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From desiccation to wetlands and outflow: Rapid re-filling of Lake Victoria during the Latest Pleistocene 14–13 ka

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ABSTRACT

Reconstructing hydrological variability is critical for understanding Lake Victoria's ecosystem history, the evolution of its diverse endemic fish community, the dynamics of vegetation in the catchment, and the dispersal of aquatic and terrestrial fauna in the East African Rift system during Latest Pleistocene and Holocene times. Whereas consensus exists on widespread desiccation of Lake Victoria ~18 – 17 ka, the re-filling history (16 – 13 ka) has remained highly controversial. Here, we present data from four new sediment cores along a depth transect. We use lithostratigraphic core correlation, sediment facies, XRF data, wetland vegetation analysis (*Typha* pollen), and ^{14}C chronologies of unprecedented precision to document Latest Pleistocene lake-level variability. At our coring site in the central basin, local *Typha* wetlands existed >16.7 ka, alternating with periods of desiccation. Moisture increased slightly between ca. 16.7 – 14.5 ka and wetlands with permanent, shallow ponds established simultaneously in the center and the marginal, more elevated parts of the flat lake basin. After ca. 14.0 ka, lake levels increased; wetlands in the central basin were submerged and replaced by lacustrine environments and a >50 m deep lake established ca. 13.5 ka, likely with intermittent overflow most of the time. The lake reached modern or even above-modern levels around 10.8 ka. This lake-level history is consistent with regional terrestrial paleoenvironmental reconstructions, notably the expansion of Afromontane and rainforest. Our data suggest a complex picture of paleoclimatic conditions in Eastern Africa and teleconnections to the North-Atlantic and Indian Ocean domains.

1. Introduction

Latest Pleistocene refilling had profound impacts on the ecological processes of Lake Victoria (Johnson et al., 1996). The most prominent example is the richness of endemic haplochromine cichlid fish species, which started evolving very rapidly after the refilling of the lake began ~16 ka ago (Stager et al., 2002). This is the fastest vertebrate species radiation known on Earth (McGee et al., 2020; Seehausen, 2002). It has

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been argued that lake-level variability with desiccation and refilling was a critical environmental constraint and driver for the radiation of cichlid fish species in Lake Victoria (Johnson et al., 1996; Muschick et al., 2018; Seehausen, 2002). Moreover, there is growing evidence that Early Holocene hydroclimatic changes (African Humid Period (AHP)) and related hydrological connectivity played an important dual role as corridors or barriers for fish and mammal dispersal in Eastern Africa. Therefore, comprehensive information on the timing and rate of past lake-level fluctuations of Lake Victoria is imperative to better understand the relation between hydroclimatic change, lake development, and biotic responses in the lake and in the catchment including the cichlid fish adaptive radiation, other evolutionary processes, species dispersal, fire history, and vegetation dynamics (Dommain et al., 2022; McGee et al., 2020; Temoltzin-Loranca et al., 2023), among others.

Sediment-based reconstructions of lake-level fluctuations reveal direct evidence of lake responses to hydroclimatic variability. Earlier studies on sediment cores, predominantly from the northern and central parts of Lake Victoria (Johnson et al., 1996; Kendall, 1969; Stager, 1984; Stager et al., 2011; Stager and Johnson, 2008; Talbot and Livingstone, 1989) provided a complex but still ambiguous and controversial picture of the lake's refilling history after the Latest Pleistocene desiccation. The desiccation period is well established and diagnosed with dry, dense crumbly sediment interpreted as paleo-Vertisol found in the basal strata of sediment cores from the deepest part of the lake (Johnson et al., 1996). According to Stager and Johnson (2008), the lake may have had multiple low stands and "*began to re-fill* ca. *15,000 years ago [...] then fell again to virtually complete desiccation some time between 15,900 and 14,200 years ago*". Later, Stager et al. (2011) proposed a substantial lake transgression between 16.0 and 14.5 ka which is, however, not supported by regional $\delta D_{leaf\ wax}$ hydroclimatic data (Berke et al., 2012; Tierney et al., 2011, 2008). Similarly, the short-term desiccation event around 15 ka (14.2 ka, Stager et al., 2011) was not found in other sediment cores (e.g., V95-1P, V96-7P; Johnson et al., 1996, Beuning et al., 2002), and the timing of these putative events remained unclear.

Inconsistencies in the interpretation of the Latest Pleistocene lake-level history, particularly between 16 and 14 ka are possibly partly attributable to large distances between the different coring and study sites (Fig. 1), different water depths in several sectors of the large lake, disparities in lithologies of the sediment cores and substantial uncertainties in the ^{14}C chronologies (Beuning et al., 2002; Stager et al., 2011; Stager and Johnson, 2000; Talbot and Lærdal, 2000). Some of the published ^{14}C dated sediments were repeatedly reinterpreted and have changed over time along with updated sediment descriptions, different and newly applied ^{14}C reservoir corrections and calibration models

