Our understanding of the impact of climate-driven environmental change on prehistoric human populations is hampered by the scarcity of continuous paleoenvironmental records in the vicinity of archaeological sites. Here we compare a continuous paleoclimatic record of the last 20 ka before present from the Chew Bahir basin, southwest Ethiopia, with the available archaeological record of human presence in the region. The correlation of this record with orbitally-driven insolation variations suggests a complex nonlinear response of the environment to climate forcing, reflected in several long-term and short-term transitions between wet and dry conditions, resulting in abrupt changes between favorable and unfavorable living conditions for humans. Correlating the archaeological record in the surrounding region of the Chew Bahir basin, presumably including montane and lake-marginal refugia for human populations, with our climate record suggests a complex interplay between humans and their environment during the last 20 ka. The result may contribute to our understanding of how a dynamic environment may have impacted the adaptation and dispersal of early humans in eastern Africa.

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2007; Kröpelin et al., 2008; Castañeda et al., 2009) may provide sufficient resources to allow the population to grow and subsequently disperse through otherwise ecologically critical zones into larger geographical space over several generations. The current debates on the way climate affects humans are hampered by the lack of continuous high-resolution terrestrial paleoenvironmental records in Eastern Africa (Brandt et al., 2012) and the limited availability of contemporaneous archaeological data of the same region (Basell, 2008; Leplongeon, 2014).

As a contribution to these discussions, we present a continuous high-resolution lacustrine record for the past 20 ka from Chew Bahir, a deep sedimentary basin in southwest Ethiopia. The record is correlated with the available archaeological record of human occupation in the region, as a way of evaluating the impact of different styles of climate change on local terrestrial ecosystems (including human societies) at various timescales (10^3–10^6 yrs). The evidence of human occupation is based on the variations in frequency of radiocarbon dates from archaeological sites in the SW Ethiopian highlands near the Chew Bahir basin and the shores of the lakes in the Main Ethiopian Rift (MER) and the Omo-Turkana basin (Fig. 1). The precipitation-rich highlands and these lake-shores are hypothesized to have been refugia and centers of innovation during times of climatic stress (Ambrose, 1998; Basell, 2008; Joordens et al., 2011; Brandt et al., 2012; Brandt and Hildebrand, 2005). The Chew Bahir basin, today a dried-out saline mudflat providing the climatic archive for our correlation, is situated in a biogeographically highly sensitive transition zone between the Main Ethiopian Rift and the Omo-Turkana basin where the fossils of the oldest known anatomically modern humans were found (e.g. Day and Stringer, 1991; McDougall et al., 2005, 2008; Sisk and Shea, 2008).

In order to evaluate how different rates of environmental change affected settlement pattern and cultural innovation for survival and adaptation, we test the extent to which gradual and rapid climatic events in the lacustrine sedimentary record are also expressed in the archaeological record of hypothesized refugia. Traditionally used for places where species survive during cold periods (López-García et al., 2010), the term refugium is used here for areas that might have permitted the survival of human populations during arid phases. We have considered the period since 20 ka BP because it encompasses both, the highest archaeological data coverage for post Middle Stone age assemblages (Basell, 2008) as well as a detailed sedimentary record of dry-wet alternation within a full precessional cycle. This is a novel experiment to compare both the paleoclimatological and archeological evidence directly from the source area of modern humans to test current hypotheses about how climate affects humans. Due to the incompleteness of the archaeological data set, the results are of course very preliminary and hypothetical, but could be an important starting point for further research in this field.

