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Late holocene trends of phytoplankton productivity and anoxia as inferred from diatom and geochemical proxies in Lake Victoria, Eastern Africa

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Abstract

Lake Victoria ecosystem has undergone major ecological changes in the recent decades. Sedimentary diatom analysis and Fe/Mn determined by Energy Dispersive X-ray Fluorescence (EDXRF) have provided phytoplankton (diatom) productivity and the resultant anoxia (Fe/Mn) in Lake Victoria at Napoleon Gulf during the late Holocene (1778 cal yr BP (calibrated years before present) to 2008 AD) with radiocarbon dates determined using Accelerator Mass Spectrometry standard method. The results showed that increased total diatom counts in Napoleon Gulf during the late Holocene correspond with increased Fe/Mn ratio (anoxia) in some of the profiles and not in others and in most cases those that correspond correlate very well with increased eutrophication from nitrate input (Total Nitrogen, TN). Therefore slightly increased anoxia not related to increased diatom productivity was recorded in Lake Victoria at Napoleon Gulf from the period 1778 to 1135 cal yr BP. There was slightly increased diatom productivity at Napoleon Gulf from the period 857 to 758 cal yr BP but it did not increase anoxia in the lake. The period 415 cal yr BP to 2008 AD recorded increased anoxia at Napoleon Gulf related to high diatom productivity especially from 415 to 390 cal yr BP and 191 cal yr BP to 2008 AD.

1 Introduction

Lake Victoria (surface area, 68 800 km^2) situated in East Africa is the second largest freshwater lake in the world and the largest in Africa (Crul, 1995). The lake basin (catchment area, 194 300 km^2) with an estimated population of 30 million people (UNEP, 2004) is densely populated recording a 3–4 % annual growth-rate (Bugenyi and Magumba, 1996). The ecosystem of the lake has undergone major changes during the past three decades, 1960s to 1990s (Bugenyi and Magumba, 1996); primary productivity of the lake appears to have risen to about 2 to 3-fold (Bugenyi and Magumba, 1996) and dominance in primary production has shifted from diatoms to blue green algae

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(Johnson, 1996). There have also been declines in hypolimnetic oxygen (anoxia below 40 m seasonally) (Bugenyi and Magumba, 1996) and bottom water anoxia of the lake has shifted from seasonal to permanent (Johnson, 1996) with 35–55 % of the bottom area now enduring prolonged anoxia (Bugenyi and Magumba, 1996). The changes in oxygenation are consistent with measurements of higher algal biomass and productivity (Hecky et al., 1994). According to Lehman and Branstrator (1993), nitrogen (N) is the most limiting nutrient element for the phytoplanktons of Lake Victoria. However, there is limited information on the long term phytoplankton (diatom) productivity as a result of enrichment of the limiting nutrient element, nitrogen (N) and the resultant anoxia in Lake Victoria at Napoleon Gulf. The aim of this study is to establish the late Holocene phytoplankton (diatom) productivity as a result of enrichment of nitrogen (N) and the resultant anoxia in Lake Victoria at Napoleon Gulf using Fe/Mn geochemical proxy.

2 Materials and methods

The 46 cm long LVNG2 sediment core was collected using Renberg corer from 11.3 m depth (Fig. 1; 00°26′56.3′′ N, 033°16′07.5′′ E, elevation, 1132 m) in 2008 by the Millenium Science Initiative Project team members in Department of Biology, Mbarara University of Science and Technology and Department of Geology, Makerere University. The stratigraphy of the sediment core according to colour and texture and Total Nitrogen (TN) content were fully described in Andama et al. (2012).

2.1 Radiocarbon dating

The four accelerator mass spectrometer (AMS) ^{14}C dates for LVNG2 sediment core in Andama et al. (2012) determined using the standard method of Stuiver et al. (1998) were used. However the radiocarbon dates in Andama et al. (2012) had no age model, age correction term for reservoir effect and were not validated with other radiocarbon dates obtained by previous researchers who did work in the same lake. A detailed age

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model and chronology for LVNG2 sediment core is therefore described in this paper. Since bulk sediment materials were dated but not plant or animal remains, some of the conventional radiocarbon ages were subjected to ∼ 600 yr radiocarbon correction for Lake Victoria sediments used by Stager and Johnson (2000), Stager et al. (1997) and also recommended by Stuiver (1970). Comparisons of the radiocarbon ages with those obtained by previous researchers in Lake Victoria especially by Stager and Johnson (2000), Stager et al. (1997) and Kendall (1969) were also done to validate them. All the conventional ^{14}C dates were analysed with 2σ errors and the suitable ages recalibrated using IntCal09 (Reimer et al., 2009).

