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Hydroclimate changes in eastern Africa over the past 200,000 years may have influenced early human dispersal

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Reconstructions of climatic and environmental conditions can contribute to current debates about the factors that influenced early human dispersal within and beyond Africa. Here we analyse a 200,000-year multi-proxy paleoclimate record from Chew Bahir, a tectonic lake basin in the southern Ethiopian rift. Our record reveals two modes of climate change, both associated temporally and regionally with a specific type of human behavior. The first is a long-term trend towards greater aridity between 200,000 and 60,000 years ago, modulated by precession-driven wet-dry cycles. Here, more favorable wetter environmental conditions may have facilitated long-range human expansion into new territory, while less favorable dry periods may have led to spatial constriction and isolation of local human populations. The second mode of climate change observed since 60,000 years ago mimics millennial to centennial-scale Dansgaard-Oeschger cycles and Heinrich events. We hypothesize that human populations may have responded to these shorter climate fluctuations with local dispersal between montane and lowland habitats.

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Reasons for the mobility and dispersal of *Homo sapiens* both within and out of Africa are still a matter of debate[1]. Recent discoveries of human fossils and related stone tools between ~315 and 75 ka in age in several parts of Africa (e.g., northern Africa[2], southern Africa[3,4], and eastern Africa[5,6]) have initiated a lively discussion of hypothesized multiregional origin and development of *Homo sapiens* within Africa[7]. This hypothesis includes a temporary availability of suitable, interconnected habitats, providing sufficient resources for our species to succeed and establish vital populations. Understanding human origins, refugia and dispersal is therefore dependent on accurate reconstructions of climatic and environmental conditions in time and space.

Today, the climate of eastern Africa is controlled by the annual migration of the tropical rain belt (TRB) following the zenith of the sun with a 3–4 week lag. This intensive insolation causes the build-up of mesoscale convective systems (MSCs), modulated by the possible influence of the West African (WAM) and South Asian (Indian) (SAM) monsoons, causing a unimodal to trimodal distribution of rainfall. On an interannual time scale, zonal atmospheric flow associated with the Walker Circulation (WC) and anomalies of the Indian Ocean sea-surface temperatures (SSTs) in combination with the Indian Ocean Dipole (IOD), modulate the intensity of the rainy seasons in eastern Africa[8,9] (Supplementary Fig. S1). These controls are subject to orbital and millennial-to-centennial scale fluctuations, which have led to significant past fluctuations in regional precipitation and to habitat change, forcing the biota to adapt, migrate, or face local extinction[10–14].

Recently, geoscientists, climate experts, and paleoanthropologists have teamed up within the Hominin Sites and Paleolakes Drilling Project (HSPDP) to examine the relationship of human origin and climate change by drilling paleolake sequences near important hominin fossil and artifacts sites in the East African Rift[15,16]. In addition, other studies of this region have investigated outcrops of lake sediment to reconstruct past climate variation and possible influences on human evolution, expansion, and technological innovation[13,17]. These studies found that eastern African climate and environment have undergone repeated profound wet-dry transformations during the Quaternary, including the formation and disappearance of extensive lake systems accompanied by regional vegetation change. These transformations are often linked to orbitally-controlled insolation variations and millennial-to-centennial fluctuations associated with the high-latitude Dansgaard-Oeschger cycles (D/O) and Heinrich events (HEs)[13,18–20]. In addition to climate change, lakes also fluctuate from non-climatic drivers, complicating reconstruction of climate fluctuations from these deposits[13].

Using archives of environmental change to test established hypotheses of the evolution and expansion of *H. sapiens* is complicated by the potentially complex and non-deterministic response of humans to external natural factors[21], which may vary due to social factors (i.e. relation to neighboring groups) and individual choices[22]. In addition, technological advances may have facilitated the ability of humans to cope with and adapt to climatic stress[23,24]. The refugial hypothesis suggests that *H. sapiens* survived times of harsher living conditions, as small populations were able to move into more suitable environments with attendant consequences for genetic drift and natural selection[25]. In eastern Africa, humans may have occupied mountain refugia along the rift margins[26–28].

To better understand the relationship between past climate change and the behavioral and migratorial response of *H. sapiens*, we reconstructed the last ~200 ka of eastern African climate change based on a sediment drill core collected in the Chew Bahir (CHB), a paleo-lake basin in southern Ethiopia (Fig. 1). Our geochemical and sedimentological data set provides the first continuous climate record from southern Ethiopia covering the entire period of existence of *H. sapiens* in eastern Africa. Fossil evidence from the key paleoanthropological sites at Omo Kibish[6] and Herto[5] show that humans have occupied parts of Ethiopia during the last ~200,000 years. Our results can contribute to the current discussion regarding the effect of environmental conditions on the mobility and expansion of our species within and beyond Africa[1,29,30].

