiation, humidity and dew point every ten minutes between September 2004 and January 2007. Meteorological equipment was calibrated at the Kumasi Airport, located 30 km from Lake Bosomtwe, and results indicated that wind speeds measured by our equipment were underestimated by on average 1.718 times per m s^{-1} , thus a correction factor of 1.718 times was applied to the measured wind speeds (m s^{-1}). Furthermore, wind speeds from the north were known to be underestimated by the northern placement of the nearshore meteorological station within the Bosomtwe crater. Lake levels were recorded biweekly on a nearshore staff gauge in the Abono harbour that was marked in centimetre intervals (Figure 3-1).

Limnological Sampling

Vertical water column profiles of temperature, oxygen, pH and conductivity were obtained during biweekly sampling using a Hydrolab H₂O Multiprobe 6SBP, alongside Secchi-disk depth measurements. Oxygen probe measurements were validated with surface water Winkler titrations to correct for possible errors caused by exposure to sulphide-rich waters. Water samples were collected during each sampling episode at discrete depths (0.3, 1, 2, 5, 8, 10, 12.5, 15, 20, 25, 30 m) using a Niskin sampler or a 6-L Van Dorn sampler. On 18 May 2004, 12 June 2005 and 18 July 2006, these same discrete depths were sampled for carbon and nitrogen stable isotopic signatures of particulate organic matter. For each depth interval, whole water samples were taken from a carboy of pre-screened water (63- μm mesh), placed in a dark cooler and transported to shore. Sampling for concentrations of chlorophyll *a* (chl *a*), particulate carbon (PC), particulate nitrogen (PN) and particulate phosphorus (PP) was performed every two weeks during June 2005 to December 2006 at each of the discrete depths.

Wedderburn numbers, which quantify the degree of stability of the column stratification between the epilimnion and hypolimnion, were calculated as the ratio of the density differences relative to the wind forcing. Hydrolab profiles of temperature and conductivity were used to establish the water

depths and density for the epilimnion, metalimnion and hypolimnion on each sampling date.

Wedderburn numbers (W) were calculated following the equation

$$W = (Q \cdot H_1^2) / (U^2 \cdot L_1).$$

Where $Q = g' \cdot (\rho_{\text{hypo}} - \rho_{\text{epi}})^{1/2} (\rho_{\text{hypo}} + \rho_{\text{epi}})^{-1}$ and defines the force of gravity g' (9.8 m s^{-2}) on the water density difference between the hypolimnion (ρ_{hypo}) and the epilimnion (ρ_{epi}) (as determined through temperature and salinity differences) (Chen and Millero 1977, 1986). H_1 is the mixed layer depth. U^2 is the square of the friction velocity in water, where $U = (\rho_{\text{air}} / \rho_{\text{water}} C_d u^2)^{1/2}$, where C_d is the drag coefficient modified for winds measured at approximately 3 m height above the water surface and u^2 is the maximum wind speeds (m s^{-1}) (Imberger and Patterson 1990). L_1 is the maximum breadth of Lake Bosomtwe (8.1 km).

Chemical Analyses

Chlorophyll *a* concentrations were determined by filtering a measured volume (0.5–1.0 L) of lake water through a Whatman GF/F filter (0.7 μm pore size), and extracting pigments into acetone solvent. Fluorescence was measured by a Turner Designs Field Fluorometer 10-AU-005 (Sunnyvale, CA) set to deliver excitation light of blue light (430–450 nm) and sense the emission of red light (650–675 nm). After the excitation was obtained, the sample was acidified with 3 drops of 1N HCl to denature the chlorophyll *a* porphyrin ring and re-measured. The difference was used to calculate the undegraded chlorophyll *a* concentrations removed from humic impurities and phaeophytin (Stainton, 1977).

Concentration of PP was measured by filtering a known volume (0.5–1.0 L) of lake water onto a pre-ashed Whatman GF/F filter, wrapping the filter in aluminum foil, sealing it in a Ziploc® bag and storing it frozen until analysis at the University of Waterloo, Waterloo. Filters were digested with potassium persulfate in the autoclave for 30 minutes under the wet cycle. After digestion, samples

were analyzed for phosphate following the blue molybdate-antimony colorimetric technique with absorbance read at 885 nm in a cuvette with a 1-cm path length on the Ultrospec 3100 pro UV/visible spectrophotometer (Stainton et al. 1977).

Concentrations of PC and PN were measured on 0.5-1.0 L water samples that were filtered onto a pre-weighed, pre-ashed Whatman GF/F filter and wrapped in aluminum foil, sealed in a Ziploc® bag and stored frozen until analysis at the University of Waterloo. Filters were dried overnight at 60°C, cut into half and packed into a nickel sleeve for combustion. Samples were processed with the elemental analyzer Exeter CEC Model 440 (Zimmermann & Keefe 1997). Carbon and nitrogen peaks were used to calculate molar units ($\mu\text{mol g}^{-1}$ dry sediment weight) to determine the molar ratio between carbon and nitrogen.

Sediment Trap Sampling

Deployment and Collection

From June 2005 to December 2006, two sediment traps were deployed at one site located in the northeast sector of Lake Bosomtwe where water depth was 42 m ($6^{\circ}31.736$ and $1^{\circ}25.050$; Figure 3-1). One sediment trap was deployed at 20 m and the other at 30 m water depth. Sediment traps were recovered every one to two months. Each trap was suspended on a rope extending from a bamboo float at the surface to an anchor at the lake bottom. Each sediment trap was constructed of a grey polyvinyl chloride (PVC) tube (76.2 cm long by 5.7 cm diameter) fitted with a drainage hole positioned 5 cm above the base of the PVC tube (Figure 3-2). We used cylindrical sediment traps with these dimensions because a low aspect ratio (1:13) was found to be the most reliable design and yield sediments in close agreement with true sediment deposition rates for flowing and still waters (Gardner 1980). A sampling cup was secured on the bottom end of each sediment trap. Four cylinders were secured in a metal cage with bungee cords for deployment at each of the two sampling depths. All four sediment traps were recovered every one to two months and then redeployed (Figure 3-2).

Sediment traps were carefully hauled up vertically through the water column and remained upright. Once aboard, the tape over the drainage hole was removed and water drained. Sediment samples from each of the four cylinders were pooled into one cup, then sealed and stored at 4 °C. The volume of pooled sediment sample was recorded and volumetric sub-samples were removed for further analyses. Dry weight per unit volume of the concentrate was calculated by drying an aliquot in a crucible at 60°C for 24 hours and divided by the volume of the aliquot. Sediment flux, as dry weight per unit area per unit time, was calculated by the formula: $w/\pi r^2/d$ where (w) is the total dry weight of the composite sample, (r) is the radius of the trap used to calculate the area for all four cylinders and (d) is the number of days deployed. Analyses of sediment trap characteristics are summarized in Table 3-1.

Physical and Chemical Analyses

Water, organic, carbonate and inorganic content of the sedimented material following the methods of Heiri et al. (2001). Briefly, a 20 mL aliquot of sediment trap slurry (0.04-1.1 g dry weight) was measured into pre-ashed, weighed crucibles, dried at 90°C for 24 hours, cooled and weighed to determine water content. Crucibles were then ashed at 550°C for one hour, cooled and weighed to determine loss of organic content. Crucibles were then combusted at 950°C for one hour, cooled and weighed to determine the loss of CO₂ from carbonate content. Carbonate content was calculated as the molar ratio from CO₂ at 950°C to CO₃ (60 g mol⁻¹/44g mol⁻¹). Inorganic content was estimated from remaining uncombusted materials. Water content is expressed a percent of wet sediment mass, while organic, carbonate and inorganic content are expressed as a percentage of dry sediment mass.

Concentrations of PC and PN from sediment trap samples were collected from a 10 mL aliquot (0.02-0.6 g dry weight) of mixed slurry filtered onto a 47 mm Whatman GFF filter (pore size 0.7 µm) that was dried at 60°C for 24 hours. Carbonates were low in Lake Bosomtwe sediment trap samples (< 3%

(wt/wt) of the carbon fraction), thus acidification was not used to remove carbonates prior to analysis. Each filter was split in half and packed into nickel sleeves for combustion in the Exeter CEC Model 440 analyzer (Zimmermann & Keefe 1997) at the University of Waterloo. Carbon and nitrogen peaks were used to calculate molar concentrations (mmol g^{-1} dry sediment weight) to represent the molar ratio between carbon and nitrogen.

Concentrations of PP in each of the sediment trap samples were determined from 1-2 mg of freeze-dried, ground sediment placed into a small crucible and ashed at 550°C for one hour (Bengtsson & Enell 1986). Sediment was weighed out into 70 mL glass test tubes and digested with potassium persulfate in the autoclave for one half hour on the wet cycle. After digestion, samples were analyzed for phosphate following the blue molybdate-antimony colorimetric technique with absorbance read at 885 nm in a cuvette with a 1-cm path length on the Ultrospec 3100 pro UV/visible spectrophotometer (Stainton et al. 1977).

Carbon and nitrogen stable isotope analyses of sediment trap samples were performed at the Environmental Isotope Laboratory (University of Waterloo). Aliquots of 10 mL of homogenized sediment trap material (0.02-0.6 g dry weight) were concentrated onto pre-ashed quartz filters (Whatman QMA, pore size $0.7 \mu\text{m}$) that were then freeze dried and stored in Petri plates prior to combustion in the Prism Mass Spectrometer GC-C-IRMS. Samples were not acidified to volatilize carbonates prior to analysis. Calculations for isotopic composition were represented as parts per thousand (‰) relative to a standard.

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3$$

δX here is $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ and R is the respective isotopic ratio $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$ (Fry 2006). The $\delta^{13}\text{C}$ standard was Pee Dee Belemnite from South Carolina (PDB), while $\delta^{15}\text{N}$ was atmospheric nitrogen (Clark & Fritz 1997). Sediment trap samples were not corrected for the Suess effect (as will be presented in Chapter 4 and 5 of this thesis) and thus $\delta^{13}\text{C}$ values in this study are 1.99 ‰ more

depleted, measuring on average -26 ‰. This value would have been -24 ‰ after the correction factor. This correction is for the release of isotopically depleted $\delta^{13}\text{C}$ CO_2 into the atmosphere through the burning fossil fuels and is applied to lacustrine sediments deposited since the industrial revolution known as the anthropocene (Verburg 2006).

X-ray fluorescence for elemental composition was conducted at the Large Lakes Observatory, University of Minnesota-Duluth by Dr. Eric Brown using the ITRAX core scanner (Croudace, 2006). Sediment trap samples were filtered onto 25-mm diameter Advantec MFS Inc. mixed cellulose ester filters (pore size 0.45 μm) until filters clogged. Each filter was stored wet at 4°C for three days until scanned at 2-mm intervals along the diameter of the filter, providing 6-7 consecutive ITRAX measures that were used to calculate a sample average and standard deviation per sediment trap sample. The XRF elemental constituents that were most abundant in Lake Bosomtwe sediment trap samples were: iron, zirconium, potassium, manganese, calcium, titanium, zinc, arsenic, selenium, lead, chromium, strontium, rubidium and silica. Potassium to titanium (K:Ti) ratios were also examined as indicators of erosion. Lower K:Ti ratios are indicative of weathered soils and high K:Ti ratios are indicative of erosion that exposes fresh soils (Burnett et al. 2010; Mischke et al. 2010). During chemical weathering, potassium is more readily released than titanium from the topsoil, while titanium is relatively inert (Burnett et al. 2010; Mischke et al. 2010). Erosion and transport of these weathered topsoils from the catchment can lead to a rise in K:Ti values.

Data Analyses

The meteorological data were exported into Excel spreadsheets and 10-minute interval readings were compiled to generate daily and monthly averages, minima and maxima. Overall, the most prominent seasonal trends were found to be in the monthly precipitation, daily maximum air temperature, and daily average wind speeds (Figure 3-3). Lake level gauge data were converted from the measured nearshore depth in centimetres to elevation in metres above mean sea level. Physical limnological

data from vertical water profiles were exported to Excel and the descending temperature profiles for each sampling date were compiled and x (water depth), y (date), z (temperature) variables were then imported and smoothed in Surfer. To represent the epilimnetic volume of water, limnological samples from 0 to 8 m water depth were averaged for geochemical and biological constituents.

RESULTS

Meteorology

Meteorological sampling from June 2005 to December 2006 characterized 18 months of climate variation during the sediment trap sampling at Lake Bosomtwe (Figure 3-3). Seasonal variability was marked by the pattern of rainfall, with reduced rainfall during both the dry Harmattan in December and January, and the short dry period in July and August (Figure 3-3a). The short dry season of July and August characterized the pattern of annual rainfall as bimodal. The coolest air temperatures occurred annually during the January and August dry periods, when reduced cloud cover facilitated greater diurnal cooling. The short dry season abruptly ended with the onset of the short rainy season, which commenced with greater storm intensity than the long rains. Maximum daily wind speed over Lake Bosomtwe was generally higher during the onset of monsoon rainfall (Figure 3-3b), especially when the storm fronts of the intertropical convergence zone approached in March of the long rain and in August of the short rain seasons.

Physical Limnology

During July and August, the cooling effect of the short dry season resulted in the cooling of the surface water temperatures of Lake Bosomtwe, which caused a marked shift in water column biogeochemistry in both 2005 and 2006 (Chapter 2 of this thesis). The persistent, high wind speeds and low air temperatures (particularly August night-time air temperatures) during the short dry period contributed to water column mixing on 12 August 2005 and 3 August 2006.

The seasonal water column mixing and circulation of nutrients followed the pattern of thermal destratification that was characterized by Wedderburn numbers (W) approaching 1 (Figure 3-3b). Low Wedderburn numbers indicate that the ratio of stratification density is the same or less than the wind forcing. In Lake Bosomtwe, density stratification was driven by thermal density differences, as there was little difference in chemical density through the water column (Chapter 2 of this thesis). Wedderburn numbers identified two periods of reduced water column stability during August of the short dry and February of the Harmattan period.

Water column temperature profiles (Figure 3-3d) emphasize the seasonal pattern of destratification that disrupt the strong thermal stratification between the homothermal deep-water temperature of 26.9°C below ~ 30 m water depth, and the diurnal mixing of waters above ~ 30 m. Vertical water column cooling occurred in August 2005 and 2006, when the surface water temperatures fell to 26.81°C and led to full water column mixing (Figure 3-3d). In particular, 12 August 2005 and 3 August 2006 were the coolest days and vertical mixing was fairly complete. These episodes are denoted by a dashed vertical line on all plots. Reports of a fish kill on 12 August 2005 and surface water hypoxia were evidence that complete breakdown of thermal stratification occurred with the upwelling of anoxic deep-waters (Chapter 2 of this thesis). In 2006, such conditions were not repeated because rainfall delivery and average temperatures were higher in August than in 2005. As a result, thermal stratification in 2006 was weakened during August, but never completely disrupted (Puchniak et al. 2008).

Chemical and Biological Limnology

Thermal destratification during the short dry season affected chemical and biological conditions, including increased concentrations of nutrients and chlorophyll a and reduced water column transparency in Lake Bosomtwe. Water column transparency exhibited a seasonal pattern with one

shallow Secchi disk depth during the short dry period in August 2005 and 2006 when the water column mixed (Figure 3-3c). Declining Secchi disk depth is most likely due to the increased phytoplankton chlorophyll *a* (chl *a*) concentrations in the water column. Chlorophyll *a* concentrations showed a seasonal peak in August 2005 and 2006 (Figure 3-4a), following the vertical water column mixing. Peak chlorophyll *a* concentrations reached $25.4 \mu\text{g L}^{-1}$, twice the average annual concentration of $10.5 \pm 4.8 \mu\text{g L}^{-1}$. Chlorophyll *a* concentrations in water column samples can fluctuate with changes in the amount of algal biomass, in the algal community composition, or in chl *a* concentration within individual phytoplankton cells in response to light conditions. Seasonal increases in chl *a* concentration would require an increased supply of essential nutrients carbon, nitrogen and phosphorus to support increased primary productivity. The same trend in algal biomass was revealed with particulate carbon and nitrogen concentrations in the water column. PC concentrations doubled from 60 to $130 \mu\text{mol L}^{-1}$ and PN concentrations from 7.2 to $15.6 \mu\text{mol L}^{-1}$ immediately following the 12 August 2005 mixing event (Figure 3-4b, 5b). The molar ratio between carbon and nitrogen (C:N) was relatively invariant in the water column, and on average 8.2 ± 0.7 , indicative of autochthonous productivity (Figure 3-5c grey circle).

Another essential growth nutrient is phosphorus (P), which was on average $0.48 \pm 0.29 \mu\text{mol L}^{-1}$ in the epilimnion. Particulate P (PP) concentrations increased more rapidly than PC or PN in the water column. Epilimnetic PP concentrations increased four-fold during July to August (Figure 3-6b), from 0.35 to $1.37 \mu\text{mol L}^{-1}$ in 2005 and three-fold, from 0.44 to $1.1 \mu\text{mol L}^{-1}$ in 2006. Highly accelerated primary production in Lake Bosomtwe caused nutrient-limited algal growth that resulted in changing particulate nutrient ratios (particularly with respect to PP). For example, C:N nutrient ratios increased due to enhanced primary production and likely CO₂-limited fixation following the August 2005 upwelling event (Figure 3-5c). Unfortunately, data for C:P and N:P ratios were unavailable for the water column during the short dry and short rain seasons (Figure 3-6c).

Sediment Trap Material

Sediment traps from June 2005 to December 2006 exhibited the same pronounced seasonality as the limnological sampling, with August being an important time for organic matter sedimentation. The burial of organic and inorganic matter (Figure 3-4c) more than doubled during July to August 2005 in association with the seasonal deep mixing event, when organic burial increased from 0.29 to 0.72 g m⁻² d⁻¹ and inorganic burial increased from 1.42 to 2.9 g m⁻² d⁻¹. Following the weakening of the thermal water column structure again in August 2006, organic and inorganic burial increased by nearly an order of magnitude from July to October 2006 (organic burial 0.10 to 0.90 g m⁻² d⁻¹ and inorganic burial 0.32 to 3.84 g m⁻² d⁻¹). The rate of PC burial (Figure 3-4d) increased more than 2-fold (9 to 26 mmol C m⁻² d⁻¹) from July to August 2005 and by five times from July to October 2006 (7 to 35 mmol C m⁻² d⁻¹). Likewise the nitrogen burial rate was three times greater in August 2005 compared to July of 2005, and nine times greater from July to October 2006 (Figure 3-5d).

Sedimenting material from the trap recorded C:N molar ratios that were on average 12.7 ± 1.3 (Figure 3-5c black circle). There was one subtle rise in trapped sediment C:N from 12 in August to 16 in December 2005. Carbon to phosphorus molar ratios in the sediment trap samples changed markedly from a C:P of 234 in August to 124,000 in December 2005 denoting severe phosphorus limitation of biomass (Figure 3-6c). The trend of increasing C:P and C:N values in sediment trap samples was likely due to accelerated PC burial (Figure 3-4d) relative to PN and PP burial rates (Figure 3-5d and 6d).

The relationship between particulate nutrients (PC and PN) and the source material in Lake Bosomtwe was explored through stable isotopic signatures of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from bulk matter for both the water column and sediment trap samples. On three separate sampling trips in 2004, 2005 and 2006, water column particulates were sampled from ten discrete water depths to determine $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures (Figure 3-7a and b). Striking vertical changes occurred through the water column that

distinguished samples above and below the oxycline based on the $\delta^{15}\text{N}$ signature of particulates (Figure 3-7a). The $\delta^{15}\text{N}$ of the epilimnion (0-10 m) was between 5.3 and 7.1‰, while values in the hypolimnion (30-70 m) were between 11.2 and 14.5‰. Thus, $\delta^{15}\text{N}$ of particulate matter was enriched by 4.1‰ with depth. The $\delta^{13}\text{C}$ vertical water column profile of particulate matter showed a high degree of variability, with a trend towards greater isotopic depletion with depth. The dissolved inorganic carbon (DIC) $\delta^{13}\text{C}$ was found to be relatively invariant at -1.44 ‰ (Figure 3-7c).

These differences in vertical water column $\delta^{15}\text{N}$ isotopic signatures provided good insight into the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of sediment trap samples (Figure 3-8b and c). The sediment trap samples during the 18 month sampling period showed a strong period of $\delta^{13}\text{C}$ depletion and $\delta^{15}\text{N}$ enrichment in August through to October 2005 and to a lesser extent in 2006 also during this period. Deep, anoxic waters upwelled on 12 August 2005 and resulted in a fish-kill event due to surface water hypoxia (Puchniak et al., 2009). The $\delta^{15}\text{N}$ enrichment of sediment trap samples following this upwelling event shifted from 11.4 to 17.5 ‰ (Figure 3-8d). Furthermore, $\delta^{13}\text{C}$ signatures of sediment trap material were depleted from -27.0 to -31.9 ‰ during the same time period (Figure 3-8b). Sediment $\delta^{13}\text{C}$ signatures began to rise after September 2005, reaching a peak in March 2006 that is similar to the trend previously seen in C:N molar ratios (Figure 3-5d). At the same time, a rise in calcium fluorescence and percent carbonate deposition occurs (Figure 3-8d). Sediment samples from October 2006 showed a similar, yet muted, trend in isotopic enrichment of $\delta^{15}\text{N}$ and depletion of $\delta^{13}\text{C}$ that displayed a reproducible annual pattern of seasonal isotopic change in the month of August.

The elemental composition of the sediment trap material was characterized by micro x-ray fluorescence of these fine particles (Figure 3-9). The most abundant fluorescing elements were iron and titanium (Figure 3-9c, d). Overall, iron and titanium XRF counts per second did not exhibit strong seasonal variability. Extensive micro-XRF analyses by Shanahan et al. (2009, 2008) found that elements Al, Si, Ca, Fe, Ti, Mn and K were the most abundant in Bosomtwe sediments and can be

used to distinguish between dark and light varves. The flocculent nature of the sediment trap material did not provide enough sediment to adequately analyze lighter elements aluminum and silica with XRF in our samples, so smear slides under the light microscope were used. Smear slides confirmed an abundance of mica within sediment trap samples in the form of muscovite (Amy Mybro and Tom Johnson personal communications). Muscovite is a potassium aluminum silicate $KAl_2(AlSi_3O_{10})(F,OH)_2$ that is composed of weakly bound potassium ions that cleave into sheets readily, as were seen in sediment trap samples.

XRF elemental content did not show strong variability in sediment trap samples, but elemental ratios offer a greater insight into the source of these inorganic sediments. When examining the K:Ti ratios of sediment trap material from 2005 and 2006 (Figure 3-9e), values from June to October 2005 were elevated to as much as 2.6. These higher K:Ti values may be derived from soil erosion in the catchment transported in with rainfall or by aeolian processes in an area of exposed soils.

DISCUSSION

Of the four seasons over the Sahel region, the meteorological conditions of the short dry period of July and August had the most pronounced effect on the water column structure of Lake Bosomtwe (Figure 3-10). Night-time evaporative cooling was induced by the decline in cloud cover and low air temperatures in August, which effectively reduced the epilimnetic water temperatures to 26.5°C and enabled destratification. The rapid change in limnological variables following the breakdown of thermal stratification and the upwelling of deep-water dissolved nutrients (Chapter 2 of this thesis) stimulated algal productivity, as observed by elevated concentrations of chlorophyll *a*, particulate nutrients carbon, nitrogen and phosphorus, and organic matter burial (Figure 3-10)

The August-October period of enhanced primary production was due to the upwelling of deep-water nutrients carbon, nitrogen and phosphorus that accumulated within the hypolimnion (> 30 m water depth) during anaerobic decomposition. The marked acceleration in algal primary production during the short dry period provided substantial evidence that internal nutrient loading through the circulation of deep-water nutrients far exceeds other sources of nutrients to the water column annually (whether it be from wet and dry deposition, riverine input or other sources). Increased algal biomass and algal diversity following the mixing period and shifted the phytoplankton community away from nitrogen fixing cyanophytes to chlorophytes and diatoms (Awortwi 2010). Furthermore, the deep-water recycled nutrients contained within this closed basin likely allowed the chemistry of the deep-water nitrogen pool to become isotopically enriched in ^{15}N . Autotrophic plankton are restricted to using surface water nutrients and use atmospheric N_2 gas (e.g. N_2 fixation with $\delta^{15}\text{N} = 0\text{‰}$) or atmospheric dissolved inorganic nitrogen (DIN). In Lake Bosomtwe, $\delta^{15}\text{N}$ of bulk matter in the epilimnion measured 5.3‰, not indicative of N_2 fixation alone, while the hypolimnion measured 14.5‰ (Figure 3-7).

The pattern of $\delta^{15}\text{N}$ enrichment in vertical profiles of the Lake Bosomtwe water column particulate matter suggests that Lake Bosomtwe is not only reliant on nitrogen fixation, but that nitrogen cycling and internal nutrient loading are critical. Water column profiles in Chapter 2 of this thesis presented the vertical distribution of dissolved inorganic nitrogen (DIN), which was predominantly composed of ammonium (Figure 2-5). Surface waters, from 0-10 m, measured an abundance of particulate N (at 5.3 ‰), followed by a large concentration of ammonium at 10 m water depth (at 7.5 ‰). Nitrogen that was fixed by cyanobacteria living in the surface waters is commonly released during decay as ammonia through ammonification (Clark and Fritz 1997). Further down the water column at the oxycline (~20 m water depth), there was a peak concentration of nitrate and a larger peak of nitrite (at 9.9 ‰), where ammonia was oxidized during nitrification (Wetzel 2001). These oxidized nitrogenous species are either assimilated or biologically reduced through the processes of denitrification and/or

anammox under low oxygen concentrations (Garvin et al. 2009). The process of denitrification in the anoxic zone of Lake Bosomtwe has likely released isotopically light N_2 to the atmosphere, leading to isotopic enrichment of the residual pool of nitrogen. Denitrification reduces nitrite or nitrate to nitrogen monoxide, then to nitrogen dioxide and finally to N_2 gas, resulting in the degassing of isotopically light nitrogenous species that, with time, result in characteristically different pools of nitrogen in solution (Clark and Fritz 1997). N_2 gas is also produced in stratified freshwater lakes through the process of anaerobic ammonium oxidation or anammox via the coupling of ammonium oxidation with nitrite (Hammersley et al. 2009, Schuber et al. 2009). Both denitrification and anammox may cause deep-water DIN $\delta^{15}N$ to be enriched in Lake Bosomtwe. Likewise, the release of ammonia during bacterial decomposition of amino acids from the surface sediments releases an enriched DIN source.

The epilimnion (0-15 m) and the hypolimnion (30-78 m) of Lake Bosomtwe were often thermally isolated and circulation provides a mechanism by which a large amount of chemically distinguished nutrients can be made available rapidly to the euphotic zone. Deep-water ammonia concentrations likely have an enriched signature and the rapid uptake of NH_4 by the aerobic autotrophs post-mixing likely imparted an enriched signature for $\delta^{15}N$ autochthonous matter. The large volume and high concentration of dissolved inorganic nitrogen that was made available during mixing, where previously conditions were of low nitrogen availability (that demands greater N_2 fixation) would have resulted in algal fractionation towards more depleted $\delta^{15}N$ particulate signatures (Peterson and Fry, 1987, Pennock et al. 1996). The observed $\delta^{15}N$ signature of particulates showed the contrary, enrichment during mixing leading to depletion with time. Thus, the pulse of DIN was likely enriched in $\delta^{15}N$ that was quickly consumed and settled out as particulate material. Ramlal (2002) found that particulate organic matter from offshore sites in Lake Victoria, East Africa, exhibited $\delta^{15}N$ enrichment supplied by deep-water recycled nitrogen species. These DIN species were found to have

become isotopically enriched because eutrophication had increased the persistence of deep-water anoxia that accelerated rates of denitrification in the water column.

In Lake Bosomtwe, the carbon isotopic signature for bulk carbon and DIC (Figure 3-7b and c), and the concentration of DIC, did not appear to differ markedly within the water column, as compared to dissolved inorganic nitrogen. Signatures of $\delta^{13}\text{C}$ in sediment trap organic matter, however, became isotopically depleted following the short dry season. This $\delta^{13}\text{C}$ depletion may be due to the supply of deep-water CO_2 or night time carbon respiration that exceeded day time carbon fixation. The initial upsurge of deep water coincided with a trend towards more depleted $\delta^{13}\text{C}$ trap carbon signatures. This is not unlike the POM vertical water column profiles of Lake Bosomtwe (Figure 3-7b), which exhibited a small, yet, obscured trend in depleted $\delta^{13}\text{C}$. Vertical water column sampling of DIC in May 2005 found that DIC concentrations varied only a small amount from surface waters to 70 m water depth, with on average $11.8 \pm 1.9 \text{ mmol L}^{-1}$ and an average $\delta^{13}\text{C}_{\text{DIC}}$ signature of -1.44 ‰ . The fixation of DIC with a small depletion in $\delta^{13}\text{C}_{\text{DIC}}$ signature may be a contributing factor to the depletion of $\delta^{13}\text{C}$ signatures from sediment trap samples, when the demand for CO_2 during rapid primary production is great. Vertical water column concentrations of DIC did, however, show that at the oxycline concentrations fell slightly to 9.5 mmol L^{-1} (Figure 2-5), likely due to the consumption of CO_2 by microorganisms that form the deep-water chlorophyll maximum (Chapter 2 of this thesis). The decline in DIC concentrations at 15-20 m suggests a high demand for CO_2 by phytoplankton, and thus a rapid uptake of CO_2 during mixing. Another potential contributor is methane generation in the deep water, which is known to result in strongly depleted $\delta^{13}\text{C}$ signatures of organic matter and could have contributed to the sediment trap bulk matter signatures. In Lake Bosomtwe, however, there was very little methane generation within the vertical water column, with concentrations ranging from 0 to $457 \text{ } \mu\text{mol CH}_4 \text{ L}^{-1}$. The amount of carbon respiration within the surface waters, however, could contribute briefly to more isotopically depleted DIC, where $\delta^{13}\text{C}$ of respired CO_2 can measure -20 ‰ (Peterson and Fry 1987). Differences between vertical water column DIC (-1.44 ‰) and our sediment

trap samples (-31.9 ‰) in August and September of 2005 may be reconciled through the biogenic respiration of carbon dioxide and phytoplankton fractionation during uptake (Rau, 1978, Peterson and Fry 1978). However, without further diurnal sampling of the carbon budget before, during and after an upwelling event, we are restricted to speculation.

During the short rainy season, accelerated primary production continued under alkaline water conditions, as $\delta^{13}\text{C}$ values of POM rebounded to more enriched, pre-upwelling signatures. This coincided with the increased deposition of calcium and carbonate within sediment trap samples. Calcium carbonate can precipitate in alkaline waters when high primary production increases the surface water pH. The accelerated primary production likely reduced the CO_2 pool available leading to biologically-induced calcite precipitation. In some cases, cyanobacteria can seed calcium carbonate precipitation in lakes, like the Laurentian Great Lakes which experience whiting events (Schelske et al. 2006). In Lake Bosomtwe, cyanobacteria were known to be the predominant contributor to the algal biomass during periods of thermal stratification (Awortwi 2010). The seasonal deposition calcium- and carbonate-rich organic matter likely represents the formation of light laminae in Lake Bosomtwe sediments, as characterized by Shanahan et al. (2008). Sediment trap sampling in Lake Bosomtwe has provided insight into the seasonal patterns of sedimentation that likely result in the formation of laminated sediments.

Varve counts by Shanahan et al. (2008) found that the thickness of the light laminae were highly variable and at times absent. There was little statistical correlation between meteorological variables and thickness of light laminae, but interestingly there appears to be a greater number of light laminations absent during the Sahel droughts of 1970 to 2000s (Dai et al. 2004), as compared to the rest of the century. Missing laminae were dismissed by Shanahan et al. (2008) as an artefact of sediment compaction that may have resulted in incomplete recovery of the varve couplets. However, local residents (personal communications) have perceived a decline in fish kill events and fisheries

yields from Lake Bosomtwe. This sediment trap data suggests that recent climate variability and increased drought frequency may be impacting the frequency of water column mixing events that are followed by formation of light coloured sedimenting particulates that lead to the formation of light coloured laminae.

After water column mixing in August, sediment trap nutrient stoichiometry indicated severe phosphorus limitation during most of the year, which emphasized the dependence of primary production on nutrient upwelling. Prolonged phosphorus depletion may be due to accelerated rates of carbon fixation and nitrogen uptake in excess of rates of cellular phosphorus uptake, or due to a discrepancy between the more effective recycling of phosphorus versus nitrogen within the surface waters and the sediments. The surface waters were known to have been enriched with dissolved phosphorus inputs during upwelling and circulation of anoxic deep-waters. The supply of readily available dissolved phosphorus is known to strongly contribute to this surge in primary productivity (Chapter 2 of this thesis). The pronounced increase in primary production following the upwelling strongly suggests algal biomass is generally phosphorus limited. During the rapid rise in primary productivity, competition amongst algal species for the uptake of phosphorus may have resulted in reduced C:P and N:P ratios in particulate organic matter. Furthermore, a re-stratified water column can result in settling of particulates that begin to leach nutrients during degradation, providing a valuable source of growth-limiting nutrients, such as phosphate (PO_4^-) that can be stripped from detrital matter before deposition. Within a meso-eutrophic crater lake like Lake Bosomtwe, phosphorus recycling (particularly by picoplankton) can contribute to the rapid turnover rate of phosphate within the pool of total phosphorus in the water column (Hudson et al. 2000, 1999). It is likely the combination of high algal biomass with low phosphorus content and effective scavenging of phosphate during settling of particulate matter has grossly altered the C:P and N:P nutrient ratios of particulate organic matter captured in the sediment traps.

Overall, the broad range in nutrient stoichiometry of C, N and P ratios and stable isotopic signatures recorded during the 18 months of Lake Bosomtwe sediment trap collection support previous paleolimnological speculations that in-lake nutrient regeneration may be the prime driver in organic matter deposition. Until now, researchers could not appreciate the extent to which autochthonous production within Lake Bosomtwe responds to climatically-driven limnological conditions. Mixing models of allochthonous and autochthonous organic matter had been proposed previously as the means to explain fluctuations in C:N ratios and stable isotopic signatures when insufficient limnological evidence was available to identify the in-lake processes (Ellis 2005, Talbot and Johannessen 1992). In a study comparing the effectiveness of using the $\delta^{13}\text{C}$ signatures of fossil grass cuticles versus the $\delta^{13}\text{C}$ signatures of bulk organic matter in lacustrine sediments from Lake Bosomtwe, researchers found that there was an irreconcilable difference between the timing and extent of isotopic depletion in each organic matter fraction (Beuning et al. 2003). Bulk organic sediment $\delta^{13}\text{C}$ shifted from -4 to -32 ‰ nearly 1,000 years earlier than terrestrial fossil grass epidermis $\delta^{13}\text{C}$, which only shifted from -11 to -15 ‰. This led Beuning and colleagues to hypothesize that the in-lake processes must dominate the stable isotopic signatures of bulk organic matter, and these $\delta^{13}\text{C}$ signatures were not necessarily the product of allochthonous and autochthonous inputs mixing (Beuning et al. 2003). Beuning's interpretations were in line with our sediment trap findings, as there is little evidence that bulk organic matter is influenced by inputs of $\delta^{13}\text{C}$ terrestrial organic matter, and bulk organic matter was found to be a good index of limnological variability. The seasonal $\delta^{13}\text{C}$ depletion of bulk matter in Lake Bosomtwe sediment traps provides convincing evidence that in-lake processes are dynamic enough to encompass a large range of $\delta^{13}\text{C}$ signatures and are not dependent on changes in external inputs.

