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Environmental Dynamics of Lake Victoria: Evidence from a 10,000 ^{14}C yr Diatom Record from Napoleon Gulf and Sango Bay

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Abstract: Bio-proxies provide relevant information on ecosystem health and environmental dynamics. In this study, diatom assemblages of two cores collected from the Ugandan side of Lake Victoria at Napoleon Gulf ("NAPG1" (GPS, 00º25'44.5" N, 033º14'10.4" E)) and Sango Bay ("SAGB2" (GPS, 00º51'48.0" S, 031º42'47.8" E)) provide evidence of long term changes in the Lake Basin from ca 10,500 years to present. Diatom information was supported by phytolith data from the same cores. The period from ca 10,500-8,100 cal·yr·BP experienced moderate precipitation, strong turbulence with reduced forest cover in the lake's catchments. During the phase ca 8,100-6,600 cal·yr·BP, the lake basin experienced increased precipitation but with reduced mixing of the water column. This period was also characterized by increased forest vegetation cover as reflected by phytolith assemblages. The period from ca 5,900-1,400 cal·yr·BP was characterized by regular changes in precipitation, turbulence and vegetation taxa in the catchment areas. The phase from ca. 1,800 cal·yr·BP to present was characterized by significant increase in *Fragilaria* and *Nitzschia* species as well as increase in *Nitzschia*: *Aulacoseira* ratio which may be attributed to human involvement in the ecological functioning of Lake Victoria ecosystem.

Key words: Diatom, Napoleon Gulf, Sango Bay, Lake Victoria.

1. Introduction

Lake Victoria is the largest fresh water lake in East Africa [1]. It is an important natural resource to communities in its basin. The aquatic ecosystem supports many organisms including humans with a population of around 30 million people depending on the lake resources for their survival either directly or indirectly [2]. However, the lake ecosystem has been experiencing enormous degradation events, attributed to anthropogenic factors as well as climate-induced changes.

The catchment areas of Lake Victoria are highly populated and a lot of pressure is put on the lake's resources [3]. Human activities have influenced different ecological aspects of the lake eg. agricultural activities in the catchment areas have increased siltation, nutrient enrichment and chemical pollution from herbicides and pesticides [4, 5]. Urbanization and industrialization have greatly contributed to devegetation of the lake's catchment areas.

Being a shallow lake yet with a large surface area, Lake Victoria is very sensitive to climate change [5]. For example, Lake Victoria has a long history of water level fluctuation. Its water levels fluctuated significantly during the Pleistocene and Holocene periods with phases of complete desiccation, for instance ca. 17,000 yr·BP; the lake dried out completely [6] and began to fill up again ca. 14,700 yr·BP [7].

The most recent climatic changes in Lake Victoria occurred in1960s [7]. Between 1961 and 1964, the level of the lake rose unexpectedly by almost 2.5 m and this was linked to heavy rainfall in East Africa in the early 1960s [8, 9]. As a result of the heavy rains, in 1961, population increases were exhibited by most

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planktonic algae such as *Aulacoseira nyassensis* (O. Müll) Simonsen, *A. agassizii* (Ost.) Simonsen, *Nitzschia acicularis* (Kütz.) W. Smith, *Surirella nyassae* (O. Müller) and *Stephanodiscus astraea* (Ehr.) Grunow [4].

Diatoms are very sensitive to environmental changes induced by anthropogenic activities as well as climate related events [10]. Their distribution, high species diversity, sensitivity and their siliceous frustules enable diatoms to function as important environmental indicators [11]. The links between climate change, the lake dynamics and diatom distributions increase the utility of diatoms in palaeo-climate reconstruction [10, 12].

Previous studies on diatoms in lake sediments mainly concentrated on the northern and eastern parts of Lake Victoria [13, 14]. This study therefore provides additional information on climate and environmental dynamics of Lake Victoria region using diatoms from sediments extracted from Napoleon Gulf (northern part of Lake Victoria) and Sango Bay (western part of Lake Victoria).

2. Materials and Methods

2.1 Study Area

The study was conducted on the Ugandan side of Lake Victoria with two sampling sites: Napoleon Gulf and Sango Bay. Napoleon Gulf is a bay located in Jinja district, Eastern region, Uganda (0º25'0.01" N, 33º15'00" E). It has an estimated terrain elevation of 1,134 m above sea level. The Gulf is characterized by a vast wetland system (Fig. 1). Sango Bay is situated north of the Uganda-Tanzania boarder (0º49'54" S, 31º44'00" E). Sango Bay joins Lake Nabugabo to the North, Lake Victoria shore line to the East and the main road between Masaka and Mutukula boarder at the Tanzania boarder to the West. The area is characterized by low land tropical wetland forests and extensive herbaceous wetlands. The wetland system of Sango Bay habours many bird species, mammals and butterflies including those that extend from West Africa finding their Eastern and Southern limits in Sango Bay. Due to the rich biodiversity of Sango Bay, it was designated a Ramsar site (Fig. 1).

2.2 Sediment Coring

Two sediment cores were extracted from Lake Victoria, one from Sango Bay, "SAGB2" (GPS, 00º51'48.0" S, 031º42'47.8" E, core depth 97 cm and elevation 1,133 m) and another from Napoleon Gulf, "NAPG1" (GPS, 00º25'44.5" N, 033º14'10.4" E, core depth, 112 cm, elevation 1,152 m) (Fig. 1) using a hand driven gravity corer. Short sediments were extruded in 1-cm increments with a fixed- interval sectioning device as described by Verschuren [15].