An age model was produced for the sediments obtained from the coring site by the computer program OxCal v.4.1.7 (http://c14.arch.ox.ac.uk/oxcal.html) (Bronk Ramsey, 2009) used to construct a Poisson-process (P-sequence) deposition model for the sediment profile. Such models consider the sediment deposition as discrete events or increments, with a parameter k as the number of increments per unit length and accommodate non-uniform deposition rates throughout the sequence (Bronk Ramsey, 2008). The P-sequence models for the core were run with varying values of k until the highest k of $16\,cm^{-1}$ which gave a satisfactory agreement with the actual dating information (using the agreement indices) (Bronk Ramsey, 2008). The threshold for acceptable agreement index is 60 % according to Bronk Ramsey (2008). In addition, LVNG2 sediment core mainly consisted of clay, silt and organic matter (Andama et al., 2012) but not coarse sand and a k value of 16 is accepted as according to Bronk Ramsey (2008), fine sediment might well have a value of k up to $1000\,m^{-1}$($10\,cm^{-1}$) or possibly even higher. Age depth model for LVNG2 sediment core is shown in Fig. 2. Sediment accumulation rates were calculated by linear interpolation between the mid-points of consecutive pairs of ^{14}C date age ranges determined by the age models and were used for interpolating and extrapolating the calibrated ages.

2.2 Diatom analysis

The diatom analysis involved the modification of the standard methods of Battarbee (1986) and Morley et al. (2004). Sediment subsamples were digested in 30 % H_2O_2, 40 mL of a 0.37 M Na-citrate solution and 5 mL of a 1M $NaHCO_3$ solution were added to remove iron oxide. To totally disaggregate the clays, a Calgon® treatment was performed by shaking the sediment sample in a 5 % Sodium bicarbonate ($NaHCO_3$) solution for 30 min and carbonates were removed by adding 10 % HCl. The samples were wet-sieved through nested 250-micron, 150-micron and 53-micron sieves to separate sand and larger particles from silt and clays. Clays of less than 5-microns were removed by allowing silts to settle and supernatants decanted. The diatom fraction (supernatant) was centrifuged at 1500 rpm for four minutes with distilled water. The supernatant containing the diatoms were then decanted using a pipette, dried on coverslips, and mounted on slides with DPX (RI = 1.525) for diatom analysis. All the diatoms on a slide were identified and counted. Diatom taxa were identified following Hustedt (1949), Patrick and Reimer (1966), Van Der Werff and Huls (1976), Germain (1981), Hartley (1986), Gasse (1986), Kramer and Lange-Bertalot (1991) and Cumming et al. (1995). The total diatom counts were computed in the respective depths (Fig. 3) to ascertain productivity.

2.3 Determination of Fe and Mn using Energy-Dispersive X-ray Fluorescence analyser

Fe and Mn in LVNG2 sediment core were determined using the standard method, Energy- Dispersive X-ray Fluorescence (EDXRF) technique for non-destructive multi-element analysis (Van Greiken and Markowicz, 1993) and Fe/Mn ratio computed. The Fe/Mn ratio was then plotted besides the chronology as shown in Fig. 3. Changes in Fe/Mn ratio in the sediments are linked to changing redox conditions at the sediment surface (Koinig et al., 2003) and generally, increased bioproduction and increased anoxia in deeper waters lead to a stronger solution of Mn compared to Fe from the

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sediment, and thus to lower Mn concentration in the sediment hence high Fe/Mn ratio (Koinig et al., 2003).