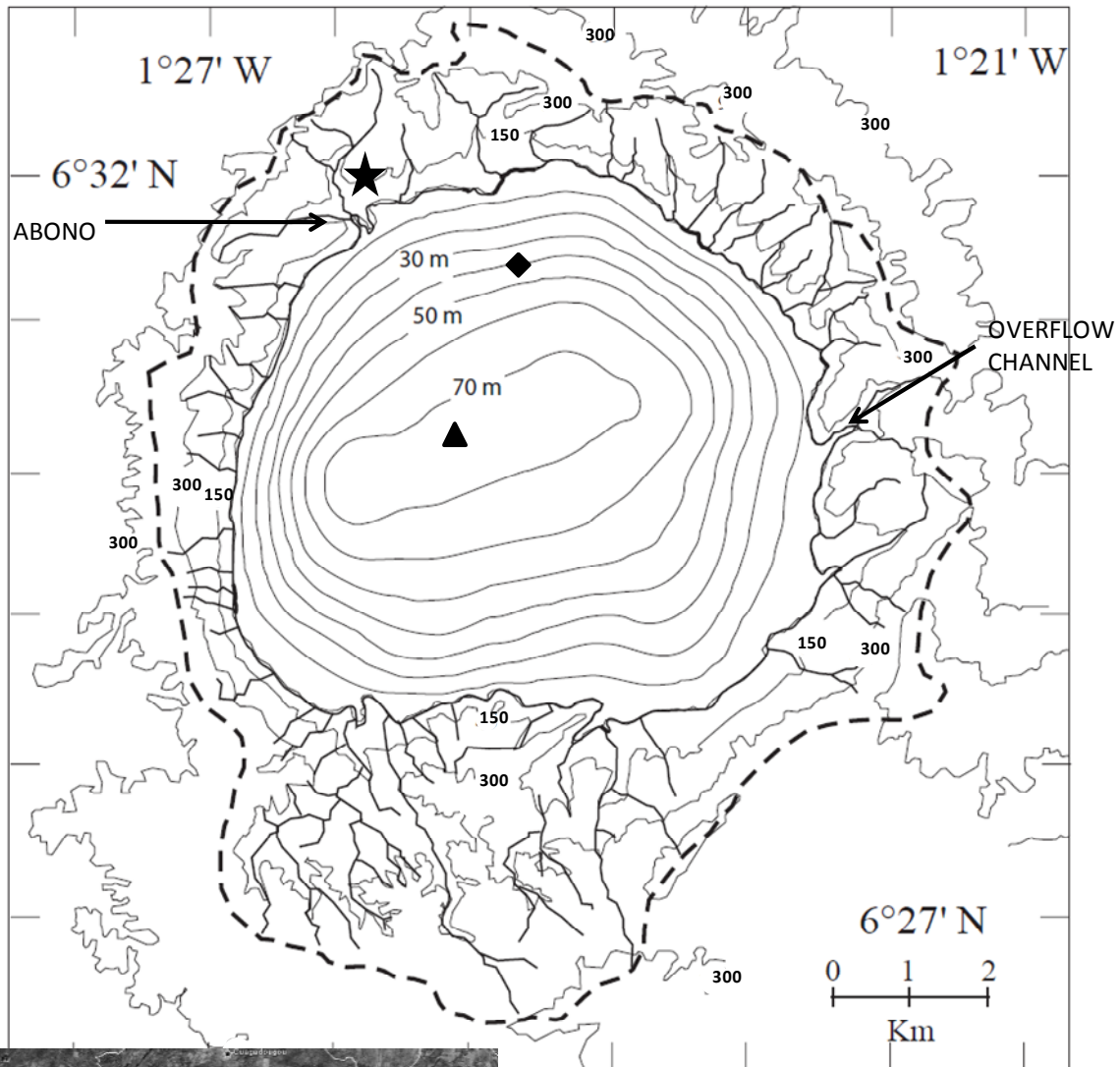
Evidence of catchment erosion playing a factor in the delivery of sediments to the lake was found in declining sediment trap K:Ti ratios in 2005, but not in 2006. The greatest deposition of inorganic matter occurred in August 2005 and October 2006 with the onset of the short rainy season. But in

2005, the increased inorganic burial coincided with high K:Ti ratios, implying that the onset of the short rains increased erosion from the catchment (Mischke et al. 2010). Residents around the lake plant two crops a year, using slash and burn practices to clear the land during the January Harmattan and August short dry period. The onset of the rainfall in February was gradual and vegetation typically becomes established before the stronger monsoon conditions arrive. The onset of the second, short rains in September can be rapid, with flashy river flow leading to riverbed washout and meandering overflow channels. In some years, vegetation does not adequately mature to protect soils from erosion. Sediment trap samples from August to October had K:Ti ratios of 2.3 on average and may be evidence for anthropogenically driven elevated soil erosion that transports sediment from deeper within the soil horizon (Mischke et al. 2010). Shanahan et al. (2008) showed that the thickness of the dark laminae has increased substantially since 1970. Cultivation of the steep hillsides by the growing human population may be contributing to increasing inputs of eroded soil to the sediment records (Shanahan et al. 2008).

CONCLUSION

This study of seasonal climate variations, limnological conditions and sedimentation patterns of Lake Bosomtwe revealed that in-lake processes are predominant in the formation of annually varved sediments, despite the recent land-use changes that enhance transport of inorganic sediment from the surrounding catchment. Conditions during the short dry season of July and August resulted in a deep-water mixing event and increased organic matter burial (Figure 3-10) that likely produced organic-rich, light-coloured laminae in the Lake Bosomtwe sediment records. The effects of deep-water mixing in the water column were distinguished by increased nutrient concentrations, turbidity and algal biomass during August. The same mixing event was distinguished in the sediment trap samples by increased organic matter content, reduced C:N ratios, $\delta^{13}\text{C}$ depletion and $\delta^{15}\text{N}$ enrichment.

Decadal-scale rainfall anomalies over the Guinea Coast region are strongly influenced by the pattern of precipitation during July and August over the Sahel region (Nicholson and Webster 2008). The interannual variability of the short dry period over Lake Bosomtwe during July and August strongly affects the biogeochemistry of Lake Bosomtwe sediments (Figure 3-10). The effects of long-term drought and future global warming on Lake Bosomtwe are profound. Sahel drought-induced prolonged thermal stratification of Lake Bosomtwe would restrict the circulation of dissolved nutrients (nitrogen and phosphorus) that would also effectively reduce primary productivity, organic matter deposition and the range of carbon and nitrogen stable isotopic signatures of organic sediments. Long-term drought also increases thermal stratification, which would likely increase surface water temperatures and limit deep-water cooling events (Vollmer et al. 2005, Verburg et al. 2003), thus, increasing the thermal density differences further between the epilimnion and hypolimnion. The effects of increased water column temperatures and reduced depth of water column mixing would be to confine algal biomass to a narrower euphotic zone, leading to greater UV exposure. This reduced water column circulation would effectively reduce the algal biomass and likely the algal diversity, as deep-water circulation resuspends algal communities and dissolved nutrients that are required for these algae to outcompete cyanophytes (Verburg and Hecky 2009). Prolonged thermal stratification of Lake Bosomtwe would ultimately reduce fisheries yields and decrease water quality by favouring production of nitrogen-fixing and potentially toxin-producing cyanophytes.



- ★ METEOROLOGICAL STATION
- ▲ CENTRAL STATION
- ◆ SEDIMENT TRAPS

Figure 3-1 Basin map of Lake Bosomtwe showing the locations of the sediment traps deployed at 42 m water depth, the meteorological station and the central water column sampling station (78 m water depth). The dashed line denotes the extent of the catchment area (modified from Brooks et al. 2005). Topographic contours for the catchment area are in 150 m increments and for the bathymetry in 10 m increments below present lake level. Inset of West Africa, with white box over Lake Bosomtwe, Ghana (Google Earth, 2007)



Figure 3-2 Sediment trap sampler constructed of four PVC tubes secured in a metal frame by bungee cords and fitted with sampling cups at the base for sediment recovery. A drainage spout at 5 inches from the cups was drilled and sealed with duct tape until retrieval.

Table 3-1 Composition of sediment from sediment trap samplers deployed at 20 and 30 m water depth in Lake Bosomtwe during June 2005 to December 2006.

Sample No.	Date Recovered (dd/mm/yr)	Water Depth (m)	Days Deployed	Dry Weight (g)	Accumulation (g/m ² /day)	% Organic (g/g)	% Inorganic (g/g)	% Carbonate (g/g)	Phosphorus (umol/g)	Carbon (mmol/g)	Nitrogen (mmol/g)	C:N (molar)	C:P (molar)	N:P (molar)	Delta 13C (per mil)	Delta 15N (per mil)
1	30/06/2005	30	20	0.31	1.49	18.8	76.6	4.6	4.4	5.1	0.47	11.7	1150	107	-27.1	11.1
2	30/07/2005	30	30	0.54	1.77	16.6	80.2	3.1	5.0	5.4	0.47	12.6	1080	93	-27.6	11.4
3	26/08/2005	30	27	1.03	3.74	19.3	77.5	3.2	3.0	7.1	0.65	11.8	2380	220	-31.3	14.3
4	23/09/2005	20	28	0.37	1.27	29.7	66.2	4.0	9.4	12.1	1.18	11.1	1290	126	-30.4	17.5
5	23/09/2005	30	28	0.20	0.70	33.7	62.9	3.5	6.2	12.8	1.25	11.2	2070	200	-31.9	16.5
6	20/10/2005	20	27	0.35	1.28	21.7	73.8	4.6	6.0	7.4	0.61	13.2	1230	101	-27.5	15.7
7	20/10/2005	30	27	0.49	1.76	18.2	77.1	4.8	0.6	5.3	0.48	12.0	8730	790	-28.1	15.2
8	16/12/2005	20	57	0.40	0.68	35.2	61.4	3.4	15.7	14.5	1.14	13.8	919	72	-26.6	10.4
9	16/12/2005	30	57	0.35	0.60	35.5	60.0	4.5	0.1	14.8	1.25	12.8	124000	10500	-26.5	10.5
10	28/01/2006	20	43	0.35	0.78	36.7	56.7	6.6	NA	15.5	1.19	14.1	NA	NA	-26.4	10.1
11	28/01/2006	30	43	0.24	0.54	32.5	56.9	10.7	0.5	14.0	1.00	15.2	28400	2020	-26.2	11.1
12	10/03/2006	20	41	0.42	1.00	28.4	65.4	6.1	2.3	10.8	0.82	14.3	4700	357	-24.5	10.9
13	10/03/2006	30	41	0.32	0.77	25.1	69.6	5.4	15.3	9.5	0.68	15.2	623	44	-24.5	11.0
14	05/05/2006	20	50	0.66	1.29	26.9	68.6	4.5	19.2	10.5	0.92	12.4	546	48	-24.6	9.9
15	05/05/2006	30	56	0.68	1.19	26.8	69.4	3.8	43.2	10.1	0.88	12.4	234	20	-24.7	10.5
16	04/07/2006	20	60	0.27	0.44	23.2	73.2	3.7	27.6	7.2	0.67	11.7	260	24	-26.4	9.9
17	04/07/2006	30	60	0.58	0.95	23.6	72.4	4.0	6.3	7.8	0.67	12.6	1230	106	-26.2	9.7
18	06/10/2006	20	94	0.73	0.76	29.2	68.3	2.5	4.2	12.3	1.23	10.9	2920	292	-28.1	13.9
19	06/10/2006	30	94	4.75	4.93	18.3	77.8	3.9	4.3	7.1	0.58	13.3	1640	133	-26.0	11.6

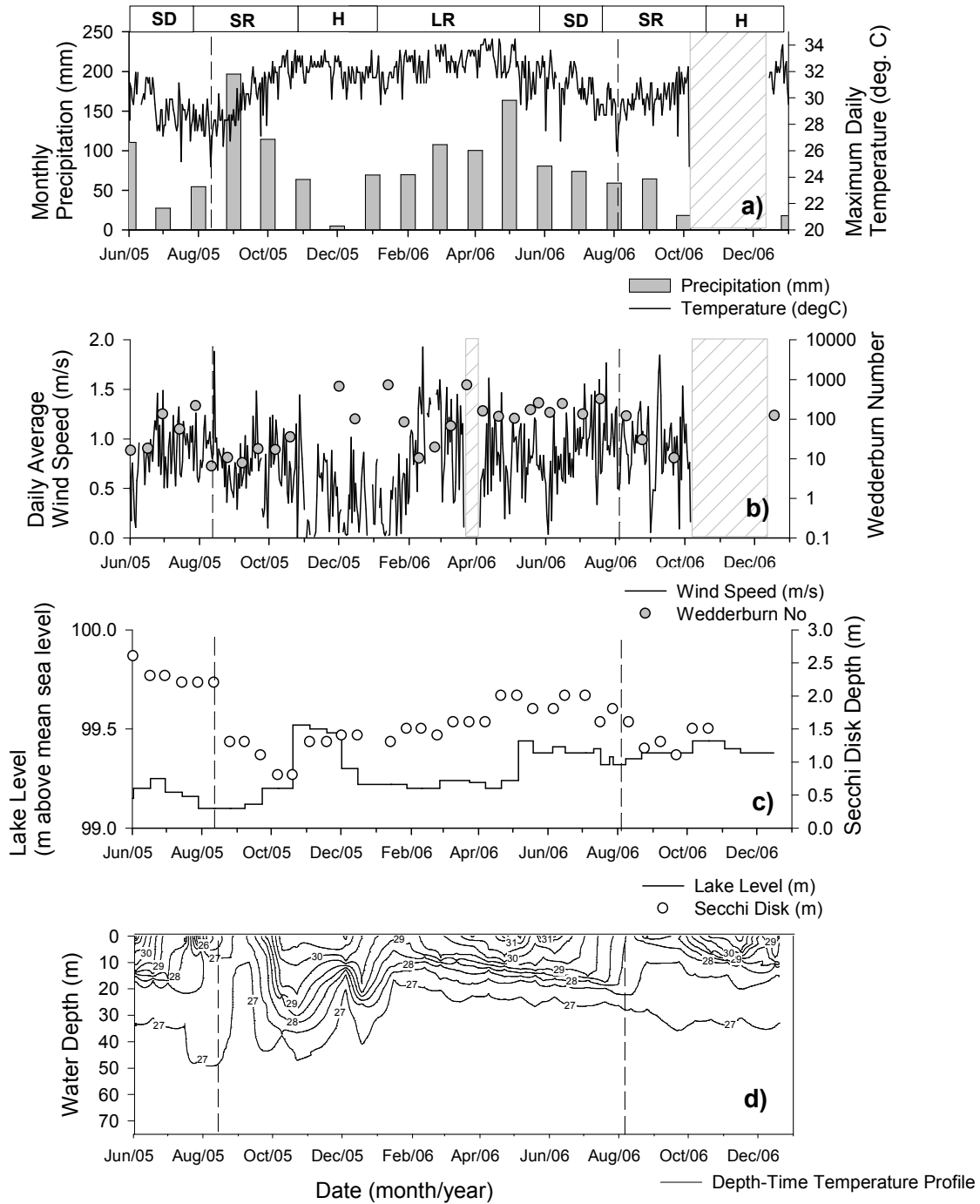


Figure 3-3 Seasonal patterns of meteorological and physical limnological conditions at Lake Bosomtwe, Ghana between 1 June 2005 and 31 December 2006. Panel a) total monthly precipitation and average maximum daily air temperature; b) average daily wind speeds and Wedderburn number (water column stratification proxy) c) biweekly lake level and Secchi disk depth (water transparency proxy), and d) depth-time water temperature contour plot in Lake Bosomtwe. Seasonal intervals denoted at the top SD short dry, SR short rain, H Harmattan and LR long rains. Note: cross-hatched boxes represent missing data. Vertical dashed lines denote August 12, 2005 (destratification) and August 3, 2006 (weakened thermal stratification).

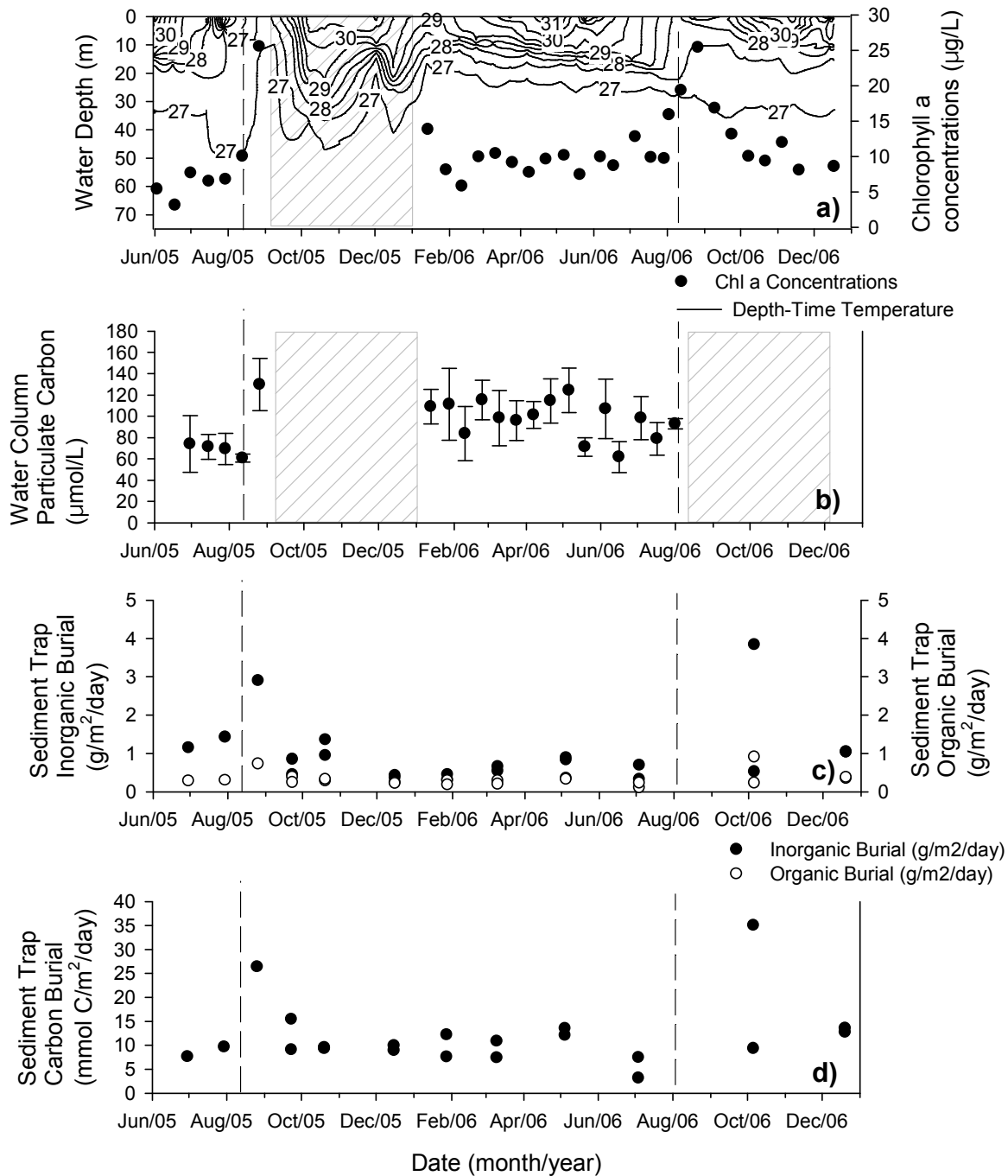


Figure 3-4 Water column data a) depth-time water temperature contour plot and chlorophyll *a* concentrations; and b) water column particulate carbon concentrations. Sediment trap data c) inorganic burial and organic burial rates; and e) carbon burial rates in Lake Bosomtwe during sediment trap sampling from June 1, 2005 to December 31, 2006. Sediment trap samples are presented graphically on the end-date of collection. Note: cross-hatched boxes represent missing data. Vertical dashed lines denote August 12, 2005 (destratification) and August 3, 2006 (weakened thermal stratification).

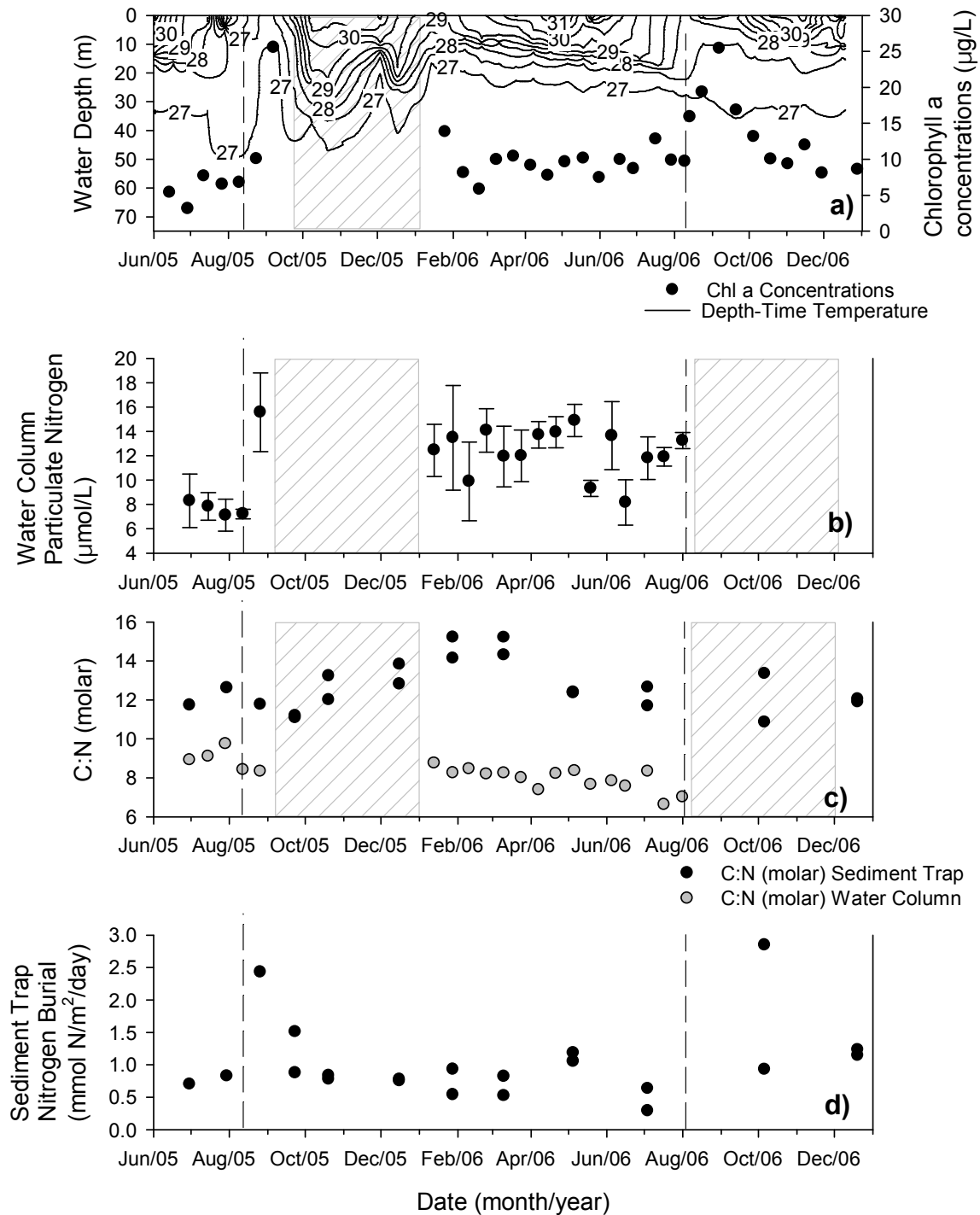


Figure 3-5 Water column data a) depth-time water temperature contour plot and chlorophyll *a* concentrations; b) water column particulate nitrogen concentrations; and c) C:N molar ratios (grey) as compared to sediment trap data c) C:N molar ratios (black); and d) nitrogen burial rates in Lake Bosomtwe during sediment trap sampling from June 1, 2005 to December 31, 2006. Sediment trap samples are presented graphically on the end-date of collection. Note: cross-hatched boxes represent missing data. Vertical dashed lines denote August 12, 2005 (destratification) and August 3, 2006 (weakened thermal stratification).

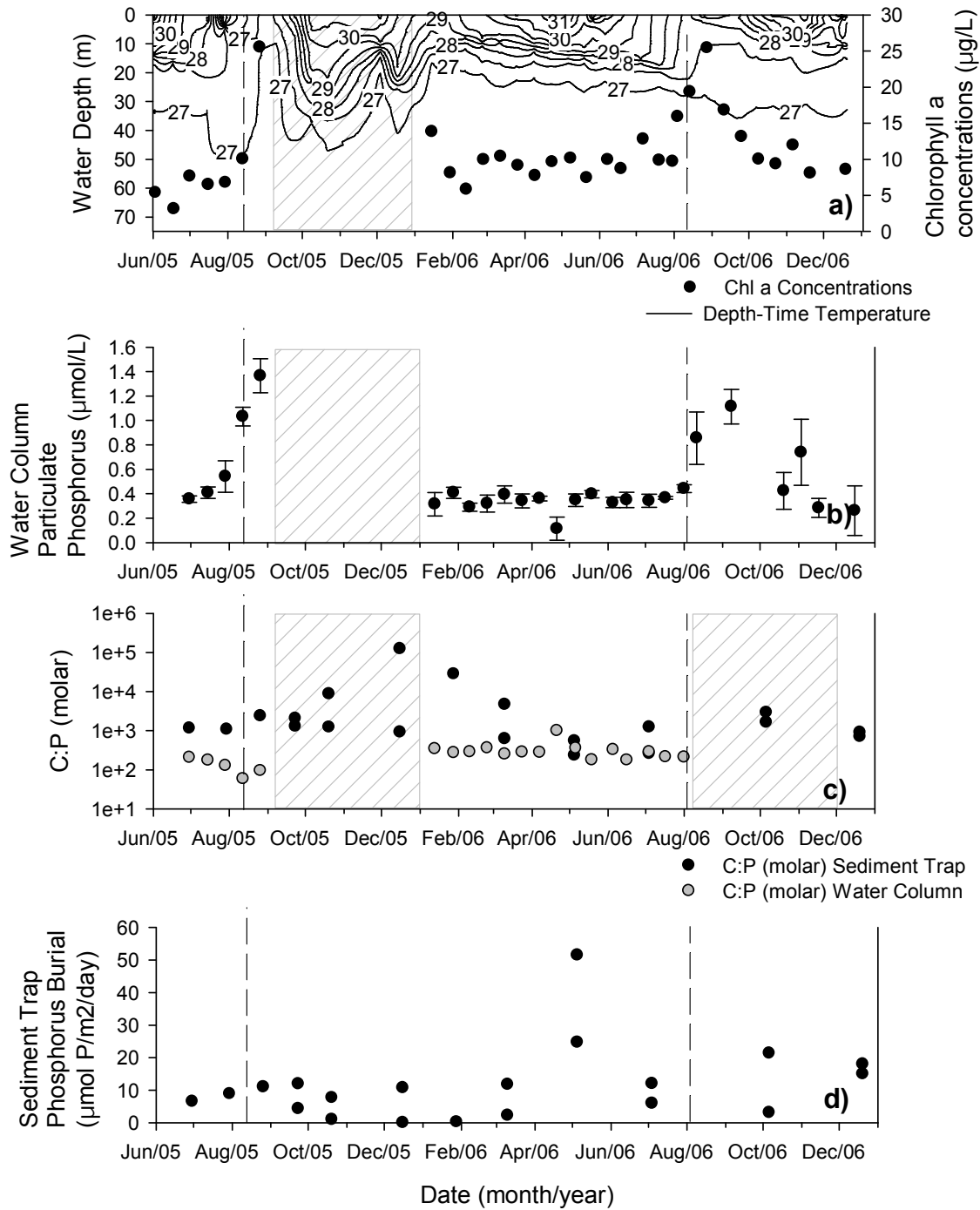


Figure 3-6 Water column data a) depth-time water temperature contour plot and chlorophyll *a* concentrations; b) water column particulate phosphorus concentrations; and c) C:P molar ratios (grey) as compared to sediment trap data c) C:P molar ratios (black); and d) phosphorus burial rates in Lake Bosomtwe during sediment trap sampling from June 1, 2005 to December 31, 2006. Sediment trap samples are presented graphically on the end-date of collection. Note: cross-hatched boxes represent missing data. Vertical dashed lines denote August 12, 2005 (destratification) and August 3, 2006 (weakened thermal stratification).

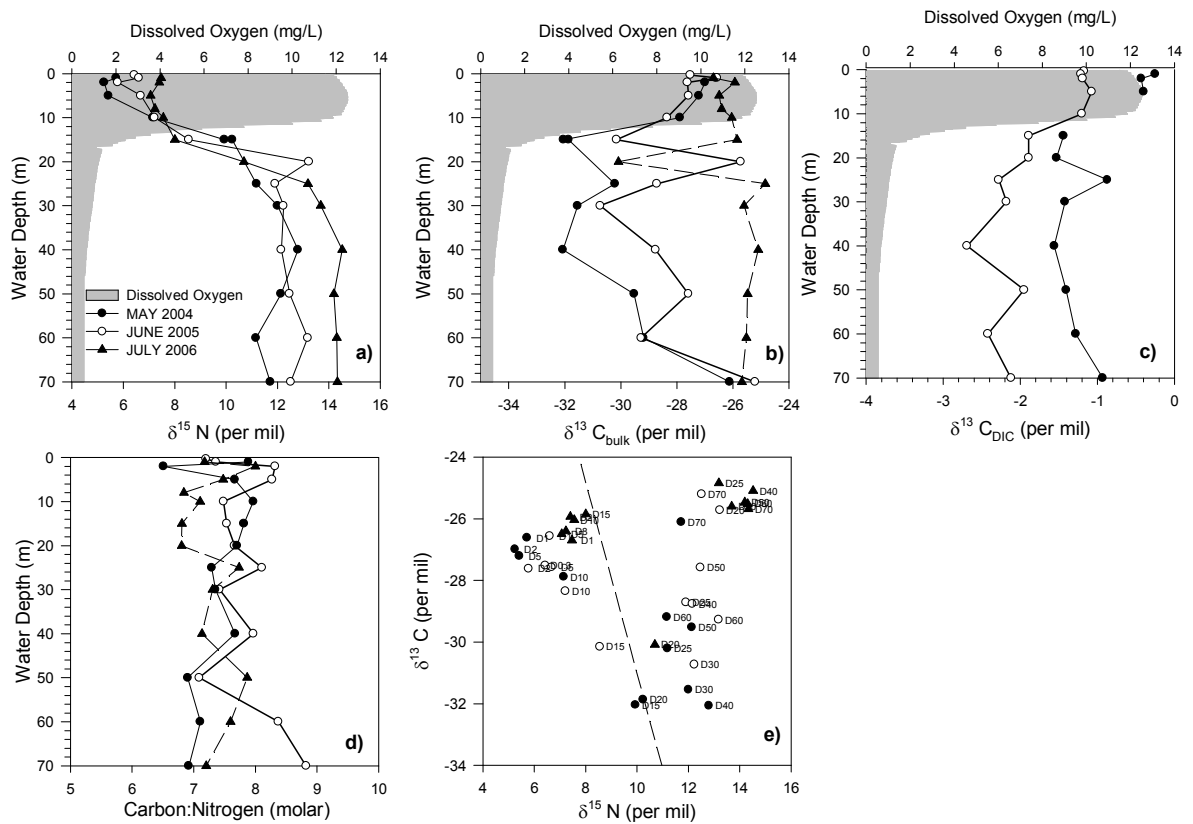


Figure 3-7 Water column particulate organic matter stable isotopic signatures a) $\delta^{15}\text{N}$, b) $\delta^{13}\text{C}$ of bulk matter and c) $\delta^{13}\text{C}$ of dissolved inorganic carbon (DIC) with respect to water column oxygenation, d) molar carbon to nitrogen ratios; e) $\delta^{15}\text{N}$ by $\delta^{13}\text{C}$ plots for the three vertical profiles from May 2004, June 2005 and July 2006. Along the $\delta^{15}\text{N}$ axis, surface waters (0-15 m depth) partition from deep-water POM (15-70m) along a slope of -3.1 denoted by a dashed line with depth denoted by the affixed labels.

