Environmental change and human occupation of southern Ethiopia and northern Kenya during the last 20,000 years

Foerster, V.; Vogelsang, Ralph; Junginger, Annett; Asrat, Asfawossen; Lamb, Henry; Schaebitz, Frank; Trauth, Martin

Published in:
Quaternary Science Reviews
DOI:
10.1016/j.quascirev.2015.10.026
Publication date:
2015

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the Aberystwyth Research Portal (the Institutional Repository) are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the Aberystwyth Research Portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the Aberystwyth Research Portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

tel: +44 1970 62 2400
e-mail: is@aber.ac.uk

Download date: 15. Sep. 2023
Environmental Change and Human Occupation of Southern Ethiopia and Northern Kenya during the last 20,000 years

Verena Foerster1*, Ralf Vogelsang2, Annett Junginger3, Asfawossen Asrat4, Henry F. Lamb5, Frank Schaebitz6, Martin H. Trauth1

1 University of Potsdam, Institute of Earth and Environmental Science; Karl-Liebknecht-Str. 24-25; 14476 Potsdam, Germany
2 University of Cologne, Institute of Prehistoric Archaeology; Bernhard-Feilchenfeld-Str. 11; 50969 Cologne; Germany
3 Eberhard Karls Universität Tübingen, Department of Earth Sciences, Senckenberg Center for Human Evolution and Palaeoenvironment (HEP-Tuebingen); Hölderlinstrasse 12; 72074 Tübingen; Germany
4 Addis Ababa University, School of Earth Sciences; P. O. Box 1176, Addis Ababa, Ethiopia
5 Aberystwyth University, Department of Geography and Earth Sciences, Aberystwyth SY23 3DB, U.K.
6 University of Cologne, Seminar for Geography and Education; Gronewaldstrasse 2; 50931 Cologne; Germany

Abstract

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.

Keywords: archeology; paleoclimate; African Humid Period; push factor; adaption; migration; hunter-gatherers; foragers; pastoralism; Chew Bahir

1 Introduction

Climatic change is broadly considered to be one of the major drivers for human migration including the dispersal of early modern humans (Beyin, 2011a; Rosenberg et al., 2011; Richter et al. 2012) and the shift from hunter-gatherers to pastoralism (Garcin et al., 2012; Lesur et al., 2014). However, it is not clear how far
climate change has really affected human migration (e.g. Brandt et al., 2012) and how other factors, such as human agency, in the sense of individual self-determination and will, under the pervasive influence of culture, might have been involved (Ahearn, 2001; Dornan, 2002). The same issue applies to the role of climatic change for the emergence of technological and behavioral innovation (Ambrose et al., 1998; Garcin et al., 2012; Ziegler et al., 2013).

If climatic change is assumed to play an important role and the mode of climatic change could have controlled the way human populations responded to climatic variations, questions arise as to whether this depended on the duration and direction of transitional states. Furthermore, the question is whether short-term events or rather long-term gradual transitions were the relevant drivers. Finally, what type of climatic conditions are associated with human dispersal and whether abrupt changes to unfavorable conditions (e.g. towards increased aridity; deMenocal, 1995; Carto et al., 2009) may have triggered the migration of surviving populations to more favorable locations. Alternatively, a change towards favorable living conditions (e.g., a humid phase; Trauth et al., 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 et al., 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 ($10^1$–$10^4$ 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 lakeshores are hypothesized to have been refugia and centers of innovation during times of climatic stress (Ambrose et al., 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-Garcia 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.

