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Expressions of climate perturbations in western Ugandan crater lake sediment records during the last 1000 years

K. Mills et al.

Correspondence to: K. Mills (k.mills2@lboro.ac.uk)

Mills et al – Supplementary Material

1 Results

1.1 Core correlation and chronological analyses

1.1.1 Lake Nyamogusingiri

Core correlation. Four cores were collected from Lake Nyamogusingiri: two Kajak cores (NCR1 0-29 cm; NCR2 0-35 cm) and two Russian cores (NCR1C1 0-85 cm; NCR2C1 0-100 cm). Only the longer Kajak core (NCR2) was used for analysis as it provided a larger overlap with the top of the Russian cores (8 cm). During the retrieval of core NCR1C1 the core chamber failed to close correctly and sediments were lost. As the integrity of this core was compromised NCR1C1 was not considered for analysis. The second core drive (NCR2C1) was successful and selected for analysis.

Due to the lack of any obvious defining stratigraphic or sedimentological indicators (e.g. banding) in the Nyamogusingiri cores, cores were first correlated on the basis of the field calculations of the coring depths. This correlation was subsequently corrected and finalised based on the loss-on-ignition and diatom analysis (Figure S1), with *Thalassiosira rudolfi* being a key species in the confirmation of the overlap (Figure 4a, main text). The composite core length for Lake Nyamogusingiri was 1.27 m.

Chronological analysis. ^{210}Pb activity in Nyamogusingiri reaches equilibrium with the supporting ^{226}Ra at a depth of c. 50 cm. The unsupported ^{210}Pb activity declines steeply and almost exponentially with depth in the upper 10 cm, but at a slower rate than in deeper sections (Figure S2a-d). This gradient change indicates a recent reduction in the sedimentation rate, but may also be attributed to the shift to lower density sediments in the upper 10 cm of the core.

The ^{137}Cs activity shows a relatively well-defined peak at 20-26 cm (Figure S2a-d) and almost certainly records the 1963 fallout maximum from the atmospheric testing of nuclear weapons (P.G. Appleby, pers. comm.). The ^{210}Pb chronology for Nyamogusingiri places 1963 at 27 cm, a little below the depth indicated by the ^{137}Cs record. The revised dates were calculated by applying the constant rate of supply (CRS) model (Appleby and Oldfied, 1978) in a piecewise way using the 1963 ^{137}Cs date as a reference point. The results suggest a relatively high sedimentation rate from c. AD 1930 through to the early 1990s, with peak values occurring in the mid-1940s and mid-1980s (P.G. Appleby, pers. comm.).

Five AMS ^{14}C dates were obtained from Lake Nyamogusingiri's composite core sequence, below the ^{210}Pb equilibrium depth (c. 52 cm). Two dates from near the base of the core sequence were rejected (Table 1, main text); the dates for these lower samples were obtained on two wood/charcoal fragments and produced younger radiocarbon ages, and hence a younger calibrated date compared to the other three dates above, which all occurred in stratigraphic sequence.

The young ages of SUERC-18396 (wood) and POZ-26361 (charcoal) were both rejected from the final age model. The young age of SUERC-18396 indicate an intrusive root fragment during a period of lower lakes levels (Krider, 1998), especially as the sample was extracted from a soil like deposit at the base of the core. It is worth noting that both of these samples overlap at the 2-sigma confidence limit and also overlap with the date obtained at 61 cm. It may therefore be plausible that during coring the nose or blade of Russian corer dragged down younger material, causing modern contamination of older sediments.

1.1.2 Lake Kyasanduka

Core correlation. Six cores were collected from Lake Kyasanduka: two Kajak cores (KYAS-1; core length 0-39 cm; KYAS-2 0-28 cm) and four Russian cores (KR1C1 31-99 cm; KR2C1 20-100 cm; KR1C2 4-97 cm and KR2C2 0-100 cm; 0 cm represents the top of the Russian Core chamber; 100 cm is the base of the chamber. Where sediment was not retrieved, the top of the core represents the depth where the intact sediment core begins). Preliminary core correlations were made using the field notes related to coring depths. Detailed core correlations were completed through the use of the core descriptions, loss-on-ignition (organic content) profiles, magnetic susceptibility profiles and high-resolution diatom analysis on overlapping sections.