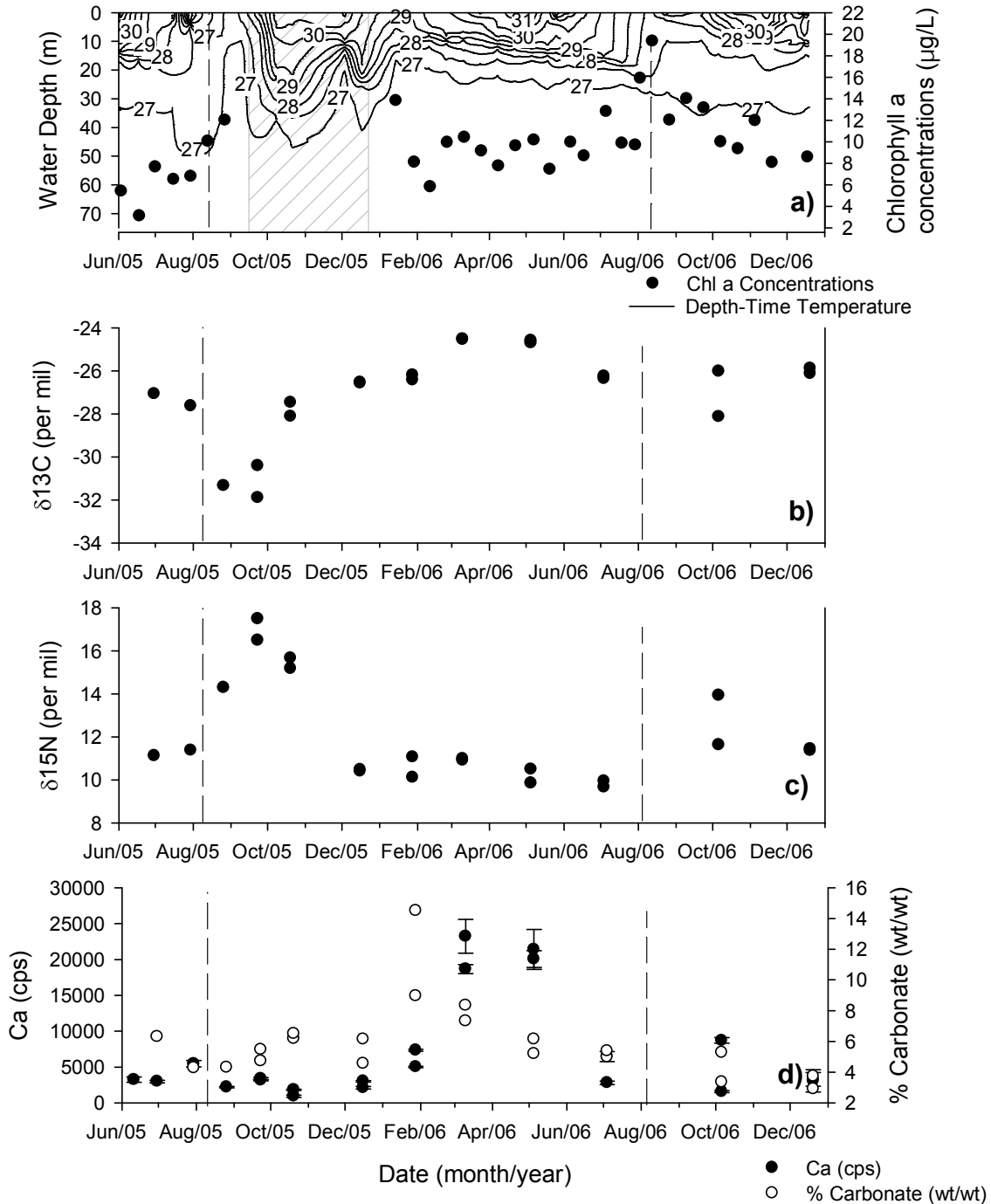


Figure 3-8 Water column data a) depth-time water temperature contour plot and chlorophyll *a* concentrations. Sediment trap data b) stable isotopic signature of $\delta^{13}\text{C}$; and c) $\delta^{15}\text{N}$ for organic material; and d) calcium concentrations (closed circle, from XRF analyses represented in counts per second units) and percent carbonate (open circle) in Lake Bosomtwe during sediment trap sampling from June 1, 2005 to December 31, 2006. Sediment trap samples are presented graphically on the end-date of collection. Note: cross-hatched boxes represent missing data. Vertical dashed lines denote August 12, 2005 (destratification) and August 3, 2006 (weakened thermal stratification).

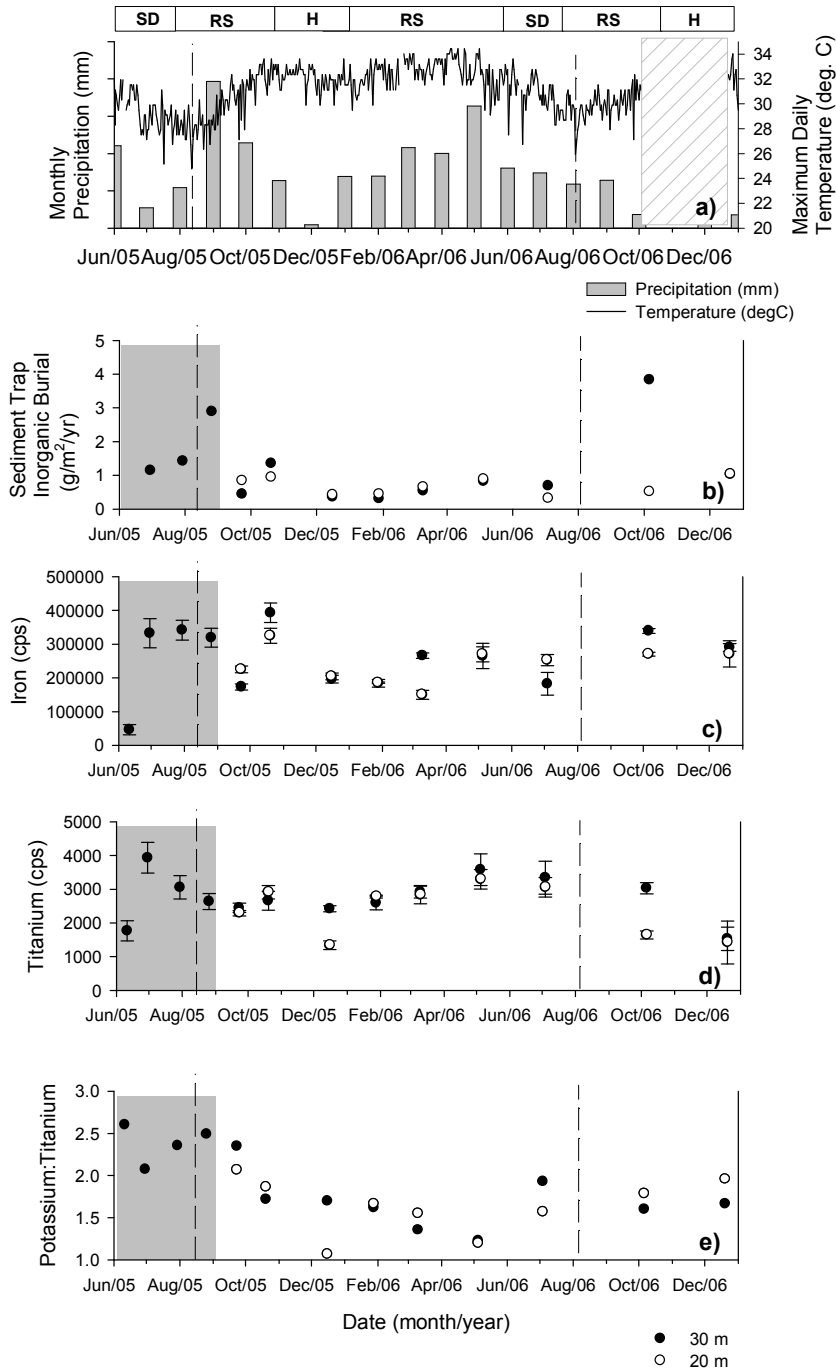


Figure 3-9 Meteorological data a) total monthly precipitation and average maximum daily air temperature. Sediment trap data b) inorganic burial rates, and XRF results c) iron d) titanium and e) potassium:titanium ratios are represented in counts per second in Lake Bosomtwe during sediment trap sampling from June 1, 2005 to December 31, 2006. The elemental compositions of sediment trap samplers were plotted separately; the 20 m trap is represented by an open circle and 30 m trap by a closed circle to show any depth differences between samplers. Sediment trap samples are presented graphically on the end-date of collection. Note: grey boxes represent missing data for the 20 m trap. Vertical dashed lines denote August 12, 2005 (destratification) and August 3, 2006 (weakened thermal stratification).

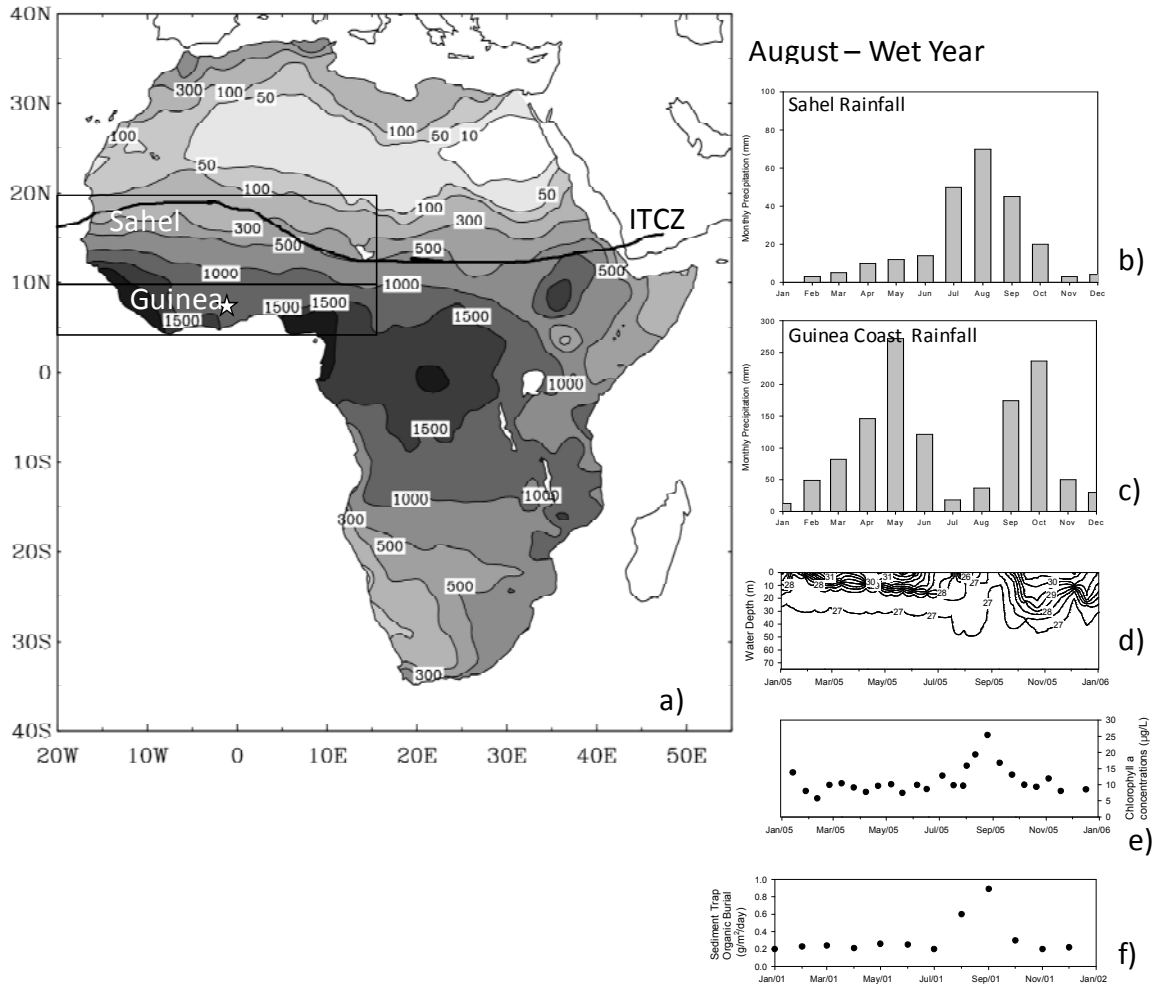


Figure 3-0-10 a) The position of the ITCZ over Africa during August of a wet year, presented on a map of annual rainfall. Bar charts represent the seasonal pattern of rainfall over b) the Sahel region and c) the Guinea Coast Region. Lake Bosomtwe, Ghana is denoted by a star. The effect of the short dry period over Lake Bosomtwe during July and August was found cool the water column temperatures and d) result in water column mixing, e) increased chlorophyll *a* concentrations (proxy for primary productivity) and f) increased organic matter sedimentation rates.

4 Chapter - The role of water depth on spatial patterns of sediment composition and preservation of laminations in a sub-Saharan crater lake, Lake Bosomtwe (Ghana, West Africa)

OVERVIEW

Evidence of lake level change has long been used in paleolimnological studies to determine past changes in climatic conditions. Here we present both spatial and temporal patterns of lacustrine sedimentation in relation to water depth within a simple bowl-shaped crater lake, Lake Bosomtwe (Ghana, West Africa). Lake Bosomtwe is a hydrologically closed-drainage lake that is known to have fluctuated in water depth during the Holocene, and it is the site where the International Continental Scientific Drilling Program retrieved a million-year-long sediment record in 2004. Our objective was to characterize the role of water depth on the composition of surface sediments and the preservation of laminae, notwithstanding the potential influence of anthropogenic activities in the crater. Analyses of organic matter, carbonate and inorganic matter, carbon, nitrogen and phosphorus concentrations, and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of bulk matter were used to identify patterns of spatial variation in sediment composition along two depth transects during the past ~40 years, and during ~1860-1958 CE at a central deep-water coring site. Spatial sediment trends found that laminations were visibly preserved at water depths greater than 35 m, which corresponds closely with the depth of the permanently anoxic hypolimnion, which was determined from biweekly thermal profiles collected during 2004-2006. Surface sediments along a transect from the northern town of Abono recorded recent accelerated inorganic sedimentation rates due to increased soil erosion. Elevated inorganic sediment delivery has persisted since the construction of a feeder road in 1958, which has continued to increase anthropogenic activity in the adjacent catchment area. The relationships between water depth and sediment variables organic matter, inorganic matter, carbon, nitrogen and phosphorus concentrations, nutrient stoichiometry and stable isotopic signatures of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ were then characterized by

linear regression. Because recent anthropogenic activities have imparted discernible changes in sediment composition, a central offshore coring site was used to examine relationships between pre-1958 sediments and historical lake depth during 1860-1957 CE. Sediment carbon concentration ($r^2 = 0.82$, $P < 0.0003$), organic content ($r^2 = 0.81$, $P < 0.0004$) and C:N ratio ($r^2 = 0.65$, $P < 0.005$) were the variables that showed the strongest relationships with lake level. Use of water-depth reconstructions based on the relationship between down-core sediment composition and historical lake levels predicted that the maximum lake depth was 56 m deep during ~1425-1720 CE before visible laminations began to form. There was a discrepancy between the water depth at which laminations are visible based on present day spatial transects (35 m) and historical lake levels inferred from the central, deep-water sediment record (56 m). Results imply that both the thermal circulation patterns and the depositional conditions that led to the preservation of laminae did not remain static, but rather changed over time as lake levels fluctuated in response to climatic variations. During ~1425-1720 CE, a low water stand was demarcated by high inorganic content and absence of visible laminations that was believed to be linked to climatic changes associated with the Little Ice Age (LIA). The LIA was a climate period identified widely throughout the northern hemisphere that also appears to have been associated with climatic changes in tropical West Africa that altered limnological conditions and sediment deposition in Lake Bosomtwe. When reconstructing paleoclimatic conditions during the past million years around Lake Bosomtwe, it is important to be cognisant of changing preservation conditions. Improving the accuracy of lake level reconstructions will improve the ability to predict the severity and frequency of drought over Lake Bosomtwe, West Africa. The climate reconstructions from Lake Bosomtwe are an important means of preparing the present day sub-Saharan population, which once was nomadic and is now sedentary, for future climate variability.

INTRODUCTION

Reconstruction of past lake level changes in closed-basin lakes has been frequently used as a source of information on pre-historic climate variability (Detriche et al. 2008; Ekblom and Stabell 2008; Garcin et al. 2006; 2009; Kiage and Liu 2009). Long-term wet periods increase the net hydrological balance through direct precipitation and catchment runoff, while prolonged dry periods decrease lake levels and concentrate solutes in closed-basin systems (Fritz 2008). Thus, lake level variation of these closed-basin lakes strongly reflects long-term variations in the balance between precipitation and evaporation. Paleolimnological reconstructions of past lake level change have applied a diversity of proxies such as carbonate deposition (Talbot and Johannessen 1992; Pienitz et al. 2000; Waldmann et al. 2009), stable isotopes of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (Pham et al. 2008; Talbot et al. 2007; Scholz et al. 2003) and $\delta^{18}\text{O}$ and δD (Pham et al. 2009; Wolfe et al. 2007; Lamb et al. 2005; Barker et al. 2001), fossil diatoms (Michels et al. 2007; Verschuren et al. 2000; Barker et al. 2002), chironomid and chaoborid assemblages (Luoto 2009; Verschuren et al. 1999; Verschuren and Eggermont 2006) and macrophyte remains (Rasmussen and Anderson 2005). The development of transfer functions from fossil assemblages of diatoms (Hassan et al. 2009; Fritz et al. 1991) and chironomid head capsules (Heinrichs and Walker 2006; MacDonald et al. 2008) ushered in an era of classifying regional climate patterns and limnological conditions through the use of surface sediment surveys of large numbers of lakes that span climatic and limnological gradients.

In sub-Saharan West Africa, however, there is only one naturally formed lake basin, Lake Bosomtwe, and no other similar basin exists in the Guinea Coast region. The Bosomtwe meteorite impact crater was formed 1.07 million years ago (Koeberl et al. 1997), creating the lake and catchment of the Lake Bosomtwe basin. The closed-basin hydrology is due to the crater walls, basement impact breccia and subsequent sediment layers that inhibit surface and ground water exchange (Talbot and Delibrias 1977; 1980; Turner et al. 1996a; 1996b). Inputs of water are from rainfall deposited directly on the

lake surface area (80%) and catchment runoff, while outputs are from evaporative losses (Turner et al. 1996a). Long-term climate variations are known to strongly regulate the water levels of Lake Bosomtwe, based on paleoenvironmental and historical evidence. In the past, villages have been displaced multiple times (Rattray 1923). Around the crater walls are relict beach deposits from peak lake levels during the Holocene, when water levels rose to over 110 m above present-day water levels and spilled out over the sill at the eastern crater wall (Talbot and Delibrias 1977; Talbot and Delibrias 1980). Drought-induced low water levels are also evident in both seismic profiling of the sediment records, where unconformities indicate a 25 m decline in water level ~1700 CE in Lake Bosomtwe (Shanahan et al. 2009, Brooks et al. 2005) and in submerged trees dated to be more than 300 years old (Shanahan 2005).

Almost 300 m of sediment has accumulated since Lake Bosomtwe was formed over 1 million years ago. In 2004, the International Continental Scientific Drilling Program recovered the entire 300 metre-long lacustrine sediment record, much of which is visually laminated (Koeberl et al. 2007). These laminated sediments may provide exceptionally informative paleolimnological reconstructions of water-level and climatic fluctuations. Thus, there is much interest in developing scientific tools that can be used to quantify past lake level changes from information preserved in the sediment record.

Knowledge of relationships between sediment composition and water depth along spatial transects within Lake Bosomtwe may provide useful information to allow reconstruction of past lake level changes. Many reconstructions of lake level do not use spatial lacustrine sedimentation patterns to understand lacustrine depositional conditions, as basin morphology and external energetic forces can be complicated (Hakanson 1977; 1982). In Lake Bosomtwe, however, the simple bowl-shaped morphometry and steep crater walls limit the input of turbulent energy from winds and convective mixing and should result in less complex sediment patterns.

Thus far, no biological indices of water depth in Lake Bosomtwe have been found that could be used to develop a transfer function. Diatoms are known to exist in Lake Bosomtwe, particularly following the deep-water mixing event of August and September (Awortwi 2010). Diatoms, unfortunately, do not appear to preserve adequately in the sediments. The high pH of the water column appears to promote dissolution of diatoms in the sediment records because they are absent from sediment samples below 10 cm depth. Remains of some invertebrates were found in the nearshore surface sediments, but their distribution was limited to only one river mouth, the Abrewa River. Furthermore, macrophytes are largely absent from the lake. The greatest nearshore epiphytic coverage consisted of filamentous green algae, *Cladophora* sp. that is heavily grazed upon by the cichlid population (Hedy Kling, pers. comm.). The index of lake level change must, therefore, be derived from geochemical proxies.

A preliminary study by Ellis (2005) characterized spatial patterns of the composition and grain size of surface sediments in Lake Bosomtwe from 63 ponar dredge samples. Ellis (2005) identified four sediment zones. Two were nearshore zones, defined as *deltaic* (near inflowing rivers with coarse-grained facies > 50 μm grain size at water depths < 25 m) and *nearshore* (with fine-grained facies < 50 μm grain size at water depths < 25 m) and two were offshore zones, defined as *hemipelagic* (water depths between 25 and 70 m) and *abyssal* (water depths >70 m). The deltaic zone consisted of seven regions that corresponded with river channels from the Abono, Obo Kwakye, Konkoma, Twiwaa and Abrewa Rivers (Whyte 1975). The spatial distribution and the larger grain size clearly distinguished the deltaic zone from the finer grained nearshore sediments. The nearshore and two offshore zones showed greater similarity with overlapping total organic carbon (TOC) content (3 to 7%) and $\delta^{13}\text{C}$ signatures (-25.7 to -27.4‰; Ellis 2005). Sediments from the hemipelagic and abyssal zones were markedly more enriched in $\delta^{15}\text{N}$ (4.1 to 20.7‰) than those from the nearshore zone. Relative to the nearshore zones, the offshore sediments also contained greater concentration of hydrocarbons with

increasing water depth, from free hydrocarbons (S1) measuring 0.07 mg HC/g in the nearshore to 12.04 mg HC/g offshore; generatable hydrocarbons (S2) measuring 0.07 mg HC/g to 53.39 mg HC/g; and increasing hydrogen indices (HI) from 0 to 703 mg HC/g and oxygen indices (OI) of total organic carbon from 0 to 1319 mg CO₂/ g. These compositional changes with water depth open the possibility of using sediment chemical composition as an indicator of past water-level change.

Laminated sediments recovered from the abyssal zone of Lake Bosomtwe's depositional region were characterized by Shanahan et al. (2008) as seasonal deposits. Laminated sediments from both piston cores and freeze cores were well-preserved and undisturbed under anoxic and sulphur-rich deep-water conditions. Laminations consisted of dark and light couplets that differed in composition. The dark laminae were comprised mainly of inorganic material dominated by quartz, feldspar and mica, and thus, contained a higher content of aluminum, silicon, titanium and potassium than the light laminae (Shanahan et al. 2008). The light laminae consisted of light brown organic matter enriched in calcium and carbonate that were believed to originate from primary production within the lake. Shanahan et al. (2008) found that the thickness (0.5 – 1.0 mm) of the dark, inorganic laminations in Lake Bosomtwe was positively correlated with precipitation measured at the Kumasi airport ($r = 0.54$, $P < 0.05$). The Kumasi airport is 30 km from Lake Bosomtwe and the data were represented as a rainfall anomaly, expressed as the deviation from the 1900-2000 mean and normalized to the standard deviation of the dataset. The thickness of dark laminae in Lake Bosomtwe increased with the amount of annual rainfall (Shanahan et al. 2008).

Lake Bosomtwe (6°30N and 1°25W), Ghana, is found in a region of West Africa with high interannual rainfall variability that can result in frequent droughts. Lake Bosomtwe is situated at the northern boundary of the semi-deciduous forested region of the Guinea Coast, south of the arid-tolerant scrubland known as the Sahel region. The climate patterns over Lake Bosomtwe are characterized by two periods of rainfall annually, the long rains from February to June and the short

rains from September to November (Beadle 1981; Puchniak et al. 2009). The monsoon rains over Ghana are delivered by the low-pressure moisture belt known as the intertropical convergence zone (ITCZ). These rainy periods are separated by a short dry season in July and August, when the ITCZ travels northward to the Sahel region, and the Harmattan dry season in December and January, when the ITCZ travels southward to the Gulf of Guinea (Nicholson and Palao 1993). Interannual rainfall variability is driven by both the amount of water vapour carried by the ITCZ and the degree of northward displacement of the ITCZ. High rainfall years over the Sahel region are years with greater water vapour content and greater northward displacement of the ITCZ. The interannual variability of water levels at Lake Bosomtwe in the Guinea Coast region are dependent on the rates of rainfall delivery relative to evaporation rates. Thus, paleoclimatic reconstructions of lake level change at Lake Bosomtwe will dramatically improve our ability to predict the frequency and severity of drought in the Sahel and Guinea Coast of West Africa.

The use of a present-day spatial survey of sediments along a water-depth gradient within Lake Bosomtwe will provide one approach to establishing a predictive relationship between geochemical proxies and water depth. This approach, however, cannot incorporate information about changes over time, which is the intended application of these relationships. An assessment of the changing geochemical proxies within sediment profiles from Lake Bosomtwe in relation to the historical records of water-level change is essential. Fortunately, the Ghana Hydrological Survey has recorded water levels since 1938 at a nearshore water level gauge in Lake Bosomtwe. Shanahan et al. (2006) found that interannual rainfall variability from meteorological records had a very strong correlation with Lake Bosomtwe water levels. For example, the Sahel region has experienced multiple drought years since 1969 (Dai et al. 2004). Similarly, Lake Bosomtwe water levels have declined from 1969 until present. In this study, we compare spatial sediment characteristics along two transects and water depth, and explore relationships between down-core variations in sediment characteristics and

historical lake level measures. Our objective is to develop an index for reconstructing past climate-driven lake level change from information in sediment cores.

From 1900 to 1969, water level rise at Lake Bosomtwe led to displacement of some townships around the crater. Twenty-two villages inhabit the shores of Lake Bosomtwe and flooding led to the evacuation of many towns, such as Assisiriwa, Pepie and Konkoma during 1956-1964. Fisherman and farmers had to re-establish homes outside the crater rim and then commute into the catchment to access fishing territories and farming plots. Lake level rise can lead to rapid shoreline erosion and restructuring of the nearshore littoral zone. Flooding can drown terrestrial vegetation and promote the succession of new emergent or submerged macrophytes or benthic colonizers (Livingstone 2008). Changes to the littoral zone affect the quality and quantity of sediment inputs delivered from the catchment to the lake, and transport of sediment from the littoral zone to the abyssal zone. For instance, the increase in thickness of the dark, inorganic-rich laminae between 1950 and 1960 in Lake Bosomtwe sediment coincided with prolonged wet years and rapidly rising lake levels that resulted in elevated inputs of inorganic material (Shanahan et al. 2008).

Climate is not the only factor that affects the spatial patterns of sedimentation. Changes in anthropogenic activities within the lake catchment can also alter the delivery of sediments to the lake bottom. In the Bosomtwe impact crater, rapid expansion of agricultural plots upslope are believed to have destabilized top soils and caused slumping, soil erosion and landslides (Boamah and Koeberl 2007; Danuor and Menyeh 2007). Commonly, riverbank erosion and siltation often result when hillslope erosion mobilizes topsoil into the streams. Local fishermen around the crater have observed a noticeable decline in water clarity in Lake Bosomtwe when diving for benthic fish traps on the lake bottom (personal communications). Villagers have postulated that the removal of trees for planting of crops along the shoreline and river banks may have contributed to the observed turbidity.

Furthermore, particulate-bound nutrients, when released into aquatic ecosystems often increase primary production, and subsequently, turbidity.

There is also a high demand for water resources by the population within the lake's catchment. Many of the 22 villages around the lake have little access to well water, so they rely heavily on Lake Bosomtwe to bathe, clean cooking utensils, launder clothes and water livestock. Villages do not have organized sewage disposal outside of a few pit latrines, and the domestic use of phosphate-based laundry detergents is also common, resulting in multiple sources of phosphorus additions to the water column that could contribute to eutrophication of Lake Bosomtwe. Presently, these human activities threaten the water quality of Lake Bosomtwe. Thus, the influence of human activities on sediment composition is an important factor to consider when establishing relationships between sediment variables and water depth.

The objectives of this study were to characterize the role of water depth on the composition of surface sediments and the preservation of laminae, notwithstanding the potential influence of anthropogenic activities in the crater. To do this, we examined the spatial patterns of sedimentation from analyses of surficial sediments during the past 40 years. Cores were obtained from sites located along two depth transects that extended from two different deltaic sites to the central deep-water region of Lake Bosomtwe (Figure 4-1). One transect ran from the well-populated Abono River, situated on the north shore. The second transect ran from the uninhabited shoreline of the Konkoma River, situated on the east shore. The depositional trends along the water-depth gradients were explored through visual assessment of stratigraphic changes in the sediment and temporal changes in sedimentation rates, inorganic and organic content, concentrations of total particulate nutrients (carbon, nitrogen and phosphorus), and carbon and nitrogen stable isotopic signatures. Then, trends in a sediment core from a central site at the maximum water depth of the modern lake were related to historic water level changes. We anticipate that a better understanding of the quantitative relationships between water

depth and sediment composition will enable more refined and quantitative interpretation of water-level changes from the million year stratigraphic record that was recently acquired from Lake Bosomtwe.

Study Site

Average annual rainfall at the lakeside meteorological station was 1,250 mm yr⁻¹ during 2004 to 2007 (Puchniak et al. 2009), slightly less than recorded at the nearby Kumasi airport (1,280 mm yr⁻¹). Interannual rainfall variability can be seen in the pattern of seasonal deposition (Figure 4-2), with either a bimodal or unimodal annual rainfall pattern depending on the duration of the short dry period. The water chemistry of this closed-drainage lake is largely dictated by the sub-Saharan climate. Evaporative concentration of the hydrological inputs has led to a specific conductivity of 1,150 µS cm⁻¹, alkalinity of 10,320 µmol L⁻¹, salinity of 0.32 g L⁻¹ and pH of 8.9 (Puchniak et al. 2009). Salts have been accumulating since the lake last overflowed out of the crater (11.6 – 8.8 cal ka; Shanahan 2006).

The hypolimnion of Lake Bosomtwe (35 -78 m) is deep, permanently anoxic water and temperatures are relatively invariant at 26.8 °C. Water column mixing is restricted below the hypolimnion by persistent thermal density differences. The greatest density difference occurs during seasonal maximum water temperatures when the epilimnion density (0.9957g cm⁻³) is less than the hypolimnion density (0.9968 g cm⁻³;Chen and Millero 1977; 1986). Salinity contributions to density at depth are relatively insignificant, with negligible differences between the epilimnion (0.996808 g cm⁻³) and the hypolimnion (0.996807 g cm⁻³). Water column mixing in Lake Bosomtwe occurs in the upper waters (0-35 m), with deepest thermal mixing occurring in August (more frequently) and/or January (less frequently). These mixing events are caused by evaporative cooling when minimum night-time air temperatures during the dry season reduce surface water temperatures. Mixing often

leads to deoxygenation of the upper waters, which typically causes a fish kill event (Puchniak et al. 2009). Today the lake mixes seasonally and can homogenize water temperatures to 35 m and provide turbulent energy to re-suspend particulates for transport further offshore. Because these deep mixing events do not reoxygenate the water column to the depth of mixing, the macrofauna that can disturb sediment microstratigraphy are restricted to water depths less than 35 m.

MATERIALS & METHODS

Sediment Core Collection

Ten short sediment cores (31-53 cm long) were collected in May 2004 (1 core), May 2005 (8 cores) and August 2006 (1 core) along two depth transects using a modified Kullenberg corer, Glew gravity corer, or mini-Glew gravity corer, Table 4-1 (Glew 1995). One modified Kullenberg core was collected from the center of the lake at 78 m water depth by D. Livingstone, referred to as core 'Central 1.' We attempted to collect the rest of the cores using the Glew corer because it provides a larger volume of sediment than either the modified Kullenberg or mini-Glew corer. Sediments at sites deeper than 50 m water depth did not build up sufficient frictional resistance along the core tube walls to allow us to retrieve sediment cores using the Glew corer (i.e., there was insufficient friction to remove the core from the lake bottom, or the sediment fell out as the corer was retrieved through the water column), so at sites > 50 m depth, cores were collected using a mini-Glew corer.

There were two coring transects. A northern Abono transect that consisted of three cores, the first taken adjacent to the Abono River at 25 m water depth out to the last at the central sampling locations (78 m, Figure 4-1). The second, eastern Konkoma transect consisted of four cores that extended from the Konkoma River at 24 m water depth out to the same central sampling locations. Sediment cores collected in 2005 were transported to the shoreline where they were visually inspected and sectioned vertically into 0.5-cm intervals that were placed into plastic Whirlpak® bags and stored in the dark at

4°C until further analyses. Kullenberg core Central 1 (collected in 2004), was sealed with mesh, foam and a cork, and transported horizontally to Waterloo where it was refrigerated. In 2005, this core was extruded vertically in the same manner as the previous cores. The gravity core Central 3 (collected in 2006) was sealed with paraffin wax and a sponge layer, and transported horizontally to the LaCore Facility, University of Minneapolis, USA. In 2006, this core was split horizontally and sectioned into 0.5-cm intervals after scanning it for physical and chemical variables. As a result of the splitting, some of the unconsolidated surface sediments were lost and needed to be accounted for when establishing a chronology.

Chronology – ^{210}Pb and ^{137}Cs

Sediment core chronologies were determined from activities of ^{210}Pb and ^{137}Cs radioisotopes estimated by gamma ray spectrometry. Sediments were freeze-dried, ground and a measured mass was packed into plastic tubes. Samples were packed to a standard volume (21 mm), sealed with 1 cc of epoxy resin and stored for at least two weeks before analysis. This permitted the sample to trap any emitted ^{222}Rn gas and establish equilibrium between parent ^{226}Ra and the daughter elements used to estimate its activity. Gamma spectrometry analysis was performed at the University of Waterloo Environmental Change Research Laboratory with measurements of total activity for radioisotopes ^{210}Pb and ^{137}Cs represented as disintegrations per minute (dpm g^{-1}). Samples were run on the gamma spectrometer (Ortec® GWL series coaxial HPGe detector) for 24 to 72 hours to capture sufficient gamma emissions to exceed minimum detection limits in excess of the neighbouring background emissions and double the values obtained from the blank samples (Blaauw et al. 2001).

Age-depth relationships can be generated accurately during the past 150 years using the ^{210}Pb activity decay curve. The background ^{210}Pb activity was determined as the minimum positive ^{210}Pb activity along the asymptote of the observed decay curve. Sedimentation rates and chronology were

established using the constant rate of supply (CRS) model, because the CRS model accommodates fluctuating sedimentation rates that may occur in Lake Bosomtwe when water levels vary (Appleby and Oldfield 1983). Lake level fluctuations can result in nearshore erosion and reworking of the shoreline that can lead to the input of ^{210}Pb -deficient sediments and alter sedimentation rates (Appleby and Oldfield 1983).

Dating of recent lacustrine sediments also relied on stratigraphic marker dates based on the ^{137}Cs activity profiles in the cores. The half life of ^{137}Cs is 33 years and is useful in determining recent sediment deposits. ^{137}Cs fallout was created by above ground nuclear bomb testing that began in 1954, with the peak in nuclear testing fallout occurring in 1964 (IAEA International Atomic Energy Agency 1991). Both ^{137}Cs and ^{210}Pb radioisotopes were used to establish the core chronologies presented in Figure 4-4.

Sediment Chemistry

Lacustrine sediment was processed for CHN analyses at the University of Waterloo following Stainton and colleagues (Stainton et al. 1977). Wet sediment from each 0.5-cm interval was subsampled into a glass vial, freeze dried and 2 mg weighed out into tin cups. The tin cups were then crimped and packed into a nickel sleeve for combustion. Samples were processed with an elemental analyzer Exeter CEC Model 440 (Zimmermann & Keefe 1997). Carbon and nitrogen peaks were used to calculate molar units (i.e. $\mu\text{mol g}^{-1}$ dry sediment weight) and used to calculate the molar ratio between carbon and nitrogen.

Total phosphorus content was measured in each of the sediment core slices following Berglund (1986), where ~5 mg of freeze-dried and ground sediment was placed into a small crucible and ashed at 550°C for one hour. The ashed sediment was weighed out into 70 mL glass test tubes and digested

with potassium persulfate in the autoclave for one half hour on the wet cycle. Following digestion, analyses followed colorimetric techniques from Stainton et al. (1977).