Fig. 1. Setting of the Chew Bahir basin and archaeological sites in potential refugia. Archaeological sites are indicated by colored circles and numbers, that correspond to site names and numbers in Supplementary Table 1, to provide complete sample ID and cultural association. The pink circle marks the site of the Chew Bahir record. Climate diagrams represent monthly temperature means in deg C and precipitation in mm/month (IRI, last accessed 2/2014). Photographs from top: (1) Mochena Borago rock shelter in the SW Ethiopian highlands; (2) mudflats of the Chew Bahir basin, with the Hammar range in the background; (3) aerial shot of Lake Turkana, NE shore. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
2. Data and methods

2.1. Paleoclimatic reconstruction using continuous lacustrine sedimentary records

In a pilot study for the deep-drilling campaign within the ‘Hominid Sites and Paleolakes Drilling Project’ (HSPDP, http://hsdps.asu.edu/), six cores along a ~16 km long NW–SE transect across the Chew Bahir basin were collected during two consecutive drilling campaigns in 2009 and 2010. The cores were 9–19 m long, spanning the last ~60 ka, and were analyzed with respect to their geochemical, geophysical, biological, and sedimentological properties (Foerster et al., 2012, 2014).

There are two age models for the environmental record of the Chew Bahir basin: (1) an age model based on six AMS $^{14}$C ages of biogenic material from a single core (CB01) collected in 2009 and published in Foerster et al. (2012); (2) an age model based on 32 AMS $^{14}$C ages of biogenic carbonate, fossilized charcoal and organic sediment from multiple cores (CB01, CB03–06) and published in Foerster et al. (2014) and Trauth et al. (2015). For the newer age model, the potassium records of cores CB03–06 were tuned to the potassium record of CB01, using a running average of 5 years to minimize noise but still allow detection of the 400 year resolution of the radiocarbon age from all cores. CB01, CB03–05 projected onto this depth scale (Suppl. Fig. 1). The age model, discussed in detail in Foerster et al. (2014) and Trauth et al. (2015), is considered to be statistically robust, even though it provides only a floating chronology for large portions of the sedimentary record. It is to be noted, although the newer age model is a lot more sophisticated, it does not much differ from the old age model published in Foerster et al. (2012) (Suppl. Fig. 2). All radiocarbon ages were calibrated with OxCal (Bronk Ramsey, 1995) using the IntCal13 calibration data set (Reimer et al., 2013). The weighted mean of the probability density function was used for the age model, which was constructed by linear interpolation between dated levels (Trauth et al., 2015). For the interpolation of all proxy records upon the age model the most reliable results were obtained by using a linear interpolation technique. We refrained from tuning our climate record to high-latitude records or other East African records. For the paleoclimatic discussion of our interdisciplinary comparison, we use the CB01 record (Foerster et al., 2012), because it is the most complete record with the highest temporal resolution (~3–10 years) for the past 20 ka in the Chew Bahir basin. As already shown in Trauth et al. (2015) we use CB03 to fill the gap in CB01 between ~9.8 ka and ~9.1 ka BP, and also for the gap at the end of the Younger Dryas, ~14.8–14.9 ka BP and past ~0.8 ka (Fig. 2).

The proxy-climate record is based on potassium (K) abundance, previously established as a reliable proxy for aridity in the Chew Bahir cores (Foerster et al., 2012) (Fig. 2). Increased influx of K occurs during dry phases, due to enhanced activity of extensive, sparsely vegetated alluvial fans fed by the potassium-rich gneisses and granites of the adjacent Hammar Range. During arid phases, the paleolake is believed to have become completely evenly distributed rainfall during humid phases, an extensive linear interpolation between dated levels (Trauth et al., 2015). For the age model, discussed in detail in Foerster et al. (2014) and Trauth et al. (2015), is considered to be statistically robust, even though it provides only a floating chronology for large portions of the sedimentary record. It is to be noted, although the newer age model is a lot more sophisticated, it does not much differ from the old age model published in Foerster et al. (2012) (Suppl. Fig. 2). All radiocarbon ages were calibrated with OxCal (Bronk Ramsey, 1995) using the IntCal13 calibration data set (Reimer et al., 2013). The weighted mean of the probability density function was used for the age model, which was constructed by linear interpolation between dated levels (Trauth et al., 2015). For the interpolation of all proxy records upon the age model the most reliable results were obtained by using a linear interpolation technique. We refrained from tuning our climate record to high-latitude records or other East African records. For the paleoclimate discussion of our interdisciplinary comparison, we use the CB01 record (Foerster et al., 2012), because it is the most complete record with the highest temporal resolution (~3–10 years) for the past 20 ka in the Chew Bahir basin. As already shown in Trauth et al. (2015) we use CB03 to fill the gap in CB01 between ~9.8 ka and ~9.1 ka BP, and also for the gap at the end of the Younger Dryas, ~14.8–14.9 ka BP and past ~0.8 ka (Fig. 2).