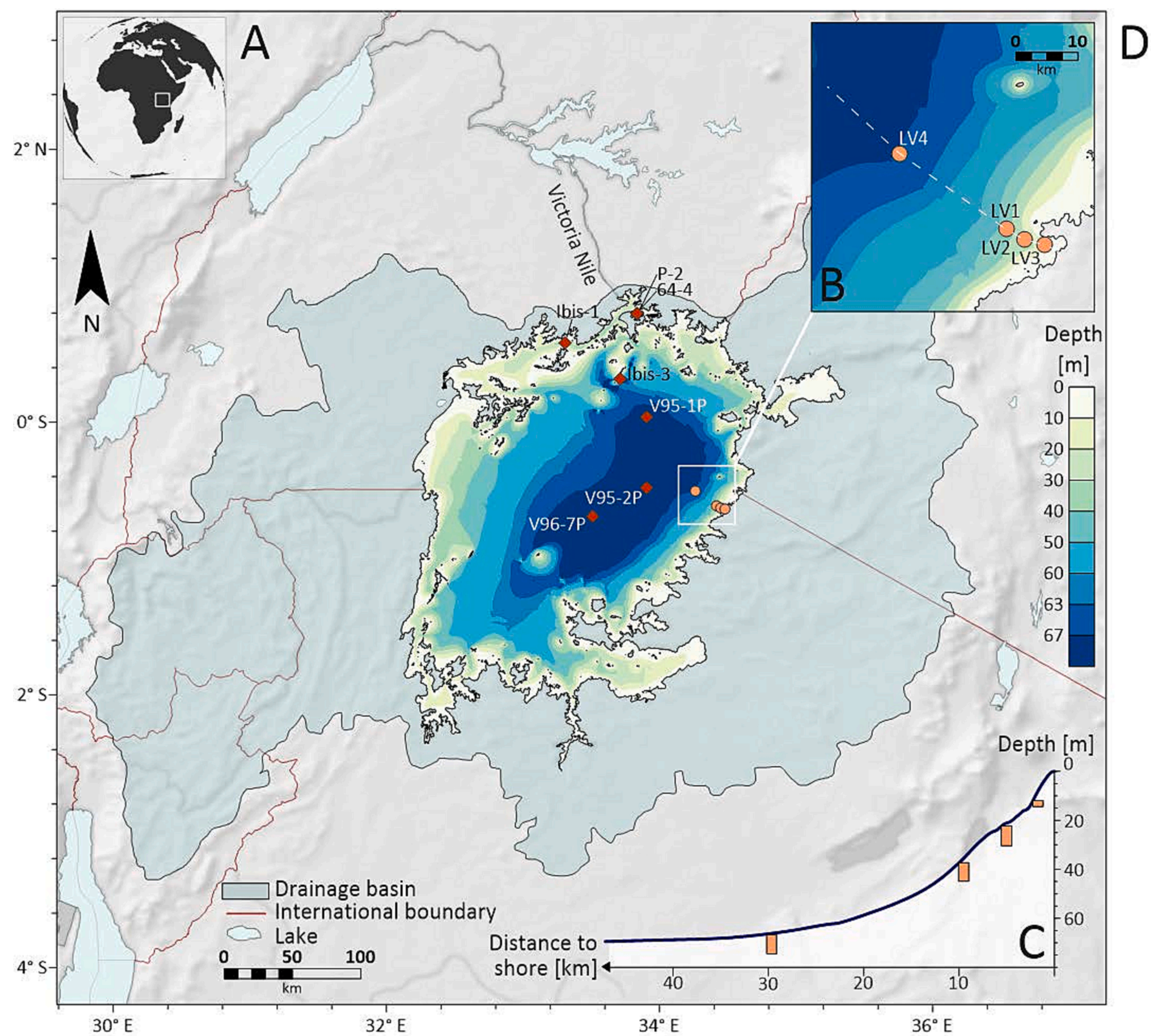

Fig. 1. (A) Catchment and bathymetry of Lake Victoria with coring sites: V95-1P (Johnson et al., 1996); V95-2P (Johnson et al., 1996); V96-7P (Johnson et al., 1996); Ibis 3 (Stager et al., 1986); LVC18-S4, LVC18-S1, LVC18-S2 and LVC18-S3 (Temoltzin-Loranca et al., 2023 and this work); Ibis 1/Damba Channel (Stager et al., 1986); P2 and 64-4 (Kendall, 1969). (B) Inset map of the coring transect with LVC18-S1 (LV1), LVC18-S2 (LV2), LVC18-S3 (LV3), and LVC18-S4 (LV4); this work; (ESM Table S1). (C) Depth profile of the coring transect in distance to the shoreline. Bathymetric data are from Hamilton (2022).

applied.

Here, we present data from a set of four new sediment cores along an offshore to nearshore transect on the eastern part of the lake (Fig. 1; Electronic Supplementary Material (ESM) Table S1). The transect is designed to reveal accurate and detailed spatial-temporal documentation of Lake Victoria's Late Quaternary lake-level history and emergence of its modern lacustrine ecosystem. We review the major findings from previous studies in light of our novel chrono-lithostratigraphic approach. We build on sediment core chronologies with unprecedented precision and discuss the paleoclimate conditions that have impacted the Late Quaternary lake-level transgression in the Victoria Basin. Finally, we place our findings into context with the fire history and vegetation dynamics in the catchment of the lake and with East African paleoclimate records.

2. Materials and methods

2.1. Study site and experimental description

Lake Victoria (0.5°N to 3.0°S, 68,800 km^2) is located in a depression between the two branches of the East African Rift (Fig. 1). Today, the lake is shallow with a maximum water depth of 68 m (Johnson et al., 1996). Bathymetric surveys reveal a bowl-shaped lake basin without major topographic features and with very gentle slopes (0.035 – 0.15°; Hamilton et al., 2022). The hydrological budget of the lake is positive and controlled by direct precipitation (1790 mm yr^{-1}; >80 % of incoming water) and lake surface evaporation (1551 mm yr^{-1}; ~70 % of outgoing water, Yin and Nicholson, 1998). River runoff from the small catchment area (drainage ratio ~2.67) is limited (runoff coefficient 9 %; Crul, 1995) and contributes 338 mm yr^{-1} to the lake's water balance (Yin and Nicholson, 1998). The northern outflow is the primary source of the White Nile River.

Precipitation occurs in two rainy seasons (March to May and October to December) as a result of the changing position of mesoscale convection (Nicholson, 2018) and is, on long time-scales, influenced by the seasonal migration of the Afrotropical rain belt, the position of the Congo Air Boundary and the strength of the Indian and Atlantic monsoons predominantly controlled by orbital, greenhouse gas and North Atlantic forcing (Beverly et al., 2020; Castañeda et al., 2016; Nicholson, 2018; Stager and Johnson, 2000; Verschuren et al., 2009).

In 2018, UWITEC piston cores were taken along a depth transect starting from the eastern shoreline (Fig. 1A-B; ESM Table S1). Overall, multiple cores were collected at four different coring sites LVC18-S1 to LVC18-S4 (hereafter LV1 to LV4) with water depths ranging from 13.4 to 63 m below modern lake level (m.b.l.l. in October 2018; Fig. 1C). A continuous master composite core was established for each coring site. The stratigraphic correlation is based on tie points inferred from XRF data (ESM Fig. S1).

3. Chronology, lithostratigraphy, and analytical methods

The chronologies for cores LV1, LV2, and LV4 were established based on ^{14}C dates from 85 sieved (50 µm mesh) and handpicked terrestrial plant-macrofossils and charcoal pieces (for details see Temoltzin-Loranca et al., 2023). The age model for LV3 is based on ^{14}C dates from 11 sieved (50 µm mesh) and handpicked charcoal pieces (this work: ESM Fig. S2, and Tables S2 and S3). ^{14}C accelerator mass spectrometry (AMS) analysis was performed for all samples with the MICADAS system at the Laboratory for the Analysis of Radiocarbon (LARA) at the University of Bern (Szidat et al., 2014). Calibration was performed with IntCal20 (Reimer et al., 2020). Freeze-dried and homogenized sediment samples from a short gravity core nearby LVC18-S3 (LVC18-S3-SC2) were analyzed for ^{137}Cs and ^{226}Ra directly by gamma-ray spectrometry using a HPGe well-type detector (GCW 2021) at the Faculty of Oceanography and Geography, University of Gdansk, Poland. ^{210}Pb activities were measured indirectly by ^{210}Po using alpha spectrometry (ESM Table S3). For details see Tylmann et al. (2016). Unsupported ^{210}Pb was calculated with the level-by-level method. Sediment ages were obtained using a Bayesian statistical approach with the software package rplum (Aquino-López et al., 2018) and with the Constant Flux-Constant Sedimentation (CF-CS) model corrected for the missing inventory (Tylmann et al., 2016).

