Pleistocene and Holocene palaeoclimates in the Gebel Akhdar (Libya) estimated using herbivore tooth enamel oxygen isotope compositions

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Abstract

The palaeoclimate of the Gebel Akhdar massif, in Cyrenaica, northeast Libya, is investigated using the stable oxygen isotope ratio ($\delta^{18}O$) of herbivore tooth enamel from the archaeological faunal assemblages of the Haua Fteah and Hagfet ed Dabba caves. Samples accumulated through human activity at the sites, thus climatic interpretations are in direct chronological association with periods of human presence in the local landscape. Wild Ammotragus lervia (Barbary sheep) and Bos sp. (auroch), and domestic Ovis sp. and Capra sp. from the Levalloiso-Mousterian (≥73.3 to 43.5 ka) to the Neolithic (~9.3 to 5.4 ka) cultural phases are analysed. Results indicate that the most arid environment represented by the samples occurred at ~32ka, when populations associated with Dabban lithic assemblages were present within the region. Climatic instability increased during oxygen isotope stage 2. Consistent with other palaeoenvironmental investigations in the Gebel Akhdar, there is no evidence for hyper-arid events during the last glacial and surface water, most probably in the form of local springs, was available throughout the time periods considered. Overall, results indicate that different cultural groups occupied the Gebel Akhdar landscape under different climatic conditions, but that climate variations appear to have been of lower magnitude than those that occurred at inland North African locations. These reconstructions provide further support to the theory that the Gebel Akhdar may have served as a refugium for human populations in North Africa during times of global climatic extremes.

Key words: Haua Fteah; North Africa; stable isotopes; refugium; caprid
1. Introduction

Climate plays a key role in determining human biogeography through influencing the
distribution and composition of floral and faunal communities within a region, and in turn the
food, water and raw material resources available to human populations (Cox et al., 1988;
Eeley et al., 1999; Snyder and Tartowski, 2006). While it is well evidenced that the millennial-
scale climatic oscillations that occurred throughout the last glacial cycle manifested as wet-
dry alternations in the North African environment (e.g. Pachur and Rottinger, 1997; Ghoneim
et al., 2007; Drake et al., 2011), variations that occurred at resolutions relevant to human
resource exploitation (sub-annual to decadal) are less well understood. This is particularly
the case for the North African coast where there is a notable deficit in high-resolution
terrestrial climate information.

Understanding the climate of North Africa is important when considering the history of
human populations in the region. Archaeological archives from across the continent indicate
variations in population densities and distributions, subsistence strategies, and technological
and cultural practices during the late Pleistocene and Holocene, which may have occurred in
step with climatic variations (Cremaschi and di Lernia, 1999; Garcea, 2006; Bouzouggar et al.,
2007; Scerri, 2013). Following the widespread distribution throughout North Africa of Middle
Palaeolithic/Middle Stone Age hunter-gatherer groups during and immediately after oxygen
isotope stage (OIS) 5, during OIS 3 and 2 there appears to have been considerable
depopulation of the continental interior potentially in response to increasing aridity (Petit-
Maire, 1991; Cremaschi et al., 1998; Castañeda et al., 2009; Cancellieri and di Lernia, 2013).
This broadly coincided with an increased human presence in some North African coastal
regions, and technological changes dating to this time period (termed the
Iberomaurusian/Oranian) have been interpreted as possible adaptations to aridity (Irish,
2000; Barton et al., 2007; Bouzouggar et al., 2008). As the climate became increasingly less
arid during the late glacial and early Holocene, populations spread further into the North
African continent once more and there is evidence for wild plant exploitation and the management of wild animals in the central Sahara, an increase in marine resource exploitation along the coast, and later the appearance of domestic caprids and bovids throughout the region (Cremaschi and di Lernia, 1999; di Lernia, 2001; Kuper and Kröpelin, 2006; di Lernia et al., 2012).