Gravimetric analyses were used to determine the water content of sediment samples for ^{210}Pb analyses and the organic, carbonate and inorganic content. Procedures followed Heiri et al. (2001) where ~0.5 g of wet sediment was weighed into crucibles and dried at 90°C for 24 hours, cooled and weighed to determine water content. Crucibles were then placed in the kiln to be ashed at 550°C for one hour, cooled and weighed to determine loss of organic content. Lastly, crucibles were returned to the kiln and combusted at 950°C for one hour, cooled and weighed to determine loss of carbon dioxide from carbonate. Carbonate content was calculated as the molar ratio from CO_2 at 950°C to CO_3 ($60 \text{ g mol}^{-1} / 44 \text{ g mol}^{-1}$). Inorganic content was calculated as the remaining weight.

Carbon and nitrogen stable isotopes of the surface (0-1.5 cm) of each sediment core and of the core Central 1 (0-50 cm) were analysed at the Environmental Isotope Laboratory at University of Waterloo. Sediment was freeze-dried, ground and weighed (1 to 6 mg) into a tin cup, sealed and combusted in the Prism Mass Spectrometer GC-C-IRMS. Isotopic composition is reported in parts per thousand as the difference from a standard.

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3$$

δX here is $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ and R is the respective isotopic ratio $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$ (Peterson and Fry 1987; Clark and Fritz 1997). The standard for $\delta^{13}\text{C}$ is Pee Dee Belemnite from South Carolina (PDB), and for $\delta^{15}\text{N}$ is atmospheric nitrogen (Clark and Fritz 1997). Precision of stable isotopic samples was $\pm 0.3 \text{ ‰}$ for $\delta^{13}\text{C}$ and $\pm 0.2 \text{ ‰}$ for $\delta^{15}\text{N}$. The $\delta^{13}\text{C}$ sediment signatures were then corrected for the effects of atmospheric carbon emissions since the industrial revolution, known as the Suess effect. The date-dependent correction followed (Verburg 2007), which was deducted from the bulk matter $\delta^{13}\text{C}$ signatures.

Data Analyses

Results from analyses of sediment characteristics along the spatial transects were explored in relationship to water depth. Data from the analyses of each sediment core along spatial transects were averaged and standard deviations calculated during the past 40 years (from roughly 0–10 cm sediment depth) with each mean containing 12 to 20 intervals analyzed (Figure 4-5). The mean values were presented as scatter plots and fitted with a linear regression to develop the sediment trends relative to the water depth. These linear regressions were then applied to the known geochemical composition of offshore core Central 1 to reconstruct pre-historic water levels.

Geochemical composition of sediments from core Central 1 were then compared with long-term lake level records for Lake Bosomtwe to assess temporal relationships between water depth and sediment variables. The Ghana Hydrological Survey recorded monthly water levels from 1938-2006 at a nearshore water level gauge in Abono (Figure 4-6a). A literature review of other water level assessments revealed that McGregor (1937) conducted a geological survey of the Bosomtwe impact crater and included a hydrological survey from 1933-1937 in Abono. Likewise, Rattray (1923) documented the Ashanti culture in the early 20th century and he recorded accounts of the displacement of the village of Abono. Rattray revisited these submerged sites, and using a weighted line, measured the water depth. Unfortunately, the exact dates were not known, however, the reigning Ashanti king was known and used to deduce the time period. The town was 1.2 m under water during King Prempeh, 1888-1895; 8.8 m under water during King Mensa Bonsu, 1874-1883; and 18.9 m under water during King Kwaku Dua I in 1836 to 1868 (Rattray 1923). Based on these historical water depths, variations in sediment composition of the deep core Central 1 were plotted in relation to the documented water-level changes. Spatial trends in sediment composition were found to have evidence of human activities post-1958 and ²¹⁰Pb-based chronology can be reliably determined until 1860, thus temporal trends in sediment composition were improved by restricting the calibration dataset to ~1860 to 1957.

RESULTS

The physical and geochemical characteristics of sediment core profiles varied markedly along a gradient of water depth, Figure 4-3 (Table 4-1). The most striking pattern was the presence of *visible* laminations in sediment cores situated below 37 m water depth and the absence of *visible* laminations at shallower depths (Table 4-1, Figure 4-3). The shallowest site that contained laminated sediments was 37 m (core Abono 3), whereas the deepest site that contained non-laminated sediments was 34 m (core Konkoma 2). This identified approximately 35 m as the threshold water depth for the formation and preservation of laminations, and was in good agreement with limnological observations of the depth of maximum mixing depths (35 m; Puchniak et al. 2009).

Along the water-depth gradient of this study, laminated sediments only occurred when the organic content was greater than 20% (Figure 4-3). Organic content increased from 10 to 40% between the shallow, nearshore sites and the deep-water, central sites. The stratigraphic variability of organic content increased as water depth increased. Interestingly, there were several organic content minima that aligned with visible inorganic-rich layers of laminated sediment cores, possibly turbidite layers, which interrupted the pattern of laminations. These inorganic-rich laminae are particularly visible in the central cores and were useful in cross-correlating among cores for chronological alignment.

Chronology was established using ^{210}Pb dating methods on six of the ten cores (Abono 1, Abono 2, Central 1, Central 3, Konkoma 1 and Konkoma 2). All six sediment cores showed intervals of a saw-toothed pattern of falling ^{210}Pb activity with depth (Figure 4-4 panel 1). Core Central 1 was found to have the highest surface activity of ^{210}Pb (55.7 dpm g^{-1}), with nearly twice as much activity as the four other nearshore cores that were dated. Cores Central 1 and Central 3 also showed an exponential decay curve, whereas shallower nearshore cores show a more gradual decay rate. The relatively high

^{210}Pb activity in Central 1 and Central 3 was likely indicative of either the effects of focusing of low density, fine-grained organic particles to the central coring sites or increased contribution of re-worked catchment material with reduced ^{210}Pb activity to the nearshore coring sites. The ^{210}Pb background activities ranged from 1.863 dpm g^{-1} to 1.614 dpm g^{-1} in all sediment cores. The ^{137}Cs activity marker dates, 1954 and 1964, corresponded with CRS model chronology (Figure 4-4, panel 2). Dates older than 1860 were calculated by determining the linear regression of the CRS derived dates and the measured cumulative dry mass during the past 150 years. The sediment cumulative dry mass down core was subtracted by the intercept of the regression and divided by the slope of the regression to extrapolate dates back to ~1425 CE. On average, the surface 10 cm of the nearshore sediment cores was ~1967 CE, containing roughly 36 years, while the average age of the surface 10 cm of the two central cores was ~1918, containing approximately 75 years. Nearshore cores, proximal to the shoreline have a higher sedimentation rate, which is suggestive of relatively higher inputs of re-worked nearshore sediments.

The average CRS-modelled sedimentation rates for all the sediment cores in Table 4-1 ranged from 1.33 to 3.06 mm yr^{-1} (and 0.0118 to 0.0760 $\text{g cm}^{-2} \text{yr}^{-1}$) in sediments deposited between 1860 and 2005. However, after ~1980, all of the nearshore sediment cores more than doubled in sedimentation rate and values continued to rise to present day (Figure 4-4). In advance of the ~1980 rise in sedimentation rate, the Abono nearshore transect showed a marked step-wise increase in sedimentation rate starting in ~1958 for Abono 1, ~1962 for Abono 2 (denoted by an arrow in Figure 4-4). This trend was not observed in cores from the Konkoma transect or at the Central sites. Accelerated sedimentation rates, especially close to the shore, may be due to increased soil erosion, fluvial deposits, deltaic sediments, reworking and transport of near-shore sediments during lake level changes that could have occurred in a crater lake like Lake Bosomtwe. Shallow-water, unlaminated core Konkoma 1 recorded multiple events of accelerated sedimentation which dated to ~1906, ~1927 and ~1946 that were not visible in other sediment core profiles.

To quantify the spatial trends between sediment geochemistry and water depth, values were averaged during the past 40 years for each coring site with an established ^{210}Pb -based chronology. For the four remaining undated cores, the past 40-year time interval was approximated by aligning neighbouring stratigraphies and the corresponding samples were averaged. Based on these data, significant linear relationships were identified between sediment chemical composition and water depths (Figure 4-5), which may be usable to hindcast pre-historic water depths (summarized in Table 4-2). Notably, sediment organic content increased linearly with water depth:

$$\% \text{ Organic matter} = 0.30(\text{Depth}) + 5.04$$

The r^2 value was 0.94 ($P < 0.0001$), indicating a strong, statistically significant linear relationship. Similarly, percent inorganic content was inversely related to water depth, as derived from the linear regression:

$$\% \text{ Inorganic matter} = -0.35(\text{Depth}) + 96.67$$

The r^2 was 0.94 ($P < 0.0001$) with the greatest abundance of inorganic particulates occurring in the near shore sediment stratigraphies.

Relationships between carbon and nitrogen content of surface sediments and water depth in Lake Bosomtwe paralleled that of organic content. Carbon and nitrogen concentrations increased with increasing water depth of the coring site. The linear regression equations are:

$$\text{Carbon concentration} = 0.17(\text{Depth}) - 0.48$$

$$\text{Nitrogen concentration} = 0.12(\text{Depth}) - 0.030$$

The relationship for carbon was slightly stronger ($r^2 = 0.94$) than that for nitrogen ($r^2 = 0.91$), but both were statistically significant ($P < 0.0001$). The lower fit with N may be a result of continuing diagenesis in the deeper-water sediments as N is lost to processes such as deamination and denitrification (Chapter 3 of this thesis). There was no significant relationship between C:N and water depth. The relationships between water depth and bulk matter stable isotopic signatures of $\delta^{13}\text{C}$ and

$\delta^{15}\text{N}$ in surface sediment in Lake Bosomtwe were not significant, with r^2 values of 0.12 ($P = 0.33$) and 0.25 ($P = 0.14$), respectively.

The relationship between phosphorus content and water depth was non-linear (Figure 4-5), which distinguished P from the previous water-depth relationships with C and N content. Sediment phosphorus concentrations remained low across all shallow coring sites to at most 50 m water depth, with an average phosphorus content of $7 \mu\text{mol P g}^{-1}$. Cores from the deepest, central sites had higher phosphorus content, with an average of $51 \mu\text{mol P g}^{-1}$. The best linear relationship for phosphorus was based on log-transformed phosphorus concentrations:

$$\text{Log(Phosphorus concentration)} = 0.018(\text{Depth}) + 0.25$$

The logarithmic relationship was fairly strong with $r^2 = 0.75$ ($P < 0.003$).

Depth relationships for C:P and N:P molar ratios (Figure 4-5) were both curved. Ratios at the deepest, central coring sites had the lowest variability during the past 40 years of sediment and mid-depth coring sites had the greatest variability, and for this reason, C:P and N:P relationships were not functional for lake level reconstructions.

$$\text{C:P} = 1372 * e^{(-0.5((\text{Depth} - 47.5) * 16.14^{-1}))^2}$$

$$\text{N:P} = 98 * e^{(-0.5((\text{Depth} - 47.7) * 15.96^{-1}))^2}$$

The trends fit the curve well at r^2 of 0.95 ($P < 0.0001$) and 0.94 ($P < 0.0002$) respectively.

Most of these relationships between sediment chemical composition and water depth during the past 40 years appear statistically significant in spite of the evidence of recent anthropogenic activities in the nearshore sediment records (particularly those from Abono). These regressions were used to reconstruct pre-historic water levels from core Central 1, a deep-water sediment core from Lake Bosomtwe that was far from the effects of recent anthropogenic activities (Figure 4-6). The linear

regressions with the best fit were organic and inorganic content and carbon concentration (all had $r^2 = 0.94$, $P < 0.0001$), because organic and inorganic content constitute the bulk of the sediment matrix, inorganic content was not used to eliminate redundancy. Lake level reconstructions (Figure 4-6) show a general trend from low water levels during ~1425-1720 CE of the Little Ice Age (LIA, Shanahan et al. 2009), to present day high water levels. However, the most recent predicted lake levels, based on spatial sediment composition during the past 40 years oscillated wildly about the present-day levels for Lake Bosomtwe. Likewise, the water level during the LIA low stand was predicted to measure ~39 m above lake bottom, which was contrary to known seismic unconformities in the sediment record of Lake Bosomtwe, which are ~53 m above lake bottom (Brooks et al. 2005).

The recent anthropogenic disturbances, particularly during the past 40 years in the Lake Bosomtwe catchment, appear to be confounding the relationships between sediment chemical composition and water depth in this spatial survey. An investigation into the relationship between water depth and sediment composition using older sediments, deposited prior to 1958, was undertaken to remove the effects of accelerated inorganic sedimentation found in the nearshore sediment cores. Sediment core Central 1 was selected because it was an offshore coring site with a well established chronology. Sediment characteristics of core Central 1 were compared through time with historical water level records (Figure 4-7a). There were ten sediment samples at 0.5-cm intervals available from 1860 to 1957 in core Central 1 used to establish the water depth-sediment characteristics down core (Figure 4-7b). There was a strong relationship between the variation in sediment characteristics and the fluctuations in water depth (Figure 4-7c), given that the 0.5-cm thick sediment intervals incorporated 5 years on average.

Water depth and sediment characteristics through time were found to have a strong linear regression for nearly all proxies but phosphorus (Figure 4-8). Table 4-2 compares between the regression equations of the spatial surface sediment trends (Figure 4-5) and the temporal trends from sediment

core Central 1 (Figure 4-8). The strongest linear relationships with historical water depth changes were carbon concentration ($r^2 = 0.82$, $P < 0.0003$), percent organic content ($r^2 = 0.81$, $P < 0.0004$), percent inorganic content ($r^2 = 0.89$, $P < 0.0001$) and C:N molar ratios ($r^2 = 0.65$, $P < 0.005$), which were used to reconstruct pre-historic water levels (Figure 4-9). Predicted lake levels from the percent organic and inorganic content from core Central 1 were similar (being interdependent proxies), therefore only organic content was represented in Figure 4-9b. Lake level reconstructions based on temporal trends in these proxies from core Central 1 again predicted a persistent low water stand during ~1425 to 1720 CE. This prolonged low water stand is characterized by laminations that were not *visible* in the sediment core, yet the estimated water depths were on average 56 ± 3 m for each of the three reconstructions, not ~39 m. This water depth estimate also better aligns with previous studies that estimate 53 m above lake bottom (Brooks et al. 2005; Shanahan et al. 2009).

After ~1720 CE, the data suggest rising water levels until present levels were reached in the 1950s. Particulate carbon and C:N measures in sediment core Central 1 (Figure 4-9c) exhibited a similar rise in content as organic matter. However, the predicted water levels from organic matter, and C:N ratios of core Central 1 show a decline in water level during ~1958 to 1990 followed by a return to present lake levels, which is not the trend in measured water levels. These predicted values underestimated water levels after ~1958, likely because of increased inorganic deposition by anthropogenically-driven soil erosion. This is one example of when water-level reconstructions based on organic content in recent sediments may be erroneous, because organic content can be diluted by inorganic deposition supplied by anthropogenic activities.

DISCUSSION

Presently, laminations are preserved below 35 m water depth, which coincides with the water depth at which permanent anoxia persists in the water column of the Lake Bosomtwe (approximately 30-35 m;

Chapter 2 of this thesis; Puchniak et al. 2009). Sediment cores with preserved *visible* laminations were found to have organic content $\geq 15\%$ from both the spatial and temporal sediment composition-water depth relationships. The lake level reconstructions based on spatial sediments estimated that the absence of visible laminations occurred above ~ 39 m water depth during ~ 1425 - 1720 CE. However, reconstructions based on core Central 1 temporal sediment composition estimated lake levels to be ~ 56 m above lake bottom at the site during the same time period. The discrepancy suggests that a reduction in lake level alone may not result in the loss of preserved visible laminations, but limnological conditions may be altered when lake level declines.

The limnological and depositional conditions in Lake Bosomtwe observed during the 2004-2006 sampling period may not have remained static over time and could have changed during the past 550 years. A change in the depth of mixing in Lake Bosomtwe could lead to temporary oxygenation of surface sediments. Oxygenation at the sediment-water interface is known to reduce the preservation of organic matter and may affect the preservation of laminae (Hedges and Keil 1995; Hedges et al. 1999). Aerobic deep waters at the central coring site during ~ 1425 -1720 CE may have been similar to the aerobic nearshore coring sites in the spatial survey. Oxygenation at depth may have supported microbial decomposition of organic matter, and to a lesser extent bioturbation, that would inhibit the preservation of laminae. The nearshore sediment cores from the spatial survey of Lake Bosomtwe may have also been exposed to a higher-energy nearshore environment that may include physical disturbances like underwater currents, wave action and winnowing of sediments (Hakanson 2005a; Hakanson 2005b). In a simple bowl-shaped crater lake, like Lake Bosomtwe, the loss of visible laminations is more likely due, however, to the oxygenation of sediments, because there is little evidence for greater wind and wave action within the crater. Periodic vertical water column mixing that could oxygenate deep-waters in Lake Bosomtwe would also hamper the preservation of organics and their constituents (C, N and P).

The log-transformed trends in phosphorus content and water depth from Lake Bosomtwe suggest that water depth alone may not contribute to characterizing the depositional conditions. Phosphorus is an important growth-limiting nutrient in the water column (Guildford and Hecky 2000) and is found at high concentrations in dissolved form within the anoxic hypolimnion of Lake Bosomtwe. The high P content in the deep-water sediments may be due to the effects of improved organic matter preservation, focusing of fine organic particulates, and the internal loading of dissolved P from the sediments and delivered from the catchment, which were released under anoxic conditions (Anderson et al. 2001; Calvert et al. 1996; Gikuma-Njuru et al. 2010). Particulate-bound P from the catchment when delivered to an anaerobic water column is known to be readily released through redox reactions. Dissolved P is then re-supplied for biological uptake and subsequently the increased primary productivity is transformed with time into P-rich organic sediments (Gikuma-Njuru et al. 2010). These surface sediment P trends likely reflect a change in the extent of deep-water anoxia in Lake Bosomtwe.

The absence of visible laminations from ca. 1425-1720 CE in sediment core Central 1 marked a prolonged low water stand for Lake Bosomtwe (Figure 4-9). This low stand was likely the result of a persistent drought period over Lake Bosomtwe during the Little Ice Age (LIA) (Shanahan et al. 2009). Shanahan et al. (2009) reported this low stand from Lake Bosomtwe sediments based on results from analysis of authigenic carbonate $\delta^{18}\text{O}$ and silica concentrations from micro x-ray fluorescence. Reduced water levels were believed to concentrate water column solutes and increase the carbonate $\delta^{18}\text{O}$ signature. During this low water stand, the increased area of erodible catchment is believed to have accelerated silica transport and deposition to the sediments (Shanahan et al. 2009). The lake level estimates of Shanahan et al. (2009) were corroborated with previous seismic unconformities that indicated a 25 m decline from present day lake levels (Brooks et al. 2005), and both correspond extremely well with the our estimate of 22 m water-level decline (or lake depth of 56 m) based on the temporal sediment composition-historical water depth relationships. This drought

period was linked to cool Atlantic sea surface temperatures that displaced the intertropical convergence zone southwards and has been identified as one of the lowest lake levels for Lake Bosomtwe during the Holocene record (Shanahan et al. 2009; 2006). The LIA low stand in Lake Bosomtwe exemplifies the effects that large-scale global circulation patterns have on the hydrological balance of this closed-basin lake and on the preservation of organic matter within the sediment records.

Based on the oral history about Lake Bosomtwe, the lake was only discovered (or potentially re-discovered) in 1648 and early habitation was sparse. Surprisingly, the lake remained hidden for several centuries, likely because the lake has no direct river channel connecting the water body to the surrounding Pra River basin. During the LIA low stand (~1425-1720 CE), the lake surface area would also have been greatly diminished (by ~19 % relative to present lake area) with encroachment of a well-developed semi-deciduous tropical forest in areas of exposed lake bottom. Lake Bosomtwe is said to have been discovered by Akora Bompe, who came upon the lake during a hunting expedition (Rattray 1923). After finding abundant fish, people from neighbouring tribes (Asaman, Kuntanase, Asansu and Akim) came to settle the shores. Early settlers are believed to have relied heavily on the artisanal fishery, local game and lumber. The story was substantiated further by several ancient, dead trees which are standing submerged in 20 m water depth and are dated, through radiocarbon analysis, up to 1600 CE (Shanahan 2006; Shanahan et al. 2006).

Results from the paleoclimatic reconstruction and oral history suggest that following the prolonged dry period during ~1425-1720 CE, conditions became wetter and increased rainfall likely resulted in lake level rise during 1720-1960 CE. Documents report that the Konkoma shore was formerly the site of the Konkoma settlement (like Assisiriwa and Pepie I, other former villages along the eastern shore) that experienced flooding and was displaced in 1956 during particularly high lake levels (Ofosu 2009). After having moved the village multiple times during continuous lake level rise, the

community decided to settle outside the crater walls. There are many farmers and fisherman who still work land in the Konkoma River drainage, but they choose to commute each day from outside the basin. A routine that likely reduces the delivery of inorganic clastics from soil erosion due to roads, housing construction and more intensive cultivation. The history of displaced villages along the eastern shore may be recorded in the rapid inorganic burial in sediment core Konkoma 1 and Konkoma 2 (Figure 4-4 panel 3e and 3f) during ~1910, 1927 and 1946. The sediment records from the Konkoma transect cores indicate that nearshore flooding events could have resulted in the in-washing of a large amount of inorganic siliciclastics. The topography along the eastern shore may be particularly susceptible to flooding and in-washing events, such that these eastern shore communities needed to abandon their settlements and retreat to outside the crater walls, while other settlements around the lake persisted.

Aside from climate patterns, the influence of anthropogenic disturbances on Lake Bosomtwe sediment records was identified by accelerated inorganic sedimentation rates. As early as 1958, the nearshore sediment cores near the town of Abono show marked rise in inorganic deposition. The town of Abono has always been the main town of trade and commerce for Lake Bosomtwe. In 1958, the Ghanaian government began the construction of a feeder road to connect the towns of Abono (on the lake) with Kuntanase, the nearest neighbour outside of the crater walls (Ofosu 2009). Over time, Abono has become the transportation and tourism centre of Lake Bosomtwe, which led to construction of hotels, such as the Lake Bosomtwe Paradise Resort (1999 construction) and Lake Inn (2006 construction). The pattern of rising burial of inorganic material since ~1958 likely captured the increased catchment erosion associated with the construction of the road to Abono and years of continued expansion of housing and cultivation on steeply sloping northern crater walls. Inorganic sedimentation rates from the 1980s to present were found to increase at both the Abono and Konkoma transects, as catchment disturbances continue to expand. A similar trend in rapid sedimentation rates occurred in a volcanic crater lake, Lago di Monterosi that was linked to the construction of a major

roadway during 171 BC (Hutchinson et al. 1970). Lago di Monterosi is in Italy and during the rise of the Roman Empire road construction was critical to the expansion of the Empire. Cowgill and Hutchnison (1970) found that accelerated runoff and erosion were the direct result of deforestation and construction of the road, where loss of trees led to increased nitrification and acidity of the soils, further enhancing leaching and soil erosion into the lake basin. With time, the Lago di Monterosi became strongly eutrophic because of these human activities and, thus, it may serve as a warning that Lake Bosomtwe, may be vulnerable to the cascading effects of eutrophication.

CONCLUSIONS

Arid periods of net evaporation that reduce Lake Bosomtwe water levels result in sediment records of visibly unlaminated gyttja, whereas wet periods that increase water depth and enhance deep-water anoxia will likely result in the preservation of laminated sediments. Nearshore sites, however, are influenced by re-worked nearshore deposits, local anthropogenic disturbances and in-washing of inorganic clastics that are likely too coarse to be transported to the central deep-water region of the lake. For this reason, deep-water sediment cores are the most appropriate for providing a robust relationship for use in paleoenvironmental reconstructions. This study showed that water-level changes in the Bosomtwe basin during the past 550 years left an interpretable record of those changes in the deepest part of Lake Bosomtwe, which can be quantified from chemical information preserved in the sediments.

Human activities during the past 40 years, however, have increased rates of soil erosion within the nearshore sediment records. Because oral histories are limited to the past 350 years, it would be of interest to investigate whether human activities previously existed around the lake in advance of the prolonged dry period that began ca. 1425. The history of population dynamics across West Africa often follows a trend of southward migration during periods of prolonged drought and northward

expansion during periods of prolonged rainfall. These migratory patterns are affected by climate variability dictated by the centennial-scale migration of the ITCZ. In the near future, West Africa may again face the socio-economic impacts of severe drought, but human populations today are constricted by political boundaries and are increasingly confined to urban centers. Without an accurate understanding of climate variability and drought forecasting over West Africa, our ability to mitigate the adverse effects of climate change may be hampered. Advancements in paleoenvironmental analyses that generate sound reconstructions will better enable future predictive models that will hopefully guide policy makers.

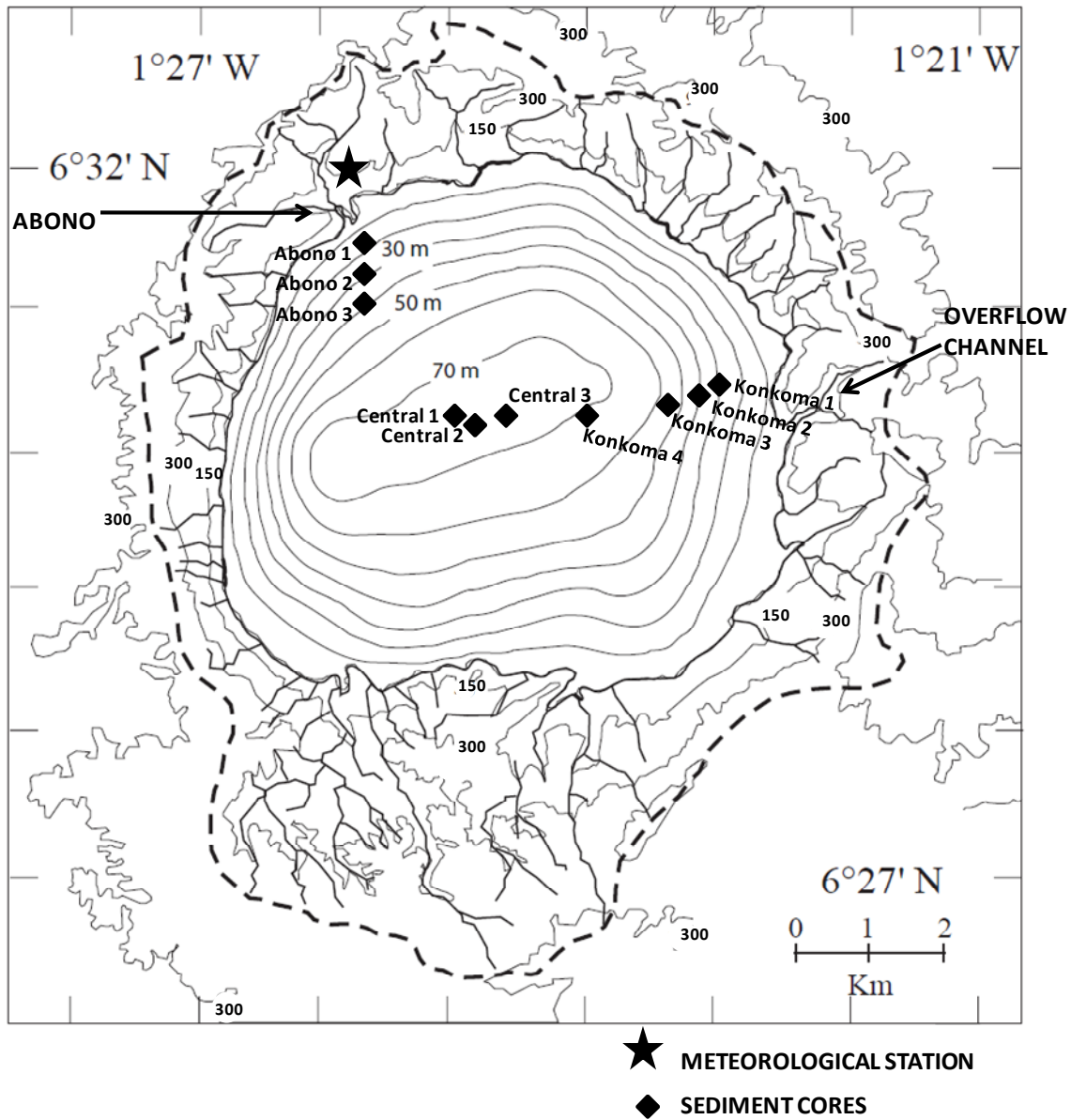


Figure 4-1 Basin map of Lake Bosomtwe showing the locations of sediment coring sites following a northern transect from Abono River with cores Abono 1, Abono 2 and Abono 3 to central station cores Central 1, Central 2 and Central 3 to the eastern transect from Konkoma River with cores Konkoma 4, Konkoma 3, Konkoma 2, and Konkoma 1. The dashed line denotes the extent of the catchment area (modified from Brooks et al. 2005).

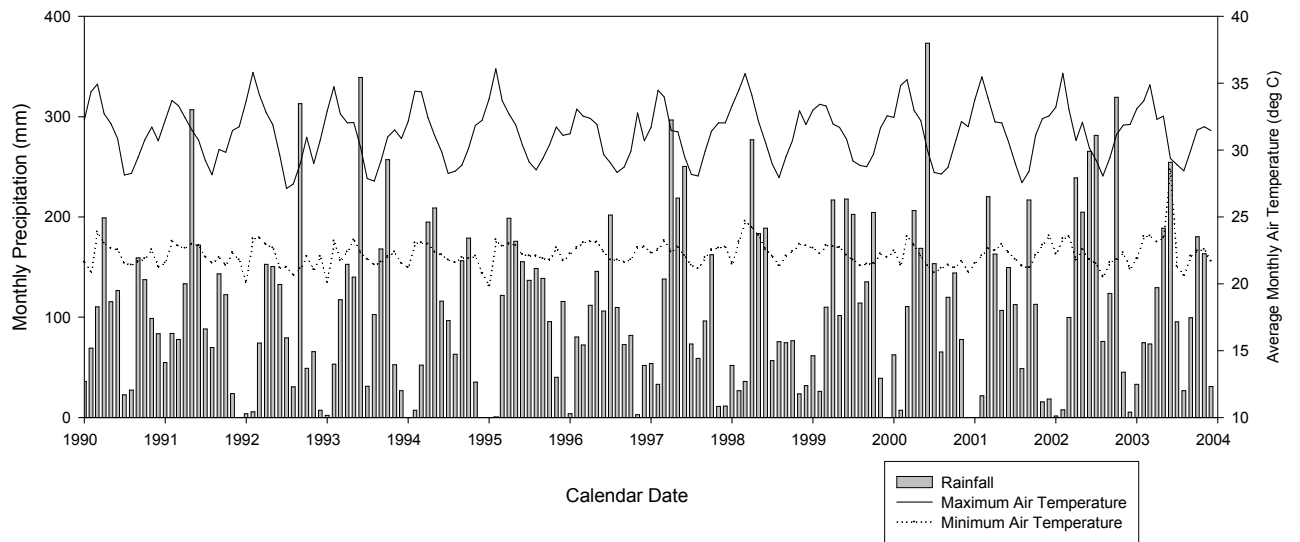


Figure 4-2 Meteorological data from Kumasi Airport located 30 km from Lake Bosomtwe from 1990–2003. Annual precipitation patterns vary between bimodal (e.g. 1990, 2003) and unimodal (e.g. 1995, 1999) delivery, depending on the duration and strength of the short dry period.

Table 4-1. Summary of coring site descriptions and sedimentation rates from lacustrine sediment cores from Lake Bosomtwe, Ghana, West Africa. * Note: the diameter of Glew gravity core tube is 7.6 cm, mini-Glew gravity core tube is 3.8 and the modified Kullenberg is 5.1cm.