Lithofacies description and interpretation of the sediment across the paleosol-wetland-lake continuum follows the model of Ashley et al. (2013) which was developed for the Loboi Swamp in Kenya. Following Richardson et al. (2022) we use the term 'wetland' for an environment inferred from >30 % emergent vegetation (here mainly *Typha* as identified by pollen analysis; Temoltzin-Loranca et al., 2023) in a mosaic with shallow (<2–3 m) ponds of up to a few ha in size with lentic water. According to Temoltzin-Loranca et al. (2023) this environment was treeless. Pollen samples with >5 % *Typha* pollen are interpreted as representative of local stands of cattail (rational pollen percentage limit, Davis et al., 1991).

Scanning X-ray fluorescence (XRF) for major elemental composition was carried out on core halves using both a Mo- and Cr-anode X-ray tube and an ITRAX core scanner at the Institute of Geological Sciences, University of Bern. XRF measurements were performed at 50 mA, 30 kV, and 30 s integration time over 5 mm intervals.

Total organic carbon (TOC) and nitrogen isotope compositions ($\delta^{15}N$) were measured on homogenized and freeze-dried samples in tin capsules using a ThermoFisher Flash-EA 1112 coupled with a Conflo IV interface to a ThermoFisher Delta V isotope ratio mass spectrometer (IRMS) at the Geological Institute, ETH Zurich. Isotope ratios are reported in the conventional δ-notation with respect to atmospheric N_2 (AIR) and VPDB (Vienna Pee Dee Belemnite) standards, respectively. Analytical reproducibility of the measurements is better than 0.2 ‰. Total sulphur was measured on 10 mg homogenized and freeze-dried samples using a CNS Vario El cube Elemental Analyser.

4. Results and discussion

4.1. Late Pleistocene lake-level variability

The lithostratigraphy at our deep-water site LV4 (63 m.b.l.l.) reveals (partial) exposure of the lake floor from at least ~20.2 ka (bottom of LV4), until prior to ~16.4 ka, as indicated by a 14 cm section of fine-grained, dry and dense mud below 763 cm sediment depth (Fig. 2 and ESM S3). The low water content and high bulk density compared with the overlying sediment (Fig. 3) suggest episodically exposed environments (Ashley et al., 2013). At 16.6 ka (777–778 cm sediment depth), *Typha* pollen > 5 % indicate local stands of cattail and wetland environments with shallow ponds. Because of the low-energy aquatic depositional environment (sedimentation rates < 0.1 mm yr^{-1}; Temoltzin-Loranca et al., 2023), wetland sediments are often difficult to distinguish from lacustrine deposits (Ashley et al., 2013). Today, heliophilous *Typha* is growing in ponds and up to tens of meters away from the lake shoreline and at water depth up to 1 m (Grace and Wetzel, 1981). Since *Typha* pollen is unlikely to travel large distances we use it as an indicator for local wetland environments (Temoltzin-Loranca et al., 2023). Basal sediments at LV4 dated between ~20.2 and 16.6–16.4 ka (Fig. 4 and ESM S3), lack features of soil formation (paleo-Vertisol), in contrast to what has been observed at other sites in the central basin at this time (Fig. 4; Johnson et al., 1996; Talbot and Lærdal, 2000). Instead, our data suggest that wetlands persisted locally at least from ~16.6 ka onwards, similar to wetlands found adjacent to modern savannas in parts of the surrounding landscapes. However, the lack of pollen in several of the basal samples (e.g., between 763 and 776 cm) is interpreted as indicating century-scale drier intervals with lower water tables and oxidation of organic matter, supporting the general view of episodic subaerial exposure of the site. Given the very flat topography of the lake basin, the presence of wetlands with small ponds at LV4 does not refute the existence of a paleo-Vertisol elsewhere in the central basin of the

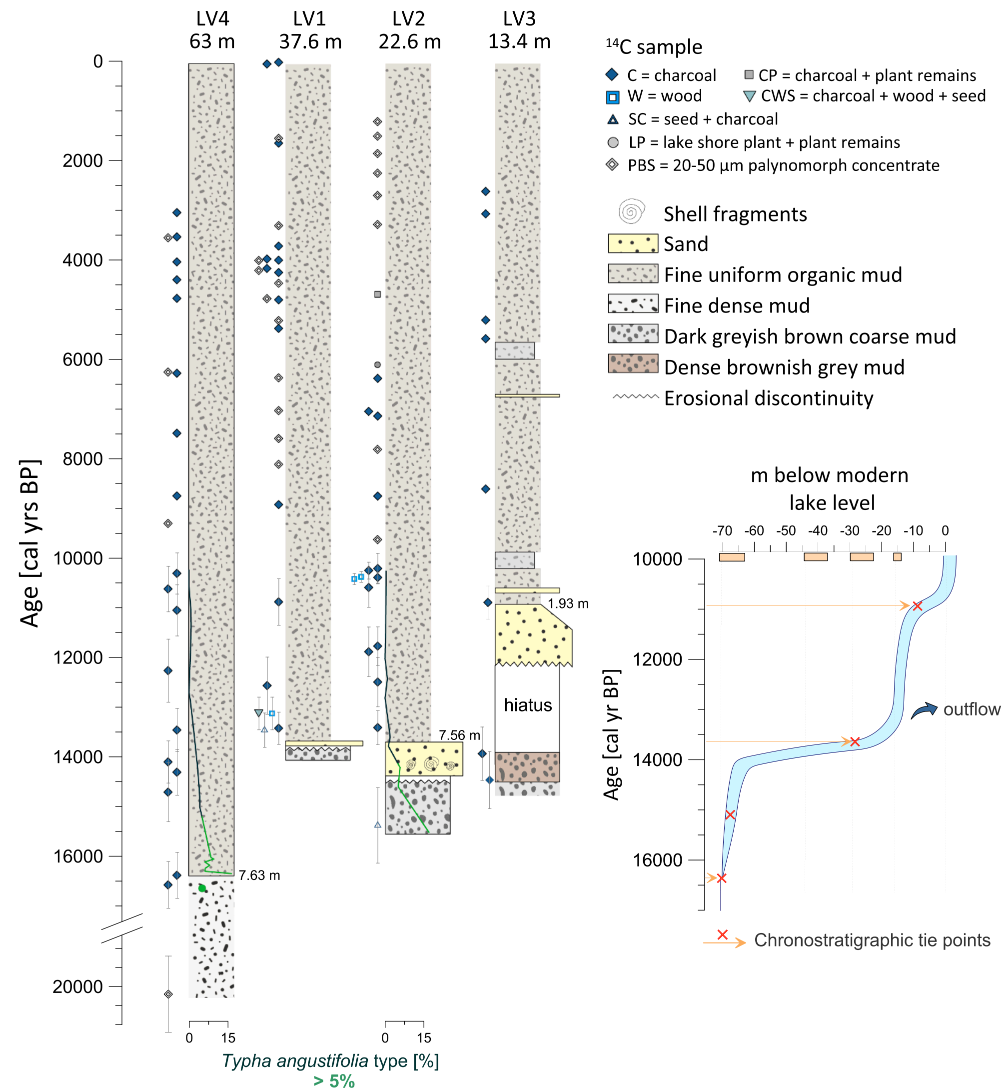

Fig. 2. Chronology and lithostratigraphy of cores LV4, LV1, LV2 and LV3 along the transect and inferred lake-level changes 20.2–10 ka. Typha angustifolia type pollen (>5 % light green) suggest local stands of cattail and wetland environments (Temoltzin-Loranca et al., 2023). The widths of the stratigraphic column indicate grain size differences. Diamonds indicate ^{14}C Bacon model ages (95 % C.I. only for dates within the discussed period > 10 ka) (Temoltzin-Loranca et al., 2023; data for LV3 in ESM Fig. S2 and Table S2). The inset shows the lake-level reconstruction including stratigraphic tie points (main text) with an uncertainty envelope (±5 m) and the lake overflow event (blue arrow). The four bares along the x-axis indicate the cores. See ESM Fig. S3 for detailed geochemical/physical properties. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lake at the same time (Fig. 5A).