3 Results

3.1 Chronology

The first AMS ^{14}C date of 106.3 ± 0.5 at 11–12 cm depth did not require 600 yr correction as it dated much younger. Neither did the 810 ± 40 radiocarbon age of LVNG2 core at 19–20 cm depth require 600 yr correction as it is already consistent with the age at a similar depth of V95–2P sediment core (Stager and Johnson, 2000) from the same lake to which the 600 yr ancient carbon reservoir adjustment was already applied. The radiocarbon age of 3390 ± 40 at 44–45 cm depth might be spurious as it seemed to be very old for a sample as shallow as 44–45 cm depth thus the sample material at this depth was most probably re-worked/re-deposited hence excluded from the chronology. This exclusion decision is supported by two factors; firstly, the age 3390 ± 40 is only comparable with the age 3510 ± 60 at a much higher depth of 217 cm of V95-2P sediment core (Stager and Johnson, 2000). Secondly the age of 3390 ± 40 at 44–45 cm depth was inconsistent with the other dates in the P_{sequence} model as it gave low agreement, below the threshold for acceptable agreement index of 60 % (e.g. Blockley et al., 2008; Bronk Ramsey, 2008). The uncorrected and corrected radiocarbon ages for LVNG2 sediment core are shown in Table 1.

The midpoints of consecutive pairs of ^{14}C date age ranges obtained from the age models (Fig. 2) were the actual ages in cal yr BP of the sediment core. These midpoints i.e. 1777.5 cal yr BP (46 cm), 1195 cal yr BP (33.5 cm), 638.5 cal yr BP (19.5) and 241 cal yr BP (11.5 cm) were used to calculate the sediment accumulation rates. The sedimentation rates were therefore 0.021 cm yr^{-1} between 46 to 33.5 cm depth, 0.025 cm yr^{-1} from 33.5 to 19.5 cm and 0.020 cm yr^{-1} from 19.5 to 11.5 cm. Each of the sedimentation rates was used to interpolate the cal yr BP between the respective

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depths and the 0.020 cm yr^{-1} sedimentation rate between 19.5 to 11.5 cm depth was used to extrapolate the 0 cal yr BP i.e., 1950 AD due to lack of access to ^{210}Pb dating facility hence 0 cal yr BP was reached at a depth of 6.65 cm which also marked the end of ^{14}C date extrapolation. The entire chronology of LVNG2 core based on only ^{14}C dates was obtained and plotted with total diatom counts and geochemical proxies as shown in Fig. 3.

3.2 Diatom counts and Fe/Mn ratio in LVNG2

The different genera of diatoms identified included Aulacoseira, Stephanodiscus, Nitzschia, Fragilaria, Achnanthes, Amphora, Epithemia, Navicula, Cocconeis and Cymbella. Total diatom accounts at the different depths of LVNG2 sediment core were got and Fe/Mn ratios obtained. The diatom record and Fe/Mn ratios were divided qualitatively into the following four sedimentary intervals (Fig. 3) for convenience of interpretation.

Zone LVNG2 A (46–32 cm): in this zone dating from 1778 to 1135 cal yr BP, diatoms were absent from depths 46–39 cm (1778–1451 cal yr BP) and recorded very low numbers of 3, 2 and 12 at 38.5 cm (1428 cal yr BP), 36.5 cm (1335 cal yr BP) and 32.5 cm (1155 cal yr BP) depths respectively. Slightly elevated Fe/Mn ratios (109.83–173.43) were recorded in this zone decreasing towards the top of the zone.

Zone LVNG2 B (32–22.5 cm): this zone dating from 1135 to 758 cal yr BP had few diatoms towards the bottom with only 22 total counts recorded at 30.5 cm depth (1076 cal yr BP). Depths between 30.5 and 24.5 cm (1076 to 837 cal yr BP) did not record any diatom counts. However, diatom counts slightly increased towards the top of this zone with 169 counts recorded at 24.5 cm depth (837 cal yr BP) followed by a decrease to 47 counts at 22.5 cm depth (758 cal yr BP). Slightly low Fe/Mn ratios (100.00–120.00) were generally recorded in this zone dating from 1135 to 758 cal yr BP.

Zone LVNG2 C (22.5–15 cm): this zone dating between 758 and 415 cal yr BP recorded a very scarce number of diatoms with only 14 and 43 total counts registered

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at 19.5 cm (639 cal yr BP) and 16.5 cm (489 cal yr BP) depths respectively while the rest of the depths did not have diatoms. Fe/Mn ratios were relatively high (120.00–185.22) in this zone dating between 758 and 415 cal yr BP and increased towards the top of the zone.