2.3 Sediment Chronology

Two sub-samples obtained from each core (NAPG1 and SAGB2) were sent to the Beta Analytical Radiocarbon Dating Laboratory in Miami, USA. The radiocarbon dates were obtained using plant remains. The AMS ^{14}C dates were treated with a correction factor of 600 years as applied by Stager and Johnson [13] to carbon dates of cores from Lake Victoria. The corrected ^{14}C dates were processed through oxcal using a deposition value, k as 10 cm^{-1} since the sediments were mainly composed of clay and the k value for fine sand is 1,000 m^{-1} as described by Ramsey [17]. Oxcal age models were developed and used to extrapolate and interpolate dates along different depths of the cores (Table 1). Sediment accumulation rates (Figs. 4 and 5) for the two cores were calculated from oxcal calibrated years before present as:

$$\boldsymbol{R} = \frac{(S_2 - S_1)}{T}$$

where:

$\boldsymbol{R} = sediment\ accumulation\ rate\ (cmyr^{-1})$;

$S_2 - S_1$
$= depth\ range\ of\ sediment\ sample\ (cm)$

$T = sediment\ deposition\ time\ (years)$,
$calculated\ from\ (T_2 - T_1)$

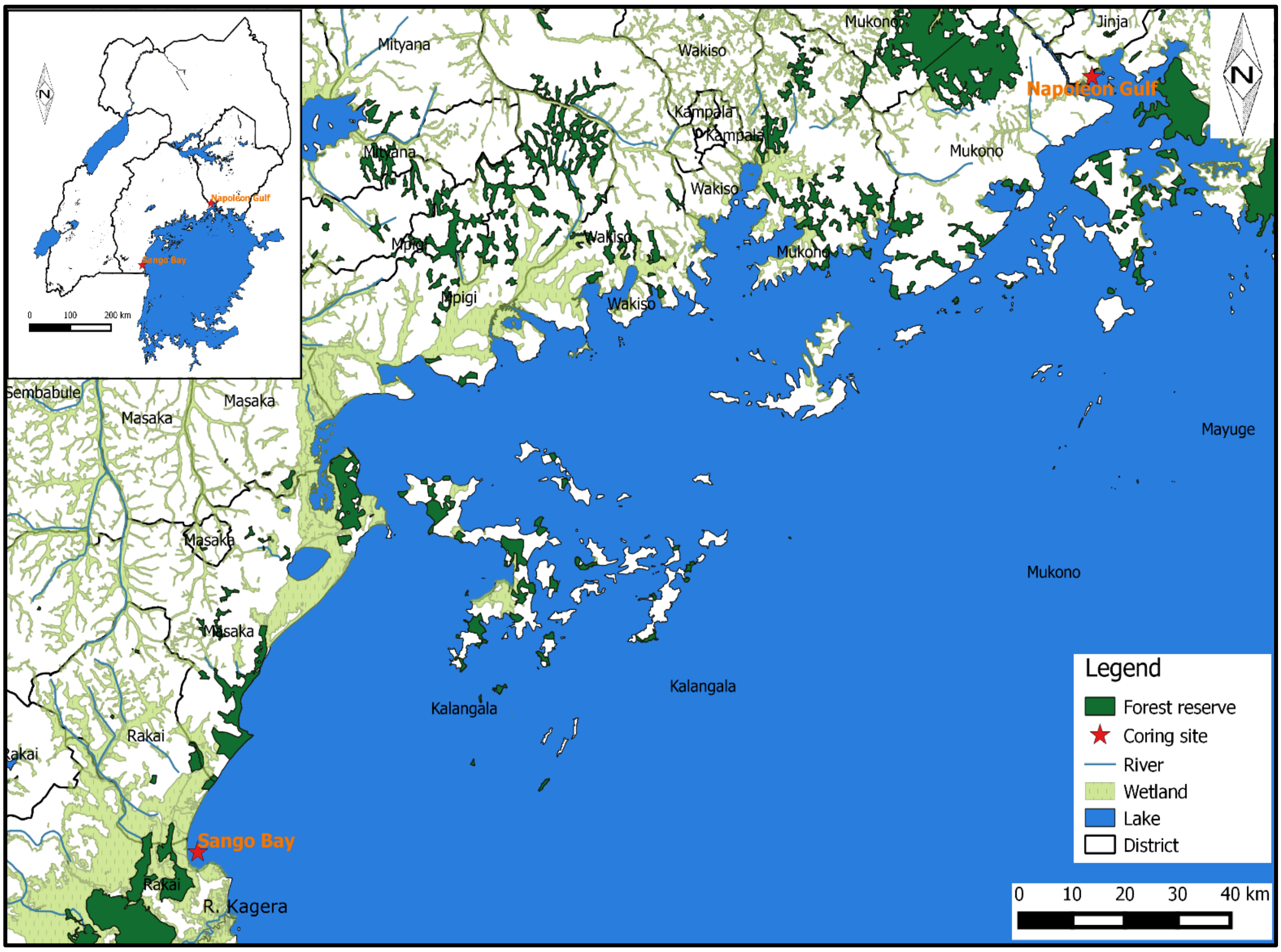

Fig. 1 Map showing the sampling sites in Lake Victoria basin (Y = Napoleon Gulf, Z = Sango Bay) generated using Brighton [16].

The reciprocal of *R* was used to determine the years needed to deposit 1 cm of sediment and to assign ages to different depths along the core.