An initial, weak, and limited increase in moisture is inferred to have occurred between 16.4 and 15.0 ka. The continuing presence of abundant *Typha* pollen (>5 %) and sponge spicules at the offshore site (LV4, 63 m.b.l.l.) and the near shore site (LV2, 22.6 m.b.l.l.; >15 % *Typha* pollen; Fig. 2) suggest extended and persistent wetland conditions at both sites. Increasing Rb/K values, interpreted as indicating erosional input from the catchment, and chemical weathering of lithogenic material (Burnett et al., 2011; Davies et al., 2015) remained at low levels (Fig. 3). This suggests that transport of poorly weathered lithogenic material from the catchment was limited under generally dry conditions. The relatively high δ^{15}N values observed in this part of the core are typical for soil organic matter N sources from a grassland-dominated catchment under still relatively dry conditions and N starvation, or caused by local N limitation in the wetlands (Temoltzin-Loranca et al., 2023; Williams et al., 2006). Our data do not support a major lake transgression for this period as proposed by Stager et al. (2011). Instead, the synchronous presence of permanent wetlands across a large horizontal and vertical gradient in the lake basin (from sites at 63 to 22.6 m. b.l.l.) suggests that shallow water bodies, possibly sustained by near-surface groundwater tables and/or local surface runoff, persisted simultaneously in large parts of the basin with its nearly flat topography. Local geomorphic processes, such as by animal activity, and/or erosion, may have played a role in promoting the formation of wetlands (Tooth and McCarthy, 2007). Nevertheless, steadily decreasing *Typha* pollen at the deep-water site LV4 suggests gently increasing water tables from 16 ka onwards and a growing distance from the local *Typha* stands at the lake shores. Given the nearly flat topography of the lake basin, only a very subtle rise in lake level would create a substantial increase in distance between the *Typha* stands and the core site. A permanent and widespread shallow lake close to the elevation of LV4 would correspond to a very shallow < 5 m-deep lake covering roughly < 25 % of the modern surface with an extensive zone of fringing wetlands (Fig. 5A). It is conceivable that perennial wetlands with ponds occupied large parts of the basin.

Evidence for a second desiccation event 15.9 – 14.2 ka (Stager and Johnson, 2008; Stager et al., 2011; Fig. 4) is absent in LV4. Instead, our record reveals continuous sedimentation of fine sediment with lower