Results

The 292.87 m long composite sediment core from Chew Bahir covers the last 617 ka of environmental change in the southern Ethiopian rift. Based on our age model, the uppermost 99.3 mcd (meters composite depth) encompass the last ~200 ka[31,32]. For this study, we have combined sedimentological and geochemical proxies of environmental change, including grain-size variability, X-ray fluorescence (XRF) scanning-based elemental ratios (K/Zr, Al/Si, Ca/Ti), as well as total organic carbon (TOC) and the oxygen isotope composition ($\delta^{18}O$) of endogenic calcite (Supplementary Figs. S2 and S3). Our results show that high amounts of coarser-grained sediments (core sections with > 50% sand marked as gray bars in Supplementary Fig. S2) mostly coincide with lower K/Zr, higher Al/Si and Ca/Ti ratios, higher TOC, lower $\delta^{18}O$ values and vice versa.

Dry climate episodes at Chew Bahir, with increased evaporation, increased lake water alkalinity and salinity, and lowered lake levels have been inferred from the low-temperature illitisation of smectites in other cores from the site[33]. During illitisation, also called reverse weathering process, which is initiated by increasing alkalinity and salinity in the pore water, Al-to-Mg substitutions lead to excess octahedral layer charge, which in turn enhances the K fixation in smectites[34]. Hence, we interpret high K values as having developed during desiccation and low lake levels, similar to modern conditions.

Hydrologic-balance modeling shows that during the last wet phase, the so-called African Humid Period (AHP) at ~15–5 ka, with significantly lower K values, a precipitation increase of ~20–30% may have raised the Chew Bahir lake level by up to ~45 m compared to the present seasonally dry playa[35]. Drier phases in the record are also generally characterized by an increase of silt-sized sediments, reduced chemical weathering (low Al/Si ratios), less organic matter accumulation reflected in lower TOC values, and higher $\delta^{18}O$ (Supplementary Fig. S3).

Changing Ca/Ti-ratios in the profile could be explained by processes dominating during contrasting hydrological conditions. For example, Ti may increase through fluvial input during wet episodes, or aeolian input during dry episodes. Additionally, the increased formation of authigenic carbonates in the sediment during dry phases could have raised Ca/Ti ratios while reduced carbonate production by organisms with calcareous shells during dry periods could have lowered them.

Clay-sized particles, indicative of deep lake conditions, are generally only a minor component of the sediment (a mean of ~3% of all grain size samples). However, sand layers often alternate with clay-rich beds (up to max. 39% clays) in the 61–100 mcd core interval (corresponding to ~200–125 ka; Supplementary Figs. S2 and S3). Silt-sized particles are much more abundant throughout the record (mean of 39%), but dominate (60–80%) in the uppermost 31 mcd (last ~60 ka). We interpret these medium-coarse silts to represent predominantly aeolian transport during more arid episodes.

Medium-grained sand layers are most common below 45 mcd (older than ~80 ka), indicative of more humid conditions when rivers were active and transporting coarser material. In addition,

Fig. 1 Location maps. a Map of Greenland and location of NGRIP ice core; **b** Map of northeastern Africa, the Near East, and southeastern Europe showing important fossil and archeological sites; **c** Map of northeastern Africa showing the location of the Chew Bahir drill site as well as important fossil and archeological sites. See text for details, data and references.

we argue that very fine silt and lacustrine clays were deposited during more humid periods when the precipitation/evaporation ratio was >1, and a deep water body covered the sedimentary deposits for extended periods of time. Individual layers of very coarse sands are interpreted as reactivation products of the extensive alluvial fans at the western shores and surrounding ranges of the Chew Bahir basin, suggesting extreme rainfall events during a generally drier climate with reduced vegetation cover in the catchment[36].

Based on similar trends in our multi proxy data, namely the records of the K/Zr and Al/Si ratios, and the $\delta^{18}O$ values, we identify five distinct climate phases (Supplementary Fig. S3). The first wet phase (Phase I) between 200–125 ka was followed by Phase II which is characterized by a pronounced trend towards a drier, but also more variable climate from 125 to 60 ka. Thereafter, a dry phase (Phase III) between 60–14 ka can be observed in the K/Zr ratios and in the $\delta^{18}O$ values, which is succeeded by a wet phase (Phase IV; 14-5 ka) spanning the Early to Middle Holocene, which coincides with the well-established AHP (~15–5 ka)[36–38]. During Phase V in the Late Holocene (between ~5–0 ka), the climate at Chew Bahir was persistently dry.