Core descriptions made in the field immediately after collection and the supplementary descriptions taken in the laboratory identified several laminated sections in all four of the Russian cores. These sections of banding provided a key tool for the visual correlation of the four core sequences (Figure S2). They included a section of discontinuous banding in the middle of KR2C1 (*c.* 45-50 cm) which was correlated with a thin black band in KR1C1 (at *c.* 85 cm). A section of banding consisting of orange, brown, red and grey laminations was identified at the base of KR2C1 (80-84 cm) and the upper sections of KR1C2 and KR2C2 (14-18 cm and 14-17 cm), providing a clear tie point for the correlation of these lower core sequences.

The correlations based on the core stratigraphy were confirmed by the loss-on-ignition analyses (organic content) and the magnetic susceptibility. However, the lower sections of the sequence (KR1C2 and KR2C2) were more difficult to correlate, due to several deviations in the organic content and magnetic susceptibility. However, detailed diatom analyses (Figure S3) revealed an almost identical stratigraphy in both cores. Using key features from the cores the offset between the accumulation rates in the two cores, the KR2C2 sequence was stretched relative to KR1C2, following Shaw (1964; Figure S3). The adjustment of the KR2C2 record resulted in the composite core sequence being 2.17 m in length.

Chronological analysis. The ^{210}Pb inventory from Lake Kyasanduka is not comparable to the value supported by the atmospheric flux (6463 Bq m^{-2}); rather it is double the fallout value (16082 Bq m^{-2}; P.G. Appleby, *pers. comm.*). This high value may be the result of strong sediment focusing at the core site, or significant inputs via catchment erosion. As a large part of the lake's catchment lies outside of the Central Forest Reserve boundary, which is subject to large-scale clearance of natural vegetation for subsistence agriculture, the high value is most likely attributed to significant inputs as a result of catchment erosion.

Kyasanduka has a number of irregularities in its unsupported ^{210}Pb activity (Figure S3a-d) suggesting several periods of major disturbances in the recent past. Total ^{210}Pb reaches equilibrium with the supporting ^{226}Ra at a depth of around 125 cm. ^{210}Pb concentrations have a maximum value 8.5 cm below the top of the core and there is a further significant non-monotonic feature between 24 and 50 cm. The presence of a layer of dense sediment between 120 and 140 cm may be related to the virtual absence of unsupported ^{210}Pb below 110 cm. This dense sediment is interpreted as a large, simultaneous deposit of catchment material that may have caused dilution of the ^{210}Pb concentrations in the lake sediments.

The ^{137}Cs activity versus depth profile of Kyasanduka shows a peak between 44 cm and 53 cm but as rapid changes in ^{210}Pb occur at the same interval in the core, but radiocaesium is present to c. 70 cm in the core and it is likely that the factors driving these changes have also modified the ^{137}Cs profile (P.G. Appleby, *pers. comm.*). Thus a more appropriate guide to the 1963 depth may be obtained by using the $^{137}Cs/^{210}Pb$ ratio (which peaks at 38-49 cm).

Figure S3a shows the ^{210}Pb dates calculated using the CRS model, together with the 1963 depth suggested by the ^{137}Cs record. Use of the constant initial concentration (CIC) model was precluded by the irregular nature of the ^{210}Pb record. The ^{210}Pb results place 1963 at ca.60 cm, significantly below the depth indicated by the ^{137}Cs record. The discrepancy appears to be due to changes in the ^{210}Pb supply rate to the sediments associated with the irregularities in the sediment record. Calculations using the ^{137}Cs date as a reference point indicate that the very high ^{210}Pb inventory in this core is mainly attributable to very high supply rates in the pre-1963 period. The mean post-1963 ^{210}Pb flux (~350 Bq m^{-2} y^{-1}) is less than 40% of the value (~950 Bq m^{-2} y^{-1}) calculated for the pre-1963 sediments. Revised dates calculated by applying the CRS model in a piecewise way using the 1963 ^{137}Cs date as a reference point suggest a relative uniform sedimentation rate of around 0.047 g cm^{-2} y^{-1} (0.60-0.90 cm y^{-1}) since the later part of the 19th century, punctuated by episodes of rapid accumulation in the 1920s, the late 1960s or early 1970s, and most recently during the past few years.