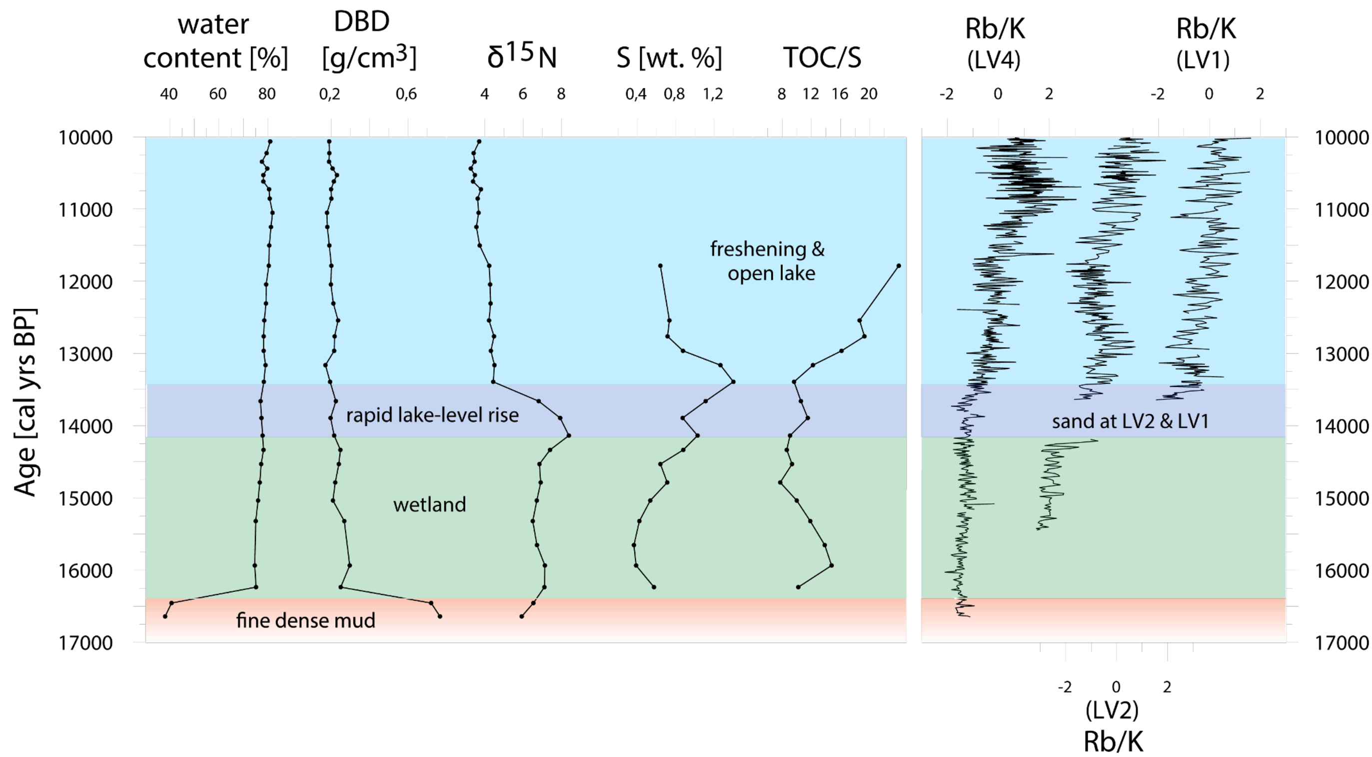

Fig. 3. Water content, dry bulk density (DBD), $\delta^{15}N$, total S and TOC/S ratios from core LV4 indicating the dry conditions prior to 16.4 ka (brown), the wetland period (green), the rapid lake-level rise 14.2–13.6 ka (dark blue) and the freshening and open system of Lake Victoria after 13.5 ka (light blue). The Rb/K ratio is standardized for better comparison between the coring sites (LV4, 1, and 2). Higher Rb/K values indicate erosion and input of poorly weathered lithogenic material from the catchment with increased humidity. The Zr/Ti ratio depicts a very similar trend as Rb/K (not shown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bulk density and higher organic matter content 15 – 14 ka (Fig. 3 and ESM S3). Rb/K (at site LV4 and LV2) and $\delta^{15}N$ remain at constantly low and high levels, respectively, suggesting that a drastic change in the environment was unlikely during this period. Also, sedimentation rates remained unchanged (5 mm yr^{-1}, Temoltzin-Loranca et al., 2023) suggesting uninterrupted wetland or very shallow lake conditions at that site (Fig. 5B) with nearby or local *Typha* stands (around 5 % *Typha* pollen). During this same time period, local *Typha* stands persisted concurrently at high elevation in the lake basin (LV2, 22 m.b.l.l.), where dark greyish, coarse mud formed at that time (Fig. 2 and ESM S3).

Between 14.0 and 13.6 ka, we observe a phase of very rapid uninterrupted lake-level rise. At site LV2 (22.6 m.b.l.l.), local stands of *Typha* disappeared, and wetland deposits were replaced by lacustrine littoral deposits (sand with mollusk fragments) prior to 13.6 ka. Continuous lacustrine environmental conditions were established at LV2 site (22.6 m.b.l.l.) by ~13.6 ka (Fig. 2). At the near-shore site (LV3, 13.4 m.b.l.l.) dense, brownish-grey mud was deposited but partly reworked and eroded possibly due to littoral wave action (hiatus in LV3, Fig. 2). The simultaneous replacement of littoral deposits with pelagic deposits at LV1 (37.6 m.b.l.l.) and LV2 around 13.8 – 13.6 ka is chronologically well constrained and suggests a very rapid lake transgression, over a timespan of a few hundreds of years. A 40–50 m deep lake was established by ~13.6 ka (Fig. 5C), an inference which is also supported by observations from the coastal cores Ibis-1 and P2 in the northern part of Lake Victoria (Dommain et al., 2022; Stager, 1984; Stager et al., 2002; Talbot and Livingstone, 1989). In the central part of the lake (LV4), Rb/K gradually increased, which is interpreted as indicating enhanced erosional input from the catchment and stronger K leaching from soils under more humid climatic conditions. $\delta^{15}N$ values decreased sharply during the lake-level rise at both LV4 and V95-P2 (Talbot et al., 2006), suggesting the rapid lake transgression between 14.0 and 13.6 ka (Fig. 5C) was a basin-wide phenomenon. Low $\delta^{15}N$ may result from greater N input from the catchment, as has been suggested in Lake Albert (Talbot et al., 2006), and/or increased atmospheric N fixation from cyanobacteria and reduced denitrification in an open basin, as has been suggested for Lake Titicaca (Ballantyne et al., 2011).

Shortly thereafter (13.5–13.2 ka), the lake level reached topographic outflow as suggested by a step change in the S and TOC/S profiles, and a stabilization of $\delta^{15}N$ at consistently lower values in LV4 (Fig. 3), very similar in the structure and timing (within the chronological uncertainty) as found in V95-2P (Talbot et al., 2006). Rb/K values further increased at both sites LV4 and LV2 (Fig. 3). TOC/S ratios, often used as a salinity indicator (Cohen, 2003) increase sharply and indicate freshening due to lake overflow 13.4 ka (Fig. 3). Likewise, the decreasing trend of $\delta^{15}N$ and the subsequent stabilization at lower values could reflect a combination of (i) a source shift away from the terrestrial soil-derived N towards more aquatic N sources, and/or (ii) a decrease in denitrification rates as the system becomes more hydrologically open (Ballantyne et al., 2011). The lake overflow and freshening at that time is temporally consistent with Sr isotope data from the White Nile domain (Talbot et al., 2000) and $\delta^{18}O_{cellulose}$ data from core V96-7P (Beuning et al., 2002).

Thereafter, Rb/K and $\delta^{15}N$ values in the central part of the lake (LV4) remained constantly high and low, respectively, suggesting sustained erosional influx of lithogenic material and nutrients in a wetter climate and hydrological boundary conditions that support a permanent large lake with an outflow during most of the time. We do not find evidence in the $\delta^{15}N$ or TOC/S data for longer periods of closed-basin conditions and prolonged periods with increased aridity, for instance during the Younger Dryas (YD, ca. 12.8 – 11.7 ka). Water levels quickly reached the near-shore site LV3 (13.4 m.b.l.l; Figs. 2 and 5D). However, sedimentation is discontinuous at that site and the large scatter of ^{14}C dates in the 20 cm sand deposit (Fig. 2, ESM S2 and S3) suggests sediment reworking under wave action and fluctuating lake levels at high stages. Following