During Phases I and II (200–125 ka and 125-60 ka) we observe periodic alternations between wet and dry episodes on time scales of ~20 ka superimposed on the long-term drying trend. This relatively low frequency climate variability is superseded during the interval between 60–14 ka (Phase III) by repeated millennial-to-centennial scale abrupt shifts back to wetter climate conditions. Hence, we can distinguish between two distinct modes of climate change with low and high frequency climate variability at CHB, as can be seen particularly well in the K/Zr ratios, but also in other proxies such as Al/Si and Ca/Ti ratios. These observations are reiterated in the wavelet time-series analysis (Supplementary Fig. S4), which shows the strong influence of orbital precession between 200–125 ka, and which diminishes after about 80 ka, consistent with modeling results for the region[18].

Discussion

We observe five climate phases including two modes of climate variability in the CHB during the last 200 ka (Supplementary Fig. S3). To explain this variability, we first compared our results to orbital eccentricity and precession (Fig. 2). Changes in these orbital parameters have been previously argued to be the dominant driver of eastern African climate variability[21,39]. Phase I (200–125 ka) coincides with high eccentricity and strongly precession-dominated insolation changes, potentially driving the ~20 ka paced alternations between the well expressed wet and dry episodes during this time interval. In this scenario, precession minima/maxima, associated with high/low summer insolation led to a more/less northerly position of the African rainbelt, which could channel moisture towards CHB. The increased eccentricity thereby amplifies the effect of precession on the monsoonal changes and leads to either strongly expressed wet or dry episodes.

In contrast, during Phase II (125–60 ka), the gradual increase in aridity was accompanied by a lowering of the precession amplitude concurrent with decreasing eccentricity (Fig. 2; Supplementary Fig. S4). This reduced precessional amplitude led to an overall reduction in moisture transport towards CHB, causing a long-term drying trend. During Phase III (60–14 ka) eccentricity reaches its lowest value of the past 200 ka, with substantially subdued precessional amplitude and thus lower summer insolation. Consequently, the overall low insolation levels led to a contraction of the African rain belt and thus a precipitation focus south of the CHB watershed.

During Phase IV (14-5 ka) eccentricity increased again, associated with slightly wetter conditions before decreasing during Phase V (5 ka to present) in alignment with a drier climate. The close match between the hydroclimate at CHB and orbital eccentricity clearly demonstrates that orbital-scale insolation changes are the dominant driver of southern Ethiopian climate during the last 200 ka. We also find indications that periods with low insolation (low eccentricity) and reduced monsoonal impact may also be subject to a different climate driving mechanism, as suggested by the observed high-frequency climate variability during Phase III.

In the wider regional context, a comparison of the CHB record with the leaf-wax based vegetation and alkenone-based SST record from Gulf of Aden core RC09-166 suggests that during high eccentricity (Phase I; Marine Isotope Stage = MIS 7a to MIS 5e) the western Indian Ocean experienced a significant warming that decreased with decreasing eccentricity during Phase II and III (Fig. 2). As the Indian Ocean presents an important moisture source for eastern Africa today[40], arguably the warm SSTs during Phase I might have led to increased oceanic convection. When the African rain belt reached CHB during summer solstice (precession minimum), this increased oceanic convection may then have fueled the transport of moisture charged air masses to CHB. These findings underline the close link between hydroclimate in eastern Africa and Indian Ocean SSTs throughout the time covered by our core.

In contrast, the comparison between the CHB K/Zr ratio and the aridity indicated by the leaf wax proxy from the Gulf of Aden[41] shows remarkable differences during Phase I (MIS 6: Fig. 2). In fact, the overall persistent humid conditions at CHB during this interval are seemingly opposite to persistent aridity in regions adjacent to the Gulf of Aden. The proposed aridity in this region seems peculiar as the neighboring Indian Ocean was relatively warm and should provide sufficient moisture for increased rainfall[41]. A possible explanation could be that convection-based precipitation during this period was more effective south of the Gulf and further inland. In this manner, the discrepancy in the moisture regime between CHB and the Gulf of Aden relates to changes in large-scale atmospheric circulation patterns[41]. Alternatively, it is possible that $\delta D_{leaf\ wax}$, which was used as the basis for the aridity proxy, records changes in moisture source rather than precipitation amount[42,43]. Due to the contraction and widening of the tropical rain belt in correspondence with glacial-interglacial periods, it is possible that the moisture source changed[43] in the Gulf of Aden during Phase I (MIS 6).

Regional climate records from the African mainland support the humidity record from CHB. For example, the wet-dry index from an ocean core at ODP site 967 in the eastern Mediterranean Sea, which is a record of terrestrial dust flux and riverine inflow from the Nile river[44], parallels the CHB record. This is anticipated, since the upper Nile and Chew Bahir catchments are in close spatial proximity[17], thus should record similar climate signals. The match between both proxy records and the sapropel layers emphasizes this tight coupling (Fig. 2) and suggests that increased humidity during Phase I at CHB was also reflected in the Nile River basin, hence into the Mediterranean realm.