Eleven AMS ^{14}C dates on terrestrial material (leaves, wood, and charcoal) were obtained Lake Kyasanduka's composite core sequence. All dates were calibrated using CALIB 5.0 (Stuiver and Reimer, 1993) using the IntCal09 calibration curve (Reimer et al., 2009). Out of the eleven dates, three were rejected (Table 1, main text): SUERC-19070 (charcoal), SUERC-18398 (charred wood) and POZ-26360 (charcoal). Whilst the pure charcoal and charred wood fragments selected for analysis were >250 μm in length, suggesting a local source, and those with rounded edges were avoided to try and limit errors due to the reworking of charcoal in the sediments, the dates all produced consistently older ages than the sediments dated above and below, or in the case of SUERC-19065, the charcoal date produced an older age than a second date obtained from the same horizon from a piece of wood. These older charcoal ages could be due to 'old wood' (containing old carbon) having been partially burned and deposited in the lake, or the reworking of older charcoal remaining within the catchment and was deposited in the lake during periods of high sedimentation as a result of rainfall events or catchment disturbance. It should be noted that not all dates obtained on charcoal were rejected. The accepted dates were those where more brittle terrestrial plant material (e.g. leaf fragments) and smaller pieces of wood and charcoal (<250 μm). These more delicate plant fragments would likely be destroyed by prolonged aerial exposure. Furthermore, when such remains are found in offshore sediments, they most likely reflect direct deposition from the air (Verschuren, 2003).

Problems with the dating of charcoal, which appear older when compared to other dates above and below the charcoal date, in the East African crater lakes has been reported (Russell et al., 2007), yet the occurrence of terrestrial macrofossils in these cores was rare, limiting the available material for dating. Dating of bulk sediment samples is not optimal in these closed crater lakes, as bulk samples have been older than expected, interpreted as a result of carbon reservoir effect (Beuning et al., 1997; Stager and Johnson, 2000; Russell et al., 2007). The dating of bulk sediments in some of the larger and smaller (crater) lakes in East Africa has proved problematic. In many instances, bulk sedimentary material may contain considerable ^{14}C from aquatic algae, which can overestimate the true age of the sediment. Aquatic algae derive their ^{14}C from the dissolved inorganic carbon from the lake water, and in many closed-basin lakes, the long residence time can cause a reduction in the $^{14}C/^{12}C$ ratio relative to the atmosphere (Verschuren, 2003). For example, radiocarbon dated sediments from Lake Victoria suggest a 500-600 year offset in core tops (Beuning et al., 1997; Stager and Johnson, 2000).

1.2 Other considerations

Sediment disturbance: Whilst Lake Kyasanduka is a shallow lake system (whose maximum depth is restricted to 3 m due to an overflow and sediment infilling), there is little evidence in both the diatom stratigraphy and in the sedimentology that suggest wind-mixing/bioturbation is not a major issue for this system. With regards to the biostratigraphy, there are no clear signs of mixing within the diatom stratigraphy many of the changes between distinct habitat groups are very clear, and there is little in the way of evidence of the mixing of signals of different diatom groupings (at the resolution of these analyses). The catchment of Lake Kyasanduka, whilst not having high crater sides, is relatively sheltered by high ground to the east and dense vegetation that surrounds the lake. Limnological profiles in terms of temperature and chemistry were also recorded during the day and show clear stratification, suggesting that, during the dry season at least, wind mixing is not prevalent.

Chronological uncertainty: There may be additional chronological uncertainty in the age models from Lakes Kyasanduka and Nyamogusingiri due to the occurrence of non-unique calendar ages (Verschuren et al., 2000). The calculation of the calendar ages is particularly problematic during the last 1000 years due to the 'de Vries effect', which causes several plateaus as well as age reversals in the radiocarbon calibration. This results in multiple calibrated ages for single samples (Table 1, main text). The de Vries effect is a natural phenomenon often linked to variations in sunspot activity, which can cause problems with the precision of calibrated radiocarbon dates from AD 1450 to AD 1950 (Stuiver and Becker, 1993). In some instances these perturbations can cause limitations when resolving the actual ages of the sediments.