2.4 Diatom Extraction, Identification and Counting

Five grams of the fresh sediment section were measured for diatom extraction. Organic matter was removed using 30% hydrogen peroxide at 80 °C in a water bath. The sediment was then washed thoroughly for four times in the centrifuge with distilled water. Iron oxides were removed by adding 40 mL of 0.37 M sodium citrate solution and 5 mL of 1 M sodium hydrogen carbonate solution and the mixture heated to 80 °C in a water bath. One gram of sodium sulphate was added with one minute of stirring. The sample was again washed with distilled water in a centrifuge. To totally disaggregate the clays, a Calgon treatment was performed by boiling the sample in 5% sodium bicarbonate solution for 30 minutes. Carbonates were removed by adding 10% HCl to the sample. The sample was then wet sieved through 250 micron sieve and centrifuged at 1,500 rpm for four minutes with distilled water. The supernatant containing the diatoms was then decanted using a pipette. The process of diatom differential setting was repeated until there was no diatom layer remaining. The mixed suspension (1 mL) was placed onto a glass slide and heated with very low heat on the hot plate for 15-30 minutes; modified from Lippiatt [18]. One drop of Naphrax was placed on a cover slip measuring 22 mm × 22 mm and inverted over the glass slide containing dried diatoms.

Identification of diatom species was based on comparisons with reference materials especially literature based sources concerning diatoms of East Africa [19-22], including other water bodies in Africa and the rest of the world [23].

Diatom valves were counted in each slide with a minimum of 400 diatom valves counted per slide using an Olympus light microscope (CX21FS1, 100-120/220-240 V, 0.42/0.25 A, 50/60 HZ).

2.5 Data Analysis

Relative abundances of diatom taxa were expressed in percentages relative to the total counts of valves per slide (per depth). From diatom abundance, ratios and graphs were obtained to aid in establishing patterns and relationships among diatom species. These were obtained using computer packages such as C2 data analysis version 1.5.1 [24], PAST [25], Adobe Illustrator 8.0 [26] and Oxcal [17]. The ratios calculated include 1. Planktonic to bethic ratio; 2. *Nitzschia* to *Aulacoseira* ratio and 3.$\frac{A}{C+S}$.

where:

$A = Aulacoseira$;

$C = Cyclotella\ or\ Cyclostephanos$;

$S = Stephanodiscus$.

3. Results

3.1 Sediment Stratigraphy

The 112-cm long composite core of Napoleon Gulf (NAPG1) (Fig. 2) consisted of a light gray (Hue 5Y, 7/1) and dark (Hue 5Y, 4/3) coloured portion, B (112-48 cm, 8,177-1,816 cal·yr·BP). The upper portion, A (48-0 cm, ca. 1,816 yr·BP-59 yr. beyond 1950, 2009 AD) was light gray (Hue 5Y, 7/1). Physical analysis of the soil showed that the first portion (112-48 cm, 8,177-1,816 cal·yr·BP) was rich in well decomposed organic material while the second portion, A (48-0 cm, 1816 cal·yr·BP-59 yr. beyond 1950, 2009 AD) contained decomposed organic rich material.

The 97-cm long composite core of Sango Bay (SAGB2) (Fig. 2) consisted of the lower portion, X (97-46.5 cm, 10,633-5,574 cal·yr·BP) which was gray coloured (Hue 5 Y, 5/1). The middle portion, W (46.5-8 cm, 5,574-1,769 cal·yr·BP) had a light gray (Hue 5Y, 7/1) colour while the top part, V (8-0 cm, 1,769-980 cal·yr·BP) was light coloured (Hue 5Y, 7/3).

Physical soil analysis (Fig. 2) showed that the lower portion, X (97-46.5 cm) contained clay rich material. The middle portion, W (46.5-8 cm) contained a mixture of clay and organic materials while the top most part, V (8-0 cm) was rich in less decomposed organic matter.

3.2 Sediment Chronology and Age Models

The results of AMS ^{14}C dates, corrected and Oxcal outputs are presented in Table 1.

From Oxcal, age models for the two cores (NAPG1 and SAGB2) were produced (Figs. 3 a and b). The top part (0 cm) of NAPG1 core dated after 1950, while the lower part (112 cm depth) dated before 10,000 cal·yr·BP. For SAGB2, the top part (0 cm) of core dated before 1950 (ca. 980 cal·yr·BP), the bottom part (97 cm) dated slightly before the Holocene (ca. 10,630 cal·yr·BP).

3.3 Sedimentation Rates

Sedimentation rates for the two cores are summarized in Figs. 4 a and b. For NAPG1, the sedimentation rate almost remains constant (0.009826 to 0.010088 cm·yr^{-1}) from the bottom part of the core (112 cm) to the middle (51.5 cm) and steadily increases (0.010088 to 0.50 cm·yr^{-1}) from the middle (51.5 cm) towards the top most part of the core (0 cm). On the other hand, the sedimentation rates for SAGB2 core are generally low and decrease (0.010195 to 0.009927 cm·yr^{-1}) from the bottom part (97 cm) to the middle part of the core (43.5 cm) however, the values increase (0.009927 to 0.010136 cm·yr^{-1}) from the middle towards the top part of the core.