	Abono 1	Abono 2	Abono 3	Central 1	Central 2	Central 3	Konkoma 4	Konkoma 3	Konkoma 2	Konkoma 1
Date cored	19-May-05	21-May-05	16-May-05	22-May-04	20-May-05	2-August-06	18-May-05	18-May-05	17-May-05	17-May-05
Gravity Core*	Glew	Glew	Glew	Kullenberg	Mini-Glew	Mini-Glew	Mini-Glew	Mini-Glew	Glew	Glew
Longitude (N)	06.31.35.84	06.31.6.41	06.30.45.80	06.30.14.06	06.30.1.91	6.30.14.75	06.30.21.70	06.30.29.70	06.30.31.20	06.30.37.10
Latitude (W)	001.25.43.60	001.25.44.80	001.25.30.91	001.24.45.29	001.24.57.20	1.24.31.59	001.23.59.70	001.23.18.10	001.23.090	001.22.50.73
Water Depth (m)	25	31	37	78	78	78	69	47	34	24
Approx. Distance from Shoreline (Km)	0.50	1.18	1.68	3.47	3.38	2.87	2.07	1.32	0.82	0.53
Length Sediment (cm)	31.0	32.0	37.0	81.0	42.0	53.0	39.0	39.0	45.0	21.0
Laminations Present	NO	NO	YES	YES	YES	YES	YES	YES	NO	NO
Depth visible laminations end (cm)	na	na	17	24	26	26	17	14	na	na
Pb-210 chronology established	YES	YES	NO	YES	NO	YES	NO	NO	YES	YES
Avg sedimentation rate (g/cm2/yr)	0.0761	0.0733	na	0.0175	na	0.0118	na	na	0.0688	0.0760
Avg sedimentation rate (mm/yr)	2.08	2.97	na	3.06	na	1.33	na	na	2.50	2.02

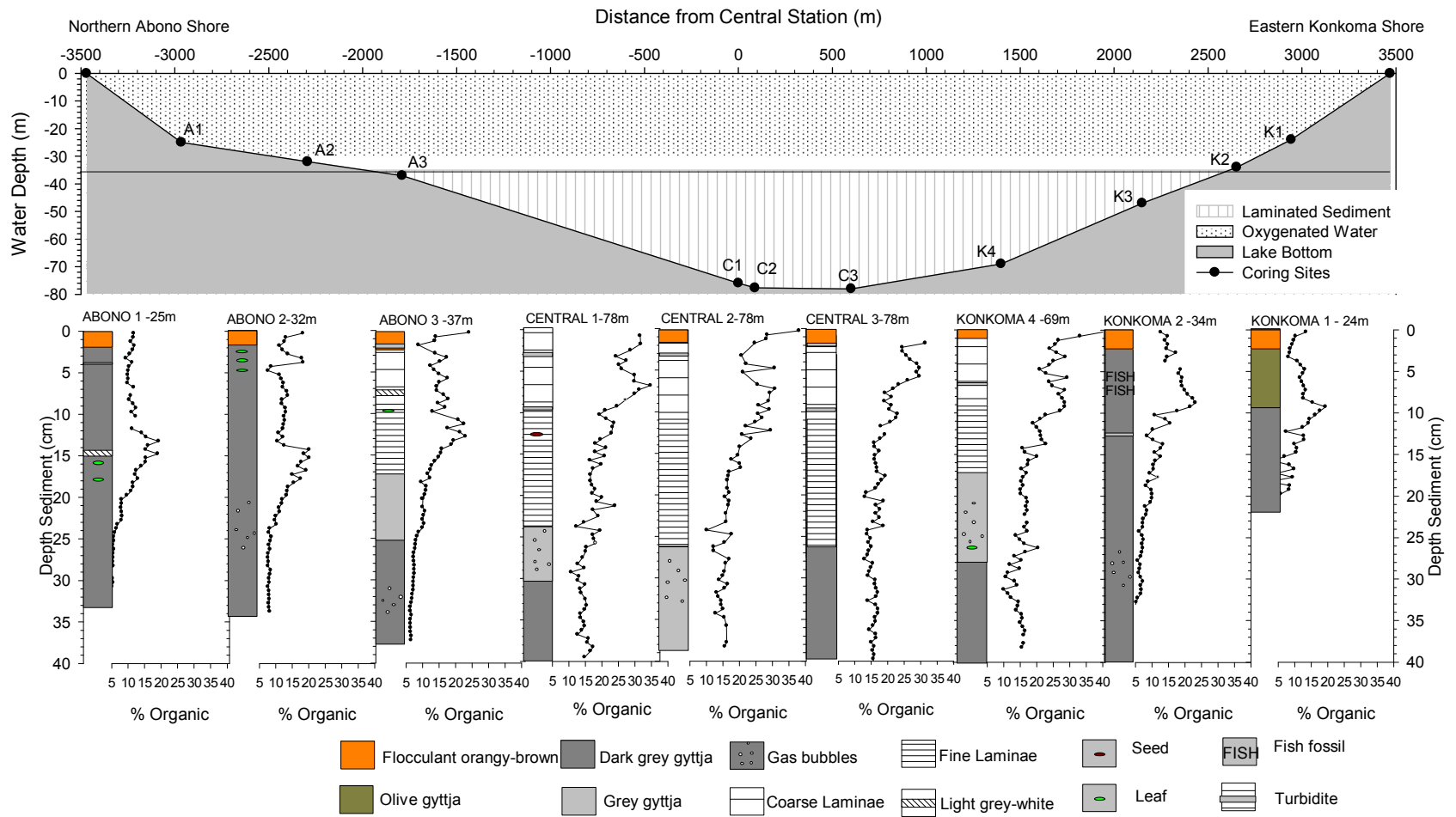


Figure 4-3 Lithology and organic content stratigraphy for sediment cores from the Lake Bosomtwe transects Abono and Konkoma Rivers, ordered by water depth and transect

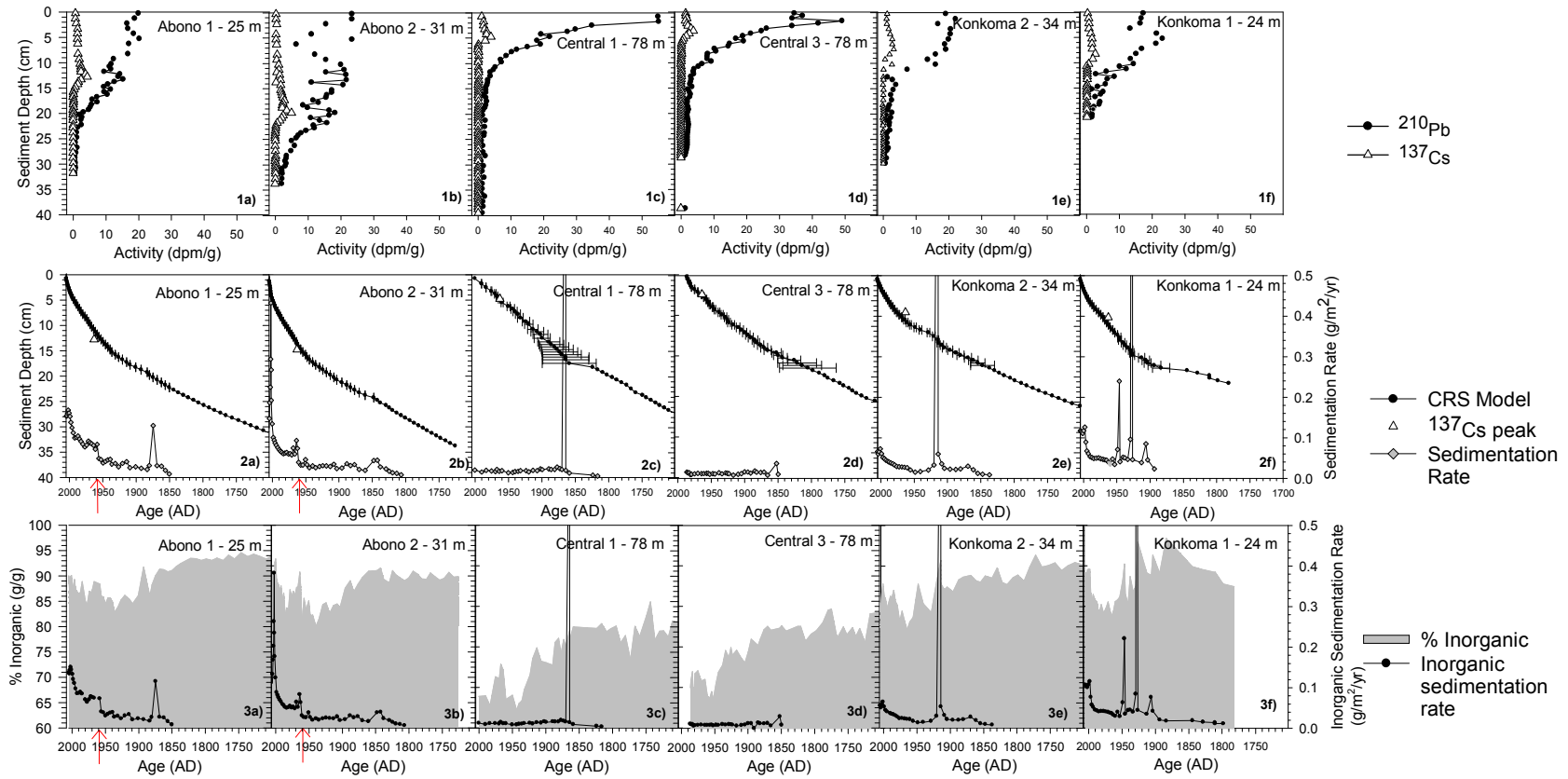


Figure 4-4 Panel 1. Total ^{210}Pb and ^{137}Cs activity profiles of sediment cores a) Abono 1, b) Abono 2, c) Central 1, d) Central 3, e) Konkoma 1 and f) Konkoma 2 from Lake Bosomtwe, Ghana. Panel 2. Age-depth relationship for constant rate of supply model and the ^{137}Cs peak denoting ~ 1964 peak emissions of radioactive Cs and CRS derived sedimentation rates. Dates beyond CRS model (~ 150 yr) were extrapolated linearly. Panel 3. Sediment core stratigraphies of percent inorganic content and inorganic sedimentation rates. Note. Arrow denotes the accelerated sedimentation and inorganic sedimentation rate ~ 1960 along the Abono transect.

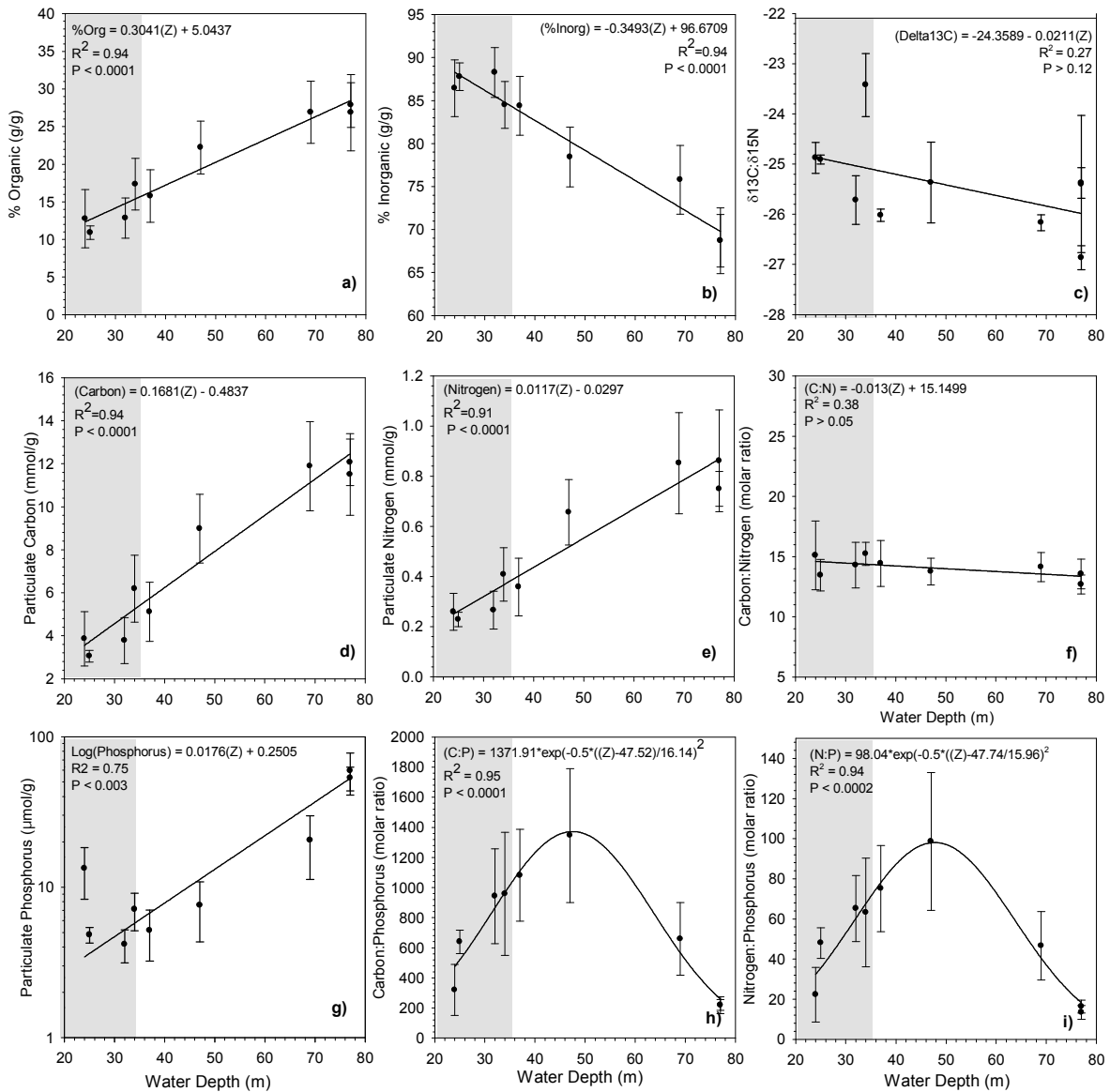


Figure 4-5 Relationship between water depth at sediment coring site and a) percent organic, b) inorganic content, c) $\delta^{13}C$ (per mil), d) particulate carbon concentration, e) particulate nitrogen concentration, f) C:N, g) log of phosphorus concentration, h) C:P and i) N:P molar ratios during the past 40 years of surface sediment from nine sediment cores arranged by water depth, from shallowest to deepest: Konkoma 1, Abono 1, Abono 2, Konkoma 2, Abono 3, Konkoma 3, Konkoma 4, Central 1, Central 2 from Lake Bosomtwe, Ghana. The grey box denotes the water depth at which sediment cores do not exhibit laminations.

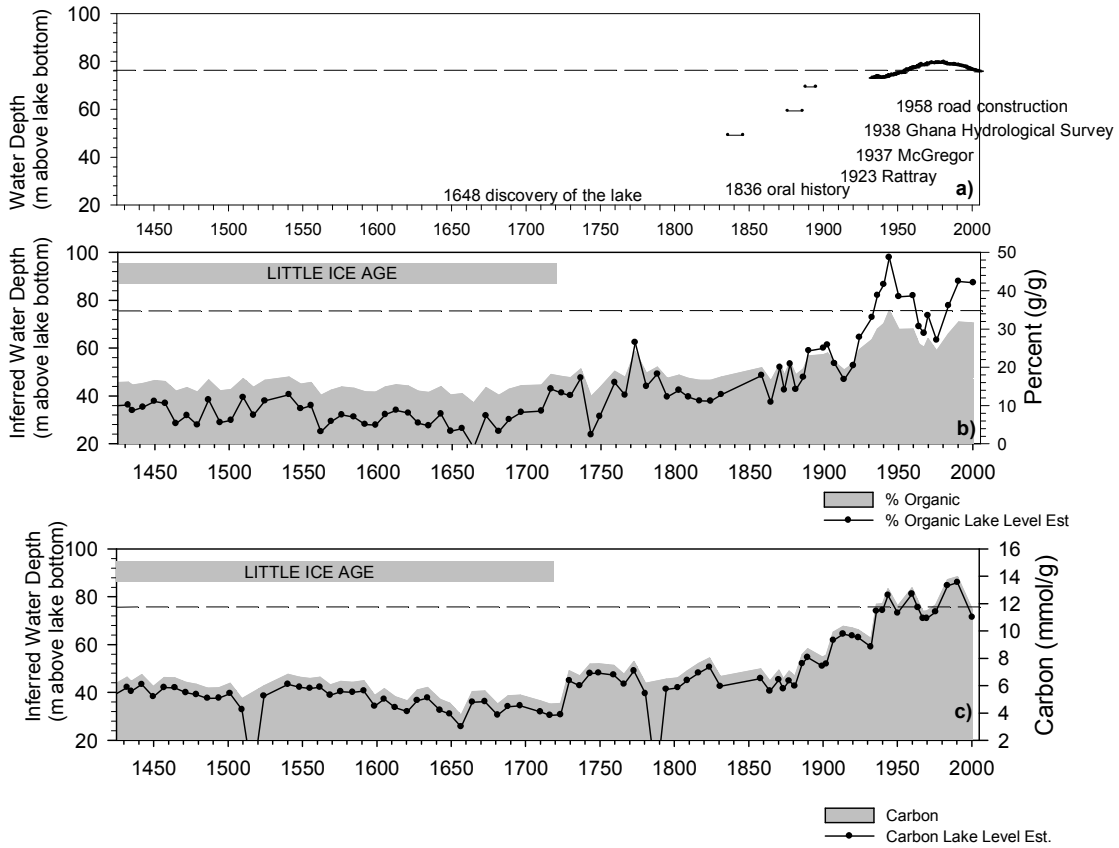


Figure 4-6 Lake Bosomtwe water levels a) from historical records, b) inferred lake level reconstruction based on sediment organic content (grey area plot) and spatial surface sediment organic matter trends (line plot), and c) based on carbon concentrations of sediment (grey area plot) and spatial surface sediment carbon concentration trends (line plot). Dates of historical significance were labelled. The dashed line denotes the present lake levels. The Little Ice Age over Lake Bosomtwe (~1425-1720 CE) was a prolonged low water stand.

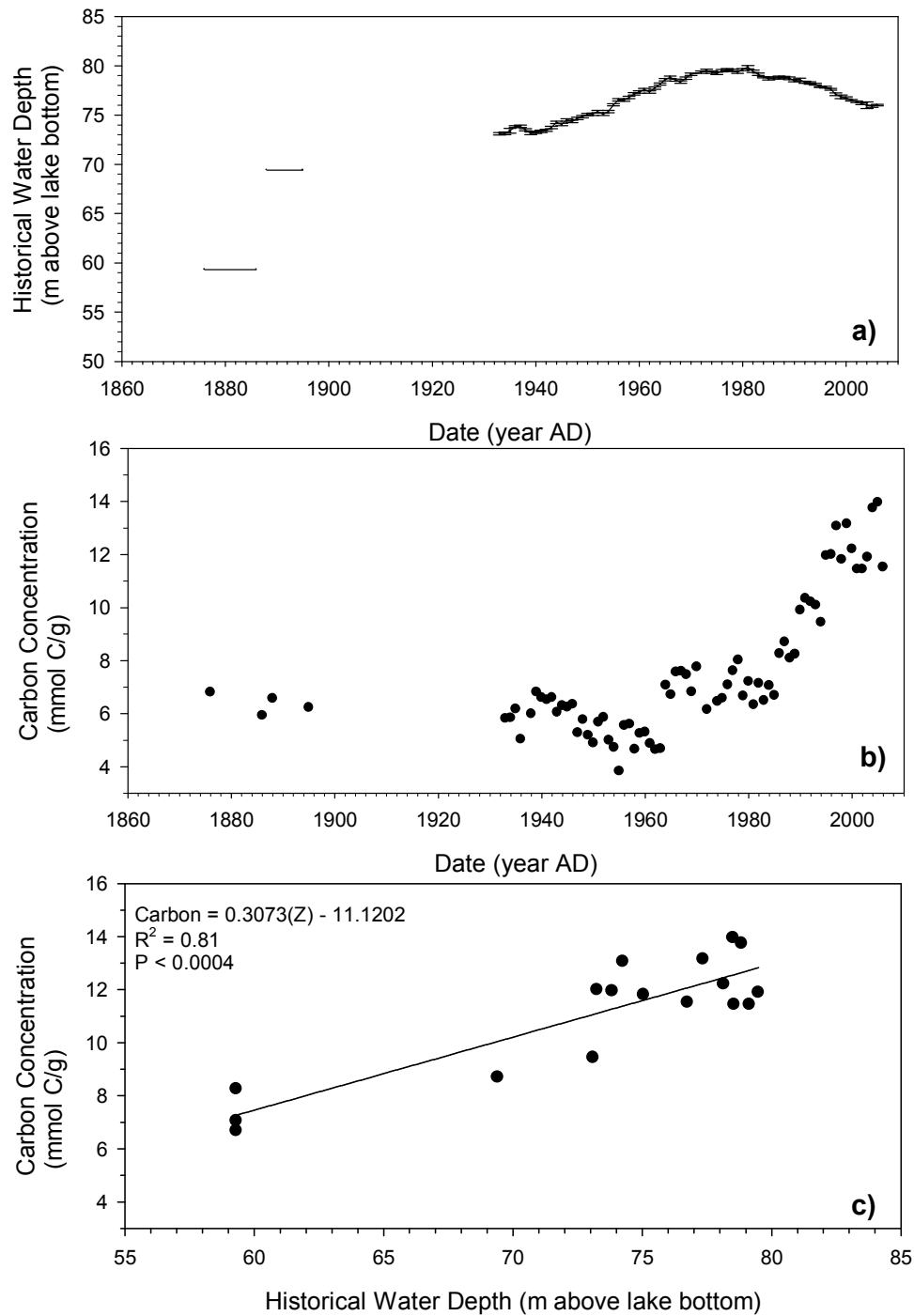


Figure 4-7 Demonstration how sediment composition, in this example carbon concentration, was used to determine the sediment characteristics in relation to historical water level data. a) Annual lake level record in metres above lake bottom from Abono water level gauge from 1938 to 2006 from the Ghana Hydrological Survey (Shanahan 2004) and 1933-1937 from geological survey (McGregor 1937) and from 1876-1895 oral history from Rattray (1923); b) sediment carbon concentrations measured at date deposited in core Central 1; c) historical lake levels with respect to sediment carbon concentrations in core Central 1.

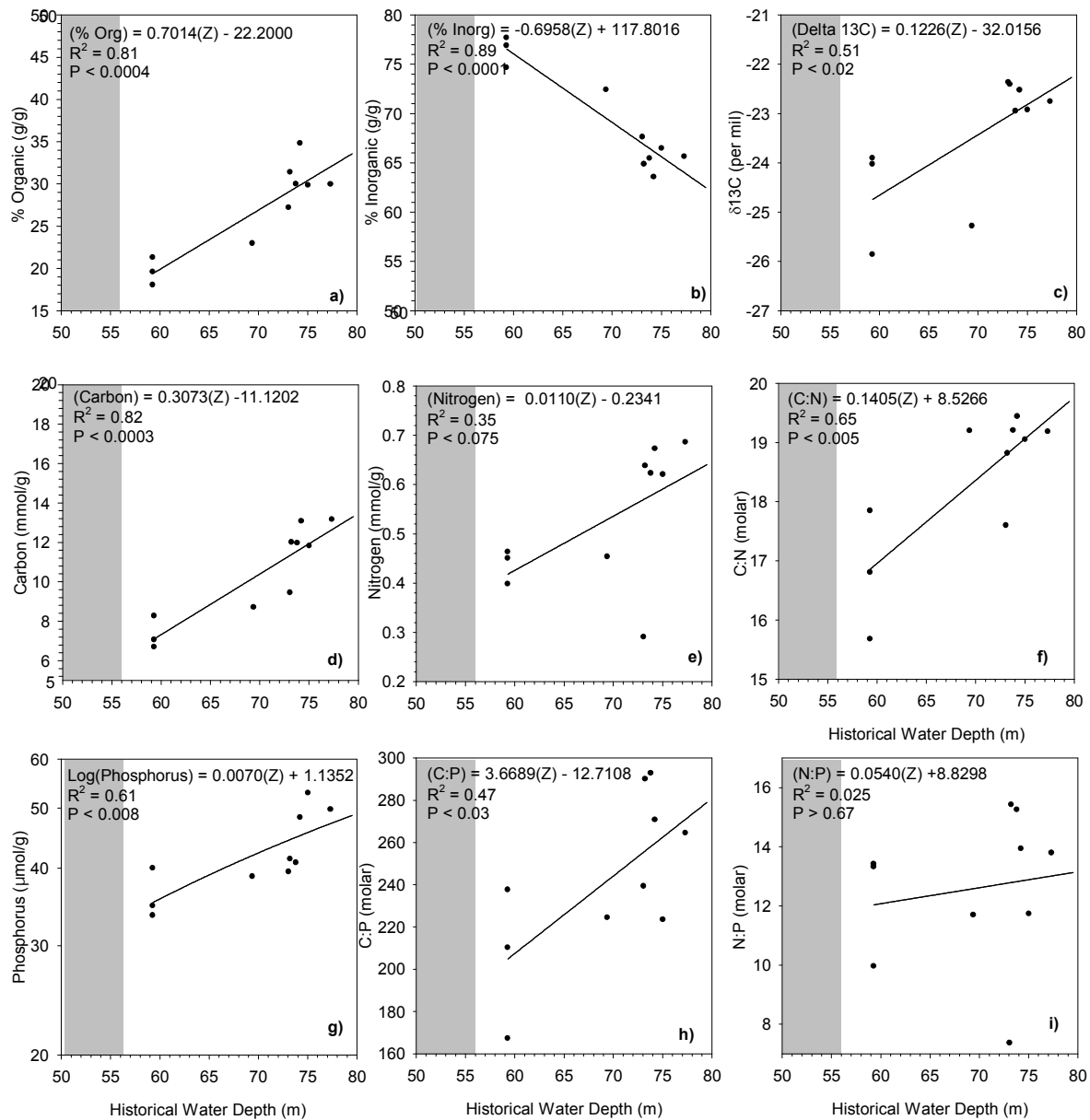


Figure 4-8 Relationship between the historical water depth (expressed as metres above Central 1 coring site in 2004) and a) percent organic, b) percent inorganic content, c) $\delta^{13}\text{C}$ (per mil), d) particulate carbon, e) nitrogen and f) C:N, g) log of phosphorus concentrations, h) C:P and i) N:P molar ratios in sediment intervals from 1860-1957 of core Central 1 from Lake Bosomtwe, Ghana. All sediments were laminated, however the grey box denotes the 56 m water depth, the average estimated water depth from 1425-1780 CE after which lacustrine sediment records do not exhibit laminations.

Table 4-2. Equations for the line of best fit for the water depth-sediment characteristics for all of the surface sediments (Figure 4-5, n = 9) and for sediment core Central 1 (grey bands) down core and through time (Figure 4-8, n = 10). P values are highlighted to show that they are statistically significant at less than 5% probability. Note: that a relationship between $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ did not exist in recent surface sediments, but a strong relationship exists down core. The line of best fit for C:P and N:P molar ratios was a Gaussian curve in recent sediments, whereas a simple linear fit was more appropriate in core Central 1.

Proxy	Source	Equation	yo	a	xo	b	r2	P
% Organic	all surface sediments	$f=y_0 + a*x$	5.04	0.30			0.94	0.0001
% Organic	central 1 (1838-1957)	$f=y_0 + a*x$	-22.20	0.70			0.81	0.0004
% Inorganic	all surface sediments	$f=y_0 + a*x$	96.67	-0.35			0.94	0.0001
% Inorganic	central 1 (1838-1957)	$f=y_0 + a*x$	117.80	-0.70			0.89	0.0001
delta 13C	all surface sediments	$f=y_0 + a*x$	-24.36	-0.02			0.27	0.125
delta 13C	central 1 (1838-1957)	$f=y_0 + a*x$	-32.02	0.12			0.51	0.02
delta 15N	all surface sediments	$f=y_0 + a*x$	10.32	0.007			0.25	0.14
delta 15N	central 1 (1838-1957)	$f=y_0 + a*x$	11.76	-0.04			0.17	0.24
Carbon	all surface sediments	$f=y_0 + a*x$	-0.48	0.17			0.94	0.0001
Carbon	central 1 (1838-1957)	$f=y_0 + a*x$	-11.12	0.31			0.82	0.0003
Nitrogen	all surface sediments	$f=y_0 + a*x$	-0.030	0.12			0.91	0.0001
Nitrogen	central 1 (1838-1957)	$f=y_0 + a*x$	-0.23	0.011			0.35	0.073
Phosphorus	all surface sediments	$f=y_0 + a*x$	-20.46	0.85			0.73	0.0032
Phosphorus	all surface sediments	$\log(f)=y_0 + a*x$	0.25	0.018			0.75	0.0026
Phosphorus	central 1 (1838-1957)	$f=y_0 + a*x$	-4.30	0.667			0.58	0.011
Phosphorus	central 1 (1838-1957)	$\log(f)=y_0 + a*x$	1.14	0.007			0.61	0.0078
C:N	all surface sediments	$f=y_0 + a*x$	15.15	-0.023			0.38	0.077
C:N	central 1 (1838-1957)	$f=y_0 + a*x$	8.53	0.14			0.65	0.0049
C:P	all surface sediments	$f=a*\exp(-.5*((x-x_0)/b)^2)$		1371.91	47.52	16.14	0.95	0.0001
C:P	central 1 (1838-1957)	$f=y_0 + a*x$	-12.71	3.67			0.47	0.029
N:P	all surface sediments	$f=a*\exp(-.5*((x-x_0)/b)^2)$		98.04	47.74	15.96	0.94	0.0002
N:P	central 1 (1838-1957)	$f=y_0 + a*x$	8.83	0.054			0.02	0.66

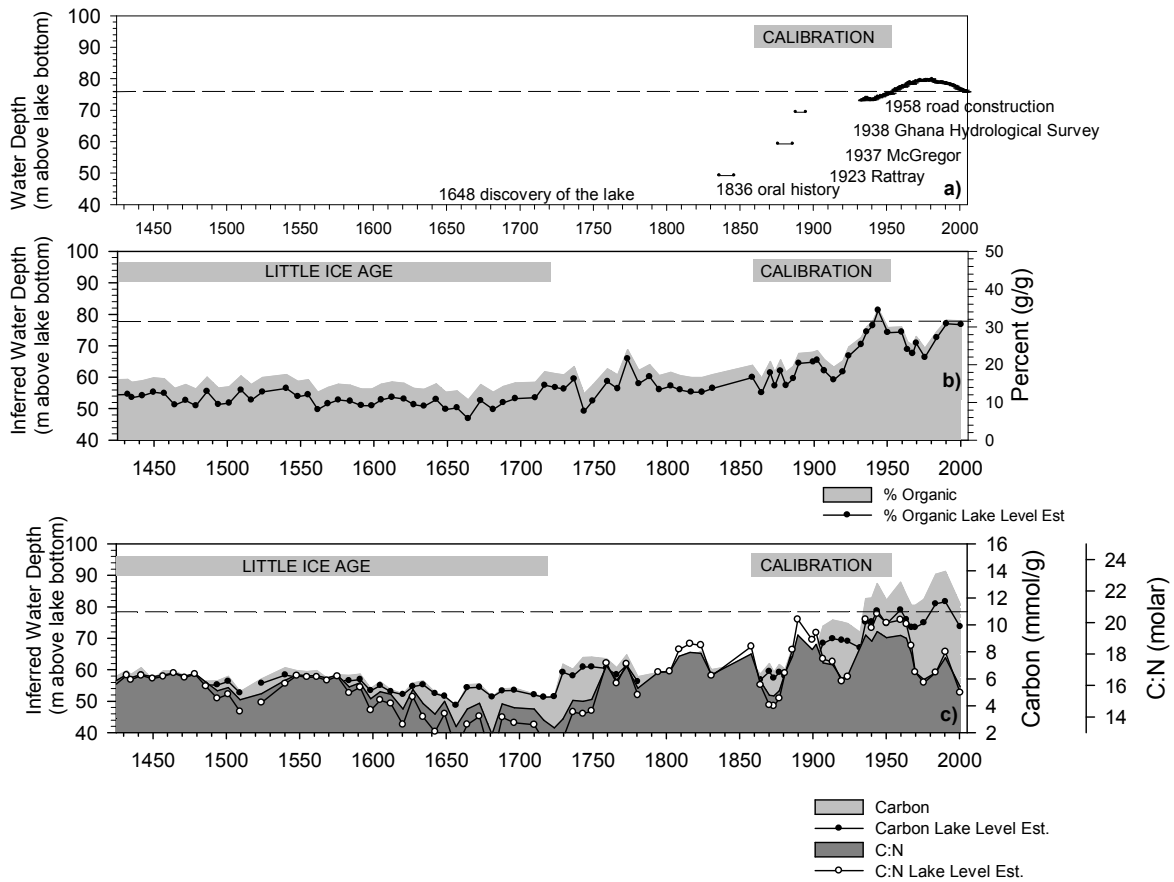


Figure 4-9 Comparison amongst different lines of evidence of past lake level change at Lake Bosomtwe, Ghana. Panel a) historical lake levels (metres above lake bottom) based on oral history and instrumental records. Panel b) percent organic (light grey area plot) in sediment core Central 1 and inferred lake depth (m above lake bottom) from the sediment percent organic content based on the linear regression from temporal trends down core, and Panel c) carbon concentration (light grey area plot) and C:N molar ratios (dark grey area plot) in sediment core Central 1 and inferred lake depth (m above lake bottom) from the sediment content of C and C:N based on the linear regression from temporal changes in lake depth based on historical records. The horizontal dashed line denotes the present day lake level. The calibration box denotes the dataset used to generate the lake level regressions during 1860 to 1957. The Little Ice Age box denotes the sediment that was not visibly laminated within core Central 1 of Lake Bosomtwe during ~1425-1720 CE.

5 Chapter - Paleolimnological reconstruction of sub-Saharan climate and human activities during the past 550 years at Lake Bosomtwe (Ghana, West Africa): how lake levels, mixing regimes and land-use practices affect the sediment record

OVERVIEW

Since the 1970s, persistent drought over the Sahel region has had grave socio-economic effects on West Africa, and anthropogenic climate change is predicted to exacerbate the situation. Long-term meteorological records that could help anticipate future climatic conditions are scant for the Sahel. Consequently, lacustrine sediment records from Lake Bosomtwe, Ghana have been identified as a potentially rich source of paleoclimate data to fill this knowledge gap. Lake Bosomtwe occupies a meteorite impact crater (1°25 N, 6°30 W) and its closed-drainage hydrology makes the lake sensitive to variations in the net flux of precipitation and evaporation. Here, we analyze lacustrine sediment deposited during the past 550 years in Lake Bosomtwe to reconstruct past climate trends, changes in lake level, lacustrine conditions and anthropogenic effects. Two short sediment cores were collected from a central sampling station in the deepest part of the lake at 78 meters water depth. Both cores were dated using ^{210}Pb and ^{137}Cs activity and analyzed for loss-on-ignition and phosphorus concentration. The first core was further analyzed for stable isotopic signatures ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and nutrient concentrations (C and N), while the second core was split and scanned with ITRAX for an x-ray radiographic image (greyscale imagery) and x-ray fluorescence of elemental components. These data were used to identify three distinct stratigraphic zones. The earliest sediments of Zone 1, dated from ~1425-1610 CE, were not *visibly* laminated and possessed low organic matter content and high iron concentrations that were suggestive of shallow water conditions exposed to periodic oxidative reduction. In Zone 2, during ~1610-1860 CE, lacustrine sediments transitioned to sediments containing sandy turbidite layers and became visibly laminated. These sediments were inferred to have been deposited under deeper water levels during wetter conditions. High rainfall events are

believed to have transported inorganic clastics from the catchment that formed large turbidite layers. The most recent lacustrine sediment deposits of Zone 3, ~1860-2005 CE, were thickly laminated with greater organic matter content (up to 30%), increased nutrient concentrations (N and P), enrichment of stable isotopic signatures ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) and higher calcium and strontium concentrations, indicative of the highest lake levels during the past 550 years. The sediment composition was inferred to indicate an increased autochthonous organic matter production and conditions of permanent deep-water anoxia. However, trends in the $\delta^{13}\text{C}$ signature of bulk matter were found to be more depleted during the most recent drought periods of 1910-1916 and 1970-2000. Sediment records show periods of more negative $\delta^{13}\text{C}$ and increased C:N ratio that were likely due to reduced annual primary production. Previous water column sampling of Lake Bosomtwe found that seasonal water column mixing in August boosted primary productivity. It is during the months of July and August that the Sahel region experiences greater precipitation, and thus links Sahel patterns of precipitation with primary productivity of Lake Bosomtwe. The depletion of bulk sediment $\delta^{13}\text{C}$ tracked the pattern of negative rainfall anomalies over the Sahel region closely during the past century ($r^2 = 0.45$). The sensitivity of Lake Bosomtwe primary productivity to Sahel rainfall anomalies is likely due to the northward displacement of the ITCZ during high rainfall years over the Sahel that generates cool air temperatures over Lake Bosomtwe during the short dry period, which induce water column mixing and stimulate primary production.

The well-preserved sediment records are useful not only for paleoclimatic reconstructions, but also for estimating the impacts of recent anthropogenic activities. Increased human and livestock populations during the past 40 years were reflected by increased organic matter burial, enriched $\delta^{15}\text{N}$ (11.4 ‰) and phosphorus concentrations. Accelerated anthropogenic activities after 1960 have likely also enhanced erosion of catchment soils to the lake, as indicated by elevated K:Ti ratios and inorganic content of sediments. Currently, the effects of increased delivery of catchment nutrients from soil erosion and effluent are likely diminished by the reduction in deep water column circulation due to the recent Sahel drought. Sediments from Lake Bosomtwe provide high resolution climate

records that will be useful in assessing and preparing for future droughts that may threaten West Africa as more drought years are anticipated.