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://hspdp.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 to 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; Foerster et al., 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, suing a minimum of tie-points, to construct a composite depth scale with the radiocarbon ages 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, when rainfall events are rare and short-lived, K, the weathering product of feldspar, feldspathoids and mica with a high solubility and reactivity, is rapidly transported from the constrained source of the Hammar Range to the Chew Bahir basin. Furthermore, high occurrences of K have been shown to be linked to changes in the lake water chemistry, that in turn is controlled by variations in precipitation influx (Foerster et al., 2014). During the most arid phases, the paleolake is believed to have become completely desiccated, or at least strongly regressed with a very low biogenic productivity (Foerster et al., 2014). With the onset of greater, more evenly distributed rainfall during humid phases, an extensive (2,000 km²) paleolake filled the basin with a maximal water depth of 50 m. Fluvial input increased and a dense vegetation cover that must be assumed for phases of increased humidity (e.g. Mohammed and Bonnefille, 1998; Dupont et al., 2000; Umer et al., 2007) on the slopes of the Rift flanks most likely constrained the influence of the alluvial fans off the Hammar Range, which represents the major source of the K-rich minerals. Other proxies support this interpretation: the diatom stratigraphy indicates that freshwater conditions prevailed during long, stable humid phases (Foerster et al., 2014). These
data, taken together with lake-level reconstructions from Lake Turkana (e.g. Johnson et al., 1991; Brown and Fuller, 2008; Garcin et al., 2012) and Lake Ziway-Shala (Gillespie et al., 1983) give an indication of the immense environmental impact of the major climatic fluctuations, especially the dry intervals that punctuate the early-mid Holocene African Humid Period (AHP, ca. 15–5 ka BP) (Suppl. Fig. 3).

2.2 Evidence of human occupation by radiocarbon date frequency

The regional and chronological distribution of archaeological sites may not be a direct indicator of settlement intensities, as it is influenced by a number of external factors. The method of using radiocarbon frequency to infer human presence and mobility has its limitations due to the presence of gaps during certain phases, that connote human absence in the area, but do not prove that humans were definitely not present during that time; the evidence of their presence may not have yet been recovered, or, also possible, was not preserved. The accessibility of the area has a clear influence on the research activities and therewith on the number of yet undiscovered sites and, consequently, the number of derived ages. Preservation conditions of datable organic material under changing climatic conditions contribute to the availability of radiocarbon dates, which also include the undocumented removal of finds by natural (degradation, inundation, erosion etc.) as well as anthropogenic forces.

However, keeping these caveats in mind, and considering that this is the only available approach to determine the settlement intensity in the area, the frequency of radiocarbon dates from archaeological sites nevertheless provides a valuable indication of changing settlement patterns, allowing inferences about where, when and, at best, how far humans were influenced by climatic conditions: Increased human occupation should give rise to a higher archaeological visibility. Human occupation is presented here using the radiocarbon date frequency from two documented ecologically favorable zones in close proximity to our climate record; the precipitation-rich highlands and around the shorelines of nearby lakes (Fig.1).

Specifically, our initial archaeological dataset is comprised of 26 radiocarbon dates from the SW Ethiopian highlands predominately from two research projects; the Kaffa Archaeological Project (sites are located between 1370 and 2260 m a.s.l.; Hildebrand et al., 2010; Hildebrand and Brandt, 2010) and the excavations at Mochena Borago rock shelter (2230 m a.s.l.; Brandt et al., 2012; Guthertz et al., 2002) (Suppl. Table 1). Due to the close proximity of these sites to the Chew Bahir catchment, climatic shifts of the highland region
should be visible in the sedimentary record of the basin. Similarly, we would expect to find an expression of
climatic extremes in the settlement activities of the probable highland refugia for the last dry-wet cycle (Fig. 1). A second dataset, the lake refugia dataset, comprises 31 radiocarbon dates from Lake Turkana and 6
dates from the Ziway-Shalla basin, which are hypothesized to have served as retreat areas for humans
during times of climatic stress (Basell, 2008; Joordens et al., 2011) (Suppl. Table 1).

In order to ensure a consistent age scale, we used conventional radiocarbon ages and calibrated them using
CalPal (version April 2013, Weninger and Jöris, 2008) with the IntCal13 calibration curve (Reimer et al.,
2013). All ages were calibrated using the 2-sigma 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 $10^4$ to $10^1$ 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 14.2–13.5 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 ~12.8–11.6 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 (2,000 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 et al., 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 ~1,000 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 ~2.2–1.3 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 ~14.0–13.7 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, Langano, 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-Langano, 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 to 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 et al., 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; Bloszies 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 ~10.8–10 ka BP. After the pronounced dry phase of the Younger Dryas, lasting for about 1,200 years, all rift lakes including the Chew Bahir and Lake Turkana rapidly re-filled. Two archaeological sites at the northeastern shore (Fig.1; FxJj 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 in the Chew Bahir record, and also
in both paleolakes Turkana and Suguta, where lake regression and a 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 refugium 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 >1,500 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 fisher-hunter-gatherer subsistence, heavily relying on aquatic resources and
restricted residential mobility. This lifestyle and its diagnostic artefacts, such as wavy-line pottery and
harpoons (Phillipson, 1977; Barthelme, 1985) link these sites with assemblages from the southern Sahara,
which are grouped under the term ‘African Aqualithic’ (Sutton, 1977) or ‘Khartoum Horizon Style’ (Hays,
1971). However, the dating of the Turkana sites is problematic. Most early dates were measured on bone
apatite, and were therefore considered unreliable and, hence, were not included in our dataset (Fig. 2).
Despite these dating problems, it is widely accepted that pottery was already produced in the area before
early domesticates arrived. The diagnostic decorated sherds can be assigned to the eastern facies of the
wavy line group, which is distributed over a large area in northeastern Africa between ~11 and ~7 ka BP
(Jesse, 2003, Tab. 61, Tab.62, p.283 ff.).