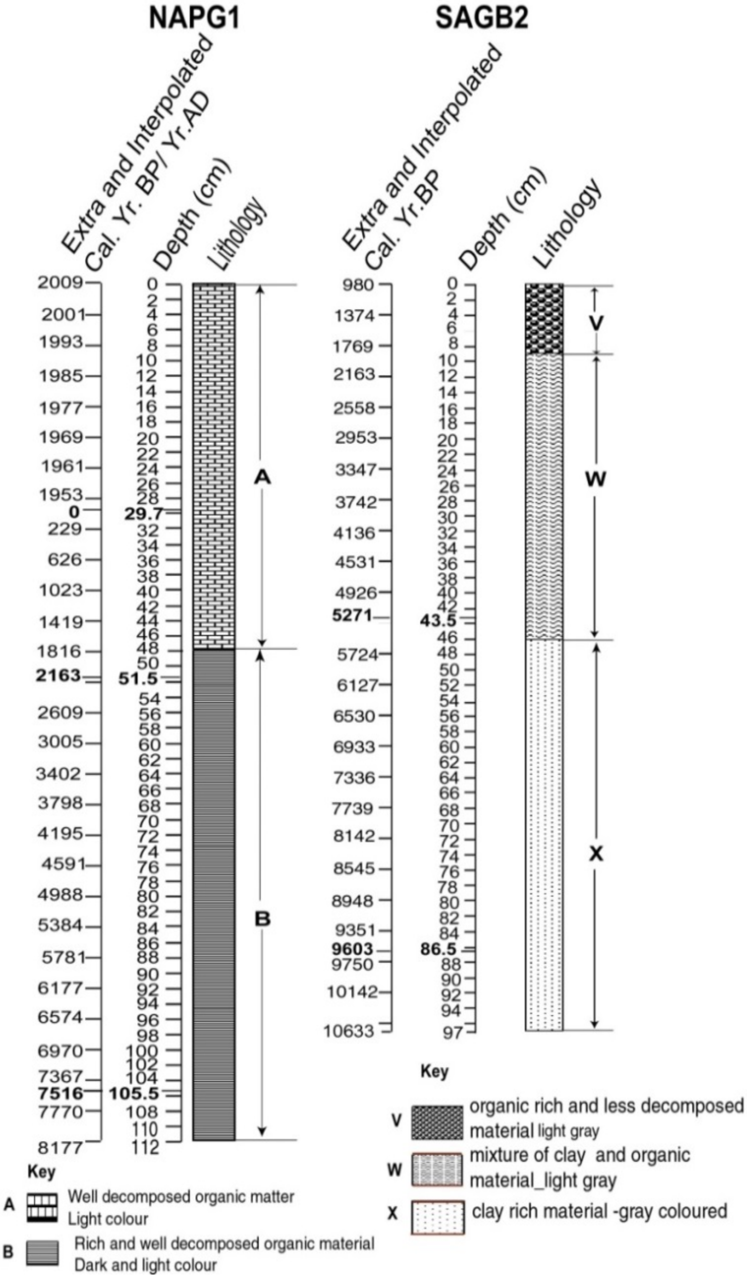

Fig. 2 Descriptions of cores at different depths.

Table 1 AMS ^{14}C dates, Corrected and Oxcal output ^{14}C ages.

	Core Depth (cm)	AMS^{14}C dates (yr·Bp)	Corrected ^{14}C dates (yr·Bp)	Oxcal Cal. age ranges (yr·Bp)	Actual Cal. Date (mid-point)
NAPG1	**Top** (0)			-2,233 to -3,689	-2,961.0
	51.5	2,760 ± 40	2,160 ± 40	2,313 to 2,012	2,163.5
	105.5	7,250 ± 40	6,650 ± 40	7,587 to 7,444	7,515.5
	Bottom (112)			8,367 to 7,987	8,177.0
SAGB2	**Top** (0)			1,738 to 221	979.5
	43.5	5,210 ± 40	4,610 ± 40	5,468 to 5,074	5,271.0
	86	9,220 ± 40	8,620± 40	9,675 to 9,529	9,602.5
	Bottom (97)			10,892 to 10,373	10,632.5

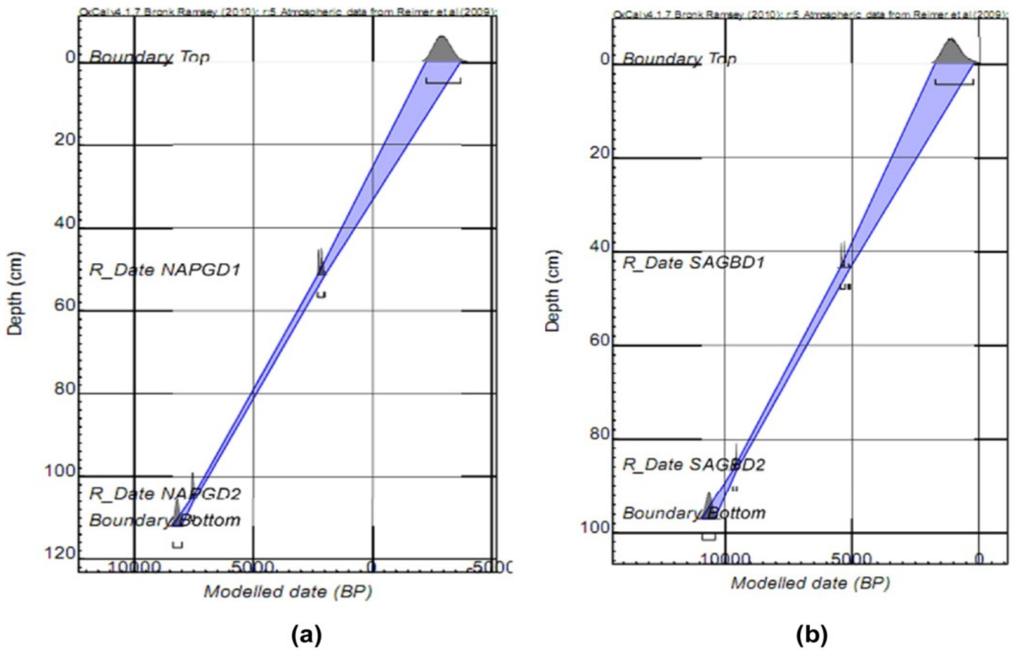

Fig. 3 Age model outputs for NAPG1 and SAGB2 cores respectively obtained from oxcal [17].