Zone LVNG2 D (15–0 cm): in this zone dating from 415 cal yr BP to 2008 AD, there was generally an increase in total diatom counts with most of the values ranging between 43 to 893 counts particularly from depths 15–14.5 cm and 10.5–0 cm. However, depths between 14.5 and 10.5 cm (390 to 191 cal yr BP) recorded very low diatom counts. The lowest diatom count of 25 was only recorded at 12.5 cm depth (291 cal yr BP) while the highest count of 893 was recorded at 8.5 cm depth (92 cal yr BP). Diatom counts rapidly decreased from 893 counts at 8.5 cm depth (92 cal yr BP) to 58 counts at 4.5 cm depth followed by a slight increase to 80 counts at 2.5 cm depth and finally a gentle decrease to 59 counts at 0.5 cm depth (towards 2008 AD). This zone dating from 415 cal yr BP to 2008 AD generally had very high Fe/Mn ratios (145.08–241.32) punctuated with some abrupt fluctuations with Fe/Mn ratios increasing towards the top of the zone.

4 Discussion

4.1 Phytoplankton (diatom) productivity and anoxia at Napoleon Gulf

The trend of phytoplankton (diatom) productivity and anoxia at Napoleon Gulf was qualitatively divided into the following four time periods for convenience of discussion.

4.1.1 1778 to 1135 cal yr BP

The scarcity of diatom counts during this period signified low diatom productivity. This should be due to insufficiency of limiting nutrient element, nitrogen (N) as total nitrogen recorded low values from 46–32 cm depths (Andama et al., 2012) which now date 1778 to 1135 cal yr BP. The relatively elevated Fe/Mn ratio during this period should have

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been possibly due to other causes but not increased diatom productivity. Johnson et al. (2000) argued that some 9800 to 7500 yr ago, from purely natural causes, limnological conditions in Lake Victoria deteriorated to a state comparable to that of today. This implies that natural causes also had great influence on the limnology of Lake Victoria in the past.

4.1.2 1135 to 758 cal yr BP

Diatom counts generally indicated relatively reduced productivity during the period 1135 to 857 cal yr BP followed by a slight increase in productivity from 857 to 758 cal yr BP. The diatom productivity patterns seemed to agree well with the pattern of the limiting nutrient element, nitrogen (N) using total nitrogen. This is in agreement with the findings of Lehman and Branstrator (1993) who found that nitrogen (N) is the most limiting nutrient element for the phytoplanktons of Lake Victoria. On overall, diatom productivity in the period 1135 to 758 cal yr BP was relatively higher than that from 1778 to 1135 cal yr BP. Total nitrogen also showed slightly increased values from 32 to 22.5 cm depths (Andama et al., 2012) which now date 1135 to 758 cal yr BP and relatively low values from 46 to 32 cm (Andama et al., 2012) dating 1778 to 1135 cal yr BP. However the Fe/Mn ratio was generally lower during the period 1135 to 758 cal yr BP than the previous period dating from 1778 to 1135 cal yr BP signifying that the diatom productivity did not increase anoxia to high levels.

4.1.3 758 to 415 cal yr BP

Low diatom productivity was also registered throughout this period and it seemed to agree very well with reduced total nitrogen only from 22.5–18.5 cm depth (Andama et al., 2012) dating 758–589 cal yr BP. The low diatom counts in the period dating from 589 to 415 cal yr BP amidst increasing total nitrogen from 18.5 to 15 cm depths (Andama et al., 2012) dating 589 to 415 cal yr BP possibly meant that there were other dominant phytoplanktons in Lake Victoria during that period but not diatoms. According

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to Thomasson (1955), phytoplanktons of Lake Victoria include diatoms, blue-greens, desmids, chlorococcalean and other green algae and dinoflagellate. The generally increasing pattern of Fe/Mn during the period 758 to 415 cal yr BP probably signified increasing anoxia from other causes but not increased diatom productivity as previously stated.