The beginning of herding in the Turkana region, at around 4 ka BP, is contemporaneous with the
construction of megalithic pillar sites and with the earliest secure dates for Nderit pottery (Hildebrand and
Grillo, 2012). In contrast, domesticates and pottery do not appear in combination in the SW Ethiopian
highlands until about 2,000 years later (Lesur-Gebremariam, 2009; Hildebrand et al. 2010; Lesur et al.,
2014). Preliminary occupation of the highlands is characterized by highly-mobile, unspecialized hunter-
gatherer groups, which exploited a broad spectrum of resources in an opportunistic way (Lesur et al.,
2007). This contrasts with the social organization of more complex hunter-gatherers, identifiable by sedentism or
substantially restricted residential mobility, and a ‘focal exploitation of a particular resource (commonly fish’)
(Kelly, 1995, 302). The lake environment of Lake Turkana may have fostered the emergence of such
complex hunter-gatherer groups. Further characteristics of such groups are ownership of resources, a more
formal leadership and an erosion of egalitarian ideology (Kelly, 1995, 302; Zvelebil, 1998, 8). Such attributes
of a socio-economic pre-adaptation to a food-producing economy might have facilitated a subsistence
change in the Turkana region.
Nevertheless, the chronological difference of 2,000 years between the earliest evidence of domestic animals in the Lake Turkana region and the southwest Ethiopian highlands has implications for the refugium hypothesis. If pastoral people retreated to the highlands during arid phases, they also changed their subsistence to a hunting and gathering way of life. Alternatively, settlement activities in the highlands were exclusively by local, possibly marginalized hunter-gatherer groups until 2,000 years ago. There is ethnographic and archaeological evidence for both scenarios, which shows once more that the strict classification into foraging or food-producing societies, is an over-simplification of a very complex and alterable situation (e.g. Smith, 1998; Kusimba, 2005).

4.2 Adaptation as a matter of timescale

An important aspect that has to be considered here, is the time scale 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 1,500-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 incalculable 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.

Acknowledgements

We thank Addis Ababa University for support in the realization of the Chew Bahir field campaign in difficult
terrain. We are also grateful to our colleagues from the Universities of Cologne and Potsdam for their lab
support and fruitful discussions. Most of all we are much obliged to Bernd Wagner, Finn Viehberg and Nicole
Stronck for providing valuable advice. We would also like to thank Steven Brandt, Elisabeth Hildebrand,
Friederike Jesse, Birgit Keding, Josephine Lesur and Clément Menard for their constant readiness to answer
our questions and their participation in discussions. We thank the two anonymous reviewers whose
comments and helpful suggestions greatly improved the manuscript. This work presented here is supported
by the CRC 806 and the International Continental Scientific Drilling Program (ICDP) (grant numbers TR
419/9-1,2 and SCHA 472/18-1,2). We thank the German Science Foundation (DFG) for funding these
projects.
References


Basell, L.S.: Middle Stone Age (MSA) site distributions in eastern Africa and their relationship to Quaternary environmental change, refugia and the evolution of Homo sapiens, Quaternary Science Reviews, 27, 2484–2498, 2008.


Beyin, A.: Recent archaeological survey and excavation around the greater Kalokol Area, west side of Lake Turkana: Preliminary findings, Nyame Akuma, 75, 40–50, 2011b.


IRI (International Research Institute for Climate and Society), Earth Institute, Columbia University, Climate and Society Maproom available at: http://iridl.ldeo.columbia.edu/maproom/ (last access: 28 February), 2014.