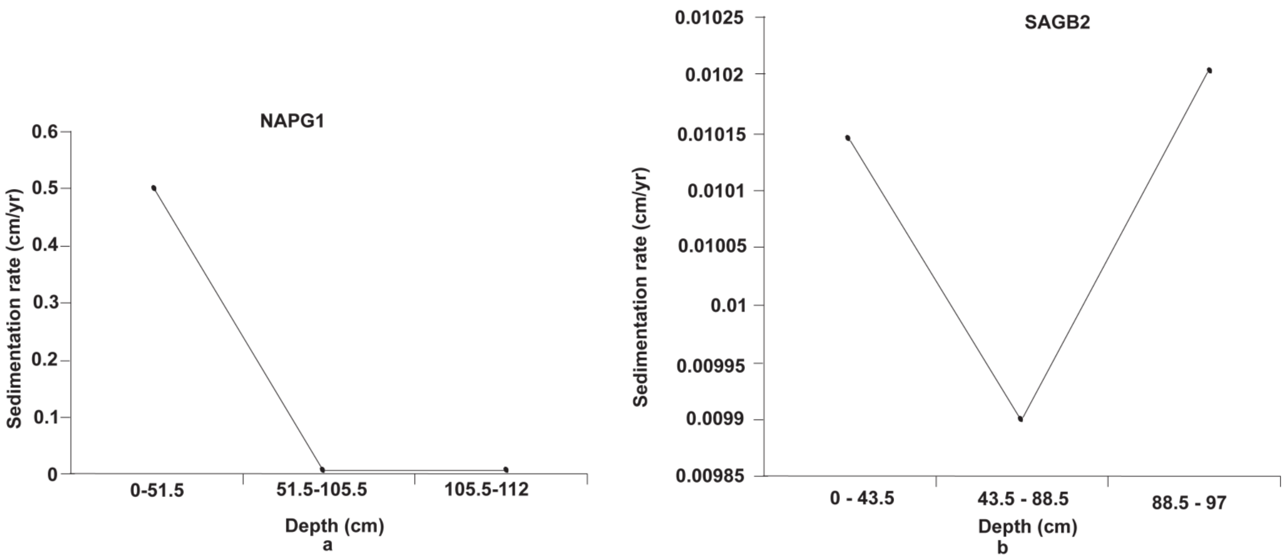

Fig. 4 Variation of sedimentation rates along NAPG1 and SAGB2 cores.

3.4 Diatom Assemblages

The results of diatom assemblages from Sango Bay (SAGB2) and Napoleon Gulf (NAPG1) are presented in Figs. 5 and 6 respectively.

3.4.1 The Late Pleistocene to Early Holocene Transition Period (ca. 10,530-6,000 cal·yr·BP)

From ca. 10,530-8,180 cal·yr·BP, the diatom assemblages at Sango Bay (Fig. 5) were dominated by *Aulacoseira granulata* (Enhrenberg) Simonsen and *A. ambigua* (Grunow) Simonsen. The planktonic to benthic ratio was moderate with negligible values of *Nitzschia* to *Aulacoseira* ratio. The phase between ca. 8,180 and 6,590 cal·yr·BP was characterized by a shift from *Aulacoseira ambigua* and *A. granulata* to *Aulacoseira nyassensis* at both sites with significant proportions of *Nitzschia fonticola* (Grunow) at Sango Bay.