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standard deviation. Age dates from bone apatite were excluded because of their large uncertainties.

3. Results and interpretation

3.1. Climatic change and phases of climatic stress

The climatic record of the Chew Bahir basin, represented here by the variability in K as an indicator for a dry climate, shows that the moisture availability has been subject to dramatic fluctuations on time scales ranging from 10⁴ to 10¹ years, with either relative abrupt or gradual transitions between dry and wet conditions (Fig. 2). Extreme dry conditions in the Chew Bahir basin prevailed prior to ~15 ka BP and were interrupted by short-term wet-spells of 200–500 year duration (Foerster et al., 2012). From 15 ka onwards an abrupt change towards extremely humid conditions during the African Humid Period (AHP, 15–5 ka BP) occurred, which was the consequence of a precession-controlled Northern Hemisphere (NH) insolation maximum (e.g. Foerster et al., 2012; Junginger and Trauth, 2013). The observed climate transition has caused a marked environmental transformation from unstable dry conditions to relatively stable humid conditions, which resulted in the establishment of large fresh water lakes and the development of a lush vegetation cover. Despite the high moisture availability, several short-term drought events interrupted this humid period. For instance, between 14.2 and 13.5 ka, an event related with the Older Dryas stadial (OD, ~14 ka, Stager et al., 2002) eventually caused the return to dry conditions immediately after the relatively abrupt onset of the AHP. Another major dry spell occurred between ~12.8 and 11.6 ka that correlates with the well known NH Younger Dryas stadial (YD, Foerster et al., 2012) and is expressed in the Chew Bahir record as an abrupt return to aridity, comparable to the conditions during the Last Glacial Maximum (LGM) has caused the complete desiccation of paleolake Chew Bahir. This arid episode is documented in many sites in Africa north of 10°S (e.g. Barker et al., 2004; Brown et al., 2007; Tierney et al., 2011; Junginger et al., 2014). The transition from the YD to the relatively stable humid climate of the early and mid-Holocene was relatively fast, probably within ±200 years. As the climate proxies and fossil records of the basin suggests, this rapidly-changing environment culminated in the development of an extensive (2000 km²), nutrient-rich freshwater lake, at least 50 m deep, with abundant fish and surrounded by dense vegetation. This paleolake Chew Bahir overflowed into the Omo-Turkana basin during high stands (Grove et al., 1975; Junginger and Trauth, 2013).

Other arid excursions during the AHP with moisture fluctuations are observed at ~10.5, ~9.5, 8.15–7.8 and ~7 ka BP which were not thought to have resulted in a complete desiccation of the paleolake and disappearance of the surrounding vegetation (Foerster et al., 2012). The most pronounced arid excursion, dated here at ~7.8 ka BP, would have affected the environment considerably, but would not have resulted in a complete lake regression or vegetation change, possibly allowing human populations to persist in the area, despite droughts that continued for several centuries. This interpretation is supported by lake-level reconstructions of nearby paleolakes Turkana and Suguta (Garcin et al., 2012;
Junginger and Trauth, 2013), that also show several excursions to arid conditions during the AHP lake interval. The dry spell at ~7.8 ka BP was preceded by a gradual ~1000 year-long moisture reduction, which has been also observed at many other low-latitude sites (e.g. Fleitmann et al., 2003; Dykoski et al., 2005; Gupta et al., 2005; Weldeab et al., 2007), and is assumed to have led into the 8.2 ka cold event observed in the NH (Benson et al., 1997). In southern Ethiopia the humid conditions of the AHP gradually declined from ~6.5 ka to ~5 ka, punctuated by several 80–20 year-long dry events (Trauth et al., 2015). Arid conditions have persisted since then, interrupted only by a short-lived event of higher moisture availability at ~3 ka BP and a distinct phase of wet conditions between ~2.2 and 1.3 ka BP.