Stager, J.C., Mayewski, P.A. and Meeker, L.D.: Cooling cycles, Heinrich event 1, and the desiccation of Lake


Tierney, J.E., Russell, J.M., Sinninghe Damsté, J.S., Huang, Y. and Verschuren, D.: Late Quaternary
behavior of the East African monsoon and the importance of the Congo Air Boundary, Quaternary

latitude forcing of Plio-Pleistocene East African climate and human evolution, Journal of Human

Environmental Stability vs. Instability in Late Cenozoic Lake Records of Eastern Africa. Journal of Human

Pleistocene and Holocene Vegetation History of the Bale Mountains, Ethiopia. Quaternary Science

Vogelsang, R. and Keding, B.: Climate, culture, and change: From hunters to herders in northeastern and
southwestern Africa, in: Baldia, M.O., Perttula, T.K., Frink, D.S. (Eds.): Comparative Archaeology and
Paleoclimatology – Socio-cultural responses to a changing world, BAR International Series, 2456,

Weldeab, S., Lea, D.W., Schneider, R.R. and Andersen, N.: Centennial scale climate instabilities in a wet
early Holocene Western African monsoon, Geophysical Research Letters, 34, L24702,

Weninger, B. and Jöris, O., A 14C age calibration curve for the last 24,000 years: the Greenland-Hulu U/Th
timescale and its impact on understanding the Middle to Upper Paleolithic transition in Western Eurasia,


Ziegler, M., Simon, M.H., Hall, I.R., Barker, S., Stringer, C., and Zahn, R. Development of Middle Stone Age
innovation linked to rapid climate change, Nature Communications 4, 1905, 1-7, 2013

Zvelebil, M. 1998 – What's in a Name: The Mesolithic, the Neolithic, and Social Change at the Mesolithic
Neolithic Transition, in: Edmonds, M. and Richards, C. (Eds.): Understanding the Neolithic of North-

Figure Captions

**Figure 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.

**Figure 2** | Comparison of (A) the 20 ka Chew Bahir climatic record (K content as a proxy for aridity) and
the variations with the earth’s precession (Berger and Loutre, 1991) with (B) settlement in the SW Ethiopian
Highlands and around lake margins (Turkana and Ziway-Shalla lakes). Climatic events: AHP - African Humid
Period (~15-5 ka BP), YD - Younger Dryas (~12.8 -11.6 ka BP), OD - Older Dryas (around 14 ka BP), H1 -
Heinrich event 1 (around 16 ka BP), LGM - Last Glacial Maximum (~24-18 ka BP). During the AHP, several
pronounced dry spells occur, modulating the wet phase; the gradual Holocene aridification (orange bar) is
punctuated by arid events on a decadal timescale (Trauth et al., 2015). Settlement activities in both potential
refugia are indicated by radiocarbon frequency of archaeological finds, as listed in Suppl. Table 1. Cultural
innovation is indicated by first documented wavy-line pottery (pot symbol) and the introduction of pastoralism
(cow symbol); red or green colors refer to SW highlands or lake margins respectively. The green star
signifies culture-related evidence of occupation that is not clearly datable.

---

Page 17
Supplementary Table 1 | Radiocarbon dates from archaeological sites discussed in the text.

Supplementary Figure 1 | Intra-basin core correlation of Chew Bahir transect cores. (A) Standardized potassium records of the Chew Bahir transect cores tuned to the depth of CB-01. Red circles indicate the minimum number of tie points. (B) All potassium records were tuned to the composite age model based on cal. $^{14}$C ages, indicated by black circles (modified after Foerster, 2014).

Supplementary Figure 2 | The composite age model of the Chew Bahir basin (Foerster et al., 2012, 2014; Trauth et al., 2015) showing a linearly interpolated vs. a cubic-spline age model, based on 32 AMS $^{14}$C ages from Chew Bahir cores CB01, CB03–06. All radiocarbon ages were converted to calibrated ages with OxCAL, using the IntCal13 calibration curves (Bronk Ramsey, 1995, 2009a,b; Reimer et al., 2013). Ages are the weighted mean of the probability density function. The grey linear age model refers to the first simplistic age-depth model as shown in Foerster et al. (2012). (A) $^{14}$C ages per tuned CB sediment cores. (B) Material used for age determination.