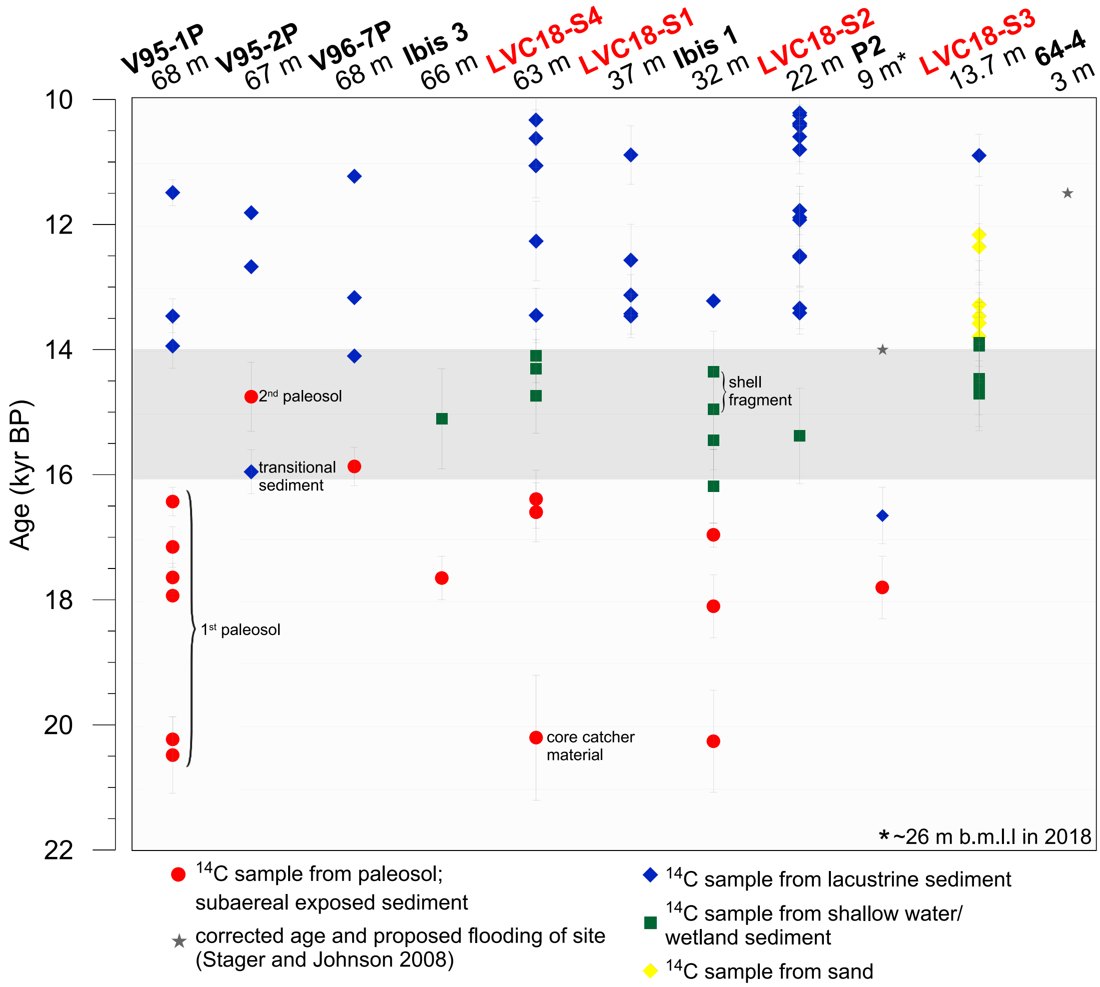

Fig. 4. Compilation of calibrated radiocarbon ages (with uncertainty ranges where available in the literature) and corresponding environmental interpretations from Lake Victoria sediment records sorted by water depth at the coring site: V95-1P (Johnson et al., 1996; Lane et al., 2018); V95-2P (Johnson et al., 1996; Talbot and Lærdal 2000; Stager et al., 2002, the basal calibrated radiocarbon ages differ between published chronologies); V96-7P (Beuning et al., 2002; Stager et al., 2002; Ibis 3: Talbot and Livingstone 1989; Stager et al., 2002); LVC18-S1-4 (Temoltzin-Loranca et al., 2023; this work marked); Ibis 1/Damba Channel (Stager and Johnson 2008, Stager et al., 2011); P2 and 64-4 (Kendall 1969; Stager and Johnson 2008). Note that coastal cores P2 and 64-4 have much higher sedimentation rates and the lacustrine sediments have a lower topographic position (26 m.b.l.l.). Red circles indicate dated sediments interpreted mostly as subaerial exposed deposits or paleo-Vertisols, possibly with local episodic wetlands, suggesting a consistent picture of very dry conditions prior to 17 ka and ending by 16 ka at latest. Green squares represent sediment interpreted as shallow water and wetland conditions. Diagnostic features include Typha pollen (>5%, Temoltzin-Loranca et al., 2023), low hydrogen index values (Ibis 1 and 3; Talbot and Livingstone, 1989) or abundant brackish water diatoms (Ibis 1; Stager et al., 2011). Blue diamonds indicate sediments deposited in deeper lacustrine conditions and flooding at the coring sites. Yellow diamonds mark ^{14}C dates in littoral sand deposits with significant reworking and age inversions. The grey shading marks the discussed period of heterogenic sediment features and diverging interpretations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

this dynamic phase, continuous lacustrine deposition started at the shallow water site LV3 10.8 ka (Figs. 2 and 5D), marking yet another lake-level increase to modern or even above modern levels (Stager and Johnson, 2008; Stager and Mayewski, 1997). Rb/K values (at LV4) reach maximum levels ca. 11 ka, possibly suggesting maximum humidity (African Humid Period), although a decrease thereafter could have results from landscape stabilization under rainforest expansion (Temoltzin-Loranca et al., 2023; Fig. 6).

5. Latest Pleistocene environmental and regional climatic change

Lake Victoria's refilling history is consistent with dry conditions in the Latest Pleistocene prior to ~15 ka and the transition to much wetter conditions at the onset of the African Humid Period, starting between 15 and 13 ka, is widely observed in equatorial Eastern African paleoclimate records (Fig. 6; Gasse, 2000; Wolff et al., 2011; Junginger and Trauth, 2013; Otto-Bliesner et al., 2014; Shanahan et al., 2015; Castañeda et al., 2016; Loakes et al., 2018).

Closed-lake basins, such as Lake Victoria prior to 13.6 ka, are excellent recorders for past hydroclimatic changes, because they respond very sensitively to changes in P-E and adjust lake levels immediately to even subtle climatic changes. Today, the water budget of the lake is mainly controlled by direct precipitation and evaporation (Yin and Nicholson, 1998). A climate-water-budget model for Lake Victoria (Beverly et al., 2020) suggests that, depending on paleoclimate scenarios including temperature, precipitation, and orbital forcing, Lake Victoria can completely dry out and re-fill to modern levels within centuries to a few millennia. Importantly, in the flat lake basin, small changes in water depth translate into large changes in lake surface area (Olaka et al., 2010). This has three important implications which that act as positive feedbacks to the lake's water balance: (i) changes in the fraction of lake surface versus land strongly influence the water balance of the lake (runoff coefficient today 9 %, Crul, 1995), (ii) a large lake has