3.2. Human occupation in a changing environment

Although derived from a sparse archaeological dataset, the frequency distribution of radiocarbon dates over the past 20 ka contains distinct patterns of human occupation, including episodes of human settlement, interrupted by periods without such activity. The record of radiocarbon dates demonstrates that the oldest evidence for human occupation in that time interval is at two brief episodes between ~14.0 and 13.7 and ~13.4–13.2 ka BP, documented from sites in the Ziway-Shalla basin (Ménard et al., 2014). During the AHP highstands this basin hosted a paleolake up to 120 m deep, which has formed by the merging of the MER lakes Abiyata, Langoano, Ziway and Shalla (Gillespie et al., 1983). The interval of ~14–13.2 ka BP may coincide with the high-latitude OD climatic event (Stager et al., 2002), recorded in Chew Bahir as a ~700 year-long drier episode after the abrupt onset of the AHP. The sites where the MER artefacts were found are situated between Lake Ziway and Abiyata-Langoano, which implies that during this dry episode the lake level had been reduced to a level where settlement between the lake systems was possible. As these settlement activities coincide with a short phase of drier conditions, lake regressions and deterioration of water quality, this region can also be interpreted as a (lake) refugia. Human occupation is also identified at ~13.9 ka BP in the SW Ethiopian highlands. Generally, no evidence for occupation is apparent before this interval, probably because of the extremely dry LGM conditions (Gasse, 2000) that could have made the area mostly uninhabitable, although it is not sure whether the SW Ethiopian highlands were also entirely abandoned and where humans were during this interval. In general, a strong hiatus on archaeological record during the period exists between 30 and 15 ka BP, presumably superimposed by the prevailing dry conditions (e.g. Leplongeon, 2014; Pleurdeau et al., 2014). At the onset of the AHP, living conditions greatly improved with significantly increased moisture availability as documented in the climate record of Chew Bahir and the abrupt and rapid development of large lakes in the area (e.g. Junginger and Trauth, 2013) (Fig. 2).

Evidence for human activity follows at the northeastern shore of paleolake Turkana between ~11.5 and 9.2 ka BP. Due to the contrasting reconstructions of the lake levels of paleolake Turkana that are based on non-continuous and/or different proxy data sets (Johnson et al., 1991; Brown and Fuller, 2008; Garcin et al., 2012; Bloeszies et al., 2015) it is not clear though whether the level of paleolake Turkana has fluctuated repeatedly by 50 m during this interval or it may have fallen gradually by 20 m between ~10.8 and 10 ka BP. After the pronounced dry phase of the Younger Dryas, lasting for about 1200 years, all rift lakes including the Chew Bahir and Lake Turkana rapidly re-filled. Two archaeological sites at the northeastern shore (Fig. 1; Fjxj 12 and Gaji 11; Owen et al., 1982) are situated almost at the highest shoreline of the paleolake, right at the river that connected the Chew Bahir with the Turkana basin during overflow times. Assuming occupation along the lake shore at ~11.5–9.2 ka BP, there was probably an additional (third) rainy season in August–September, between the regular spring and autumn rainy seasons linked to the insolation maximum at the equator. This additional rainy season would have resulted in almost continuous rainfall from April to November (Junginger and Trauth, 2013; Junginger et al., 2014). Lake-level records indicate that this extra rainy season may have been unstable, causing pronounced fluctuations in the water budget of the lakes (Junginger et al., 2014). The apparent break in the occupation record after ~9.2 ka could be explained by the highly fluctuating lake levels, simply washing away all archaeological evidence. It is also possible that the lake-marginal environment was unfavorable for occupation during periods of high rainfall, when relatively dense woody vegetation would have made hunting more difficult and could have favored the spread of diseases.