Lake Tana, close to the source of the Blue Nile in northern Ethiopia, shows increased moisture availability at least during late Phase I, in line with CHB climate results[45]. The repeated wet phases during Phase II (MIS 5e-5c) are also in agreement with wet phases inferred from the stalagmite record of the Mechara caves situated in the highlands northeast of the Chew Bahir basin[46] (Figs. 1 and 2). The authors also argue for a northern displacement of the African tropical rain belt caused by stronger summer insolation during times of stalagmite growth. The

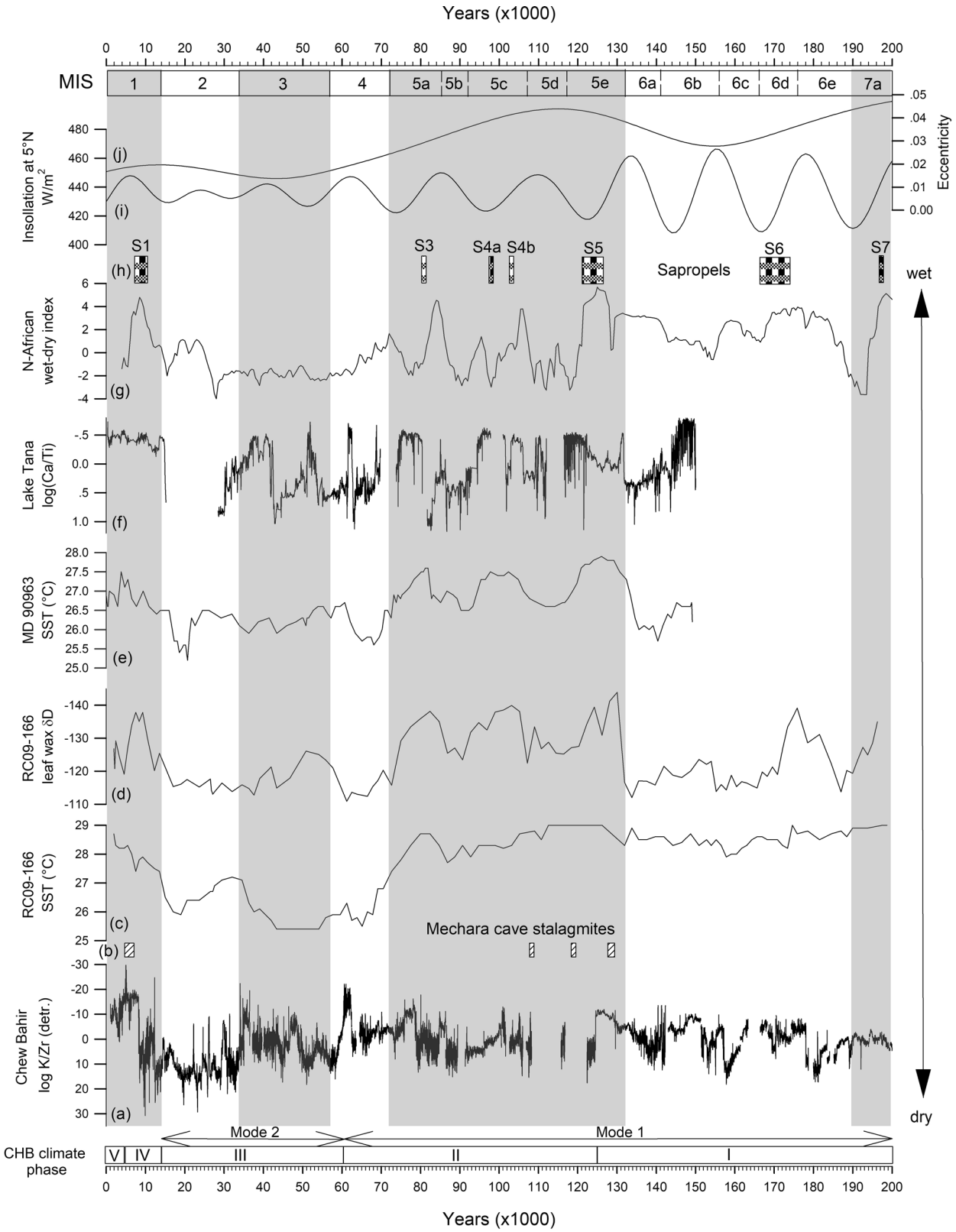

Fig. 2 Comparison of the log(K/Zr) record of the last 200 ka from the Chew Bahir basin (CHB) with other environmental records. a Detrended log(K/Zr) record from Chew Bahir; **b** Rectangles = Mechara cave stalagmite growth phases[46]; **c** Alkenone-based SST and **d** Leaf wax based vegetation record from core RC09-166 from the Gulf of Aden[41]; **e** Indian Ocean sea-surface temperatures (SST)[70]; **f** Detrended log(Ca/Ti) record from Lake Tana[45]; **g** Wet-dry index from ODP 967[44]; **h** Rectangles = sapropel layers[51]; **i** Insolation at 5°N and **j** Eccentricity variation[71]. Gray and white bars correspond to Marine Oxygen-Isotope Stages (MIS) according to[72].