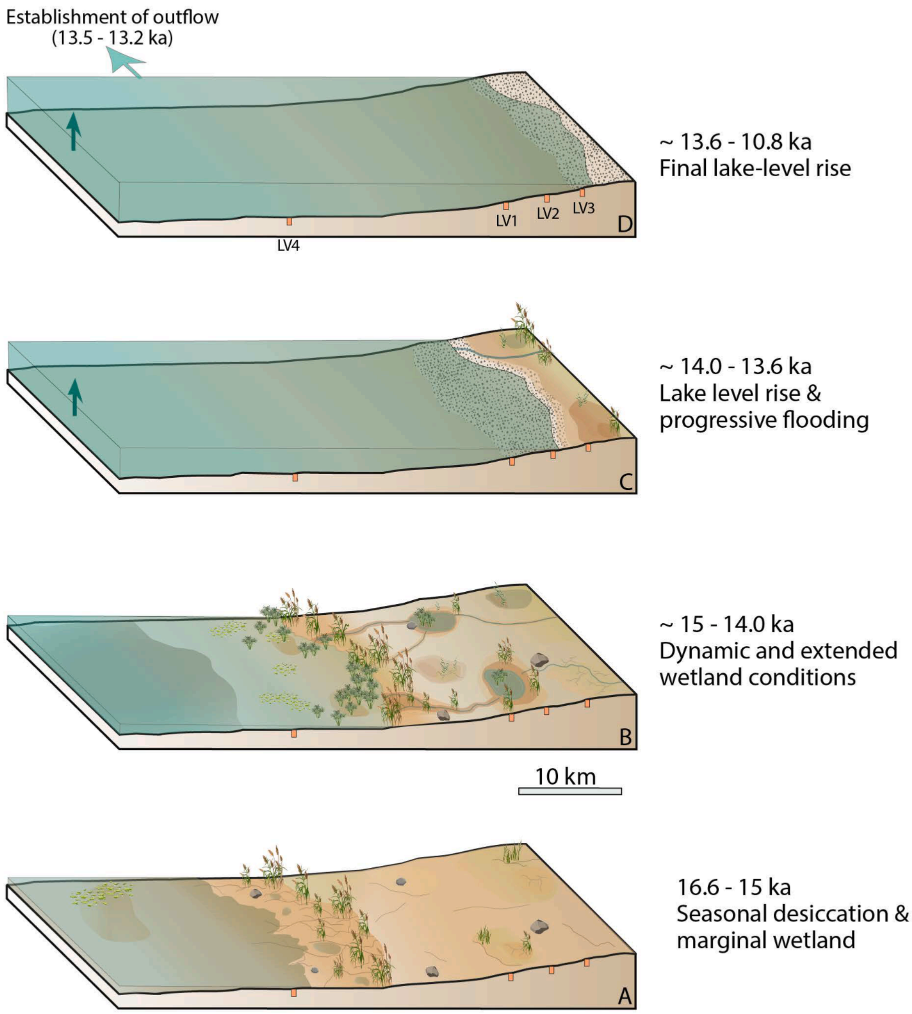

Fig. 5. Lake transgression and wetland formation in the Lake Victoria basin across the transect LV1-4 from 16.6 to 10 ka with coring sites (orange bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

higher cloudiness which reduces evaporation (Yin and Nicholson, 1998) and, (iii) the size of the lake controls precipitation in the catchment; today ca. 80 % of the inflow in Lake Victoria is recycled moisture from the large lake itself (Beverly et al., 2020; Yin and Nicholson, 2002). Accordingly, Lake Victoria would dry out within centuries if precipitation rates fell below 75 % of modern values (Beverly et al., 2020). Conversely, and depending on the temperatures, the Latest Pleistocene dry lake basin would fill up to modern levels within a few centuries if precipitation rates are close to modern and runoff is generated in the catchment (Beverly et al., 2020), implying that there is only a narrow hydroclimatic range that keeps the lake between desiccation and overflow. This paleoclimatic scenario and hydrological response of Lake Victoria (Beverly et al., 2020) could well explain the rapid lake-level increase inferred from our data between 14 and 13.5 ka.

Hydroclimate also directly influences terrestrial vegetation and fire regimes in the catchment of Lake Victoria (Karp et al., 2023; Temoltzin-Loranca et al., 2023). Therefore, information on past vegetation dynamics and fire regimes serves as an independent validation of the lake level reconstruction's implications for paleoprecipitation. Pollen analysis on LV4 (Temoltzin-Loranca et al., 2023) shows that, prior to 13.5 ka, the area was dominated by savanna grasslands with only very small traces of mesophilous Afromontane vegetation (e.g., *Olea, Podocarpus*). Flammable biomass and fire activity was persistently low but increased slightly between 15 and 14 ka (Temoltzin-Loranca et al., 2023). This corresponds well with generally dry conditions and only weakly increased moisture after 15 ka as inferred from the lake level reconstruction (Figs. 3, 5, and 6). The rapid lake-level rise after 14 ka is largely synchronous with a substantial increase in Afromontane vegetation after 13.5 ka; local stands of *Olea* and *Podocarpus* established after 13.5 ka (Temoltzin-Loranca et al., 2023). Rainforest expands continuously after 10.7 ka, synchronously with the shift in $\delta D_{leaf\ wax}$ (Fig. 6, Berke et al., 2012) and the final lake-level rise to modern or above modern levels. Rb/K values reach their maximum and decrease with the expansion of the rainforest after 11 ka.

The temporal link between Lake Victoria's low lake levels and Heinrich Event H1 at ~16 ka and shifts in the monsoon and Congo Air Boundary is well described and emphasizes the orbital and greenhouse gas forcings as well as teleconnections with North Atlantic meltwater/SST and Indian Ocean forcings (Castañeda et al., 2016; Otto-Bliesner et al., 2014; Stager et al., 2002). Similar observations have been made for other lakes in the East African Rift (Junginger and Trauth, 2013; Loakes et al., 2018, among others). Relative aridity has been documented in multiple records from tropical Africa and the Nile Basin between 18 and 16 ka, followed by an increase in humidity until 14–13 ka and a marked drying during the Younger Dryas (YD) ~12 ka (Fig. 6; Berke et al., 2012; Castañeda et al., 2016; Loakes et al., 2018). Our findings are consistent with this picture, although the moisture increase in Lake Victoria after 16 ka was rather weakly expressed and delayed compared with lipid-biomarker records from Lake Tanganyika (Fig. 6) and the northern Nile Basin (Castañeda et al., 2016). But the timing in