Supplementary Figure 3 | Potassium (K) content of Chew Bahir cores CB-01 (basin margin), CB-03 (transition), CB-05 (basin center) for the last 20 ka BP. Dashed lines refers to the African Humid Period (~15–5 kyr BP, AHP), grey bars mark arid phases during the Younger Dryas (YD) and the Older Dryas (OD) stadials as well as during the Last Glacial Maximum (LGM). Age control along the Chew Bahir record is shown as grey squares (radiocarbon ages) and red triangles (CB correlation tie points). The CB records are compared to the earth’s precession cycle (Berger and Loutre, 1991), lake-level fluctuations for Ziway–Shala from Gillespie et al. (1983) and Turkana from Garcin et al. (2012; filled curve), Johnson et al. (1991; dotted curve), and Brown and Fuller (2008; dashed curve).
Figure 1
Figure 2
Supplementary Figure 1 | Intra-basin core correlation of Chew Bahir transect cores. (A) Standardized potassium records of the Chew Bahir transect cores tuned to the depth of CB-01. Red circles indicate the minimum number of tie points. (B) All potassium records were tuned to the composite age model based on cal. ^14C ages, indicated by black circles (modified after Foerster, 2014).
Supplementary Figure 2 | The composite age model of the Chew Bahir basin (Foerster et al., 2012, 2014, Trauth et al., 2015) showing a linearly interpolated vs. a cubic-spline age model, based on 32 AMS ¹⁴C ages from Chew Bahir cores CB01, 03–06. All radiocarbon ages were converted to calibrated ages with OxCAL, using the IntCal13 calibration curves (Bronk Ramsey, 1995, 2009a,b; Reimer et al., 2013). Ages are the weighted mean of the probability density function. The grey linear age model refers to the first simplistic age-depth model as shown in Foerster et al., (2012). (A) ¹⁴C ages per tuned CB sediment cores. (B) Material used for age determination.
Supplementary Figure 3 | Potassium (K) content of Chew Bahir cores CB-01 (basin margin), CB-03 (transition), CB-05 (basin center) for the last 20 ka BP. Dashed lines refers to the African Humid Period (~15–5 kyr BP, AHP), grey bars mark arid phases during the Younger Dryas (YD) and the Older Dryas (OD) stadials as well as during the Last Glacial Maximum (LGM). Age control along the Chew Bahir record is shown by grey squares (radiocarbon ages) and red triangles (CB correlation tie points). The CB records are compared the earth's precession cycle (Berger and Loutre, 1991), lake level fluctuations for Ziway-Shala from Gillespie et al. (1983) and Turkana from Garcin et al. (2012; filled curve), Johnson et al. (1991; dotted curve) and Brown and Fuller (2008; dashed curve). Figure modified after Foerster et al. (2014) and Junginger et al. (2014).
### Supplementary Table 11 Radiocarbon dates from archaeological sites discussed in the text

<table>
<thead>
<tr>
<th>Site</th>
<th>Excavation unit</th>
<th>Cultural complex</th>
<th>Sample ID</th>
<th>Sample material</th>
<th>¹⁴C age [yrs BP]*</th>
<th>Age [cal BP]*</th>
<th>AMS Conv.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1s1</td>
<td>1</td>
<td>Unit XIV</td>
<td>Terminal Pleistocene LSA</td>
<td>Beta-292524</td>
<td>charcoal</td>
<td>11,480 ± 50</td>
<td>13,340 ± 70</td>
<td>AMS</td>
</tr>
<tr>
<td>B1s1</td>
<td>1</td>
<td>Unit VIII</td>
<td>Terminal Pleistocene LSA</td>
<td>LY-6059</td>
<td>charcoal</td>
<td>11,480 ± 60</td>
<td>13,330 ± 90</td>
<td>AMS</td>
</tr>
<tr>
<td>DW2s2</td>
<td>2</td>
<td>PS4</td>
<td>Early Holocene LSA</td>
<td>Beta-295889</td>
<td>charcoal</td>
<td>10,040 ± 50</td>
<td>11,560 ± 100</td>
<td>AMS</td>
</tr>
<tr>
<td>DW2s1</td>
<td>2</td>
<td>PS3</td>
<td>Early Holocene LSA</td>
<td>Beta-320183</td>
<td>charcoal</td>
<td>9,830 ± 50</td>
<td>11,250 ± 50</td>
<td>AMS</td>
</tr>
<tr>
<td>B1s4</td>
<td>1</td>
<td></td>
<td>Terminal Pleistocene LSA</td>
<td>Beta-332588</td>
<td>charcoal</td>
<td>12,040 ± 50</td>
<td>13,900 ± 90</td>
<td>AMS</td>
</tr>
<tr>
<td>Eth-73-3-III</td>
<td>3</td>
<td></td>
<td>LSA</td>
<td>SMU-86</td>
<td>charcoal</td>
<td>10,330 + 90</td>
<td>12,190 + 140</td>
<td>Conv.</td>
</tr>
</tbody>
</table>