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Table S1. Variables used in the RDA prior to forward selection of the statistically significant variables for each core

Variable	Description	Reference
LOCAL DRIVERS		
DMAR	Dry mass accumulation rate (g cm^2 yr^{-1})	Mills, 2009
Organic flux	Calculated flux rate of organic matter (LOI)	Mills, 2009
Minerogenic flux	Calculated flux rate of minerogenic matter (LOI)	Mills, 2009
$\delta^{13}C_{org}$	Bulk organic isotope data	Mills, 2009
CN ratio	Carbon: nitrogen ratio (bulk sediments)	Mills, 2009
REGIONAL DRIVERS		
Lake Pallcacocha	ENSO frequency (red colour intensity)	Moy et al., 2002
Atmospheric $\delta^{14}C$ residual series	Relationship to sunspot minima	Stuiver and Brauzanias, 1989
Lake Naivasha	Reconstructed lake level (m)	Verschuren et al. 2000
Lake Edward	Mg in calcite (%)	Russell and Johnson, 2007
Lake Victoria	Shallow water diatoms (% SWD)	Stager et al., 2005
Lake Kibengo	$CaCO_3$ (%)	Russell et al., 2007
Lake Kitagata	Magnetic susceptibility (SI Units)	Russell et al., 2007
Lake Kasenda	Inferred lake level	Ryves et al., 2011

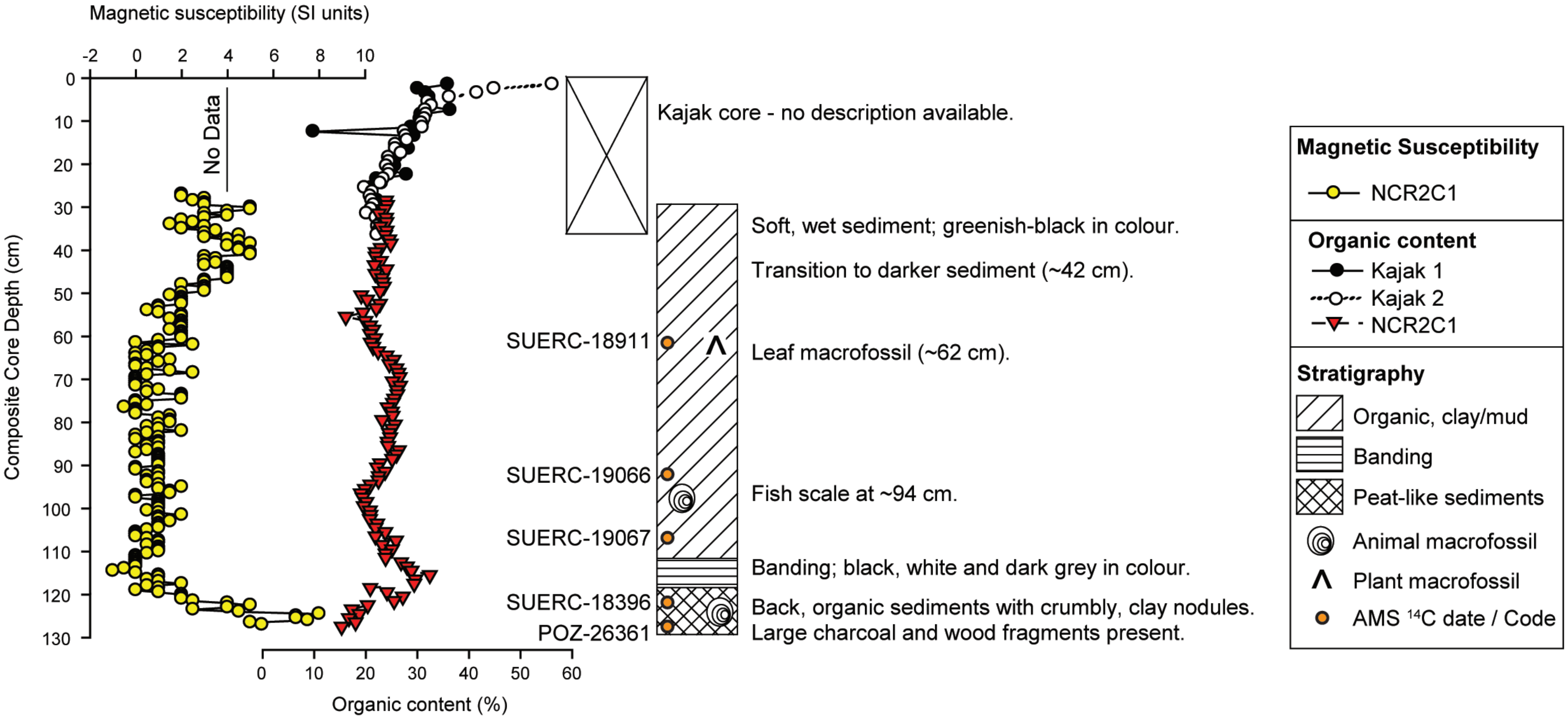

Figure S1. Correlation of the overlapping core sections recovered from Lake Nyamogusingiri. Results of magnetic susceptibility, loss-on-ignition and core stratigraphies are displayed alongside brief descriptions.