Considering phytolith assemblages from the same

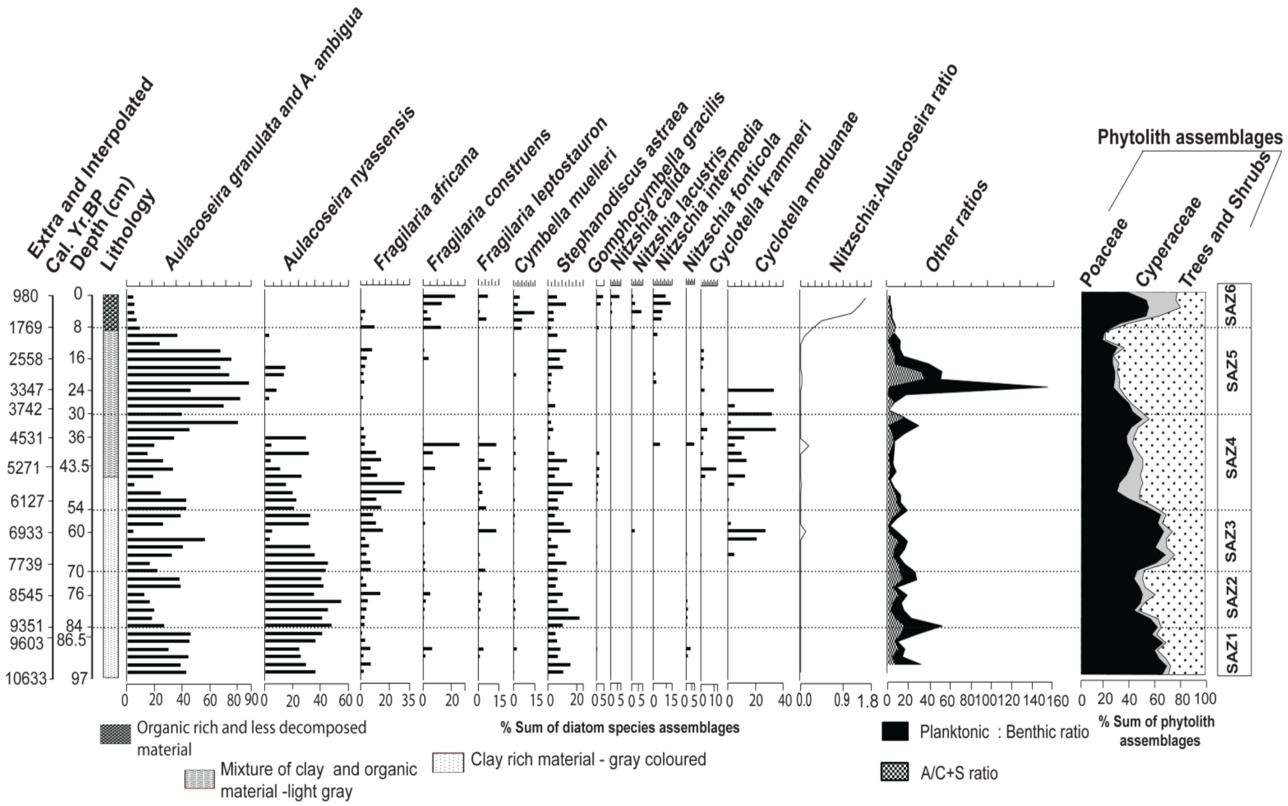

Fig. 5 Selected diatom species, ratios and phytolith assemblages for SAGB2 core.

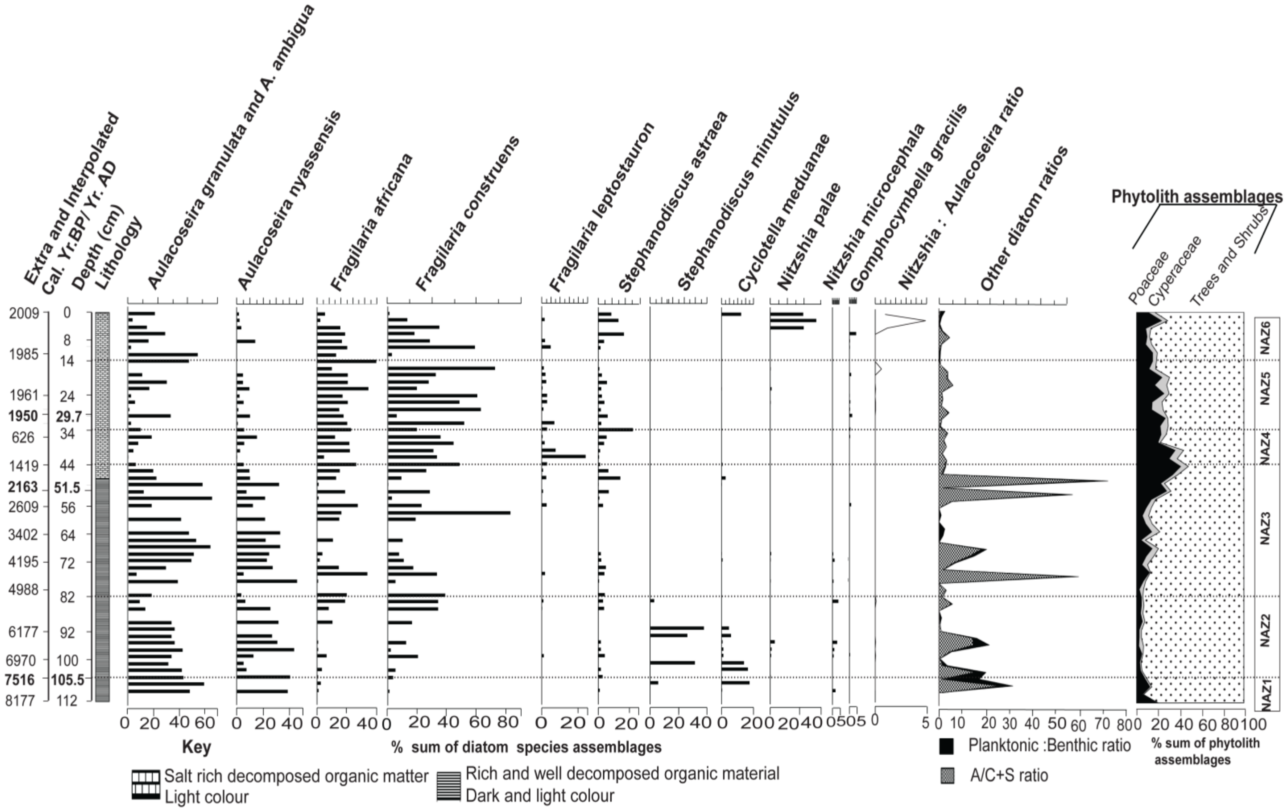

Fig. 6 Selected diatom species, ratios and phytolith assemblages for NAPG1 core.

cores, the period from ca. 10,530 to 9,350 cal·yr·BP at Sango Bay was characterized by a reduction in forest taxa assemblages at the expense of Poaceae and Cyperaceae. A similar trend occurred in Napoleon Gulf, but from ca. 8,177-7,566 cal·yr·BP. The periods from ca. 9,351 to 7,739 cal·yr·BP in Sango Bay and from ca. 7,566-6,000 cal·yr·BP in Napoleon Gulf, were characterized by increase in forest taxa and a decrease in Poaceae and Cyperaceae. Significant reduction in forest taxa was evident in Sango bay from ca. 8,000-6,500 cal·yr·BP.