### Turkana; eastern shore

| Gaji’3 | 12 | Beach sands Unit B | Fishing settlement | Gx 5475 A | bone (fish) | 4,560 ± 185 | 5,240 ± 280 | Conv. | Owen et al., 1982; Barthelemy 1985, 131 |
| Gaji’1; Nderati Wells | 12 | Beach sands | Pre-ceramic LSA | Gx 5478 | ? | 15,550 ± 120 | Conv. | Mgomozuelu, 1981 |
| Gaji’11 | 12 | Sand bar | Fishing settlement; (pre-pottery LSA?) | Hel-1276 | shell | 8,920 ± 130 | 9,920 ± 250 | Conv. | Owen et al., 1982 |
| Gaji’11 | 12 | Sand bar | Fishing settlement; (pre-pottery LSA?) | Hel-1277 | Etheria shell | 10,250 ± 230 | Conv. | Owen et al., 1982 |
| Fxj’12 | 12 | Sand spits | Fishing settlement; (pre-pottery LSA?) | Gx-5479 | shell | 11,030 ± 50 | Conv. | Owen et al., 1982 |
| Fxj’12 | 12 | Sand spits | Fishing settlement; (pre-pottery LSA?) | R1-954 | shell | 9,940 ± 260 | Conv. | Owen et al., 1982 |
| Gaji’2 | 12 | Beach sands; Lower horizon | Pastoral Neolithic; (cattle bones) | P-2609 | charcoal | 4,160 ± 110 | 4,680 ± 180 | Conv. | Owen et al., 1982; Barthelemy 1985, 131 |
| Gaji’2 | 12 | Beach sands; Lower horizon | Pastoral Neolithic; (cattle bones) | SUA-634 | charcoal | 4,160 ± 110 | 4,680 ± 180 | Conv. | Owen et al., 1982; Barthelemy 1985, 131 |
| Gaji’4; Dongodien | 12 | Beach sands; Unit 5C | Pastoral Neolithic; (cattle bones) | SUA-637 | charcoal | 3,945 ± 135 | 4,410 ± 290 | Conv. | Owen et al., 1982; Barthelemy 1985, 181 |
| Gaji’4; Dongodien | 12 | Beach sands; Unit 5C | Pastoral Neolithic; (cattle bones) | SUA-637 B | humic acid | 4,100 ± 125 | 4,550 ± 210 | Conv. | Owen et al., 1982; Barthelemy 1985, 181 |
| Gaji’4; Dongodien | 12 | Beach sands; Unit 5C | Pastoral Neolithic; (cattle bones) | P-2610 | charcoal | 4,380 ± 110 | 4,800 ± 110 | Conv. | Owen et al., 1982; Barthelemy 1985, 181 |
| Gaji’4; Dongodien | 12 | Beach sands; Unit 5C | Pastoral Neolithic; (cattle bones) | Beta-252056 | charcoal | 4,480 ± 110 | 4,710 ± 90 | Conv. | Ashley et al., 2011 |
| Jargole Obj’1 | 14 | Pillar site; Pastoral Neolithic | AA85131 | OES-bead | 4,380 ± 39 | 4,950 ± 70 | AMS | Hildebrand and Grillo, 2012 |
| Jargole Obj’1 | 14 | Pillar site; Pastoral Neolithic | AA85132 | OES-bead | 4,251 ± 39 | 4,780 ± 50 | AMS | Hildebrand and Grillo, 2012 |
| Jargole Obj’1 | 14 | Pillar site; Pastoral Neolithic | AA85133 | OES-bead | 4,401 ± 39 | 4,970 ± 80 | AMS | Hildebrand and Grillo, 2012 |
| Jargole Obj’1 | 14 | Pillar site; Pastoral Neolithic | AA85134 | OES-bead | 4,146 ± 53 | 4,680 ± 110 | AMS | Hildebrand and Grillo, 2012 |
| Il Lokeridede Gaji’23 | 12 | Pillar site | TO-4911 | charcoal | 4,180 ± 60 | 4,690 ± 110 | Conv. | Koch, 1994; Koch et al., 2002 |