profound aridity during Phase III in Chew Bahir, at a time of reduced insolation levels, is also recorded in the Mediterranean realm and at Lake Tana from 60 to 55 ka, from 50 to 42 ka as well as after 35 ka[45].

The high-frequency climatic shifts during Phase III resemble northern hemisphere climate oscillations known as D/O cycles and HEs (Fig. 2 and Supplementary Fig. S5)[19,20,47]. If the continental African site of CHB is indeed responding in phase with these oscillations, it suggests that at times of low eccentricity and hence diminished precessional amplitude, high-latitude processes increasingly influenced the climate at CHB. During HEs, the increased discharge of meltwater from the Northern Hemisphere ice cover led to a reduction of northward heat transport via the global oceanic conveyer belt[48]. Consequently, heat and warm water accumulated in the tropics and subtropics of the southern hemisphere and the equatorial Atlantic, which led to a strong contraction or southward shift of the monsoonal rainbelt around the globe[49]. This may have resulted in a reduction in monsoonal precipitation at CHB, thus explaining the observed millennial-scale dry spells coincident with HEs. The increased humidity during late Phase IV, corresponding to the AHP, is similar to the moisture variability during Phase I, in alignment with increased eccentricity and precession amplitude. The latter led to a more northward position of the African tropical rainbelt and thus increased humidity at CHB. The inferred moisture increase is again recorded at Lake Tana[45], the Mechara stalagmites[46] and the Mediterranean realm[44].

The significant precipitation changes inferred from the Chew Bahir record would have had a decisive influence on the living conditions of *H. sapiens* present in eastern Africa for at least the last 200 ka. Those profound transformations of the habitat of *H. sapiens* would have required adaptations in behavior or cultural development. The humid conditions observed in the oldest parts of the CHB record presented here (Fig. 3) coincide with the earliest *H. sapiens* fossils recovered to date in eastern Africa at ~195 ka, at Omo Kibish (~430 m asl), 90 km west of the Chew Bahir basin[6]. During this wettest episode of the record (~200–125 ka), with at least 20–30% more precipitation compared to today[35], extensive lakes and connected hydrological networks developed along the East African Rift System (EARS). This may have facilitated the long-distance movement of early modern humans, gathering food and finding sufficient water nearly everywhere in the lowlands of southern Ethiopia and the adjacent regions.

Between 200–190 ka and 185–170 ka, wetter conditions, and thus an expansion of favorable living conditions in large parts of northern and northeastern Africa and the Arabian Peninsula, are suggested by sapropel S7 and S6 at ODP site 967 in the Mediterranean Sea[44,50,51]. This time interval also coincides with the first documented appearance of modern humans in the Levant, at Misliya Cave, with fossils dated at 194–177 ka[29]. We therefore suggest that regions with favorable conditions were episodically connected from southern Ethiopia as far north as the Levant, opening early dispersal routes for *H. sapiens* out of eastern Africa[52] as early as MIS 7a and during some intervals of MIS 6 (Fig. 3). The alignment between wet phases in the CHB record and other paleoclimate records to the NE[44] suggest that these favorable living conditions existed at multiple times not only in the lowlands of eastern Africa but also along the course of the Nile River, providing a pathway for early modern humans to move north.

Pronounced wet conditions were also prevalent during MIS 5e and 5c (Fig. 2) in the highlands northeast of the Chew Bahir basin, as interpreted from the stalagmite $\delta^{18}O$ record from the Mechara caves[46], implying favorable living conditions for humans over nearly all of northeastern Africa. Modern human fossils have been recovered in northeastern Africa and the Levant that date back to these times[4,5]. Moreover, human occupation layers in the Sodmein cave in the Eastern Egypt desert[53] and artefacts and human fossils from Al Wusta in Saudi Arabia[54], Skhul and Quafzeh[55] as well as human footprints in ancient lake sediments[56] also fall into MIS 5. These time windows have also been proposed by population modelers as possible episodes for early modern human expansion[57] (Fig.3).