The evidence for human occupation in the SW Ethiopian highlands during the AHP is particularly noteworthy: here, several short-term occupation episodes are dated at ~10.5–10.2 ka BP; ~9.5–9.3 ka BP; ~8.0–7.8 ka BP and ~7.0–6.5 ka BP. These intervals coincide (within the dating errors) with short-term events of pronounced aridity punctuating the AHP. These climatic events are found likely in the Chew Bahir record, and also in both paleolakes Turkana and Suguta, where lake regression and rapidly-changing environment would have been accompanied by marked deterioration in water quality. Paleolake Chew Bahir would have been increasingly saline and alkaline, probably similar to Lake Turkana today (e.g. Odada et al., 2003).

The short-term changes in moisture availability during the AHP may have been driven by variations in solar irradiance due to varying numbers of sunspots (Solanki et al., 2004; Junginger et al., 2014). These solar variations are assumed to have caused the absence of the third rainy season in August–September as well as attenuation of the other two wet seasons, as documented in the records of many basins from the Victoria basin along the East African Rift to Oman (e.g. Burns et al., 1998; Neff et al., 2001; Stager et al., 2002). This caused short-term episodes of pronounced aridity within a few decades, which caused unfavorable conditions for humans in large parts of the lowlands. As the radiocarbon frequency record suggests, the SW Ethiopian highlands seem to have served as a refuge during these episodes with increased environmental stress, on decadal to millennial time scales during otherwise long-term favorable conditions. Although the dates are too few for a reliable interpretation, and also the limited dating precision is a problem, the striking correlation of settlement episodes in the highlands with the occurrence of a series of pronounced aridity events at least deserves further research, specifically on the locations of human occupation during more favorable climate conditions. To date, our correlation suggests that a wetter climate punctuated by a series of droughts is reflected by multiple phases of increased settlement activity in areas that might have been used as refugia, most likely by short-term vertical migration of mobile hunter-gatherers. We thus carefully interpret the correlation between pulsed aridity and occupation of a hypothesized retreat area as the result of drought as a push-factor for a refugium-directed movement that would have otherwise been against the preference of hunter-gatherers.

At the onset of the >1500 year-long Mid Holocene aridification trend (~6.5–5 ka), there is a striking coincidence between moisture decrease and colonization of the lake basins and the highlands. It is very likely that this movement was even further pushed by the series of short drought events, 20–80 years long, previously described by Trauth et al. (2015). These, at least 19 events of extreme aridity, punctuating the gradual transition to present-day arid conditions, are presumed to have had considerable effect on
humans and may have contributed to the climate-driven cultural change presented hereafter. Between ~4.5 and 2 ka BP, extreme aridity could have ended habitation even in the two ecologically-favored regions; where human populations survived afterwards is still an open question. The Chew Bahir climate record suggests that aridity reached a level where lakes became highly saline and alkaline, rivers dried up, and the vegetation cover diminished in conditions of sparse, irregularly distributed rainfall. There is a significant discontinuity in the record of human occupation over the same interval, which could imply that movement to nearby refugia was an inadequate strategy for survival, and mortality was high throughout the region, with survivors dispersed to more distant regions. Renewed human occupation of both the lake and montane refugia occurred only during the inferred moisture increase at around ~2 ka BP, accompanied by an amelioration of living conditions (see Suppl. Table 1) (Fig. 2).

4. Discussion

4.1. Indications of climate-driven cultural change

The environmental shifts recorded in the Chew Bahir sediments most likely influenced the living conditions of prehistoric humans. One possible impact of these shifts are variations in the human occupation of the area, as we have derived it from the presence or absence of archaeological data during certain periods, particularly during the period before 15 ka ago (e.g. Pleurdeau et al., 2014). Some human populations may not have survived aridity; others would have adopted novel or modified subsistence strategies. Garcin et al. (2012) interpreted the chronological synchronism of low lake levels and the emergence of pastoralism in the Turkana Lake region in a similar manner. Wright et al. (2015) have recently suggested that this climate transition in the Turkana basin has caused for the transition from foraging to food production. However, a simplistic model of cause and effect between environmental parameters and human behavior is an inadequate conception of their complex interplay. Examples of economic transformations from other regions, such as northern Africa (e.g. Manning and Timpson, 2014), show that external conditions reduce the range of possible developments, while socio-cultural conditions favor particular concepts (Keding, 2009; Vogelsang and Keding, 2013). In addition, further incalculable factors, which may be summarized under the ambiguous term of ‘human agency’ play a determining role in the human decision making (Dobres and Robb, 2000). The role of individuals as active social agents is, however, hardly detectable in the archaeological material.