4.1.4 415 cal yr BP to 2008 AD

The generally increased diatom counts during the periods 415 to 390 cal yr BP and 191 cal yr BP to 2008 AD though decreasing towards 2008 AD signified high diatom productivity during those periods. This was due to sufficient limiting nutrient element, nitrogen (N) in the lake as according to Andama et al. (2012), total nitrogen recorded very high values from 15 to 0 cm depths dating 415 cal yr BP to 2008 AD. Stager et al. (2009) found out that the changes in diatoms in Lake Victoria more likely reflect responses to long-term nutrient enrichment and climatic instability in the region. The very low diatom counts recorded from the period 390 to 191 cal yr BP and the decreasing pattern of diatom counts after 1950 AD towards 2008 AD possibly signified decreased diatom productivity during the period 390 to 191 cal yr BP and decreasing trend of productivity after 1950 AD towards 2008 AD. This implies that primary productivity in Lake Victoria should have been dominated by other phytoplanktons during the period 390 to 191 cal yr BP and those periods after 1950 AD towards 2008 AD other than diatoms. This partly concurs with the findings of Johnson (1996) who found out that dominance in primary production of Lake Victoria has shifted from diatoms to blue green algae during the past three decades, 1960s to 1990s. Sitoki et al. (2010) also found out that algal species composition in Lake Victoria has changed from dominance of diatoms to toxic nitrogen fixing cyanobacteria along with an increase in algal biomass, which resulted in more severe deoxygenation of deeper waters (Bugenyi and Makumba, 1996).

The generally high Fe/Mn ratio during the period 415 cal yr BP to 2008 AD possibly signified increased anoxia from high diatom productivity especially from 415 to 390 cal yr BP and 191 cal yr BP to 2008 AD. This is partly in agreement with the find-

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ings of Lipiatou et al. (1996) who found out that anoxic conditions have existed in Lake Victoria for the last 200 yr. According to the study, the last episode of increased anoxia in the lake occurred from the period 190 cal yr BP to 2008 AD. Ostenfeld (1908) and Worthington (1930) found out that anoxic, "putrifying" bottom sediments occurred both inshore and offshore of Lake Victoria as early as 1904–1905 and 1927–1928, leading Worthington (1930) to classify the lake as eutrophic. In addition, global climatic change has affected thermal stratification of lake Victoria (Hecky et al., 1994) and thermal stratification enhances chemical reactions favouring the accumulation of toxic organic compounds and anoxic conditions (Njiru et al., 2011). Increases in temperature affect the levels of dissolved oxygen in the water column, which is inversely proportional to temperature (Hauer and Hill, 1996). Lake Victoria is now warmer and thermal stratification more stable which increases the occurrence of hypoxia (Hecky et al., 1994; Sitoki et al., 2010). On average, the surface waters of Lake Victoria have warmed by almost 1.2 °C in 82 yr since 1927 while the temperature rose by 1.57 °C in water > 50 m deep over the same time period (Sitoki et al., 2010). According to Mackay (2007), higher Lake Victoria levels were positively associated with increased sunspot numbers in the last 200 yr. Therefore, there was a possibility of warming of the lake leading to thermal stratification and anoxic conditions in the bottom waters in the last 200 yr. Mugidde et al. (2005) obtained low dissolved oxygen levels at the bottom during stratification in Lake Victoria at Napoleon Gulf, Uganda, an inshore shallow station compared to surface dissolved oxygen levels during periods of thermal stability of the lake. The increased intensity of deoxygenation during the stratified period, when > 50 % of the water column was said to become anoxic (Fish, 1956; Schofield and Chapman, 2000). The increased anoxia during the period 390 to 191 cal yr BP can be attributed to other causes but not increased diatom productivity.

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5 Conclusions

- Increased total diatom counts in Napoleon Gulf during the late Holocene correspond with increased Fe/Mn ratio (anoxia) in some of the profiles and not in others and in most cases those that correspond correlate very well with increased eutrophication from nitrate input (Total Nitrogen, TN).
- Slightly increased anoxia not related to increased diatom productivity was recorded in Lake Victoria at Napoleon Gulf from the period 1778 to 1135 cal yr BP.
- Lake Victoria experienced slightly increased diatom productivity at Napoleon Gulf from the period 857 to 758 cal yr BP but it did not increase anoxia in the lake.
- The period 415 cal yr BP to 2008 AD recorded increased anoxia in Lake Victoria at Napoleon Gulf related to high diatom productivity especially from 415 to 390 cal yr BP and 191 cal yr BP to 2008 AD.