Genetic evidence points to the interval 70–60 ka for the most recent common ancestor (TMRCA) of mitochondrial haplogroup L3 from eastern Africa[58], fitting reasonably well to the subsequent 60–50 ka interval proposed as the oldest genetically based interval for dispersal from Africa of *H. sapiens* carrying L3 subtypes[59,60]. The genetic time frame of 70–50 ka for "last long-range dispersal" coincides both with a more arid phase at CHB and overlaps with only a brief pronounced return to humidity in eastern Africa (60–62 ka, Fig. 3). This wet event may have offered a sufficiently long interval of suitable habitat in the lowlands of the EARS to facilitate dispersal of our species[16].

The pronounced high-frequency climate fluctuations since ~60 ka, modulating the predominant trend towards an increasingly drier climate, could have repeatedly pushed *H. sapiens* populations to respond to the decrease of available surface water and food resources. These abrupt and frequent fluctuations may have exerted a level of climatic stress on humans that prompted new coping strategies and technological innovation, possibly reflected in the transition from Middle Stone Age (MSA) to late Stone Age (LSA) tool assemblages[22]. In addition, during this interval, *H. sapiens* employed other strategies to respond to environmental boundary conditions in the rift system: groups moved up to the Ethiopian highlands on both sides of the rift, as cave archeological records at Goda Buticha[61], Mochena Borago[26,62], Fincha Habera[28], and Sodicho[63] suggest (Fig. 3).

Although chronological uncertainties in these records including CHB do not allow a precise comparison, the timing of the driest episodes in the CHB record generally agree with those of the highland occupations by *H. sapiens*. Settlement in higher-elevation sites persisted longer, encompassing the intervening short wet phases. The paucity of archeological and fossil records older than ~80 ka on the Ethiopian highlands limits our ability to test the refugia hypothesis during 80–200 ka. However, the oldest known high-elevation archeological site in the region shows evidence of Acheulian-aged occupation at Dendi volcano[64] (Fig. 1) in the northwestern Ethiopian highlands. This underscores that high mountain areas have long been tapped as favorable habitats by hominins.

This strategy of orographic mobility has been previously discussed in more detail for the much wetter southwestern Ethiopian highlands for several dry pulses during the youngest (15–5 ka) AHP[27]. Generally, these findings support the idea that *H. sapiens* sought refuge at higher elevations as a potential coping strategy for fading resources and increasingly precarious living conditions in the rift valley. Thus, living in higher altitude zones could have been a climatically-triggered response to millennial scale droughts in the EARS. However, during the very dry Last Glacial Maximum (~20 ka), the highlands of Ethiopia seem to have remained largely unpopulated, possibly due to reaching an environmental threshold[27].

Documented wet phases at CHB, comparable to other sedimentological records of northeastern Africa during the last 200–60 ka, indicate recurrent availability of favorable living conditions in the lowlands of the EARS and adjacent regions for *H. sapiens*, which would have provided opportune corridors for our species to disperse into the Levant and Arabia. Increasing aridity in the lowlands of the southern Ethiopian rift valley starting during MIS 4 and intensifying aridity since 60 ka may