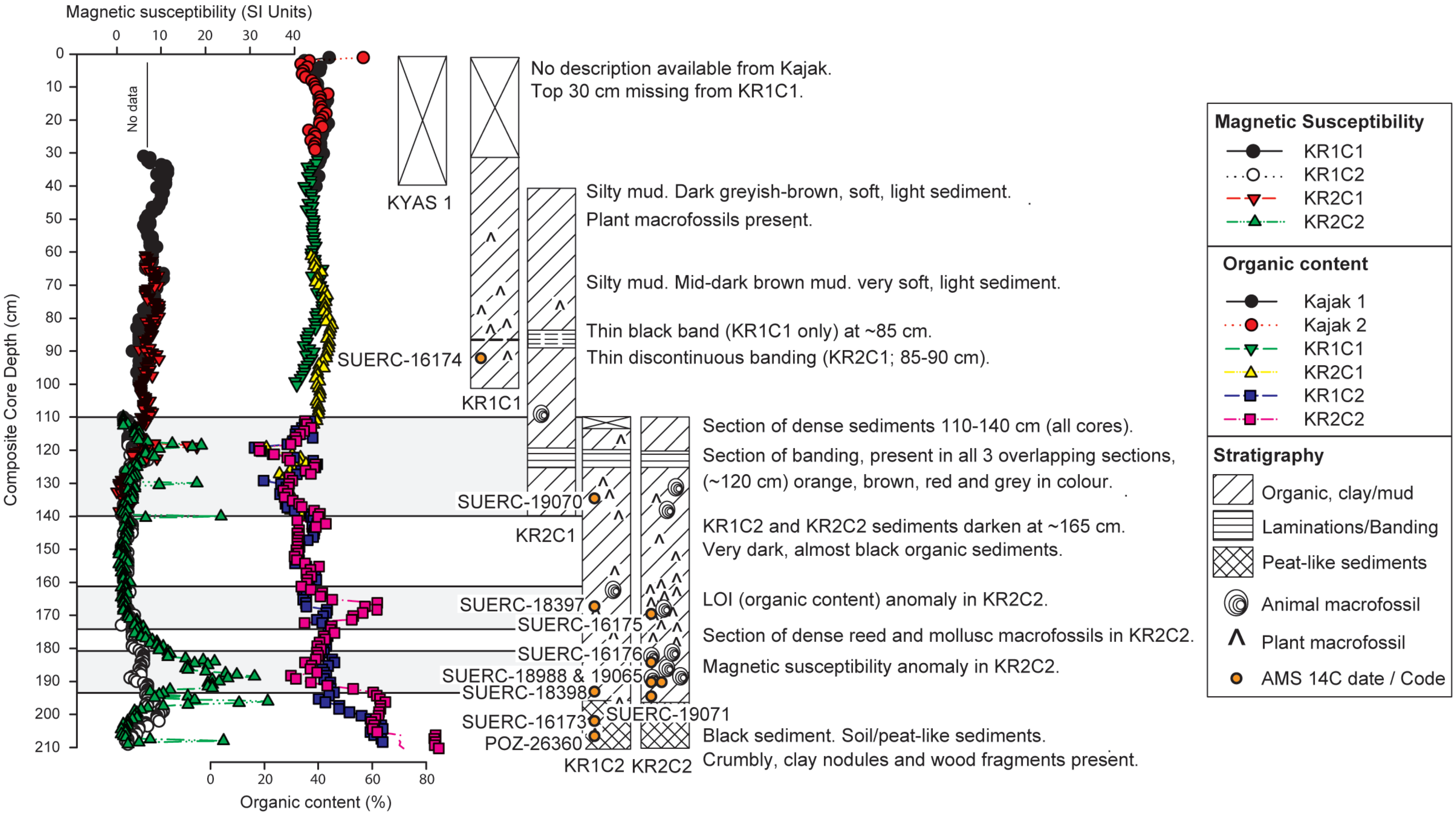

Figure S2. Correlation of the overlapping core sections recovered from Lake Kyasanduka. Results of magnetic susceptibility, loss-on-ignition and core stratigraphies are displayed alongside brief descriptions.