### Turkana; southern shore


### Turkana; western shore

<p>| Lopoyo | 16 | | UCLA 2124J | charcoal | 950 ± 80 | 860 ± 110 | Conv. | Lynch and Robbins, 1979 |
| Lopoyo | 16 | | UCLA 2124G | charcoal | 870 ± 80 | 810 ± 90 | Conv. | Lynch and Robbins, 1979 |
| Lothagam North; Gej’9 | 17 | Pillar site | ISGS-A1491 | OES-bead | 4,385 ± 15 | 4,940 ± 60 | AMS | Hildebrand and Grillo, 2012 |
| Lothagam North; Gej’9 | 17 | Pillar site | ISGS-A1505 | OES-bead | 4,165 ± 20 | 4,720 ± 60 | AMS | Hildebrand and Grillo, 2012 |
| Lothagam North; Gej’9 | 17 | Pillar site | ISGS-A1492 | OES-bead | 4,265 ± 15 | 4,840 ± 20 | AMS | Hildebrand and Grillo, 2012 |
| Lothagam West; Gej’9 | 17 | Pillar site | ISGS-A1494 | charcoal | 4,290 ± 20 | 4,850 ± 20 | AMS | Hildebrand and Grillo, 2012 |
| Kalokol; GcJj3 | 15 | Pillar site | ISGS-A1493 | OES-fragment | 3,890 ± 15 | 4,330 ± 60 | AMS | Hildebrand and Grillo, 2012 |
| Manenamya; GcJj5 | 15 | Pillar site | ISGS-A1504 | OES-bead | 4,255 ± 20 | 4,840 ± 20 | AMS | Hildebrand and Grillo, 2012 |
| Manenamya; GcJj5 | 15 | Pillar site | ISGS-A1490 | OES-bead | 3,805 ± 15 | 4,190 ± 30 | AMS | Hildebrand and Grillo, 2012 |
| Kokito 01; GcJj11 | 15 | Unit A | ISGS-A1714 | charcoal | 9,785 ± 35 | 11,220 ± 30 | AMS | Beyin, 2011b |
| Kokito 01; GcJj11 | 15 | Unit A | ISGS-A1715 | charcoal | 9,060 ± 30 | 10,220 ± 30 | AMS | Beyin, 2011b |</p>
<table>
<thead>
<tr>
<th>Location</th>
<th>Level</th>
<th>Sample Type</th>
<th>Dating Method</th>
<th>Age (calibrated)</th>
<th>Age (conventional)</th>
<th>Conversion Method</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kumali 6</td>
<td>TU3 Level 5B</td>
<td>ceramic LSA</td>
<td>ISGS 5998</td>
<td>1,740 ± 70</td>
<td>1,665 ± 87</td>
<td>Conv.</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Kumali 6</td>
<td>TU4 Level 7</td>
<td>ceramic LSA</td>
<td>ISGS 5999</td>
<td>1,920 ± 70</td>
<td>1,863 ± 85</td>
<td>Conv.</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Kumali 6</td>
<td>TU3 Level 19</td>
<td>LSA</td>
<td>ISGS 6000</td>
<td>4,780 ± 100</td>
<td>5,486 ± 115</td>
<td>Conv.</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Duba 8</td>
<td>TU4 Level 6</td>
<td>LSA</td>
<td>GX 31763</td>
<td>1,840 ± 40</td>
<td>1,781 ± 47</td>
<td>AMS</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Sheli 10</td>
<td>TU2 Level 6</td>
<td>LSA</td>
<td>GX 31762</td>
<td>1,330 ± 80</td>
<td>1,235 ± 75</td>
<td>Conv.</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Koka 9</td>
<td>TU2 Level 15</td>
<td>LSA</td>
<td>GX 31765</td>
<td>2,110 ± 40</td>
<td>2,085 ± 55</td>
<td>AMS</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Koka 9</td>
<td>TU2 Level 20</td>
<td>LSA</td>
<td>GX 31766</td>
<td>2,090 ± 90</td>
<td>2,097 ± 131</td>
<td>Conv.</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Shapa 7</td>
<td>TU1 Level 3</td>
<td>Ceramic LSA</td>
<td>ISGS A1368</td>
<td>970 ± 25</td>
<td>879 ± 45</td>
<td>AMS</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Chiri 11</td>
<td>TU1 Level 3</td>
<td>LSA</td>
<td>ISGS A1366</td>
<td>305 ± 15</td>