INTRODUCTION

The climate over West Africa is highly sensitive to changes in regional and global circulation patterns, but the ability to predict future drought conditions is currently a challenge for climatologists, paleoclimatologists and climate modellers (Biasutti et al. 2009; Dessai et al. 2005; Hely et al. 2009; Mitchell and Hulme 1999; Paeth and Thamm 2007). The frequency and severity of drought periods over West Africa have increased during the past 40 years, as compared to the latter half of the century (Nicholson and Paleo 2004). Prolonged dry periods during the past 40 years have had devastating effects on the region's population and economy (Nicholson 1993; Nicholson 1998; Benson and Clay 1994). Unanticipated droughts have reduced food security in the region, due, at least in part, to limited ability to irrigate crops, maintain soil moisture, mitigate soil erosion and control bushfires (Benson and Clay 1994; Hulme 1994; Nicholson et al. 1998; Swaine 1992). The region of greatest concern is the Sahel, which has experienced a 20-40% reduction in rainfall since the latter half of the 20th century (Nicholson 1993; Nicholson 2001a). The arid-tolerant scrubland of the Sahel region occupies a transition zone between the barren Sahara Desert to the north and forested Guinea Coast. Unfortunately, drought periodicity remains poorly understood in the Sahel region because accurate and continuous long-term climatic records are scarce; a feature that continues to hamper our ability to anticipate future climatic changes (Hulme 2001).

Meteorological records extending beyond 1900 CE for West Africa are not readily available (Nicholson 2001b). Anecdotal evidence of climate change has been inferred by population dynamics of indigenous cultures along the trans-Saharan trade route (Nicholson 2001a). Alternatively, lacustrine sediment records can offer continuous long-term data on regional climate variability.

However, West Africa contains very few lakes that have persisted for long periods of time. Instead, the landscape consists of a network of rivers and streams that have been dammed during the past half century. Consequently, man-made lakes have only accumulated sediment for the past few decades. One exception is Lake Bosomtwe, a freshwater lake that formed within a meteorite impact crater about 1 million years ago at the northern boundary of the Guinea Coast region (Koeberl et al. 1997).

Lake Bosomtwe, Ghana (1°25 N, 6°30 W) is the only naturally formed lake in West Africa, and has accumulated nearly 300 m of sediment during the past ~1 million years (Brooks et al. 2005). Lake Bosomtwe has a closed-drainage hydrology, due to the basement impact breccia and subsequent deposition of lacustrine sediment that restrict ground water exchange (Turner et al. 1996b). The surface water level is 99 m above mean sea level, while the crater walls formed by the meteorite impact rise to 210 m above mean sea level (minimum rim elevation). These crater walls reduce wind stress, causing weak mixing of the lake and allowing deep-water anoxia to persist throughout the year below 30 m depth (Puchniak et al. 2009; Chapter 2 of this thesis). In the deep-water region of the lake, continuous anoxia and high concentrations of hydrogen sulphide at the sediment-water interface restrict bioturbation and aid in the preservation of finely laminated, organic-rich sediments (Chapter 4 of this thesis). These laminations are believed to be annual couplets of light and dark laminae that are deposited seasonally (Shanahan et al. 2008).

Lake Bosomtwe's hydrological balance is highly responsive to interannual variability in precipitation and evaporation. Turner (1996) found that the rates of precipitation relative to evaporation dictate the water level today and in the past. Water chemistry data collected in 1934 (McGregor 1937) and again in 1993 (Turner et al. 1996b) showed that solutes became diluted over this time period, particularly the chloride ions (103 mg L^{-1} to 94 mg L^{-1}) that are known to be conservative. Turner (1996b) estimated that the water volume increased by 13% based on the reduction in chloride ion concentrations, where the increased lake volume was due to a prolonged wet period over much of

West Africa during the 1930s and 1940s (Nicholson 2001a). Through the development of hydrological budgets that model lake level change, both Turner et al. (1996a) and Shanahan et al. (2007) found increasing lake levels during 1934-1969 were sensitive to relatively small-scale changes in annual precipitation. In another study, Shanahan (2007) simulated lake levels using different meteorological conditions and catchment variables, specifically: precipitation, temperature, cloud cover, duration of solar radiation, runoff and deforestation. All factors were found to contribute to the sensitivity of the lake-level model; however, rates of precipitation relative to evaporation in the region were the prime cause of lake level change (Shanahan et al. 2007).

Large-scale lake level fluctuations in Lake Bosomtwe have been noted by even the earliest researchers to the crater. The Gold Coast Geological Survey (Junner 1937) found abandoned sandy beach deposits, exposed bedded clays abundant in fish and plant fossils embedded in the crater walls 40 m above the lake level and up to 7.5 metres thick, indicating persistent pre-historic high water stands. Talbot and Delibrias (1977; 1980) dated turbidite silts and deltaic sands exposed along the crater walls and pieced together the historical water-level variations of Lake Bosomtwe during the late Pleistocene and Holocene.

The first paleolimnological investigations of the lacustrine sediments found large-scale changes in lake level driven mainly by global climate patterns. During the African Humid Period (AHP - 11.72 ka to 3.2 ka), wet conditions resulted in an extremely high water stand that produced *Anabaena*-rich sapropel with relatively depleted stable isotopic signatures of $\delta^{13}\text{C}$ carbon in bulk sediment -28 ‰ from lacustrine sediment cores (Talbot and Johannessen 1992). The highly negative stable carbon isotopic signatures were believed to be the result of weaker vertical water column circulation during these extreme high stands (Talbot and Johannessen 1992). The bulk organic matter $\delta^{15}\text{N}$ of this sapropel layer measured 0-2 ‰, reflecting the dominance of cyanobacterial N-fixation (Russell et al. 2003). During recent periods of strong thermal stratification, particulate organic matter from Lake Bosomtwe

was found to have more depleted $\delta^{15}\text{N}$ signatures from N_2 fixation when compared to periods of seasonal, deep-water mixing (Chapter 3 of this thesis). Conversely, low lake levels and extreme evaporative enrichment in Lake Bosomtwe have led to the preservation of dolomite and enrichment of $\delta^{13}\text{C}$ signatures (-8 ‰) during such arid periods as the Younger Dryas (Talbot and Kelts 1986; Talbot and Johannessen 1992). Magnetic mineralogy of lacustrine sediments showed high-coercivity iron sulphides were deposited during the arid Younger Dryas (YD) and Heinrich events (H1, H2), due to high aeolian dust inputs that brought iron-rich particles southward from the Sahara Desert (Peck et al. 2004). The YD, H1 and H2 are known commonly as northern hemispheric climatic events during the last glacial period and have been shown to exert an influence on the sedimentology of Lake Bosomtwe in equatorial West Africa.

While, previous paleoclimatological studies at Lake Bosomtwe have identified marked changes in response to long-term climate periods, the ability to differentiate smaller regional-scale climate patterns remains undetermined. Short-term drought periods over West African are driven by smaller variations in the position of the intertropical convergence zone (ITCZ) and have not been adequately explored over the Sahel region. Recently, sediment analysis of authigenic carbonate $\delta^{18}\text{O}$ and silica concentrations from micro x-ray fluorescence of Lake Bosomtwe's sediments has revealed that recent droughts correlated with Atlantic sea surface temperatures (Shanahan et al. 2009). Results found that a high silica content and enriched $\delta^{18}\text{O}$ signatures were indicative of a low stand (-25 m below present level) at Lake Bosomtwe during 1400-1750 CE. This low stand is evidence of the effects of the Little Ice Age (LIA), a climatic period that has been identified at higher latitudes. Further evidence of this low stand in Lake Bosomtwe was corroborated by a seismic unconformity in the sediment record, situated 25 m below present lake level (Brooks et al. 2005), and lake level reconstruction based on geochemical content that estimated 22 m below present lake levels (Chapter 4, this thesis). This centennial-scale low stand was caused by a period of protracted aridity when weakened Atlantic meridional overturning circulation (AMOC) displaced the ITCZ southward (Shanahan et al. 2009).

This study aims to refine paleoclimatological and paleolimnological reconstructions by comparing analyses performed on two sediment cores spanning the past ~550 years from the central deep-water region of Lake Bosomtwe. To explore the effects of climatic variability and anthropogenic activities in the catchment, we dated these lacustrine sediment cores using ^{210}Pb and ^{137}Cs activity methods and analyzed them for organic matter, nutrient content (carbon, nitrogen and phosphorus), stable isotopic signatures of bulk sediment ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), magnetic susceptibility (χ), x-ray imagery (greyscale) and x-ray fluorescence of elemental components. Based on evidence provided by limnological and paleolimnological data in previous chapters of this thesis, we expect that drought conditions reduce water levels. A decline in water level is expected to reduce primary productivity, resulting in a decrease in $\delta^{15}\text{N}$ signatures, organic matter content and sediment content of C, N, P as well as an increase in C:N and absence of visible laminations. Arid conditions are also expected to increase aeolian dust deposits, thus increasing magnetic susceptibility and concentrations of iron and titanium, and to increase the area of erodible catchment that would increase silica and carbonate content of the sediments. Here, we present the biotic and abiotic sediment characteristics from the two sediment cores that were used to assess past changes in in-lake processes, regional climate patterns and anthropogenic activities.

MATERIALS & METHODS

Site Description and Local Meteorology

Lake Bosomtwe (1°25 N, 6°30 W) is a tropical closed-drainage crater lake (Figure 5-1). The lake measures 8 km in diameter and lies within the 11-km diameter Bosomtwe Meteorite Impact Crater. The climate which controls Lake Bosomtwe's water levels is governed largely by the migration of the intertropical convergence zone (ITCZ), a low pressure belt that delivers monsoon rainfall over the equatorial tropics. The northward passage of the ITCZ from the Gulf of Guinea brings the onset of the long rainy season, which commences as early as February and continues until July (Beadle 1981,

Puchniak et al. 2009). In most years, the rains are interrupted by a short dry period, July to August, when the ITCZ travels well north of the crater and towards the Sahel. The second short rains follow in October to November with migration of the ITCZ southwards. The dry, northeast Harmattan winds ensue during November to January, blowing in from the Sahara Desert.

The interannual displacement of the ITCZ has been found to be influenced by the baroclinic instability between continental Africa and the Atlantic Ocean (Grist and Nicholson 2001). The interannual variability in the sea surface temperatures between the North Atlantic and South Atlantic affect the monsoon winds that carry moisture from the Atlantic Ocean over West Africa (Opoku-Ankomah 1994, Nicholson and Kim 1997). This moist air passes northward when the African Easterly Jet is weakened, and the ITCZ travels northward (Nicholson and Kim 1997). The average annual rainfall recorded at the Lake Bosomtwe lakeside meteorological station was 1250 mm yr⁻¹ during 2004 to 2006 (Puchniak et al. 2009), slightly below the average annual rainfall recorded at the Kumasi airport of 1280 mm yr⁻¹, just 30 km northwest of the lake (Ghana Meteorological Agency). However, annual rainfall in the region has fluctuated considerably during the past century, with particularly high rainfall during the 1940s and 1950s (T Mitchell, 2009 <http://jisao.washington.edu/data/sahel>, see also Figure 5-6).

Coring and Sectioning

Core ‘Central 1’ was collected from 78 m water depth at a central sampling station (6°30’14” N, 1°24’45” W, Figure 5-1) in 2004 by D.A. Livingstone using a modified Kullenberg corer (internal diameter 5.1 cm). Core ‘Central 3’ was also collected from 78 m water depth at a nearby central lake location (6°30’14” N, 1°24’31” W) in 2006 by M. Puchniak using a Glew gravity corer fitted with a Lucite® tube (internal diameter 7.6 cm). Both cores were kept in their core tubes and transported upright to the shore station. Core Central 1 was left open upon retrieval for a few days to dewater and then covered with a circular, fine plastic mesh, followed by a 3”-thick sponge and a cork. Upon

retrieval of core Central 3, the surface water was removed slowly with a 60-ml syringe fitted with tubing until the flocculent surface sediment was at the surface water boundary. Core Central 3 was covered with paraffin wax used in canning and secured with a sponge layer. Both sediment cores were transported horizontally in a black plastic bag within a cooler with ice until arrival at the University of Waterloo. Core Central 1 was sectioned in 2005 into 0.5-cm intervals using a vertical platform and samples were placed into plastic Whirlpak® bags and stored at 4°C in the dark prior to analyses. Core Central 1 was analyzed for particulate carbon and nitrogen concentrations, and $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ stable isotopic signatures of bulk sediment.

Core Central 3 was transported to the National Lacustrine Core Repository (LacCore) at the University of Minnesota, where it was split horizontally down the length of the core tube in 2007 using a dual medical cast saw. The split sediment core sections were then labelled as an ‘archive half’ (stored at LacCore Facility) and a ‘working half’ (used for analyses). The working half was then lightly scraped with the edge of a glass microscope slide across the core to expose fresh sediment. The working core half was then scanned with a Geotek standard multi-sensor core logger for gamma density, acoustic (p-wave) velocity, electrical resistivity and magnetic susceptibility at 20-mm resolution. At the Large Lakes Observatory, University of Minnesota, the working half of core Central 3 was then scanned at high resolution (400 μm) using state-of-the-art XRF elemental scanning and x-ray imaging.

Sediment core chronology

Sediment core chronologies were determined using ^{210}Pb and ^{137}Cs radioisotopic analyses by gamma ray spectrometry. Sediment from core slices were freeze-dried, ground and packed into plastic test tubes, weighed and sealed with epoxy resin. ^{226}Ra was allowed to equilibrate with daughter isotopes in the sample tubes for at least 2 weeks before the total activity for radioisotopes ^{210}Pb and ^{137}Cs was

measured (in disintegrations per minute (dpm g^{-1})) using an Ortec© digital gamma ray spectrometer (DSPEC) housed at the University of Waterloo Environmental Change Research Laboratory. Samples were analyzed for 24 to 72 hours to ensure activities exceeded the minimum detection limit required to capture sufficient gamma emissions in excess of the background emissions and double the measure of the blank treatment, a tube with the epoxy resin but no sediment (Blaauw et al. 2001).

Measured ^{210}Pb activities were converted to estimated sediment ages using the CRS model, because we assumed that changes in water level and human activities during the past 150 years affected sedimentation rates, denoted by ^{210}Pb activity curves that exhibited a small saw-toothed pattern of decay. ^{210}Pb activity profiles for cores Central 1 and Central 3 displayed an overall exponential decline in activity with increasing sediment depth and increasing cumulative dry mass (Figure 5-2). The background ^{210}Pb activity was determined by the minimum positive ^{210}Pb activity along the asymptote of the decay curve. Since two different gamma ray spectrometers were used to analyze the two cores, independent measures of background ^{210}Pb activity were employed. For core Central 1, background activity of 1.513 dpm g^{-1} was reached at a sediment depth of 17.5 cm (2.54 g cm^{-2} cumulative dry mass). For core Central 3, background ^{210}Pb activity of 1.863 dpm g^{-1} was reached at a sediment depth of 15.25 cm (1.58 g cm^{-2} cumulative dry mass; Figure 5-2). When comparing between these two cores, there appeared to be a couple of centimetres of material missing from core Central 3 that was due to the method of horizontal splitting and unconsolidated, wet sediment.

Before developing the chronologies, ^{137}Cs activity was used to help determine the quantity of sediment that was missing in the surface of cores Central 1 and Central 3 (Figure 5-2). ^{137}Cs activity can be measured in sediments and has a relatively short half life of 33 years. ^{137}Cs activity profiles typically show an initial increase in 1954, with the onset of above ground nuclear bomb testing and deposition of radiocesium peaked in 1963. Typically, peak ^{137}Cs fallout to sediments is estimated to

have occurred in 1964 (IAEA International Atomic Energy Agency 1991). These two dates for ^{137}Cs activity (1954, 1964) were used to align the cores with respect to time (described below) and estimate the amount of missing surface sediment from the ^{137}Cs activity profiles of the sediment cores (Figure 5-2 inset).

Activities of ^{210}Pb and the constant rate of supply model (CRS) were used to establish sediment ages during the past 150 years (Figure 5-2). After 1860, the age of older sediments was estimated by calculating the linear regression of the CRS derived dates and the measured cumulative dry mass. To extrapolate dates down core to as old as ~1425 CE, the sediment cumulative dry mass was then subtracted by the intercept of the regression and divided by the slope of the regression. These spreadsheet calculations were dependent on the date of the retrieval of surface sediments, which was in question. This start date can be adjusted should you have reasonable evidence of missing surface sediments.

Magnetic Susceptibility

In 2007, the Geotek XYZ multi-section automated split core logger was used to take point sensor measurements at 0.5-cm resolution of the working half of core Central 3 at the LacCore Facility. Magnetic susceptibility (χ) was then calibrated to remove the effects of the sensor proximity to the aluminum core tray using the direct measurements taken from Geotek XYZ dimensions relative to the laser profiler (X) to quantify the offset (Y) of SI values:

$$Y = -3e^{-9}X^6 + 5e^{-7}X^5 - 3e^{-5}X^4 + 0.001X^3 - 0.0256X^2 + 0.6219X - 6.5523$$

XRF Elemental Analysis

X-ray fluorescence was conducted at the Large Lakes Observatory, Duluth using the ITRAX core scanner, Cox Analytical Systems, Gothenburg, Sweden (Croudace et al. 2006). The working half of sediment core Central 3 was covered with fine Mylar® film and scanned at $400 \mu\text{m min}^{-1}$ for a run

time of over 18 hours. The ITRAX system was used to produce a digital radiograph, an optical image and the non-destructive X-ray fluorescence multi-elemental analysis of core Central 3. ITRAX scanning of sediments with over 90% water content causes a considerable amount of XRF absorption by the water film. The minimum detection limit for accurately measuring elemental concentrations was 1,000 counts per second. Elements potassium, calcium, chromium, manganese, titanium, iron, selenium, rubidium, strontium, zirconium and lead all met or exceeded this detection limit throughout the core sequence. Elements like aluminum and silica have been useful in long sediment core records (Shanahan et al. 2009, 2008), but these light elements have a reduced fluorescence emission and were below detection limits. Following XRF analyses, the working sediment core was sectioned at the LacCore Facility into 0.5-cm intervals, packaged in plastic Whirlpak® bags and stored in the dark at 4°C at the WATER lab, University of Waterloo until further analyses.

Greyscale Imaging of the X-radiograph

The ITRAX x-radiograph imaging of the working half of sediment core Central 3 was scanned at 400- μ m resolution. The optical .tif file was then imported to Northern Eclipse software where the image was entered into a line scan at highest resolution. This converted the greyscale image into an excel file, ranging from 0 (black) to 65,535 (white). Values for the x-radiograph of core Central 3 were on average $20,200 \pm 9,500$. Sediment depth alignment was calibrated with initial and final readings, as well as with three peaks from the magnetic susceptibility scan and high iron concentrations in the XRF scan.

Sediment Carbon and Nitrogen Content

Sediment core samples were processed for carbon and nitrogen analyses at the University of Waterloo following Stainton et al. (1977). Wet sediment from each 0.5-cm slice was sub-sampled into glass vials, freeze-dried and weighed out into 2 mg tin cups, crimped and packed into a nickel sleeve for combustion. Samples were processed with elemental analyzer Exeter CEC Model 440 (Zimmermann

& Keefe 1997). Carbon and nitrogen peaks were used to calculate concentrations in molar units ($\mu\text{mol g}^{-1}$ dry sediment), to calculate the molar ratio between carbon and nitrogen.

Sediment Phosphorus Content

Total phosphorus was measured in each of the sediment core slices following methods described by Berglund (1986), where 5 mg of freeze-dried and ground sediment was placed into a small crucible and ashed at 550°C for one hour. Combusted sediment was then weighed into 70 mL glass test tubes and digested with potassium persulfate in the autoclave for one half hour on the wet cycle. Following digestion, analyses followed colorimetric techniques described by Stainton et al. (1977).

Loss-on-ignition

Gravimetric analyses were used to determine the water content for ^{210}Pb analyses and for the analyses of organic, carbonate and inorganic matter content. Procedures followed Heiri et al. (2001), where ~ 5 mg of wet sediment was weighed into crucibles and dried at 90°C for 24 hours, cooled and weighed to determine water content. Crucibles were then placed in a muffle furnace and ashed at 550°C for one hour, cooled and weighed to determine loss of organic matter. Lastly, crucibles were returned to the muffle furnace and combusted at 950°C for one hour, cooled and weighed to determine loss of carbonate matter. Carbonate content was calculated as the molar ratio from CO_2 at 950°C to CO_3 ($60 \text{ g mol}^{-1}/44 \text{ g mol}^{-1}$). Inorganic content was then calculated as the remaining clastics. Water content was expressed as a percentage wet weight, and all other calculations were represented as a percentage of the dry sediment mass (wt/wt) on which chemical analyses were done.

Stable Isotope Analyses of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

Carbon and nitrogen stable isotopes for core Central 1 were analysed at the Environmental Isotope Laboratory at University of Waterloo. Sediment samples were freeze-dried, ground and weighed (1.5

to 4.0 mg) into a tin cup, after which they were sealed and combusted in the Prism Mass Spectrometer GC-C-IRMS. Isotopic ratios were reported as parts per thousand for the ratio of the sample relative to a standard.

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3$$

δX here is $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ and R is the respective isotopic ratio $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$ (Peterson and Fry 1987). The $\delta^{13}\text{C}$ standard was Pee Dee Belemnite from South Carolina (PDB), while the $\delta^{15}\text{N}$ standard was atmospheric nitrogen (Clark and Fritz 1997). The precision for $\delta^{13}\text{C}$ was ± 0.31 ‰ and for $\delta^{15}\text{N}$ was ± 0.20 ‰. The $\delta^{13}\text{C}$ sediment profile for core Central 1 was then corrected for the effects of atmospheric carbon emissions since the industrial revolution known as the Suess effect following Verburg (2006).

RESULTS AND INTERPRETATION

Core Central 1 (recovered in 2004) surface sediments were pooled from 0 to 1.5 cm (midpoint = 0.75 cm) during sample preparation for gamma ray spectrometry and sediments were not representative of the 2004 coring date. Using the CRS model equations, the surface sediment date that is typically determined by the date of core recovery was in question and was estimated based on the fit of ^{137}Cs activity curve. In core Central 1, the average age of 2000 was selected because it best represented the age of surface sediment from core Central 1 relative to the ^{137}Cs marker dates, 1954 and 1964.

However, core Central 3 (recovered in 2006) was horizontally split and sectioned with visible loss of surface sediment. The surface interval (0.25 cm midpoint) of core Central 3 was also estimated based on the ^{137}Cs activity curve, and an assigned age of 1987 (or approximately 2 cm of surface sediment loss) was chosen, which best aligned ^{137}Cs marker dates along the core chronology.

To assess the reliability of the chronologies for cores Central 1 and Central 3, and to assess the ages that correspond between these two cores, dates were compared with another nearshore core from

Lake Bosomtwe, Konkoma 2 from 34 m water depth (Figure 5-1). Core Konkoma 2 possessed a distinctive sediment-water interface that was indicative of minimal disturbance of the surface sediments during coring. Konkoma 2 was sectioned vertically in the field in 2005 without the loss of any surface sediment. The location of core Konkoma 2 was sufficiently far from the effects of nearshore flooding events or road construction. In Chapter 4, the Konkoma 2 ^{210}Pb activity profile shows a gradual decline with increasing sediment depth and a peak in ^{137}Cs activity that is visible near the 1964 CRS date (Figure 4-4). Two marker bands were found in all three cores that were associated with low organic content and high inorganic content (up to 80% wt/wt) that were likely deposited at the same time. Using CRS model chronology for each of the sediment cores, after having aligned the ^{137}Cs dates in cores Central 1 and Central 3, the first marker band was at 10.25 cm in core Central 1, 9.75 cm in Central 3, 12.75 cm in Konkoma 2 and all dates measured on average $1916 \text{ CE} \pm 1.5$ years with very little discrepancy. A second marker band that contained a peak of inorganic content occurred at 3.25 cm in core Central 1, 2.75 cm in Central 3 and 6.75 cm in Konkoma 2, which all dated on average to $1976 \text{ CE} \pm 2.3$ years. The alignment of these CRS chronologies, which had been adjusted to the ^{137}Cs activity dates, confirmed that the estimated surface sediment dates for both cores Central 1 and Central 3 are reasonable and provide acceptable core chronologies.

CRS model sedimentation rates were on average $0.0149 \text{ g cm}^{-2} \text{ yr}^{-1}$ and 1.41 mm yr^{-1} for cores Central 1 and Central 3. Episodes of reduced ^{210}Pb activity in a few samples corresponded with periods of rapid sedimentation of older material (low ^{210}Pb activity). For instance, in 1959, core Central 1 sedimentation rate jumped from 0.0117 to $0.0168 \text{ g cm}^{-2} \text{ yr}^{-1}$.

When plotted by each established chronology, the sedimentary content of organic matter, carbonates and phosphorus, which were the variables that were measured independently on samples from both cores, corresponded very closely (Figure 5-3). This finding, plus the observation that marker bands in both cores were estimated to have nearly identical ages, suggested that the chronologies of these two

cores were sufficiently similar to present the profiles of the sediment variables analysed from both cores on one stratigraphy, as in Figure 5-4. Core Central 1 was analyzed at 0.5-cm intervals, while much of the scanning of core Central 3 was at 400 μm , thus, to improve the visual comparison between the core profiles, the high-resolution scanning data were represented as the mean for each 0.5-cm interval.

There were three major zones that were visibly distinguishable in the sediment cores. Zone 1 (~1425-1610 CE) consisted of dark grey, homogenous gyttja that lacked well-defined laminations (Figure 5-4). Zone 2 (~1610-1860 CE) consisted of increasingly lighter grey gyttja with an abundance of gas bubbles and coarse-grained sandy bands that transitioned into a pattern of visible laminations. Zone 3 (~1860-present) consisted of well-laminated sediments with fossil seeds, and remains of fish and plants. Results from the chemical analyses of sediments from these three zones were then interpreted with respect to the potential influence of climate change and limnological variability on the composition of Lake Bosomtwe's sediments.

ZONE 1 (~1425 – 1610 CE)

Visually, the sediment stratigraphies from cores Central 1 and Central 3 of Zone 1 (~1425-1610) consisted of homogenous dark grey gyttja. However, the greyscale image of the x-radiograph of core Central 3 shows that sediments of Zone 1 contained more dense sediment embedded within a finely laminated structure (Figure 5-4). The inorganic content was high for this period (average 81% g/g dry mass). The dark colouration of this inorganic-rich zone corresponded with relatively elevated magnetic susceptibility and concentrations of iron and titanium. The high inorganic content and absence of *visible* laminations in Lake Bosomtwe sediments during Zone 1 may be indicative of a low water level, based on evidence obtained from a spatial survey of cores collected along a water-depth transect (Chapter 4 of this thesis). Previously, we found that visible laminations from sediments in a deep-water central part of the lake likely occurred at water depths more than 56 m. The lack of *visible*

laminae suggested that the water levels were at least 22 m lower than at present. If the water depth was at most 56 m from the lake bottom, the surface area during ~1425-1610 would have been 19 % smaller than at present (surface area today is 48.6 km²). Evidence suggests that reduced water levels and an increased catchment area could have facilitated greater delivery of inorganic clastics to the sediment record due to mobilization of exposed nearshore sediments.

The organic matter (16 %), carbon (6 mmol C g⁻¹) and nitrogen contents (0.35 mmol N g⁻¹) of Zone 1 sediments were low compare to sediments of the other zones. The molar ratio between carbon and nitrogen, C:N, was 16 on average. All proxies were found to have less variability in Zone 1, as compared to subsequent zones. These low values may be due to poorer organic matter preservation or to lower primary productivity. Organic matter preservation during periods of low water levels can be depressed because of oxygenation in the deep waters, which may have persisted for longer periods. Should deep waters become aerobic, particularly when seasonal or episodic oxygenation extends to the sediment-water interface, microbial decomposition can be facilitated (Hedges and Keil 1994). Oxygenated waters also have a more positive redox potential that can affect the sequestering of negative ions like phosphate onto metallic oxides. Transport of particulate-bound phosphorus from the catchment into an oxygenated water column can inhibit the chemical dissolution of P and restrict its bioavailability (Gikuma-Njuru and Hecky 2005). The loss of phosphorus from the oxygenated water column to the sediment layer can reduce the pool of soluble reactive phosphorus available for internal nutrient loading, and thus, reduce the organic-bound phosphorus deposition to the sediments (Gikuma-Njuru and Hecky 2005). Total phosphorus concentrations in Zone 1 were relatively low compared to the rest of the core and may be due to either dilution of TP by inorganic matter deposition or deep-water oxygenation (Chapter 4 of this thesis).

The concentrations of calcium and strontium in Zone 1 were also relatively low, yet the Sr:Ca count ratios were elevated with respect to the rest of the core. Shallow-water conditions can produce high

sediment strontium to calcium ratios because of aragonite formation. Aragonite forms naturally in calcareous mollusc shells and corals under biological control. However, Talbot and Kelts (1986) found that authigenic aragonite needles and diagenetic calcite and dolomite were formed in the organic-rich sediments of Lake Bosomtwe during high evaporative enrichment and methanogenesis. Such high evaporation and low lake level conditions may have persisted during the 15th to the 17th centuries, which would favour aragonite formation authigenically in the sediments (high Sr:Ca). It would be expected then, if carbonate deposition were solely controlled by this process and evaporative enrichment were pronounced that carbonate concentrations would be greater. Carbonate content however was relatively low (2 %), which may be due to dilution by terrestrial inorganic material or minimal calcite and aragonite formation.

ZONE 2 (~1610 – 1860 CE)

Zone 2 was readily distinguished by the change in sediment colour from dark grey to lighter grey gyttja, the onset of *visible* laminations after ~1720 CE and greater range of variability in the sediment proxy values. Even though sediments became visibly laminated at 23 cm, ~1720, sediment depth, the x-radiograph shows that sediments became more coarsely laminated at the start of Zone 2. Also, the greyscale image of the x-radiograph in Zone 2 revealed black, dense bands that were inorganic-rich deposits (Figure 5-4). There were two prominent bands of high inorganic content at ~1725 and ~1790 CE in core Central 3. These two bands were evident as peaks in magnetic susceptibility with up to 11 SI, denser sediment in x-radiography, and high concentrations of iron and titanium. These high-resolution micro-x-ray scans of the laminations from Lake Bosomtwe found that the dark laminae were rich in iron, manganese and titanium, which agrees with previous thin sectioning by Shanahan et al. (2009). Shanahan et al. (2009) found that material in these dark laminae was transported from the catchment to the lake and correlates with the amount of annual rainfall. The characteristics of these inorganic deposits suggest high-energy clastic inputs characteristic of elevated rates of precipitation or lake level change (up or down), as aeolian transport has limited potential to rapidly deposit

inorganic layers of substantial thickness, and anthropogenic activities in the catchment were low in the catchment at this time. The shift from a prolonged arid period during a low water level (~1425-1610) to a wetter climate during a high water level (~1610-1860) may have led to episodes of high inorganic sedimentation due to riverine inputs or reworking of nearshore sediments.

Zone 2 was further subdivided based on the organic content sediment profiles into Zone 2a (~1610-1750 CE) and Zone 2b (~1750-1860 CE). During ~1610-1750 CE, carbon and nitrogen concentrations (Figure 5-4) were on average $5.4 \text{ mmol C g}^{-1}$ and $0.37 \text{ mmol N g}^{-1}$ and rose further in 1750-1860 to $6.8 \text{ mmol C g}^{-1}$ and $0.41 \text{ mmol N g}^{-1}$. The rising sediment concentrations of carbon, nitrogen and phosphorus likely reflect increased autochthonous primary productivity as lake size and depth increased. Elevated water levels increase primary production in Lake Bosomtwe and likely stimulate bacterial decomposition that consumes oxygen in the deep hypolimnetic waters. Once deep-water anoxia is established, organic matter preservation improves markedly by inhibiting bioturbation and aerobic microbial metabolism (Hedges and Keil 1995). During Zone 2, higher phosphorus concentrations in the sediment ($25.7 \pm 7.9 \text{ } \mu\text{mol g}^{-1}$; Figure 5-3) suggest both increased organic matter preservation and likely increased release and recycling of particulate bound P (Chapter 2 & 3 of this thesis, Gikuma-Njuru and Hecky 2005).

Increased organic matter content during Zone 2 coincided with a marked increase in strontium and calcium and a subtle rise in carbonate, with on average 0.5% greater carbonate. Organic-rich laminae that have high calcium, strontium and carbonate concentrations in Lake Bosomtwe that were distinguished as light laminae by Shanahan et al. (2008). The greater thickness and frequency of these laminae by 1610 suggests a period of increased primary productivity. The start of Zone 2a (~1610-1750) was also marked by a strong enrichment of $\delta^{13}\text{C}$ of bulk matter and a decline in C:N ratio (Figure 5-4), while Zone 2b (~1750-1860 CE) was characterized by the inverse trends. In Zone 2a, autochthonous production is believed to have increased, based on the declining C:N ratios (< 14), the

3.2 ‰ enrichment of the stable carbon isotopic signatures (-22.9 ‰), the doubling of Sr and Ca concentrations, and to a small extent increased carbonate content (by 1%). Periods of rapid primary production can result in reduced dissolved carbon dioxide concentrations that elevate pH. Under conditions of high alkalinity, increased pH can induce precipitation of calcium carbonate out of solution (Hodell et al. 1998), hence the increased calcium and carbonate sediment concentrations during Zone 2a. Low CO₂ availability also reduces the isotopic discrimination caused during photosynthetic carbon uptake and can even lead to a reliance on isotopically enriched CO₂ or dissolved bicarbonate for carbon fixation (Hecky and Hesslein 1995).

δ¹⁵N values of bulk matter increased from 8.1 ‰ to 10.2 ‰ in Zone 2a, which likely denotes a change in nitrogen cycling. The stable isotopic signatures of nitrogen were not indicative of atmospheric nitrogen fixation (near 0 ‰), but rather a strong dependence on internal recycling of nitrogen. Enrichment of the DIN pool through denitrification would generate a pool of isotopically enriched dissolved nitrogen (Chapter 3 of this thesis). Evidence suggests that the increased organic matter production that increased rates of decomposition in the hypolimnion likely enhanced conditions of deep-water anoxia required for denitrification. Nitrogen fixation by cyanophytes would still likely contribute to the δ¹⁵N signature of bulk matter, but these signatures would be integrated. As well, the effects of isotopic fractionation of nitrogen in the water column are such that the fixed N₂ from the euphotic zone has a lighter isotopic signature and would be preferentially selected during degradation for transformation into the gaseous form through denitrification (Fry 2003, Robinson 2001), resulting in the further δ¹⁵N enrichment of bulk matter in Lake Bosomtwe sediments.

ZONE 3 (~1860 – Present)

Lacustrine sediments deposited throughout Zone 3 (past ~ 150 years) consisted of thicker *visible* laminations compared to sediments deposited earlier. Organic matter content rose to nearly 30 % in Zone 3, with the most rapid increases during ~1915-1945. Zone 3 differed markedly in sediment

chemistry (Figure 5-5 and 5-4), with a declining upcore trend in titanium fluorescence ($r^2 = 0.73$, $P < 0.0001$) and increasing upcore trend of total phosphorus concentrations ($r^2 = 0.30$, $P < 0.0002$). Both are strongly linked to the increased organic matter content, which is high in TP and low in Ti. Carbon, nitrogen and phosphorus concentrations were all high in Zone 3, with on average, $12.0 \text{ mmol C g}^{-1}$, $0.63 \text{ mmol N g}^{-1}$ and $46 \text{ } \mu\text{mol P g}^{-1}$. The high organic content, C, N and P concentrations, as well as high Ca and Sr fluorescence counts in Zone 3 suggest a period of high primary production accompanied by continued deep-water anoxia.