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Table 1. Accelerator mass spectrometer (AMS) radiocarbon dates from LVNG2 core. Asterisk designates samples that required no 600 yr correction.

Sample depth Range (cm)	Sample depth (cm)	Lab ID Number # ^{14}C age	Uncorrected ^{14}C age	Corrected ^{14}C
11–12	11.5	Beta-276809	106.3 ± 0.5	106.3* ± 0.5
19–20	19.5	Beta-278725	810 ± 40	810* ± 40
33–34	33.5	Beta-276810	1830 ± 40	1230 ± 40
44–45	44.5	Beta-276811	3990 ± 40	3390 ± 40

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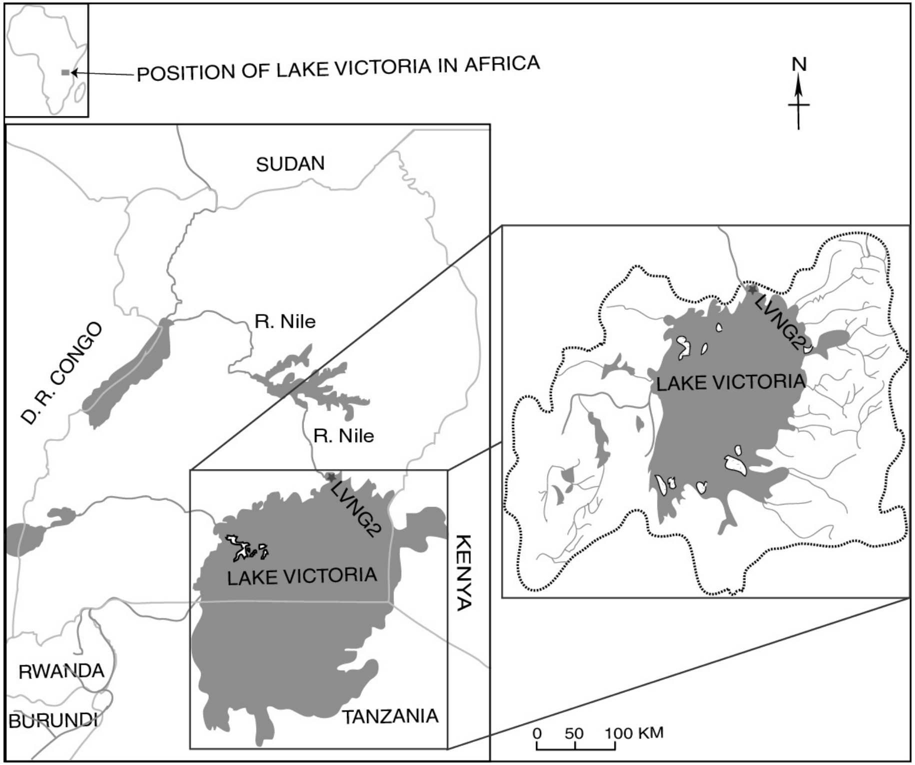

Fig. 1. Map of Uganda showing Lake Victoria and Lake Victoria Napoleon Gulf 2 (LVNG2).