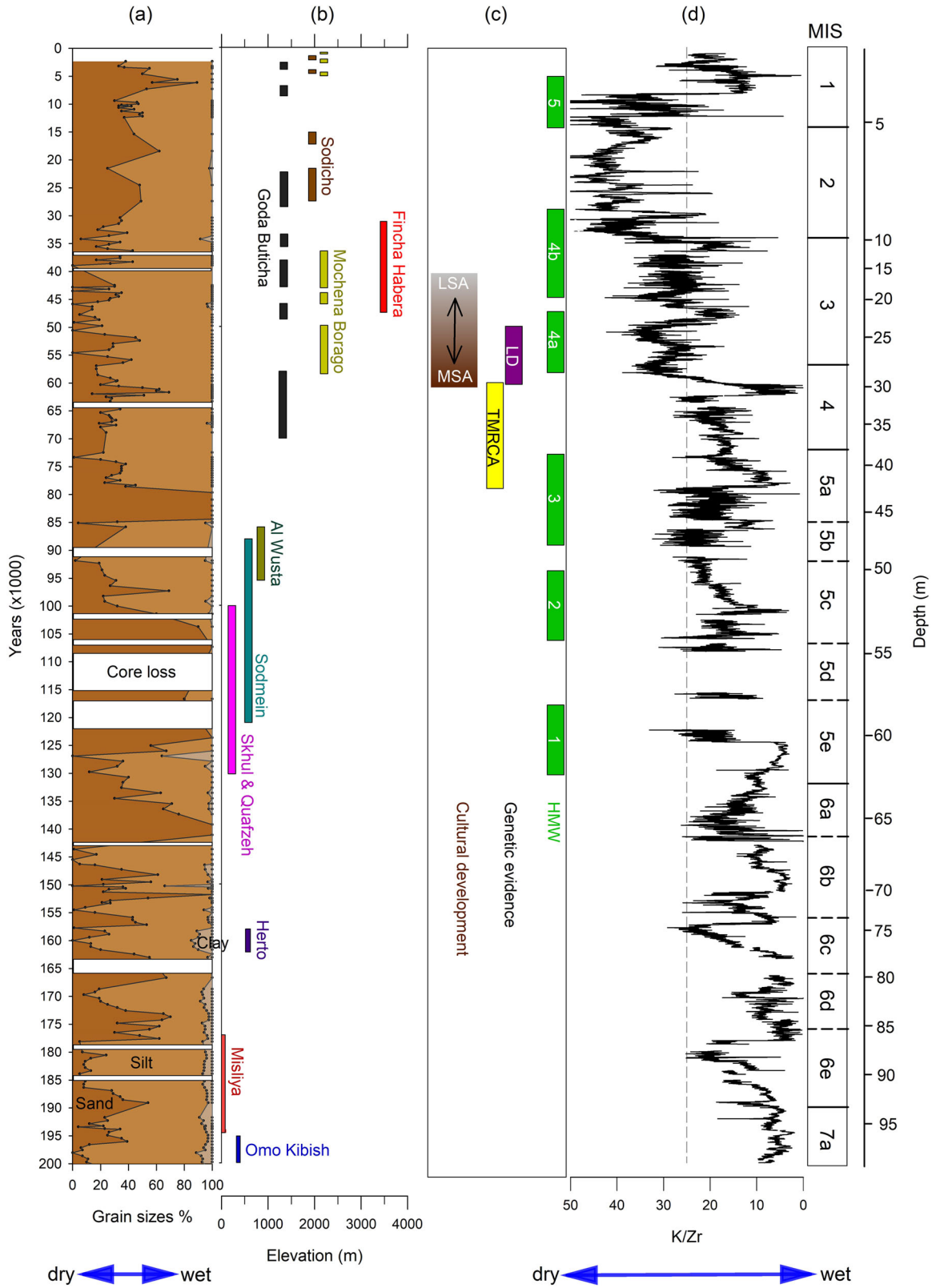

Fig. 3 Environmental record of the last 200 ka from the Chew Bahir basin (CHB). a Grain size distribution; **b** Chronological range of archeological/fossil sites with corresponding elevation of sites (for archeological/fossil sites location, see Fig. 1; for references see text); **c** Modeled Human Migration Windows (HMW = green rectangles)[57], genetic evidence (TMRCA = *time to most recent common ancestor*[58] and LD = last dispersal of *Homo sapiens*[59, 60]; **d** Record of K/Zr ratio from the Chew Bahir basin; Marine Oxygen-Isotope Stages (MIS) according to[72].

have induced *H. sapiens* to develop, test and use new strategies to survive, including occupation of high mountain refugia and the development of new tools.

Methods

During the CHB deep drilling campaign in Nov. 2014, two sediment cores were recovered: HSPDP-CHB14-2A and −2B (Fig. 1; N 4.7612° E 36.7668° and N 4.7613° E 36.7670°; 500 m asl) reaching down to 278.58 mbs (= meters below surface) and 266.38 mbs, respectively[15]. The cores were collected ~20 m apart and a composite record of 292.87 mcd (= meters composite depth) was constructed using a multi-parameter approach[31,32]. Technical difficulties during coring through sand layers (Supplementary Fig. S2; white bars in the grainsize column) led to some core loss at ~78–80, 58–59 and 55–57 mcd, and to a lesser extent also at 13, 15.5, 33.5, 49, 87.5 and 90.5 mcd. Core recovery rate in the upper 100 m is ~89.5%.

A total of 743 discrete samples collected every ~32 cm through the whole core were analyzed for their particle size distribution, 250 samples from 0.6 to 99.2 m depth represent the uppermost 200 ka. Prior to grainsize measurements the organic and carbonate components were removed. For this purpose, the samples (fine-grained fraction, <2 mm) were pretreated with H_2O_2 (30%) and with 15% HCl. For the final aggregate dispersion 0.5 N $Na_4P_2O_7$ (55.7 g/l) was added. The particle size distribution of each sample was measured three times with a Beckman Coulter LS 13320 laser particle analyzer with 116 particle size classes from 0.04–2000 µm using the Fraunhofer optical model. The calculation of the univariate statistical particle size values was performed with the software GRADISTAT[65].