Despite their proximity, cultural development in the Ethiopian highlands, and lakes and their marginal lands differ considerably. At Lake Turkana, early pottery is found at forager sites as early as ~10 ka BP. Diagnostic features of these sites are still an open question. The Chew Bahir climate record suggests that aridity reached a level where lakes became highly saline and alkaline, rivers dried up, and the vegetation cover diminished in conditions of sparse, irregularly distributed rainfall. There is a significant discontinuity in the record of human occupation over the same interval, which could imply that movement to nearby refugia was an inadequate strategy for survival, and mortality was high throughout the region, with survivors dispersed to more distant regions. Renewed human occupation of both the lake and montane refugia occurred only during the inferred moisture increase at around ~2 ka BP, accompanied by an amelioration of living conditions (see Suppl. Table 1) (Fig. 2).

4.2. Adaptation as a matter of timescale

An important aspect that has to be considered here, is the timescale on which climate is changing. Assuming the climatic record of the Chew Bahir basin reflects prevailing wet conditions between ~15 ka and ~5 ka BP, punctuated by several pronounced dry spells (~14.2—13.5 ka BP, around ~10.5 and ~9.5 ka BP, between 8.15 and 7.8 and at ~7 ka BP), causing a rapid change of the habitat with strongly regressed and increasingly alkaline and saline lakes and a sparse vegetation cover, hunter-gatherers were forced to expeditiously find alternative subsistence strategies. Such short-term solutions may be reflected in the higher frequency of dated settlements in the highlands during arid spells, which is interpreted as vertical migration of hunter-gather groups into more favorable environments. The change from a foraging subsistence to a productive mode of economy is intrinsically tied to changes in the social structure and ideology of the society (Vogelsang and Keding, 2013, 56ff.). Consequently, it is implausible that an abrupt transition of 50 years or even less might have triggered such a fundamental transformation. In contrast, the gradual and more than 1500-year-long transition from wet to dry characterizing the end of the AHP in the Chew Bahir record could indeed have fostered an important socio-economic transition.

5. Conclusions

A 20 ka long paleoclimate record from the Chew Bahir basin in southwest Ethiopia shows both orbitally-driven long-term transitions from favorable to unfavorable living conditions, including several and short abrupt excursions towards drier or wetter episodes. The history of Chew Bahir is important in this context in
providing a high resolution and continuous climate record rather than providing archaeological data which are not available for the studied timeframe (nor beyond), and is not within the scope of this study. The comparison of prehistoric settlement activities in the surrounding potential refugia, indicated by radiocarbon date frequency distribution with important events of climate stress indicates a significant correlation of short dry events with population movements into refugia, particularly the Southwest Ethiopian Highlands. Long-term climatic deterioration seemed to have caused large-scale migration. An adaption to a changing environment by changing the subsistence strategy is sometimes assumed to be the beginning of herding in the Late Holocene period and can only be a long-term process, eventually caused by long-term climatic shifts. However, the comparison of the climate and archaeological history indicates that not all climatic stress events correlate with increased occupation of refugia. Despite all data limitations, this suggests that external environmental factors merely reduce the range of possible developments, while socio-cultural conditions favor particular concepts. Further calculable factors play a role and human behavior has not been entirely climatically triggered. This concept of decision-making within certain environmental boundaries, the ‘human agency’, has a crucial influence on the final development of culture as well as on societal decisions about the timing and direction of mobility.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2015.10.026.

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