<td>372 ± 50</td>
<td>AMS</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Chiri 11</td>
<td>TU1 Level 3</td>
<td>LSA</td>
<td>ISGS A1367</td>
<td>130 ± 100</td>
<td>136 ± 100</td>
<td>AMS</td>
<td>Hildebrand et al., 2010</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>H9, Level 5; RCA</td>
<td>LSA</td>
<td>ISGS-6013 charcoal</td>
<td>6,050 ± 110</td>
<td>6,930 ± 190</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>N42E36, Level 9; HEP</td>
<td>LSA</td>
<td>ISGS-A1010 charcoal</td>
<td>7,720 ± 600</td>
<td>8,800 ± 930</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>G9, Level 2 RCA</td>
<td>LSA</td>
<td>ISGS-A1011 charcoal</td>
<td>8,440 ± 20</td>
<td>9,480 ± 30</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>TU2S, Level 6 OST</td>
<td>LSA</td>
<td>ISGS-A1012 charcoal</td>
<td>7,055 ± 20</td>
<td>7,890 ± 40</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>C9, Level 10</td>
<td>LSA</td>
<td>ISGS-A1532 charcoal</td>
<td>5,760 ± 20</td>
<td>6,650 ± 50</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>C9, Level 11 MRS</td>
<td>LSA</td>
<td>ISGS-A1533 charcoal</td>
<td>4,625 ± 25</td>
<td>5,380 ± 60</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>C9, Level 12 MRS</td>
<td>LSA</td>
<td>ISGS-A1534 charcoal</td>
<td>9,215 ± 35</td>
<td>10,380 ± 90</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>N42E35, Le. 2 ACW</td>
<td>LSA</td>
<td>COL-1875 charcoal</td>
<td>166 ± 33</td>
<td>160 ± 100</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>M14, Level 13 ACH</td>
<td>LSA</td>
<td>COL-1876 charcoal</td>
<td>3,942 ± 36</td>
<td>4,390 ± 80</td>
<td>AMS</td>
<td>unpubl.</td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>G10, hearth1, cutting 5</td>
<td>Ceramic LSA (?)</td>
<td>GIF-11242 charcoal</td>
<td>1,480 ± 80</td>
<td>1,420 ± 90</td>
<td>Gutherz et al., 2002</td>
<td></td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>Layer 6</td>
<td>Ceramic LSA</td>
<td>GIF-11244 charcoal</td>
<td>2,180 ± 45</td>
<td>2,190 ± 100</td>
<td>Gutherz et al., 2002</td>
<td></td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>Layer 9, sub-phase 1</td>
<td>Ceramic LSA</td>
<td>GIF-11246 charcoal</td>
<td>4,370 ± 70</td>
<td>5,060 ± 160</td>
<td>Gutherz et al., 2002</td>
<td></td>
</tr>
<tr>
<td>Mochena Borago 4</td>
<td>F2?</td>
<td>Ceramic LSA</td>
<td>?</td>
<td>1,915 ± 65</td>
<td>1,860 ± 100</td>
<td>Gutherz et al., 2002</td>
<td></td>
</tr>
<tr>
<td>Harouruna 4</td>
<td>Layer 3</td>
<td>LSA</td>
<td>Beta-174905 charcoal</td>
<td>12,070 ± 70</td>
<td>13,930 ± 110</td>
<td>AMS</td>
<td>Bachechi, 2005</td>
</tr>
</tbody>
</table>

---

*a* Radiocarbon age with 2-sigma standard deviation.

*b* Calibrated radiocarbon ages, mean.

Conventional radiocarbon ages were converted to calendar years using the IntCal13 data set (Reimer et al., 2013) and CalPal (Weniger and Jöris, 2008).

*c* Number refers to archaeological sites as indicated in Figure 1a.

*d* Ages from Mochena Borago are in preparation to be published by S. Brandt, L. Hildebrand, R. Vogelsang and coll.