Elemental variations were determined by X-ray fluorescence (XRF) core scanning at 5 mm resolution along the CHB composite profile with an Itrax core scanner at the Large Lakes Observatory (LLO) of the University of Minnesota Duluth. Following HSPDP protocols, a Chromium (Cr) tube was used with a tube voltage of 30 kV, current of 30 mA and scanning time of 10 s[66]. All XRF data were normalized by dividing elemental counts by coherence scattering and multiplied by a correction factor to compensate for e.g. the aging of the Cr tube. Subsequently, all data sets have been cleaned sub-cm wise to avoid coring artifacts such as cracks and voids[32,67]. According to the age model, the 5 mm spacing of the XRF data corresponds to ~10 years[31]. High K values have been established as an aridity proxy for paleolake Chew Bahir, controlled by increasing pore water alkalinity under dry conditions[16,32,33]. The XRF K values are normalized with Zr as a proxy for detrital influx into the lake. For better comparison to other records we also used the log K/Zr (detrended) values.

High Al/Si ratios are interpreted as indicator for the intensity of chemical weathering of feldspars, micas, amphiboles and pyroxenes in the catchment under generally wetter conditions that showed more uniformly distributed rainfall. Ca/Ti is used as a proxy for both biogenic calcite production in the water column and precipitation of authigenic calcite in the sediment, normalized for Ti as a proxy of the influx of clastic material into the lake[68].

The concentration of total carbon (TC) was measured in a total of 842 samples (32 cm intervals; 239 samples represent the uppermost ~200 ka) with a non-dispersive infrared sensor (Dimatec Ltd.) to analyze the thermic-catalytic oxidation process for both total inorganic carbon (TIC) and total carbon. To determine the content of total organic carbon (TOC), the difference between TC and TIC was calculated. Higher TOC values indicate more organic material in the sediments due to higher production in wetter climate conditions. An elemental analyzer (vario MICRO cube, Elementar Ltd.) was used to verify the TC values. Where reproduced values differed by > 5% samples were remeasured.

Excluding calcite nodules and dolomite in the bulk sediment samples, the $\delta^{18}O$ composition of bleached endogenic calcite was analyzed using a Thermo Finnigan MAT 253 mass spectrometer at the British Geological Survey, UK, following standard vacuum techniques[69]. Data are given as per mil (‰) deviations from the VPDB standard. Based on standard materials, analytical reproducibility was < 0.1‰. Lower $\delta^{18}O$ values indicate wetter conditions. 152 $\delta^{18}O$ samples represent the uppermost ~200 ka of the CHB record.

Prior to time-series analysis, the data were interpolated to an evenly-spaced time axis with 0.012 ka resolution. We calculate a continuous wavelet transformation (CWT) from the log(K/Zr) record using the MATLAB function *cwt*. We chose *Morlet* as the mother wavelet, which is very well suited to reproduce the cyclical characteristics of environmental variability in the Chew Bahir record.

Data availability

The proxy data of CHB is available online for download at LacCore Institute (Minneapolis USA, http://lrc.geo.umn.edu/laccore/; https://doi.org/10.17605/OSF.IO/M8QU5) and at the Collaborative Research Centre 806 Database (Cologne, Germany: http://www.crc806db.uni-koeln.de; https://doi.org/10.5880/SFB806.66).

Code availability

The script to compute the wavelet power spectrum will be made available through the MRES blog of M.H. Trauth, hosted at the University of Potsdam (http://mres.uni-potsdam.de).

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Author contributions

A.A., A.C., H.L., F.S., and M.H.T. initiated the Chew Bahir Drilling Project (CBDP) as part of the Hominin Sites and Paleolakes Drilling Project (HSPDP) and the A3-project of CRC 806 organized & guided by F.S.; field work and coring was led by A.A. & F.S. and assisted by V.F., A.J.; V.F. F.S. and M.H.T designed the study that led to this manuscript; chronology data were generated by H.M.R. and M.S.C. (OSL), C.B.R. (^{14}C), A.D. (^{40}Ar/^{39}Ar), C.S.L. and C.V. (tephrochronology), and H.M.R. and C.B.R. created the age model; quantitative XRF analysis was done by V.F.; F.A.V. contributed to the general discussion and provided TC, TIC and TOC data; J.D. performed the oxygen isotope measurements in collaboration with M.J.L.; S.O. & F.S. performed the grainsize analysis; hydrology and micro-paleontological interpretation was done by A.J.; proxy interpretation and discussion was coordinated by V.F., F.S. and M.H.T together with S.K.B. and H.L.; wavelet spectral analysis was performed by W.D. in collaboration with M.H.T.; paleoanthropological and archeological discussion and interpretation was done by F.S., R.V. and R.T.; R.T. provided expertize on evolutionary genetics, R.V. provided archeological context; data were provided by A.A. (catchment geology), V.F. (core stratigraphy, ICD and mineral composition); the manuscript was written by F.S., all authors contributed to the discussion and interpretation of the data and provided comments and suggestions to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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