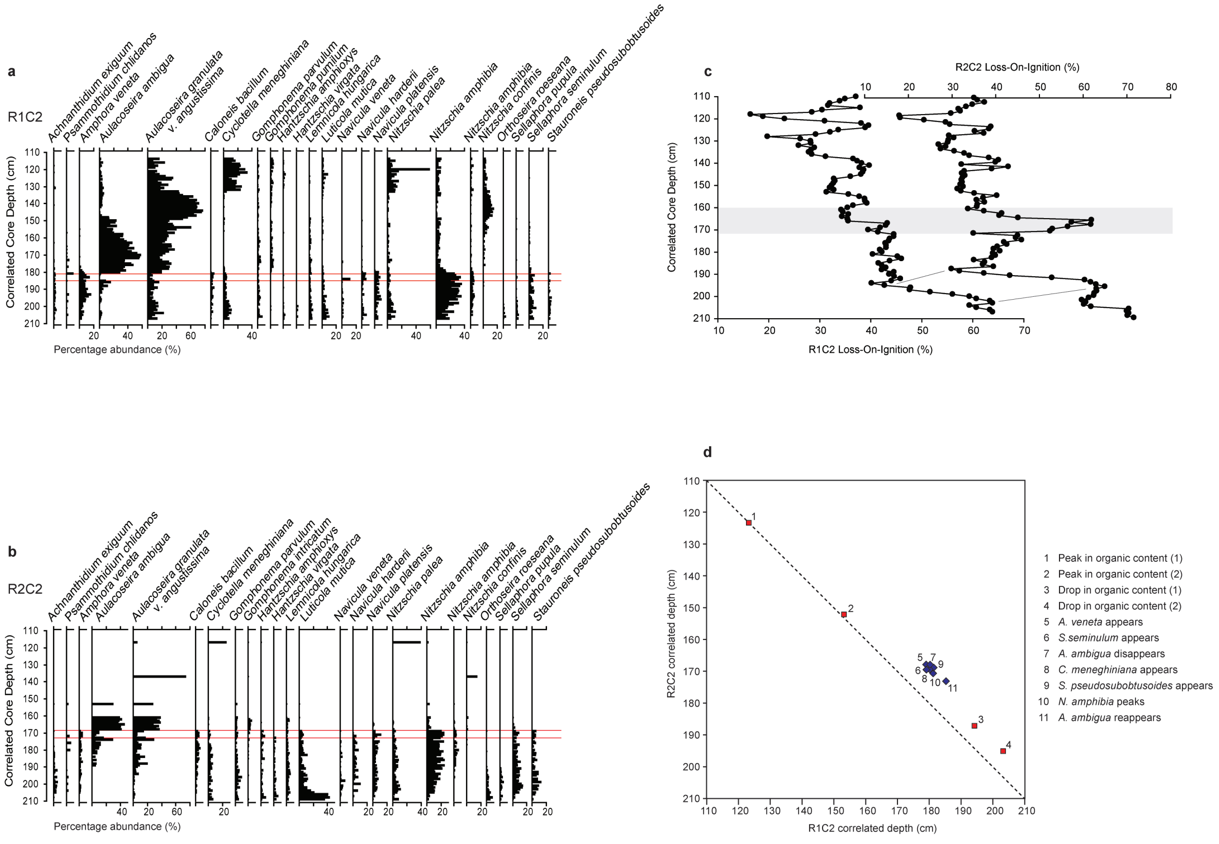

Figure S3. Detailed diatom counts from Kyasanduka cores (a) KR1C2 and (b) KR2C2. The red boundaries highlight the key feature (a reduction in the percentage of *Aulacoseira* species) that was used to confirm the core correlation, (c) loss-on-ignition profiles of cores KR1C2 and KR2C2. The shaded box indicates the excursion in the LOI profile as noted in KR2C2 only, which corresponds to a reed mat deposit in the core and (d) Shaw diagram for the overlapping cores KR1C2 and KR2C2. Each point (1-11) represents an assumed synchronous feature, derived using loss-on-ignition and diatom biostratigraphy. The deviation from the 1:1 line towards the bottom of both cores suggests a change in sedimentation rate between the two cores and their depositional environments.