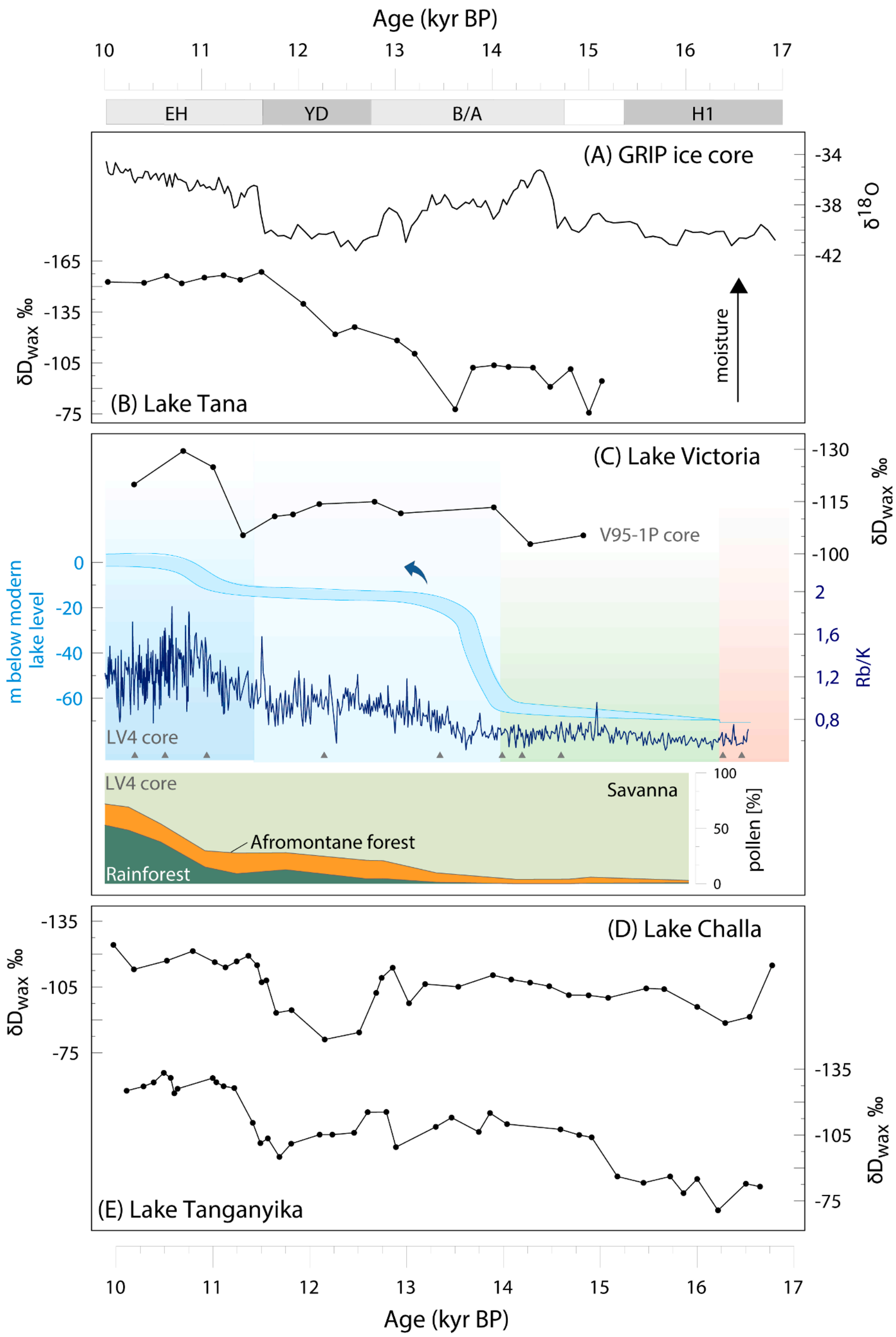

Fig. 6. The Lake Victoria record (this study) in the context of regional and global paleoclimate records 17–10 ka including the Oldest Dryas/H1 Event, the Bølling–Allerød B/A, the Younger Dryas YD, and the Early Holocene EH. δD leaf wax indicates hydroclimate variability (amount and source effects). A) δ18O from NGRIP (Grootes et al., 1993), B) δD leaf wax of Lake Tana (Costa et al., 2014), C) Lake levels from Lake Victoria and Rb/K of LVC18-S4 (this study); catchment vegetation (Temoltzin-Loranca et al., 2023); δD leaf wax of Lake Victoria (Berke et al., 2012), The colored background highlights the periods of seasonal desiccation, extended wetland conditions and high lake levels in Lake Victoria, the blue arrow indicates the outflow event (Talbot et al., 2000, Beuning et al., 2002). Grey triangles indicate ^{14}C ages for LV4 (Temoltzin-Loranca et al., 2023). D) δD leaf wax of Lake Challa (Tierney et al., 2011), E) δD leaf wax of Lake Tanganyika (Tierney et al., 2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Lake Victoria goes along with most records in tropical West and Eastern Africa 0-5°N that do not show the significant and abrupt hydroclimatic change before 14 ka (Shanahan et al., 2015; Loakes et al., 2018). Aside of chronological disparities, it is most conceivable that, depending on (i) the paleoclimatic proxy used and (ii) the type of site-specific (eco)-hydrological linkage between water in precipitation and plants (Bodé et al., 2020), the timing of the reconstructed hydroclimatic change differs from site to site. Additionally, orographic effects might determine regional, and site-specific atmospheric hydroclimate conditions. Given the flat topography of the Lake Victoria lake basin, the role of runoff from the catchment, positive cloud-evaporation feedbacks and the overflow at the level of the sill, the lake level variability of Lake Victoria was mostly driven by non-linear processes and thresholds (of surface runoff and/or overflow). As a consequence, the response would be expected to be somewhat different from other sites in tropical Eastern Africa. This may also explain why, compared with other records from lakes Challa and Albert and model simulations (Fig. 6; Tierney et al., 2011; Otto-Bliesner et al., 2014), the Younger Dryas (YD) drying is poorly expressed in our records, possibly with the exception of the sediment hiatus and sand layer in LV3 (Fig. 2) and a plateau or even a local minimum in the general Rb/K increase in LV2 and LV4 between 13 and 12 ka (Fig. 3). The YD drying was apparently not long and/or strong enough to convert the open lake system into a closed lake system, which would be clearly detectable in our proxies from the more profundal sites.

In general, the two periods of rapid lake-level rise in Lake Victoria (14.0–13.5 ka and 11 ka) align with major northern hemisphere warming events: the onset of the Bølling–Allerød (here mostly the Allerød) and the onset of the Holocene. Both events are associated with abrupt intensification of the East African monsoon system (Overpeck et al., 1996; Shanahan et al., 2015). Paleoclimate model simulations suggest that these abrupt increases in precipitation in tropical and subtropical Africa are attributable to a combination of orbital and greenhouse gas forcings, North Atlantic meltwater forcings and western Indian Ocean sea surface temperatures (Otto-Bliesner et al., 2014), possibly enhanced by land surface – climate feedbacks (Shanahan et al., 2015).

However, when examined in detail, Latest Pleistocene hydroclimatic variability in Eastern Africa between 14 and 13 ka seems to show a spatially and temporally heterogeneous pattern that is still not fully understood (Berke et al., 2014; Loakes et al., 2018). This seems particularly to be the case for $\delta D_{leaf\ wax}$ proxies which are not only related to the ‘amount effect’ (effective moisture) but also to the ‘source effect’ (Costa et al., 2014; Atlantic versus Indian Ocean moisture sources). Accordingly, shifts in $\delta D_{leaf\ wax}$ may also be modulated by topographic features and/or displacements of the Congo Air Boundary which further complicates a convergence of different single-site interpretations into a consistent paleoclimatic picture (Junginger and Trauth, 2013; Costa et al., 2014; Berke et al., 2014; Castañeda et al., 2016; Loakes et al., 2018; Fig. 6).

6. Conclusions

We conclude from our data that Lake Victoria experienced widespread desiccation with localized seasonal wetlands between ~20.2 and 16.7 ka. A first moisture increase 16.7–15.0 ka established permanent wetlands with very shallow ponds in the center of the Lake Victoria basin surrounded by a savanna landscape with predominance of grasses. Subsequently, moisture levels further increased; a shallow permanent lake was formed and wetlands extended across most of the lake basin around 14.5 ka. A final lake-level increase occurred between ~14.0 ka until 13.5 ka, when the lake reached outflow levels with concurrent expansion of Afromontane and rainforest vegetation. The beginning of the Holocene (after 11.5 ka) is marked by a second significant increase to modern, or even above-modern lake levels and a landscape dominated by rainforest vegetation. This revised history of the Lake Victoria drainage basin hydroclimate variability may serve, among others, as a basis to further test ecosystem responses to hydroclimate change. It can also help to assess to which extent the desiccation and refilling history and subsequent lake-level changes, as well as emerging hydrological connectivity of river systems in Eastern Africa were constraining and driving pacemakers for the evolution of the lake’s endemic species richness and the species dispersal and range dynamics of terrestrial species.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jglr.2023.102246.

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