3.4.2 The Mid to Late Holocene Period (ca. 6,000 cal·yr·BP-2009 AD)

The period from ca. 5,930-2,000 cal·yr·BP was characterized by frequent changes in planktonic diatoms, benthic pennales and A/C+S ratio at both sites.

At both sites, the period from ca. 5,000-4,000 yr·BP was dominated by *A. granulata* and *A. ambigua* with reduced proportions of *A. nyassensis*. The period was generally characterized by low abundancies of all diatom species. In the same period, Cyperaceae phytolith assemblages showed a significant reduction.

Results showed significant increase in *Fragilaria* and *Nitzschia* species in the last ca. 2,000 years at both sites, with *Fragilaria africana* (Hustedt) and *Fragilaria construens* (Enhrenberg) dominating during this period in Napoleon Gulf.

The period from ca. 1,700 yr·BP to ca. 1,000 yr·BP at both sites was characterized by a significant reduction in planktonic species (eg. *Aulacoseira*, *Stephanodiscus*, *Cyclotella* and *Nitzschia* species). Some species were not represented at all (eg. *A. nyassensis*, *N. fonticola*, *Cyclotella krammeria* and *Cylotella meduanae* at Sango Bay and *Stephanonodiscus minutulus*, as well as *Nitzschia* species at Napoleon Gulf). The same period, showed a significant increase in Poaceae phytoliths attaining a maximum abundance of (70% at ca. 1,370 yr·BP at Sango Bay and 45% at ca. 1,400 yr·BP at Napoleon Gulf).

There was an abrupt increase in *Aulacoseira* species in Napoleon Gulf from 1960 to 1970 AD, while the period from 1980 to 2001 AD wasdominated by benthic species (eg. *Fragilaria africana* and *Fragilaria construens*) with significant reduction in the planktonic to benthic ratio.

The period between 1993 and 2009 AD in Napoleon Gulf was dominated by *Nitzschia palae* with the maximum *Nitzschia* to *Aulacoseira* ratio being recorded during this period. The increase in *Nitzschia* to *Aulacoseira* ratio was also recorded in Sango Bay but much earlier, ca 2,000 yr·BP.

4. Disscussion

4.1 Sedimentation

In Napoleon Gulf, the sedimentation rate remained constant from 112 cm to 51.5 cm (7,510-2,160 cal·yrs·BP). An implication of contant rate of sediment deposition which may be attributed to stable forest vegetation cover evident from forest phytolith taxa recorded during this period. The sedimentation rate however rapidly increased from a depth of 51.5 cm to 0 cm (2,000 cal·yr·BP to present) indicating reduced vegetation cover which may be a result of human influence that altered the vegetation sructure in the catchemnt area enhancing erosion, hence increased accumulation of sediments [27]. Domination of benthic diatom species and significant reduction in the abundances of *Aulacoseira granulata*, *A. ambigua* and *A. nyassensis* during this period indicate a reduction in water level which may be attributed to siltationas a result of human activities in the catchment areas as well as low to moderate precipitation.

In Sango Bay, the decrease in sedimentation rate from 97 cm to 43.5 cm (ca. 9,600-5,271 cal·yr·BP) may be attributed to vegetation regeneration around the lake catchment as supported by increase in forest tax phytoliths during this period resulting into reduced windiness and erosion. This is further supported by reduction in the abundance of *Aulacoseira granulata* and *A. ambigua* at the expense of *A. nyassensis*, since *A. granulata* and *A. ambigua* thrive in thoroughly mixed waters while *A. nyassensis* survives in calm water. More evidence is provided by presence of *Nitzschia fonticola* which characterizes deeper and less mixed waters. The increase in sedimentation rate from 43.5 to 0 cm (ca. 5,271-980 cal·yr·BP) may be due to increased windiness and erosion as reflected by dominance of *Aulacoseira granulata* and *A. ambigua*.

4.2 Diatom Interpretation

4.2.1 The Late Pleistocene to Early Holocene Transition Period (ca. 10,530-6,000 cal·yr·BP).

The dominance of planktonic diatoms, moderate planktonic: benthic ratio and higher proportions of *Aulacoseira granulata* and *A. ambigua* than *Aulacoseira nyassensis* from ca. 10,530-8,180 cal·yr·BP indicate a phase of moderate water levels and thorough mixing of the entire water column in the two sites in Lake Victoria. *A. granulata* and *A. ambigua* are reported to thrive well in shallower water [28] than *A. nyassensis* [29, 30]. This period coincides with a phase of post desiccation and refilling of Lake Victoria [6, 31].