Based on the modern spatial surface sediment analysis of phosphorus concentrations, values over $40 \text{ } \mu\text{mol P L}^{-1}$ were strongly correlated with water depths greater than 70 m and the occurrence of deep-water anoxia (Chapter 4 of this thesis). This predicted water depth fits well with the Ghana Hydrological Survey data, which show that Lake Bosomtwe water levels from 1940 to 2000 rose from 72 m to 79 m. Rising lake levels increase land inundation that supplies nutrients and increase the water volume for primary production, as well as increase the volume of anoxic deep water that would expose greater, previously oxidized sediments to anoxia and release particulate bound P. The recycling of nutrients like soluble reactive phosphorus from the deep-water would support greater primary production and greater sedimentation of organic matter and organic-bound nutrients (Gikuma-Njuru et al. 2010).

Declining values of magnetic susceptibility, Ti and Fe concentrations, and x-ray density likely reflect the increased supply of organic matter relative to inorganic matter. Increased organic matter and calcium carbonate deposition in Lake Bosomtwe sediments correlates with increased thickness of the light laminae (Chapter 2 of this thesis; Shanahan et al. 2008). The increased thickness of organic-rich light lamina during Zone 3 is likely not due just to increased water content in the sediments due to less sediment compaction, but to increased organic matter and calcite deposition during elevated lake

levels (Chapter 4 of this thesis); and possibly increased nutrient inputs from increased anthropogenic activities during the past 150 years.

Zone 3 was further subdivided into Zone 3a (~1860-1960) and Zone 3b (~1960-present), as the most recent sediments differed in their $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signatures. Stable isotopic signatures of bulk matter $\delta^{13}\text{C}$ became relatively enriched to -22.5 ‰ in Zone 3a, and then fell to -24.9 ‰ in Zone 3b. During Zone 3a, $\delta^{15}\text{N}$ was near 9 ‰ (with one exception 6.9 ‰ in ~1932) and during Zone 3b became more enriched, at 11.4 ‰. Prolonged deep-water anoxia and greater volume of anoxic deep water has likely led to greater denitrification and the build up of more isotopically enriched ammonia. These dissolved inorganic nitrogen species would be made available to the euphotic zone for primary production during seasonal water column mixing. However, these nitrogen cycling processes have likely been in place and the further 2.4 ‰ enrichment during the past 40 years may be due to increased human population releasing nitrogenous wastes that impart a higher $\delta^{15}\text{N}$ value.

During Zone 3a, K:Ti ratios increased gradually. Increased K:Ti is believed to be indicative of accelerated soil erosion. The soil horizon is exposed to the effects of chemical weathering that leads to the more rapid loss of K (relatively mobile) compared to Ti (relatively stable) in the top soils (Krauskopf and Bird 1995). Top soils would be expected to have a low K:Ti value and sediments from deeper within the soil horizon would have higher K:Ti values (Mischke et al. 2010). Estimated sedimentation rates did not change markedly during Zone 3a and 3b (Figure 5-2), however the low K:Ti values of the sediments since ~1860 may be reflecting a period of erosion. The continued population increase since ~1860 has likely resulted in greater land clearance for agriculture and more recently tourism. Deforestation is known to result in greater destabilization of the top soils through a decline in soil moisture, exposure of soils to solar radiation and faster surface water flows that can accelerate rates of erosion (Nicholson et al. 1998).

During Zone 3b, K:Ti values fell, as the inorganic matter content, magnetic susceptibility, Ti and Fe fluorescence counts and x-ray density increased. These findings are consistent with evidence from other cores presented in Chapter 4 of this thesis, which revealed that the construction of a feeder road led to greater inorganic sedimentation rates in nearshore sediment cores. Road construction to the town of Abono led to the expansion of the population and of farming and tourism activities. The clearance of previously undisturbed lands delivered weathered top soils with low K:Ti and high Fe and Ti content to the lake bed, but did not affect the sedimentation rate at the central coring sites. The transport of coarse inorganics did not extend to the deepest sediment depositional zones to increase sedimentation rates, but evidence suggests some fine inorganics did. During the same time, however, persistent drought over much of the Sahel, West Africa, has prevailed (Dai et al. 2004) and may also have delivered greater aeolian dust inputs from the continental interior to the sediment record (Peck et al. 2004).

DISCUSSION

Lake Bosomtwe is a closed-drainage lake and water levels are sensitive to changes in precipitation relative to evaporation within the crater (Turner et al. 1996a, 1996b). Sediments deposited at the central deep-water region of Lake Bosomtwe during the past ~550 years contained interpretable information about climate-driven changes in lake level, internal limnological changes and anthropogenic disturbances. Three distinct sediment zones were identified and the paleolimnological interpretation between these zones is clarified in a schematic diagram (Figure 5-6). The stratigraphic changes identify long-term centennial-scale climate variability that has included low water levels during a protracted drought period ~1425-1610 CE (Zone 1). This low water stand was found to be ~22 m shallower than present lake levels and was exposed to seasonal mixing with oxygenation of the sediment-water interface. Wetter conditions during ~1610-1860 CE (Zone 2) raised lake levels, increased primary productivity and developed conditions of prolonged deep-water anoxia. The

highest water levels persisted during ~1860-2000 (Zone 3) and conditions were characterized by strong thermal stratification with seasonal mixing events resulting in internal loading of nutrients. These recent sediments (~150 years) are also impacted by human activities that generate greater soil erosion, in particular the construction of a feeder road in the late 1950s. During the past 40 years, human activities may be increasing nutrient enrichment to the lake as well with increased phosphorus concentrations and $\delta^{15}\text{N}$ signatures.

The pronounced aridity during Zone 1, ~1425-1610 CE, corresponded with a recent paleoclimate reconstruction by Shanahan et al. (2009) who identified that this low water period was the effect of climatic changes during the Little Ice Age (LIA). Shanahan and colleagues (2009) found that $\delta^{18}\text{O}$ enrichment and increased silica concentrations in Lake Bosomtwe sediments were indices of lake level drawdown during the LIA. Evaporative generation of carbonates was attributed to the enrichment of $\delta^{18}\text{O}$ and increased size of the erodible catchment was linked to elevated silica concentrations. XRF-based Si concentrations in sediment core Central 3 were not presented here because the fluorescence counts were below our detection limit (1000 counts/s). Shanahan and colleagues (2008) inferred that the LIA drought caused a 25-m decline in water level from 1400-1750 CE, a finding which is corroborated by a seismic unconformity within the basin. The sediment records from cores Central 1 and Central 3 have identified the same decline in water level, but over a shorter duration (~1425-1610 CE compared to 1400-1750 CE) than Shanahan and colleagues have suggested.

Zone 2 (~1610-1860 CE) commences with a wetter climate with increased precipitation from 1610-1750 (Zone 2a) that resulted in a lake level rise, but contained two periods of differing primary productivity (Zone 2a, 2b). The increased water level submerged the nearshore, expanded the lake surface area and likely introduced more nutrients that accelerated primary productivity. Greater

organic matter deposition likely led to seasonal deoxygenation of the sediment-water interface. By 1750, however, many of the indices for primary productivity ($\delta^{13}\text{C}$, C:N, Sr, Ca and concentrations of C,N,P) reverted to measures that resembled Zone 1, a relatively more arid climate period.

Evidence of decadal-scale climate variability appears to be preserved in the carbon stable isotopic signature of bulk matter and in Sr and Ca XRF counts. The most pronounced change was a 3 % enrichment of $\delta^{13}\text{C}$ bulk matter in Zone 2a. Since the enrichment of $\delta^{13}\text{C}$ signatures and increased concentration of Ca and Sr were contemporaneous, it may be that calcium carbonate content was driving the $\delta^{13}\text{C}$ enrichment. However, no relationship between carbonate content and $\delta^{13}\text{C}$ was present ($r^2 = 0.004$, $P = 0.57$), but there did exist a relationship between organic content and $\delta^{13}\text{C}$ ($r^2 = 0.24$, $P < 0.0001$) and carbon concentration and $\delta^{13}\text{C}$ ($r^2 = 0.17$, $P < 0.0002$). Thus, the $\delta^{13}\text{C}$ signature of bulk matter was likely driven by autochthonous organic matter generation. Previously, water column samples found that the initial peak primary production in Lake Bosomtwe occurred during the months of August and September when atmospheric temperatures fell (Chapter 2 of this thesis). Low air temperatures and clear night skies allowed for greater surface water cooling and eventually upwelling of nutrient-rich deep waters. Organic matter deposition during August and September was on average 45 % of the annual organic matter deposition (Chapter 3 of this thesis). This seasonal deep-water recirculation brings up essential nutrients (dissolved phosphorus and nitrogen) from the hypolimnion and stimulates algal production (MacIntyre et al. 2002, 2006). The water chemistry during periods of high algal productivity and CO_2 drawdown can eventually lead to biologically-induced calcite precipitation late in the growing season (Schelske and Hodell 1991). In the sediment trap records from Lake Bosomtwe during the period from October to December, calcium and carbonate deposition increased and, at the same time, particulate organic matter exhibited enrichment of $\delta^{13}\text{C}$ of bulk matter (Chapter 3 of this thesis). The climate conditions during the short dry season that mix the water column of Lake Bosomtwe generate organic- and calcium carbonate- rich sediments. The formation of light laminations in Lake Bosomtwe is influenced by northward

displacement of the ITCZ over the Sahel region (Chapter 2 of this thesis). High rainfall years over the Sahel region are most pronounced during the months of July and August when peak rainfall is delivered over the Sahel, and when atmospheric temperatures are cooler over Lake Bosomtwe in the Guinea Coast.

The interannual variability of net rainfall is affected by the amount of water vapour contained within the ITCZ and the degree of latitudinal displacement of the ITCZ (Hulme 2001). There are particularly strong teleconnections from August to September between the Sahel region and the Guinea Coast (Nicholson and Paleo 1993). The positive rainfall anomaly years in the Sahel are often positive rainfall years in the Guinea Coast region, and at Lake Bosomtwe. High rainfall years over the Sahel are also strongly associated with a bimodal pattern of precipitation over Lake Bosomtwe, where greater northward displacement of the ITCZ results in a cooler short dry period over Lake Bosomtwe during July and August.

The pattern of Sahel rainfall anomaly from 1900-2000 was strongly correlated with fluctuations in the $\delta^{13}\text{C}$ of matter in core Central 1 (Figure 5-7a). Rainfall anomalies are calculated as the standardized departure from a long-term mean. Mitchell calculated the rainfall anomaly for the Sahel region (Figure 5-7) by taking the average rainfall during June to October for each year in a region of 10°N-20°N over West Africa. The difference between this annual average and the long-term mean during June to October of 1900 to 2009 is divided by the standard deviation of the 1900-2009 record, to normalize the data. There were two recent drought periods in the Sahel, during 1968-2000 (Dai 2004) and 1910-1916 (Batterbury and Warren 2001), which correspond with depletion of $\delta^{13}\text{C}$ bulk matter in Lake Bosomtwe sediments. The Lake Bosomtwe water levels declined during the 1968-2000 Sahel drought period, but did not respond as rapidly or as dramatically as stable carbon isotopic signatures. The relationship between $\delta^{13}\text{C}$ bulk matter in our record and the Sahel rainfall anomalies is strongly positive (Figure 5-7b; $r^2 = 0.45$, $P = < 0.002$) even though sediment intervals incorporate on average

4-7 years. Expanding the timescale to incorporate the entire 550 year record, $\delta^{13}\text{C}$ bulk matter measures from Lake Bosomtwe sediments in Figure 5-7c indicate that prolonged droughts occurred during 1425-1610, 1750-1860, 1910-1916 and 1969-2000. Trends in the sediment record of $\delta^{13}\text{C}$, Sr, Ca and carbonate all appear to be related, however none of these other climate proxies show a significant relationship with Sahel rainfall anomalies ($P < 0.05$). $\delta^{13}\text{C}$ provides the best proxy for tracking Sahel rainfall anomaly years because the magnitude of the $\delta^{13}\text{C}$ signatures of bulk matter shifts rapidly and well in advance of lake level changes. Ultimately, $\delta^{13}\text{C}$ stable isotopic signatures of the sediment records capture climate-driven in-lake productivity that does not rely on large changes in lake level.

The mixing regime of Lake Bosomtwe appears to be strongly affected by the pattern of interannual rainfall variability over the lake and if drought years impede deep-water mixing events, drought likely impedes fish kill events. Annual fish kill events are perceived by local residents to have declined during the past 40 years, when deep-water mixing may have become more restricted. Rattray (1923) describes the annual occurrence of an upwelling of anoxic deep-water capable of asphyxiating fishes, known as 'gas explosions.' These gas explosions released volatile gases like dihydrogen sulphide, methane and ammonia, producing a sulphurous odour. The occurrence of nearly annual fish kills resulted in a bumper fish harvest that was considered a blessing and Lake Bosomtwe was deemed a sacred water body by the Ashanti people. Negative rainfall anomalies began in 1968 and persisted for much of the past 40 years, interrupted by only a few recent positive years (Figure 5-7). These mixing events are known to result from episodes of evaporative cooling and low evening air temperatures that reduced water temperatures (Verburg et al. 2003; Vollmer et al. 2005). It may be that periods of drought over West Africa, which are associated with a decline in rainfall and warmer air temperatures, result in both a decline in water levels and warmer water temperatures in Lake Bosomtwe.

The effects of the anthropogenic activities in the catchment of Lake Bosomtwe were preserved in the sediment records during the past 40 years or longer. A decline in sediment K:Ti ratios and a rise in inorganic content and inorganic proxies (Ti, Fe, magnetic susceptibility, density of the x-radiograph) suggest the transport of top soils from newly cleared land. Previously, nearshore sediment cores from Lake Bosomtwe showed evidence of accelerated rates of inorganic matter sedimentation, but these coarse sediments were not transported far offshore.

During the past 150 years, anthropogenic activities have been continually increasing, however, and the sediment records exhibit a gradual rise in K:Ti, organic matter deposition, nutrient concentrations N and P, and $\delta^{15}\text{N}$ that may be attributed to lake level rise or anthropogenic influence. Lake levels are known to have risen from 1930-1969 (Figure 5-7a) and would result in increased organic matter deposition and slumping of the flooded shoreline. Since 1969, the trend in elevated lake levels and annual rainfall has ceased and sediment records should not be indicative of large hydrological changes that would affect inorganic transport to the lake basin. The effects of land use change and increased population size in the Bosomtwe crater could be contributing to the eutrophication of Lake Bosomtwe when both soil-bound nutrients and effluent are released into the water column. $\delta^{15}\text{N}$ signatures during the past 40 years are strongly suggestive of nitrogenous waste products from increasing human and livestock populations (Hinkle et al. 2008). The sediment phosphorus concentrations were at a maximum concentration during 1960-2000. Currently, the effects of catchment soil erosion and poor waste management on Lake Bosomtwe are not known, but increased suspended sediments, algal blooms, turbidity and water fouling are all known to be the result of eutrophication at other tropical African lakes (Verschuren et al. 2002). Potentially, the effects of recent anthropogenic activities in the Lake Bosomtwe catchment may be damped by the Sahel drought during the past 40 years and may have restricted the extent of seasonal circulation of deep-water nutrients.

Comparison between the paleoclimatological reconstruction of Lake Bosomtwe's water levels and other tropical hydrological records (Figure 5-8) show that reduced water levels occurred over much of Africa (Nicholson et al. 2000). These low water levels were concomitant with the cooler air temperatures in the northern hemisphere during the LIA (1500-1850 CE). Colder north Atlantic sea surface temperatures were found to influence the African monsoon through the weakening of the air currents that result in the displacement of the intertropical convergence zone northward (Saenger et al. 2009). The reconstructed drought records for East African lakes appear to have a reduced duration as compared to Lake Bosomtwe's sediment record from West Africa. There are no other high-resolution drought records for West Africa during the past 550 years, as paleoclimatological reconstructions have focused on longer timescales. This discrepancy between East African records and Lake Bosomtwe, West Africa could be because drought periods over East Africa were offset by wet monsoonal air currents from the southern Indian and Atlantic Oceans (Legesse et al. 2002). For this reason, the need for paleoclimate reconstructions from West Africa is pertinent to forecasting future climate trends over West Africa.

CONCLUSION

Results from paleolimnological analyses of lacustrine sediment cores from Lake Bosomtwe have revealed extremely arid climate conditions during the Little Ice Age that reduced lake levels by 22 m (~1425-1610) and shorter-term drought periods with reduced water column mixing (~1750-1860, 1910-1916 and 1969-2000) when water levels were higher than the LIA. Shallow water levels during ~1425-1610 enhanced deep-water oxygenation of the sediments, increase inorganic content due to the increased source area of the erodible catchment and reduced organic matter content, which created conditions that did not preserve *visible* laminations.

Consecutive drought years have devastating effects on the nearshore residents of Lake Bosomtwe who experience reduced crop yields and reduced fisheries yields. Drought likely suppresses seasonal fish kill events, which are an important means of harvesting their bumper crop. However, drought conditions may also restrict the recruitment success of fish populations, as there is evidence of a mechanism that leads to reduced primary productivity. The subsistence farmers and fishers around Lake Bosomtwe are particularly vulnerable to prolonged drought as they have few alternative sources of income or sustenance available. West African populations require accurate climate reconstructions to hindcast drought frequency and severity to constrain future climate projections of temperature and rainfall variability. Meteorological patterns over the African continent as a whole do not act in complete synchrony. West Africa, and in particular the Sahel region, appears to be poised for more prolonged drought and the devastation that drought brings.

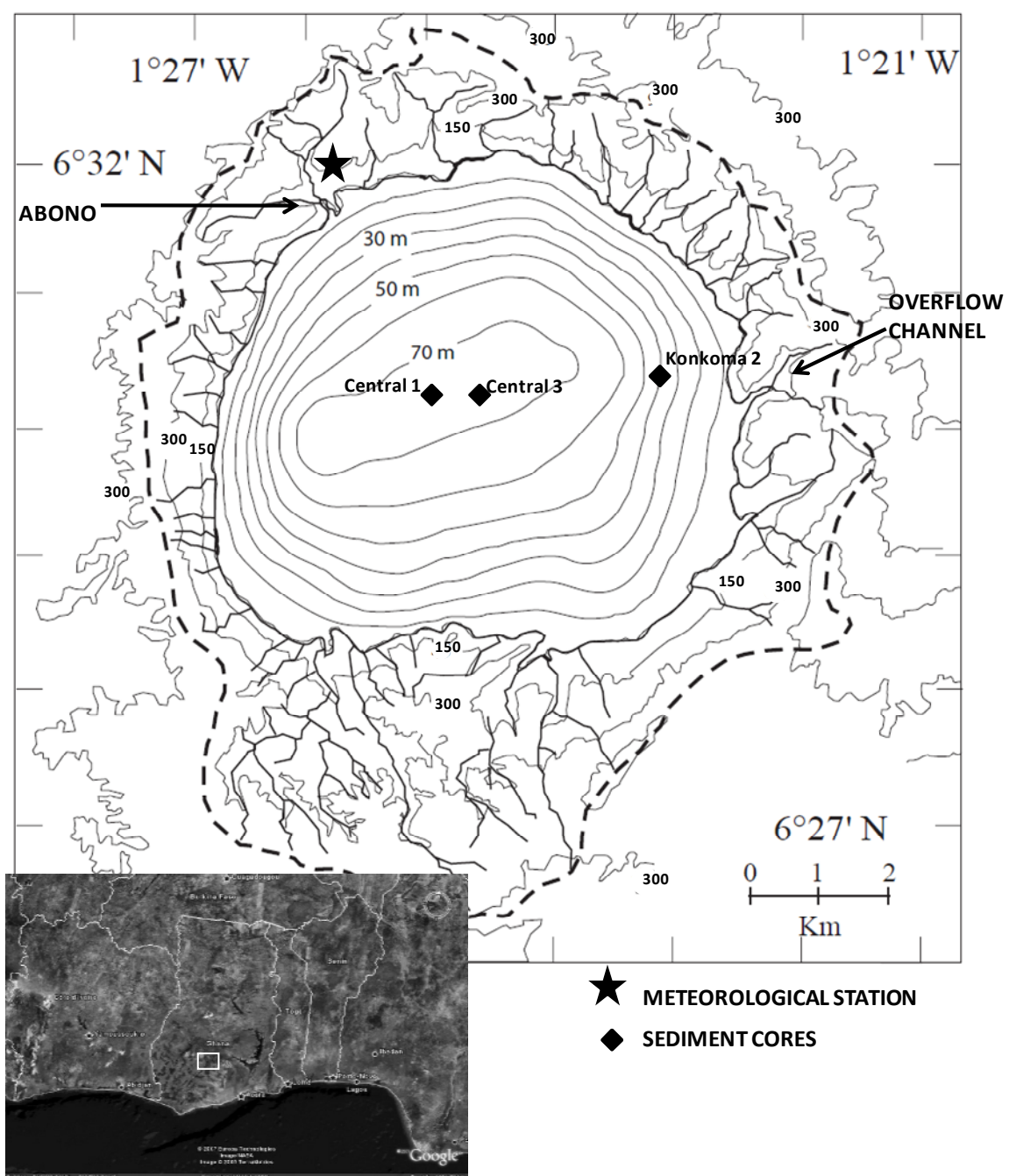


Figure 5-1 Basin map of Lake Bosomtwe showing the locations of coring sites for cores Central 1 2004 (6°30'14" N, 1°24'45" W), Central 3 2006 (6°30'14" N, 1°24'31" W) and Konkoma 2 (6°30'31" N, 1°22'50" W). Dashed line denotes the extent of the catchment area (modified from Brooks et al. 2005). Inset of West Africa, with white box over Lake Bosomtwe, Ghana (Google Earth, 2007).

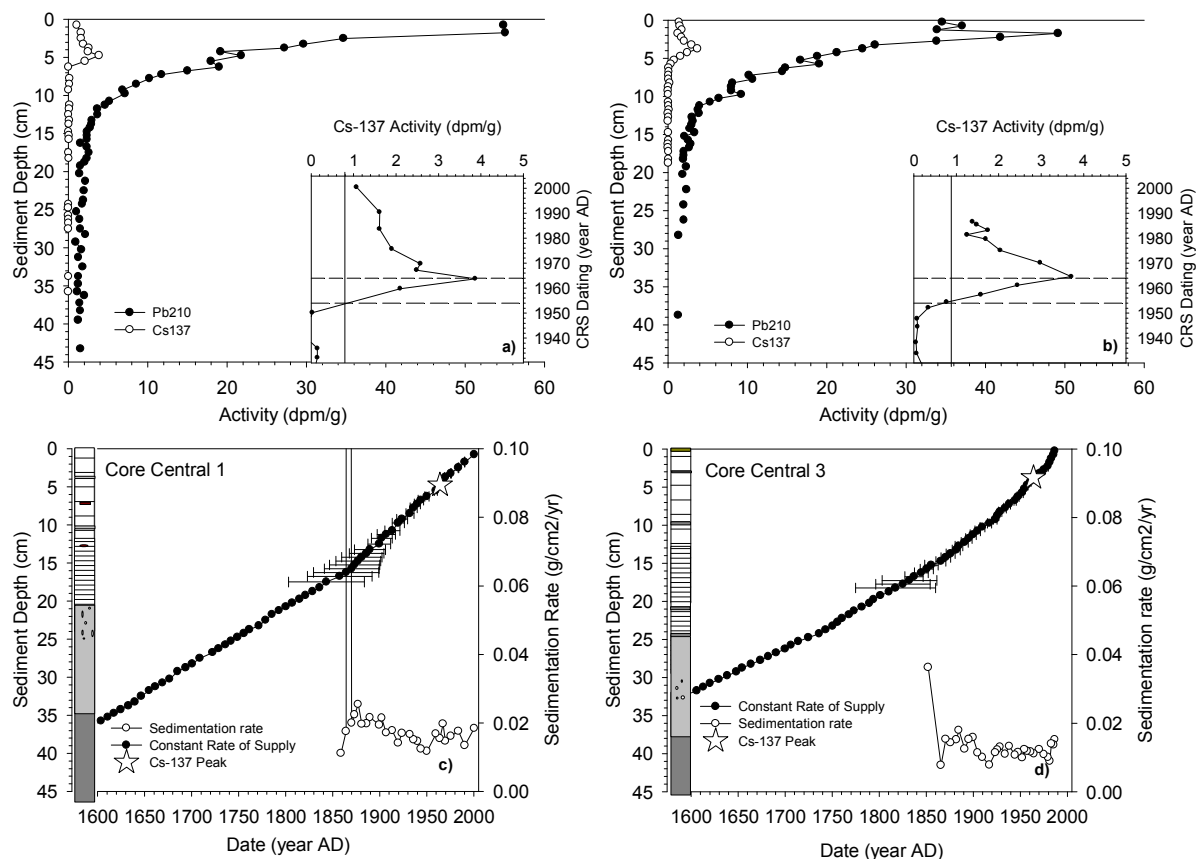


Figure 5-2 a) ^{210}Pb and ^{137}Cs activity profiles for cores Central 1 and b) Central 3, Lake Bosomtwe, Ghana with inset of ^{137}Cs peak plotted versus estimated sediment age (based on the Constant Rate of Supply model). Upper vertical, short dashed line denotes 1964 peak fallout of ^{137}Cs from nuclear bomb testing and lower, long dashed line denotes 1954 the onset of nuclear weapons testing. The solid vertical line denotes the minimum detection limit of ^{137}Cs activity. Sediment chronologies, error bars and sedimentation rates were established using CRS model for cores c) Central 1 and d) Central 3. The peak ^{137}Cs activity dated to 1964 is denoted by a white star.

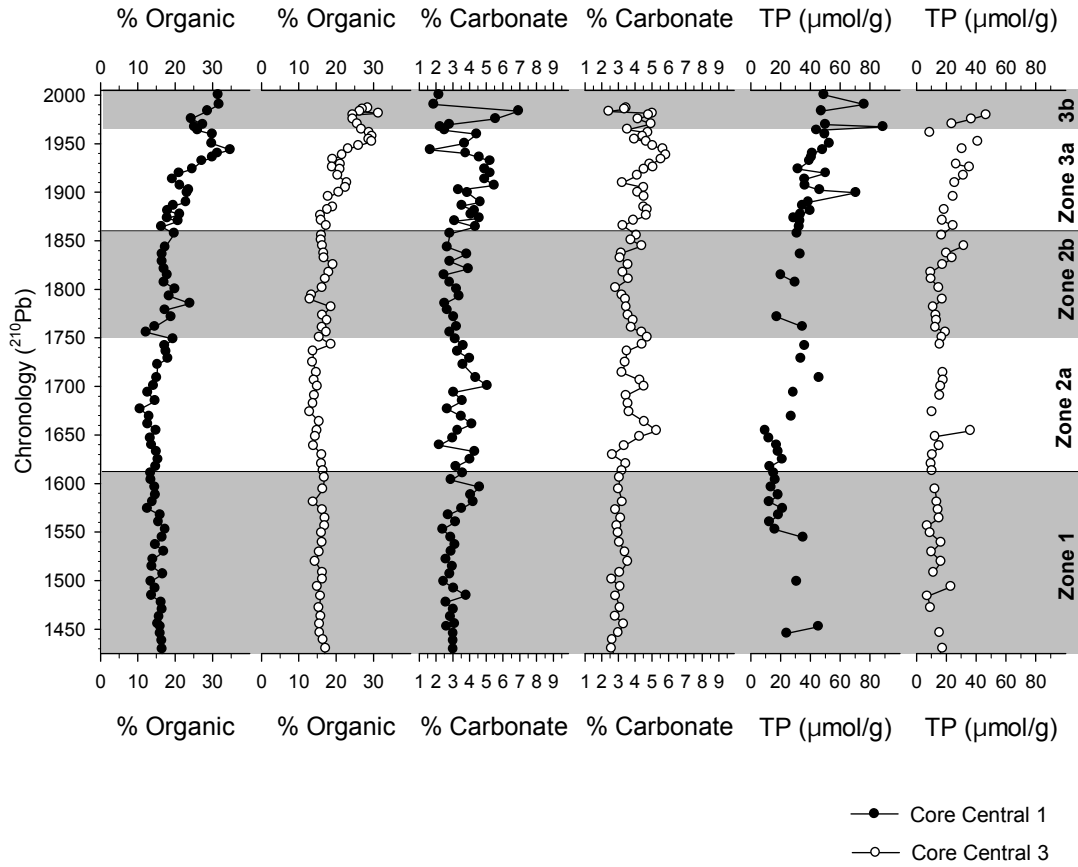


Figure 5-3 Comparison of stratigraphic changes between Lake Bosomtwe sediment core Central 1 and Central 3 using percent organic matter (% wt/wt) and percent carbonate (% wt/wt) and total phosphorus concentrations ($\mu\text{mol/g}$) to assess how well the estimated ages correspond between independently dated cores.

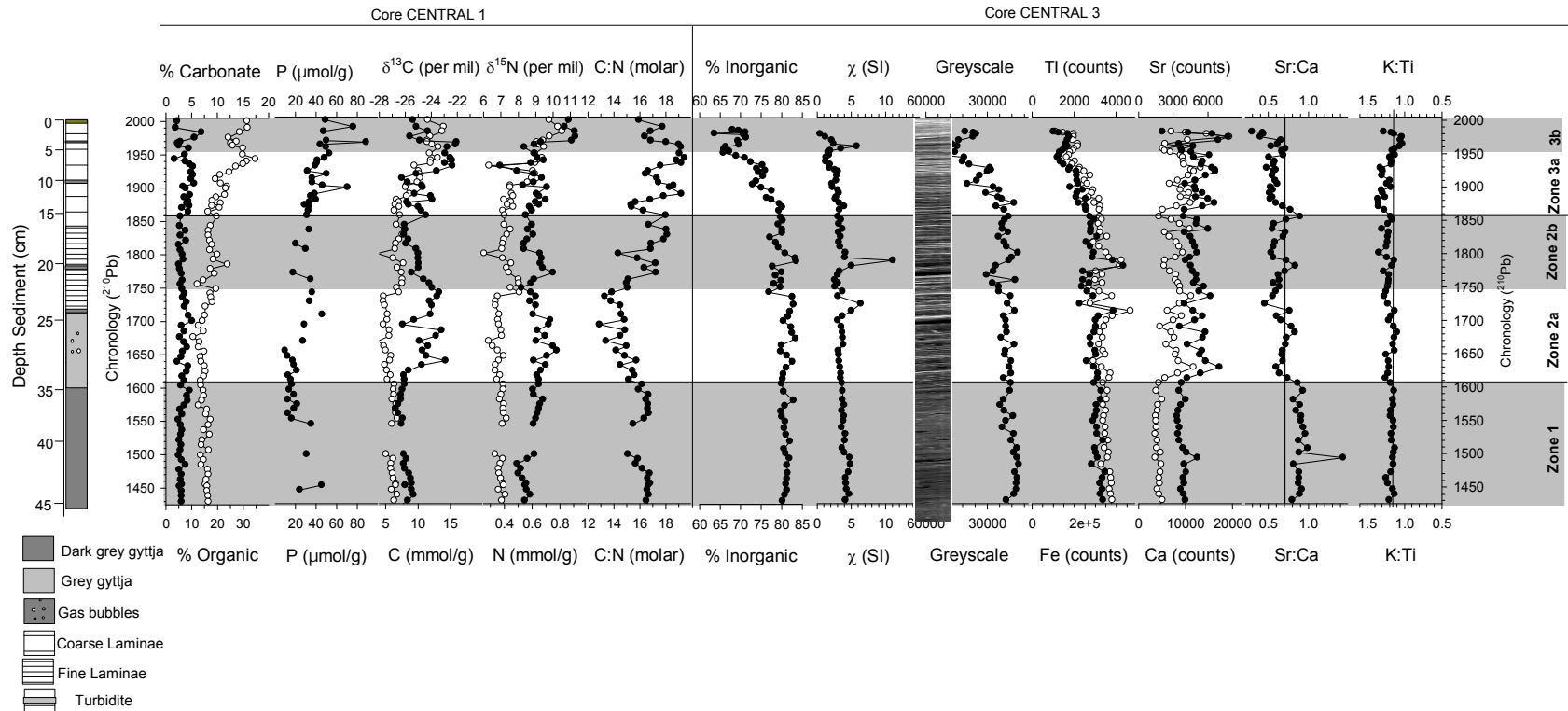


Figure 5-4 Stratigraphic changes in core Central 1 (collected in 2004) including organic matter (\circ), carbonate (\bullet), nutrient concentrations (phosphorus, carbon (\circ) and nitrogen (\circ)), stable isotopic signatures of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ (\bullet) in bulk sediment, molar nutrient ratios (C:N); and core Central 3 (collected in 2006) sediment magnetic susceptibility χ , x-ray radiographic image, greyscale imagery of the x-radiograph (darker x-ray image approaches 0), x-ray fluorescence of elements iron (\circ), titanium (\bullet), calcium (\circ), and strontium (\bullet), Sr:Ca and K:Ti ratio (count:count) with the core average values 0.71 and 1.17 respectively denoted by vertical lines.