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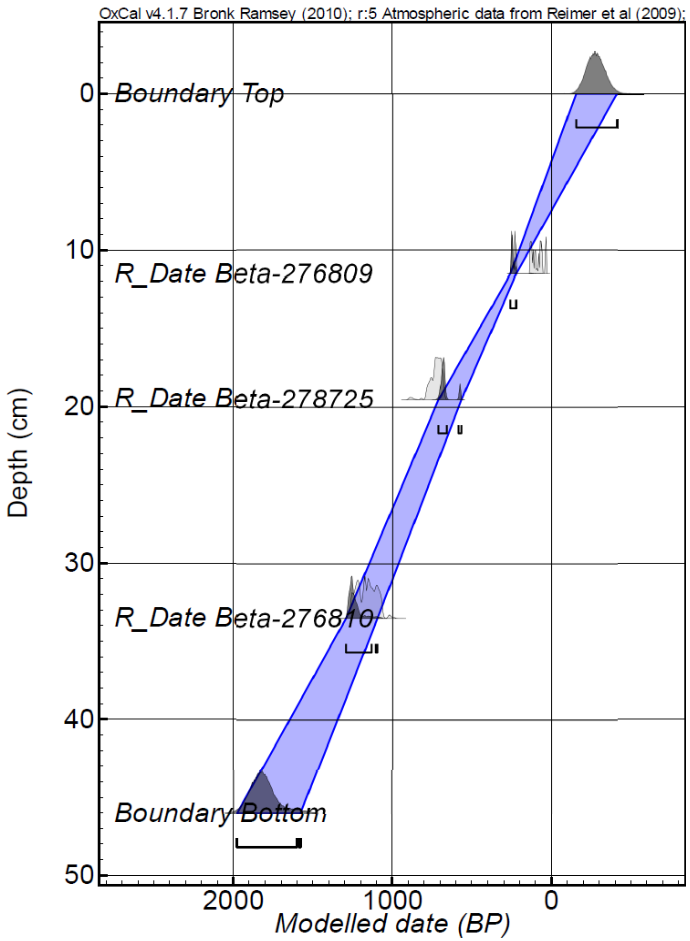

Fig. 2. Age depth model for LVNG2 sediment core using depth as the variable and assuming the deposition is a Poisson process (P_{sequence}), k =16.

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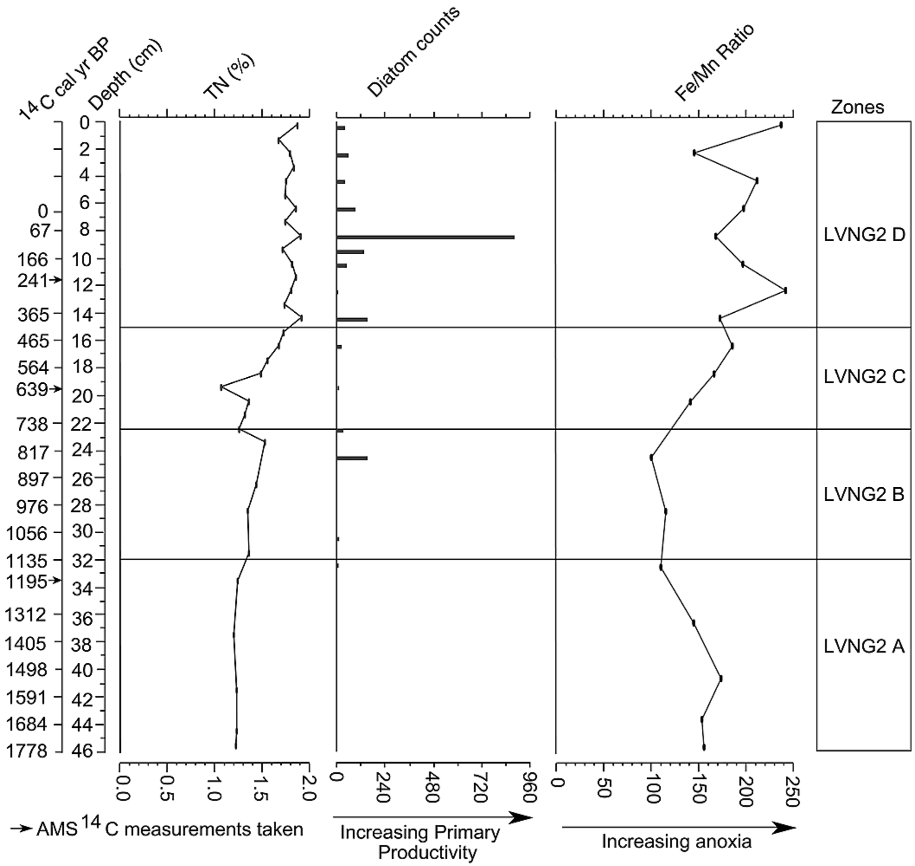

Fig. 3. Total Nitrogen (TN) (Andama et al., 2012), diatom counts and Fe/Mn composition of bulk sediment of LVNG2 core.

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