The increase in *A. nyassensis* and *Nitzschia fonticola* during the period ca. 8,180-6,590 cal·yr·BP shows a phase of increased lake level, however with reduced mixing since *A. nyassensis* survives in deeper waters with reduced mixing compared to other *Aulacoseira* species [30, 32, 33]. *Nitzshia fonticola* is reported to exist in stratified and less mixed conditions in African lakes, Lake Victoria inclusive [14]. This suggests a period of increased precipitation that led to high water levels and increase in forest cover in the catchment area. The forest cover might have blocked the wind preventing thorough mixing of the entire water column.

The low proportions of forest taxa phytoliths as well as high abundance of *Aulacoseira granulata* and *A. ambigua* which require strong mixing to keep them in the euphotic zone [32, 34] indicate a period of reduced forest vegetation in the catchment area of Lake Victoria from ca. 10,530-9,350 cal·yr·BP. This created an open environment in the catchment that exposed the lake water to wind allowing thorough mixing of the water column. The increased relative abundance of *Aulacoseira* species that require strong turbulence indicates a period of tree disappearance to increase wind-induced mixing. A similar trend occurred in Napoleon Gulf, but from ca. 8,180-7,570 cal·yr.

Increase in the proportion of forest taxa phytoliths and *Aulacoseira nyassensis* taking over *Aulacoseira granulata* and *A. ambigua* from ca. 9,350 to 7,740 cal·yr. BP in Sango Bay and from ca. 7,570 cal·yr·BP in Napoleon Gulf, characterized a period of forest regeneration.

4.2.2 The Mid to Late Holocene Period (ca. 6,000 cal·yr·BP-2009 AD)

The frequent changes in planktonic species, benthic pennales and the *A*/*C* + *S* ratio as well as phytolith assemblages from ca. 5,930-2,000 cal·yr·BP characterized a period of regular fluctuations of climatic and environmental conditions hence, lake levels, mixing of the water column and the vegetation structure were constantly fluctuating during this phase.

The period between ca. 5,000-4,000 yr·BP was a phase of low precipitation, moderate lake water levels and a well-mixed water column since *A. granulata* and *A. ambigua* successfully multiply in well mixed water with moderate levels. This was further supported by a decrease in Cyperaceae phytoliths which indicated a decline in precipitation. The low abundancies of all diatom species indicate stressful conditions during this period. Reduction in precipitation as well as moderate lake water levels may be attributed to the drought after ca. 5,000 yr·BP [35].

The increase in the less silicified *Fragilaria* and *Nitzschia*s pecies at both sites in the last ca. 2,000 years is probably attributed to low Si:P ratio [36, 37] hence reducing the production of diatoms that need high Si: P ratios like *Aulacoseira* species [4, 33, 36, 38, 39]. The dominance of *Fragilaria* species which thrive in reduced light conditions is an indication of reduced light penetration. Reduced light penetration in Lake Victoria was also reported by Hecky [4] and attributed it to eutrophication. This is an indicator of human involvement in influencing the ecological properties of Lake Victoria.

The significant reduction in planktonic species (eg. *Aulacoseira*, *Stephanodiscus*, *Cyclotella* and *Nitzschia* species) with complete absence of some species (eg. *A. nyassensis*, *N. fonticola*, *Cyclotella krammeri* and *Cylotella meduanae* at Sango Bay and *Stephanonodiscus minutulus*, as well as *Nitzschia* species at Napoleon Gulf) and dominance of Poaceae phytoliths for the period ca1. 700 to 1,000 yr·BP testify to a dry climate. The pollen record potrayed the same result during this period [40].

The abrupt increase in *Aulacoseira* species around 1960 to 1970 AD infer abrupt increase in water level attributed to the rains of the early 1960s [38]. Dominance of benthic species as well as significant reduction in planktonic to benthic ratio from 1980 to 2001 AD characterized low precipitation to evaporation ratio in Lake Victoria basin.

The observed increases in *Nitzschia* to *Aulcoseira* ratio suggest increase in nutrient input [41]. The increase in this ratio however occurred earlier at Sango Bay (ca. 2,000 yr·BP) and later at Napoleon Gulf (1993 to 2009 AD) suggesting earlier human-environment interaction at Sango Bay.

5. Conclusion

The late Pleistocene to early Holocene transition period (ca. 10,530 to 8,180 cal·yr·BP) was a phase of moderate water levels, reduced forest cover in the lake's catchments and strong turbulence. The early Holocene period ca. 9,350 to 7,740 cal·yr·BP in Sango Bay and ca. 7,570 to 5,190 cal·yr·BP at Napoleon Gulf were phases of high P: E ratio.

The mid Holocene period from ca. 5,930 to 2,000 cal·yr·BP was characterized by regular fluctuations of climatic and environmental conditions with a drought period from ca. 5,000 to 4,000 cal·yr·BP. The vegetation was dominated by grass and forests.

The late Holocene phase ca. 2,160 cal·yr·BP to 2000s AD was characterized by significant reduction in the amount of biogenic silicon and water transparency (take off of eutrophication in Lake Victoria). The period from ca 1,700 to 1,000 cal·yr·BP experienced dry climate.

From 1960 to 1970 AD, the Lake Victoria region experienced wet conditions. However, between 1980 and 2001 AD; the lake was characterized by low water levels hence low precipitation to evaporation ratio.

Results portrayed human interaction in the catchment of Lake Victoria dating back to ca. 2000 BP with Sango Bay experiencing human influence earlier than Napoleon Gulf.

The use of diatom information in combination with phytolith proxy has proved essential in assessing aquatic ecosystems and revealed climatic changes as well as human influence on Lake Victoria ecosystem.

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