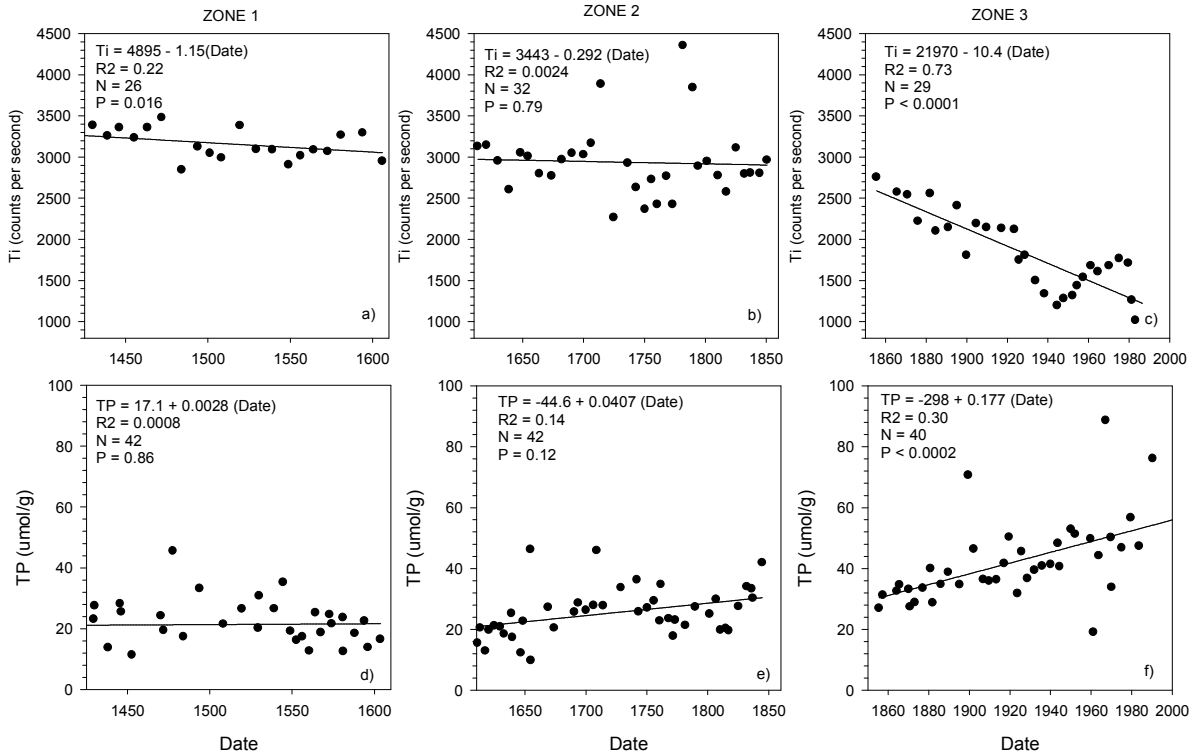


Figure 5-5 The linear regression through sediment measures of a)-c) titanium (counts per second from ITRAX) and d)-f) total phosphorus from sediment Zones 1 (~1425-1610), Zone 2 (~1610-1860) and Zone 3 (~1860-2000)

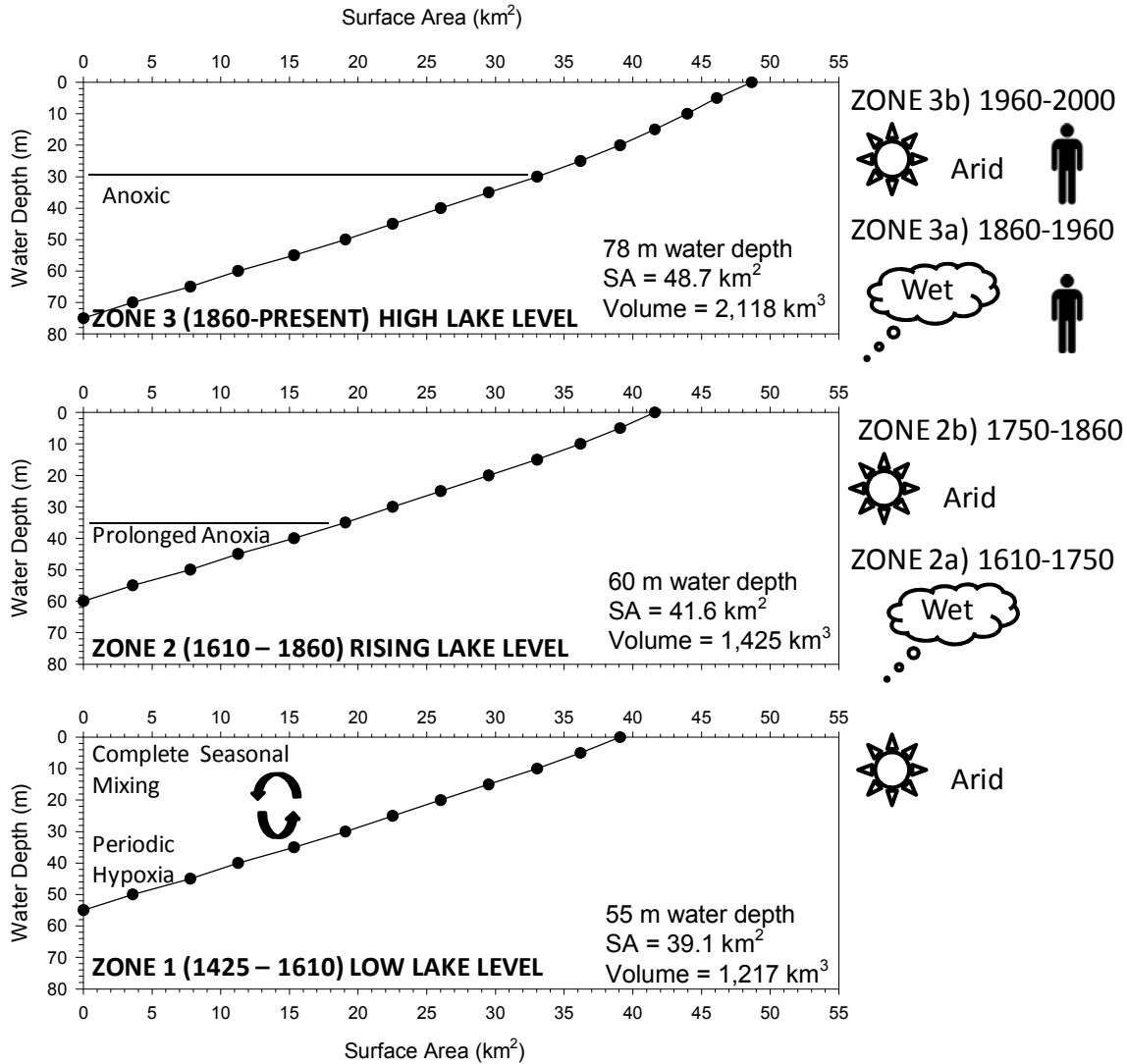


Figure 5-6 Schematic diagrams depicting changes in Lake Bosomtwe during the past ~550 years, as interpreted from information in the sediment cores, from a low water stand during arid conditions from ~1425-1610, to rising water levels from ~1610-1860, to a high water stand and anthropogenically derived soil erosion from ~1860-present.

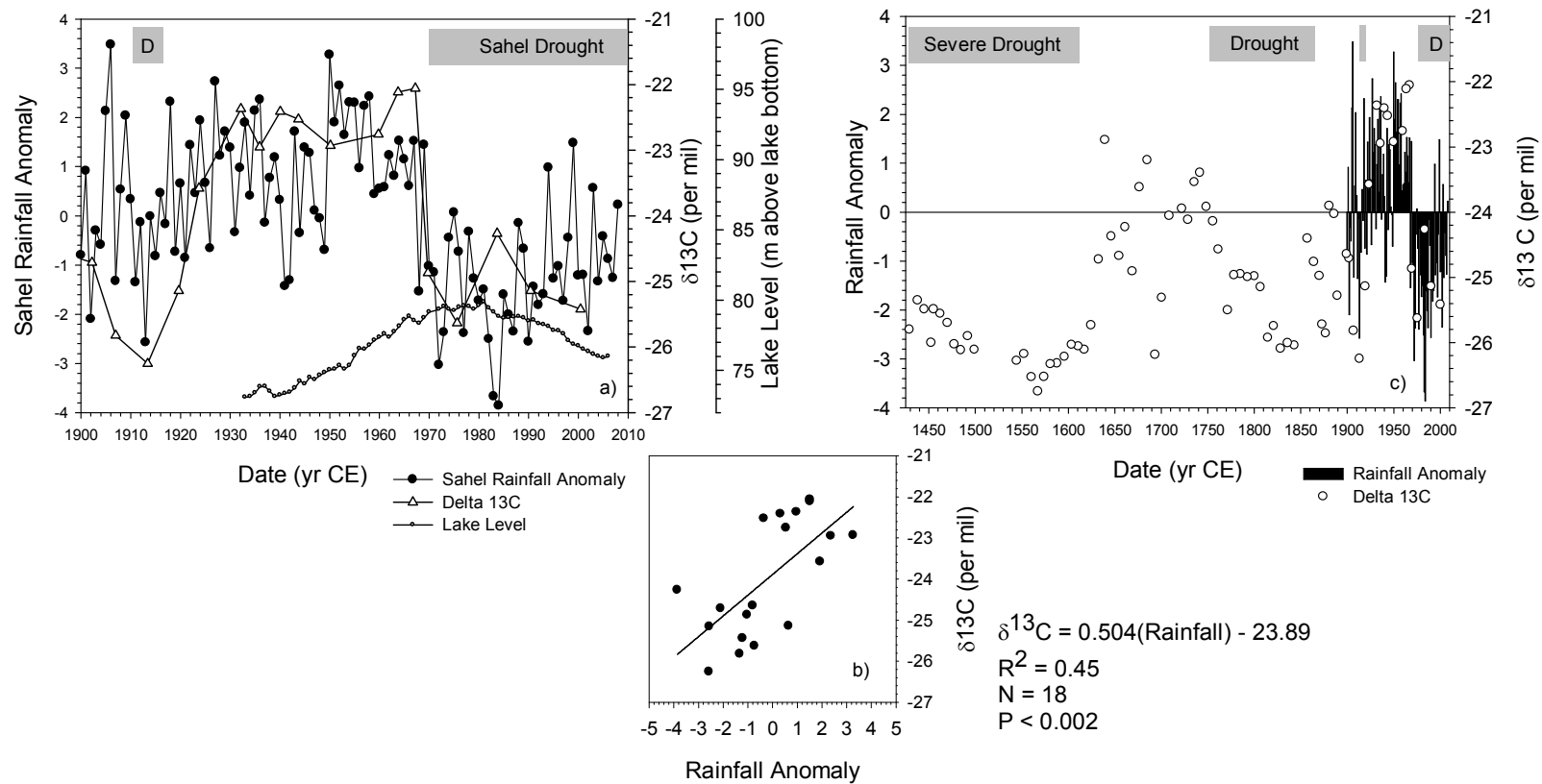


Figure 5-7 a) The Sahel rainfall anomaly from June to October during 1900-2009 with the $\delta^{13}\text{C}$ of bulk matter of Lake Bosomtwe sediments core Central 1 and the measured Lake Bosomtwe levels from the Ghana Hydrological Service. b) Linear regression between the annual rainfall anomaly for the Sahel region and the sediment $\delta^{13}\text{C}$ of bulk matter from the same time period as in panel a). c) The $\delta^{13}\text{C}$ of bulk matter (open circle) from core Central 1 Lake Bosomtwe 2004 over the complete sediment record (~1425-2000 CE) and rainfall anomaly (vertical bar) for June through to October of the Sahel region (20°N-10°N, 20°W-10°E) during 1900 to 2009 (provided by Todd Mitchell, March 2009, <http://jisao.washington.edu/data/sahel> from the Global Historical Climatology Network (GHCN) of the NOAA Satellite and Information Service).

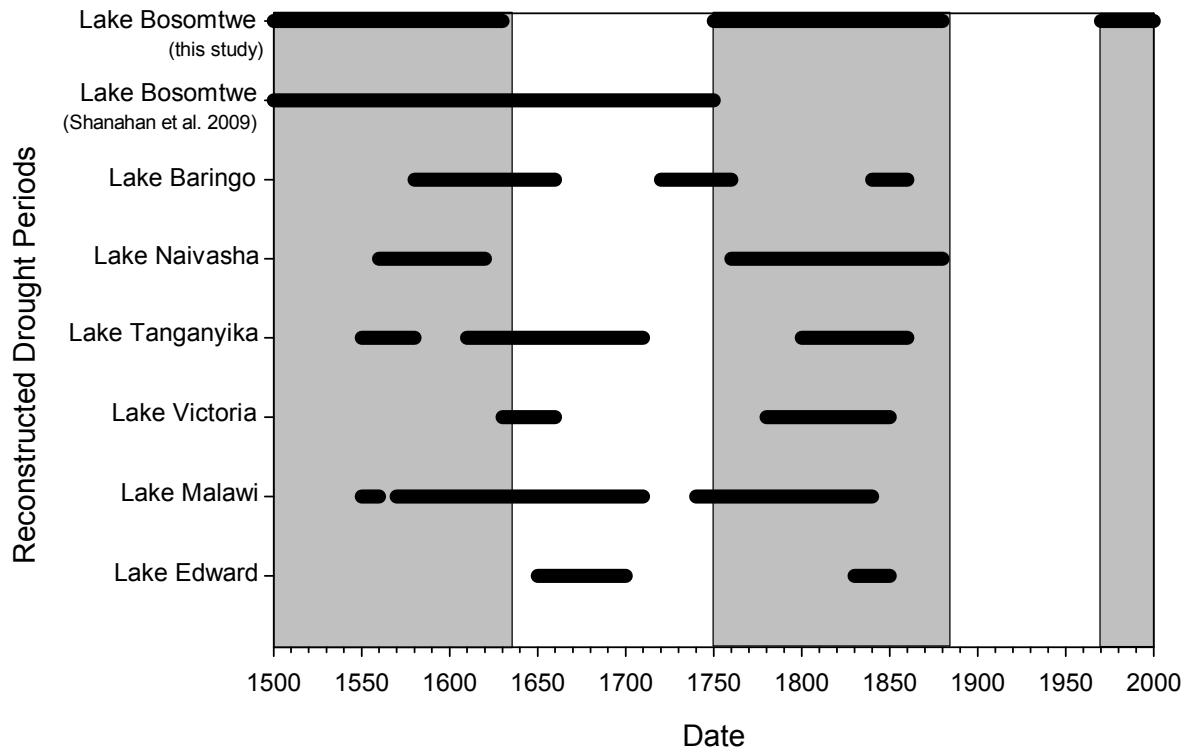


Figure 5-8 Reconstructed drought records and low lake level stands in African lakes during the past 550 years. Grey regions identify the drought periods recorded in Lake Bosomtwe sediments. Lake Bosomtwe, Ghana West Africa (this study) and (Shanahan et al. 2009); Lake Baringo, Kenya East Africa (Kiage 2009); Lake Naivasha, Kenya East Africa (Verschuren 2000); Lake Tanganyika, East Africa (Kiage 2006); Lake Victoria East Africa (Stager 2005); Lake Malawi East Africa (Johnson 2001); Lake Edward East Africa (Russell 2005).

6 Chapter - Conclusion

SUMMARY

Results from the previous four data chapters have highlighted the effects of the regional climate patterns on in-lake physical, chemical and biological processes in Lake Bosomtwe that impart interpretable information to the sediment records. Chapter 2 revealed the seasonal mixing regime of Lake Bosomtwe that was largely driven by cool air temperatures and clear night skies during the short dry season, which disrupted thermal stratification in August and led to water column mixing and nutrient circulation. The short dry period over Lake Bosomtwe in the Guinea Coast region occurs when the monsoon rains of the ITCZ move northward to the Sahel region during the month of June, July and August. The circulation of dissolved nitrogen and phosphorus resulted in the rapid rise in particulate organic matter, chlorophyll *a* concentrations and reduced Secchi disk depth. Afterwards, when thermal stratification was re-established, stratified conditions persisted for the remainder of the year.

Evidence for seasonal sedimentation patterns were revealed in Chapter 3, where peak organic matter sedimentation occurred in September to October, following the mixing period in August. The deep-water mixing affected the organic matter composition with marked enrichment in $\delta^{15}\text{N}$ and depletion in $\delta^{13}\text{C}$, which was indicative of circulation of deep-water nutrients to the photic zone. The high organic matter deposition was later followed by the moderate calcium and carbonate deposition due to biologically-induced calcite precipitation after phytoplankton drawdown of CO_2 . These organic-rich seasonal sediments are characteristic of the 'light laminae' described from Lake Bosomtwe laminated sediment records by Shanahan et al. (2008).

Spatial patterns of sediment composition were shown to have strong relationships with water depth in Chapter 4. Nearshore sediment records were found to have accelerated inorganic flux since ~1959,

believed to be the result of road construction in 1958 and land clearance for agriculture and hotel construction. Sediment composition from these ten cores found that the formation of laminae was related to the water depth, where water depth had a strong positive correlation with organic matter content and C and C:N ratios. Spatial sediment trends found that presently laminations were formed at water depths greater than 35 m. The preservation of laminations down core in Lake Bosomtwe sediment records, however, were found to commence in ~1720 CE, when lake levels were predicted to measure ~55 m above lake bottom, as determined by an the assessment of historical water level variations. These findings suggest that limnological conditions shifted from shallow-water conditions with deep-water oxygenation during seasonal mixing, to elevated water levels with persistent deep-water anoxia.

Chapter 5 reconstructed the > 550-year sediment record from two central deep-water cores from Lake Bosomtwe, which found that a low stand measuring ~ 55 m water depth was likely the result of prolonged drought during the Little Ice Age (~1425-1610 CE). This low water stand was characterized by low organic matter content and low variability in geochemical composition. Drought periodicity over Lake Bosomtwe was not restricted to the LIA, but strongly depleted $\delta^{13}\text{C}$ signatures from bulk matter were indicative of Sahel drought, as expressed by negative rainfall anomalies. The depletion of $\delta^{13}\text{C}$ was believed to be the result of interannual rainfall variability, where drought years in the Sahel resulted in restricted water column mixing in Lake Bosomtwe, and hence lower primary productivity.

FUTURE RESEARCH

This thesis has highlighted the effects of drought and anthropogenic activities on Lake Bosomtwe, but there is a need to improve our understanding of the significance of drought on the ecology and water quality. The one-million-year sediment record from Lake Bosomtwe provides an excellent long-term

record of climate variability and the affect of climate on in-lake processes. The analysis of $\delta^{13}\text{C}$ of bulk matter from these sediment records will be a valuable contribution to understanding drought patterns over West Africa. The ability to reconstruct past climate variability does not however exclude the need for future measures of climate variability. Long-term monitoring of the nearshore crater meteorology has provided an important baseline of data that should be continued at Lake Bosomtwe. There is both regional variability over the Guinea Coast and local variability within the crater walls, which can alter wind intensities and rainfall patterns within the catchment. These meteorological records are an important resource that is currently lacking in West Africa and greater emphasis needs to be placed on maintaining these monitoring stations.

The dynamics of thermal stratification of Lake Bosomtwe is an important component to understanding the seasonal primary productivity and diversity that supports the local artisanal fishery. Two years of water column thermistor sampling (Figure 6-1) were collected at the sediment trap sampler site (Figure 3-1). Thermistor data can provide valuable insight into the physical mixing dynamics and the diurnal cycle of heating and cooling within the water column of Lake Bosomtwe. The need to construct a heat budget and quantify the thermal heat loss required to mix the water column will better improve our ability to predict water column mixing based on predicted meteorological conditions. Climate change models have predicted that air temperatures will increase and circulation patterns that affect monsoon rains over West Africa will be altered in the future. The assessment of water column thermal profiles will be a valuable asset when considering the effects that future global climate variability may have on the primary productivity of Lake Bosomtwe.

The net primary productivity is affected by the extent of the seasonal mixing regime, but little is known about the affect of drought on phytoplankton communities in Lake Bosomtwe. Results from this thesis and F. Awortwi (2010) suggest that the diversity of phytoplankton would be affected. Assessment of the changing fossil algal community composition was attempted by this author through

diatom enumeration (Figure 6-2) and pigment analyses (Figure 6-3). Diatom community composition from ten sediment cores taken along transects described in Chapter 4 found that although diversity was high, distribution was limited to one predominant genera. The preservation of diatoms was extremely poor and the preservation of siliceous frustules declined rapidly down core. There was a change in community composition down core, but the fact that thinly silicified *Nitzschia* sp. were absent after the first few sediment layers and replaced by thickly silicified *Fragilaria* sp., suggested that dissolution of silica in the pore space was a predominant factor in these highly alkaline waters. Pigment analyses were discouraged because tropical lakes with hypolimnetic temperatures > 25 °C, with greater bacterial metabolism and high UV exposure, is believed to lead to poor preservation and quantification of fossil pigments. Samples from the water column, sediment trap and sediment core were compared to assess the fidelity of these records and results proved promising. During the June 2005 period, the upper five metres of the water column is dominated by filamentous and colonial cyanophytes, to an abundance of the photosynthetic pigments echinone and myxoxanthophyll that correspond with the species *Merismopedia punctata*, *Cylindrospermopsis raciborskii*, *Aphanizomenon bergii*, *Aphanocapsa* and *Pseudoanabaena limnetica*. The measures of water column samples and pigment concentrations were an accurate representation of the recent algal community composition. The trend in pigment concentrations in sediments down core were also promising, since the trend was not unlike the declining trend in organic matter content (Chapter 4 and 5 of this thesis) and in diatom abundance, as total fossil pigments like pheophytin strongly decline with sediment depth. An attempt to reconstruct pre-historic phytoplankton communities would be valuable to understanding long-term changes in fisheries yields and water quality.

This thesis represents two years of consecutive water column sampling at an offshore site, which had never been attempted before in Lake Bosomtwe. However, little is known about the nearshore littoral zone. Transportation of pollutants and silt into the lake through the nearshore riparian zone and into the shallow littoral zone is not well understood. Residents have expressed concern for the changing

nearshore littoral habitat, which is perceived to have changed over the past 50 years. Residents reported increased land clearance at the water's edge, with less shady vegetation cover and greater siltation and turbidity. The effect of siltation and inorganic flux to the nearshore may impact habitat availability for benthic invertebrates, refugia and fish breeding. Water in the nearshore zone can reach extremely high temperatures in the afternoon sun, dramatically reducing oxygen concentrations, a stress for littoral fish species. Previously, a study by Whyte (1975) found that Lake Bosomtwe was inhabited by a number of fish species in the mouth of the tributaries. A recent food web study by A. Poste (2008) found that many fish species were extirpated and one species of *Tilapia* was now restricted to only the Abrewa River. Study of these observed declines in fish diversity and in fish catch size may be critical to understanding the potential effects land use change and climate change have on the aquatic ecology.

The domestic use of water for cooking, cleaning, bathing, swimming, watering livestock and laundry puts a greater importance on studying this nearshore area that is perhaps most vulnerable to pollutants and pathogens. These shallow waters can retain greater nutrients and support a diversity of potentially harmful algae, bacteria, and invertebrates. Currently, *Schistosomiasis* has not been measured in Lake Bosomtwe, but it is commonly contracted from other water bodies around West Africa and found to cause disease in humans. As more nearshore organic matter is sequestered in Lake Bosomtwe, however, there will be greater detrital material to support snails, the vector. Harmful pollutants, like methyl mercury, are known to enter the food web through the detrital pathway and nearshore littoral zones can be an important site of mercury methylation. Recently, analyses of mercury and PCBs by A. Poste (2008) found that *Tilapia* consumed from Lake Bosomtwe have low Hg levels and do not pose a threat to human consumption. The fishes from Lake Bosomtwe are an important source of protein to the riparian population and monitoring of the biomagnification of pollutants is critical to ensure the health and safety of residents. Fecal coliforms, from poor waste management, were found to be high in water samples from deep water in Lake Bosomtwe. The need

for data from the littoral zone is essential and may reveal that much greater loads are concentrated in the nearshore area, posing a great risk to the local communities (Boamah and Koeberl 2007). Within the crater basin, residents have little access to medical attention, and there is no monitoring or advisories regarding consumption of the water, but lake water may already be a source of harmful pathogens and pollutants.

RECOMMENDATIONS

This thesis found that land use practices and soil erosion are currently a threat to Lake Bosomtwe, but pollution from poor waste management and expanded livestock rearing may be an additional threat. Land use practices such as deforestation and slash-and-burn agriculture increase surface albedo over West Africa. There is a great need to develop and implement sound farming practices along the steep crater slopes. The loss of valuable topsoil from the catchment to the lake bottom reduces crop yields and alters water quality. Combined with the effects of drought in the region, which also reduces soil moisture and destabilizes topsoils, the transport of soil to Lake Bosomtwe may be accelerated. On a larger scale, the increased surface albedo and land clearance directly affect the West African continental air pressures that, along with Atlantic sea surface temperatures, can affect drought periodicity in the region (Govaerts and Lattanzio 2008). Future predictions of climate over the Sahel region point to more severe droughts, interspersed with more severe precipitation events (Hulme 1998; Hulme et al. 1999) that will have devastating effects to the Sahel region and Lake Bosomtwe. The siltation of Lake Bosomtwe must be addressed to meet the current needs of the burgeoning population and protect the water quality for the future generations.

There is an obligation of governments to prepare for future drought events where the economies are largely dependent on rain-fed agriculture. The communities that are particularly hard hit are the subsistence farmers away from urban centers (Benson and Clay 1994). The reduced rainfall reduces

agricultural production and the quality of produce. The strain of drought on the domestic household can rapidly lead to the reduction of personal assets, loss of savings, malnutrition and consequences to human health. Reduced water availability has been found to add a considerable burden to women of the community, who experience increased workloads, with greater distances to travel for water and higher demands to meet the needs of offspring. Under these circumstances, when the government fails to provide assistance to farmers who require better food security, it is difficult to contemplate the environmental impacts of human activities on the ecosystem. Families must take the needed resources, resorting to land clearance for fire wood, rather than purchasing charcoal. Or logging for timber rather than purchasing building supplies. Or burning and expansion of agricultural plots in search for better soil fertility rather than purchasing soil amendments. These measures can lead to further decline in the economy and the environment under the added strain of drought in impoverished regions of West Africa.

Currently, efforts have been made in communities around Lake Bosomtwe to start mitigating pollution. The Ghanaian waste disposal company, Zoom Lion, has recently employed people around the lake to pick up and remove waste. Thirty people are currently employed to sweep the road and beach at the town of Abono for one hour each morning for a monthly wage of 60 Ghana cedis, which is the minimum wage for full-time employees in Ghana. Town meetings have routinely addressed issues of environmental protection, promoting the use of public toilets; preventing public bathing, laundering and washing utensils in the lake waters; caging livestock and shepherding flocks to watering locations. These small changes are reverberating around the lake and have an important effect on the mindset of the future generation, who will be inheriting this sacred water body.

However, the growing need for outside finances in this impoverished region has led many communities to sell or lease a number of plots to foreign investors who are interested in tourism around the lake. Inadequate compensation of farmers who lose their agricultural plots to foreign

investors has led to political squabbles around the lake. The expansion of hotels and guest houses has been increasing: Lake Inn, Paradise Hotel, Lake Point, Rainbow Gardens and a new equestrian hotel, with many more anticipated. The government plans to build a paved road around the whole lake in response to pressure from foreign investors. The road expansion would greatly improve resident's access to the outside market and facilitate trade, but it can also lead to greater corruption of the local economy. The discontent among local residents facing extreme poverty has led some to take advantage of foreign tourists. The latest Brant tour guide to Ghana warns visitors not to visit Lake Bosomtwe, as many residents extort money from tourists.

The need for better education on environmental awareness of Lake Bosomtwe will generate greater respect for the ecosystem and humanity. James Addai, Secretary of the town of Abono, has recently constructed a Jakad Business and Information Centre in Abono, which offers the natural history of the lake and circulates announcements over a loud speaker. This author created and designed the posters, with assistance from collaborating research scientists and printing was funded by the ICDP. The Center opened in early January 2010 and will better inform locals and visitors of the natural wonder of Lake Bosomtwe. With continued efforts to study Lake Bosomtwe and involve the local communities in management decisions, future environmental degradation may be prevented and greater prosperity may be generated.

If we lose our relationship with nature,

We lose inevitably our relationship with humans. ~Krishnamurti

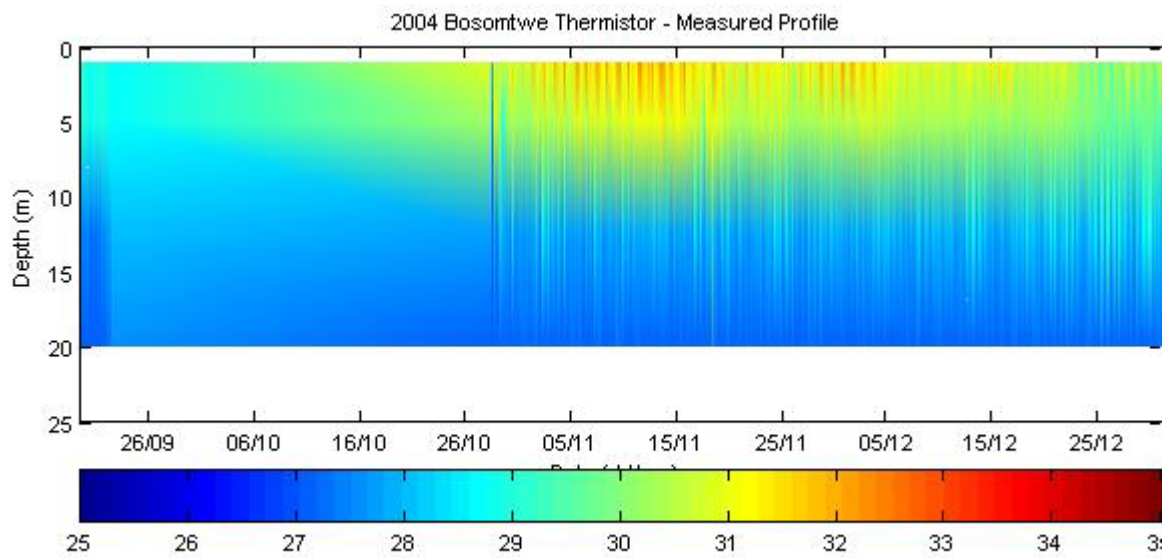


Figure 6-1 Thermistor chain data from Lake Bosomtwe from September 2004 to January 2005 where the thermocline stability is strongly re-established below 10 m water depth by October and persists.

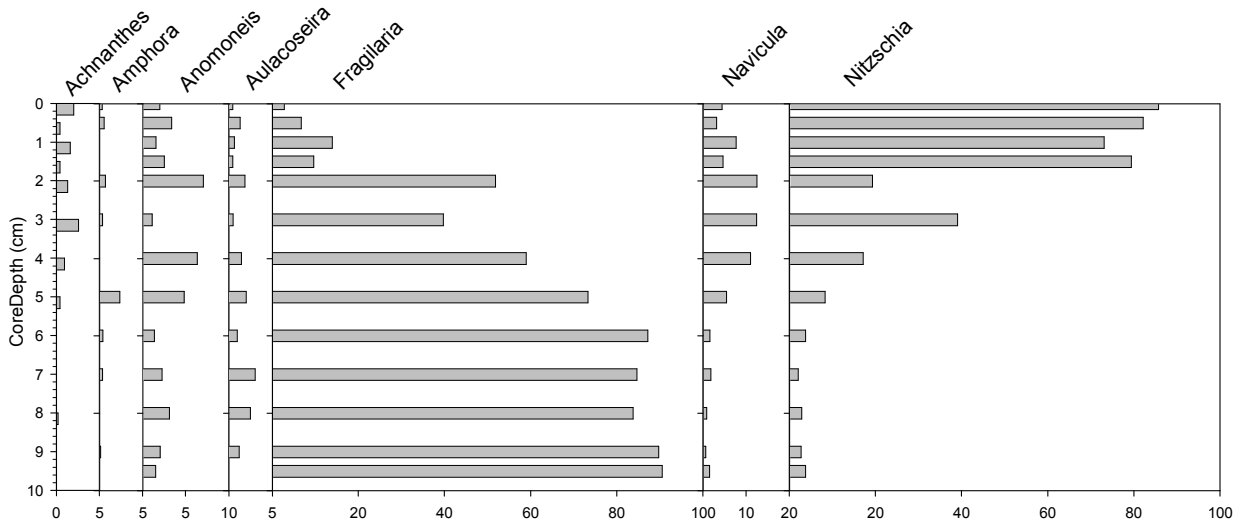


Figure 6-2 The fossil diatom community composition from sediment core Abono 2 (31 m water depth) collected in 2005 from Lake Bosomtwe, Ghana.

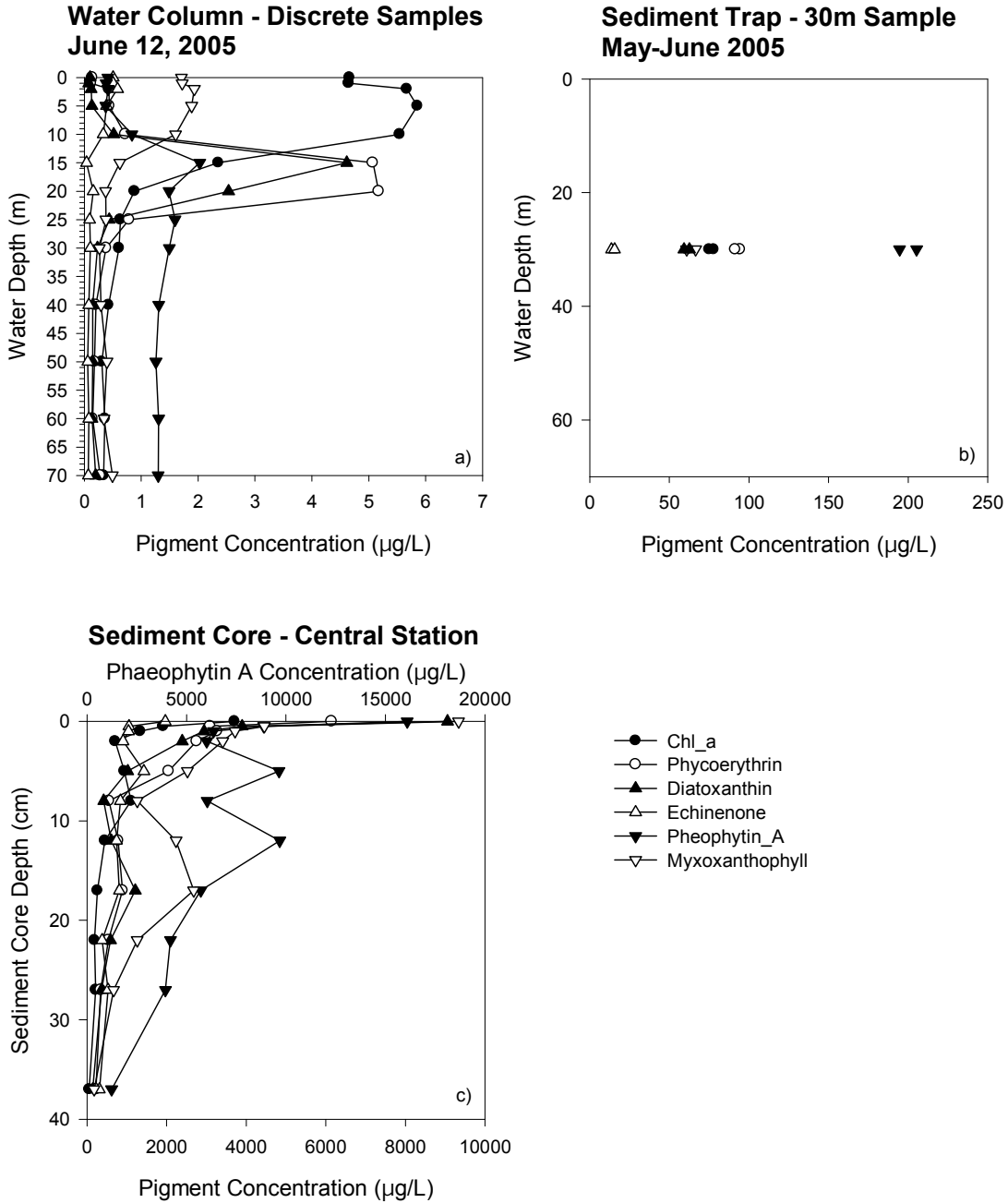


Figure 6-3 Pigment concentrations from a) vertical water column sampling of filtrate from ten discrete water depths in June 12, 2005, b) a sediment trap sample from May to June 2005 and c) a central deep-water core Central 4 collected in 2005 at 78 m water depth from Lake Bosomtwe, Ghana West Africa.

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