However, while many of these changes have been interpreted as responses to variations in climate, there are few archives from which palaeoclimatic conditions in direct chronological association with human activities can be established. The Gebel Akhdar in northeastern Libya presents one such opportunity. The region's archaeological record indicates people were present in the region during each of the OlIs of the last glacial-interglacial cycle, albeit likely in varying numbers and not necessarily continuously (McBurney, 1967; Barker et al., 2007; 2008; 2009; 2010; 2012; Jones et al., 2011; Douka et al., 2014). This raises questions of whether favourable environmental conditions in the Gebel Akhdar made the region attractive for occupation and a refugium during periods when other areas of North Africa appear to have been largely abandoned, and whether variations in the technologies and subsistence strategies that occurred within the Gebel Akhdar were influenced by the local climatic characteristics.

This paper provides palaeoclimatic data for the Gebel Akhdar between approximately 73 and 5 ka, which are directly associated with the archaeological record. The oxygen isotope composition ($\delta^{18}$O) of herbivore tooth enamel carbonate is analysed and results are principally used to infer past aridity. Samples come from two caves, the Haua Fteah and Hagfet ed Dabba, that contain extensive archaeological deposits. The analysed material comes from the major prey species found at the two sites and was excavated from spits/levels that also contained other archaeological materials (predominately lithics) (McBurney, 1967; McBurney and Hey, 1955).
2. Background

2.1 Environmental Context

The Gebel Akhdar massif (maximum elevation ~780m) is situated in Cyrenaica, northeast Libya, on the Mediterranean coast (Fig. 1). Present day mean annual temperatures range from 16 to 21°C and mean annual precipitation, which typically occurs between October and April each year, ranges from ~200-600 mm (Elfadli, 2009; El Kenawy et al., 2009; Ageena et al., 2014). Surrounded by the Sahara Desert to the south and east, and by the Mediterranean Sea to the north and west, there is high ecological diversity and notable endemism in the floral communities within the region (El-Darier and El-Mogaspi, 2009). Such endemism is characteristic of prolonged isolation, suggesting that the Gebel Akhdar’s climate may have differed to adjacent regions over an extended period of time. This climatic setting is therefore of interest when considering the late Pleistocene and Holocene human populations that inhabited the region, and their connections to/isolation from other areas in North Africa.

Today the region sits at the southern extent of the mid-latitude Mediterranean climate system, which is typified by hot dry summers and mild wet winters, influenced by North Atlantic ocean-atmosphere circulation and Mediterranean cyclone activity (Alpert et al. 1990; Lionello et al., 2006). To the south, beyond the Sahara Desert, seasonal temperature fluctuations are lower in magnitude, and summer rainfall is the predominant source of moisture, driven by monsoonal circulation patterns and the seasonal movement of the Inter-Tropical Convergence Zone (ITCZ) across the region (Camberlin et al., 2001; Pomposi et al., 2014). While the maximum southward and northward extents of these two rainfall regimes have varied in the past, throughout the time period considered in this study, the dominant source of moisture to the northern African coastline has consistently been from North Atlantic and Mediterranean sources (Yan and Petit-Maire, 1994; Sultan et al., 1997; Abouelmagd et al., 2012).
To date, only a limited amount of palaeoenvironmental data from the Gebel Akhdar are available. These data suggest that the variations in temperatures and rainfall amounts that occurred over the last ~100,000 were less extreme than elsewhere in North Africa (Inglis, 2012; Prendergast, 2013). Alluvial, tufa and dune deposits are all found within the region indicating variations in the amount of moisture available in the landscape varied with time, but a lack of precise chronological understanding of these deposits hinders comparisons with the archaeological record (McBurney and Hey, 1955). Mollusc isotope data from the Haua Fteah cave suggest a more arid phase during OIS 2 (Prendergast et al., submitted). The Haua Fteah cave sediments also highlight periods of increased landscape instability during OIS 3, although taphonomic processes complicate climatic interpretations from these archives (Barker et al., 2010; Hunt et al., 2010; Inglis, 2012). Thus there remains a need to gain further local palaeoenvironmental information from additional archives that are directly linked to the archaeological record.

2.2 Archaeological Context

To infer past climate in the Gebel Akhdar during periods of human activity, we consider the oxygen isotope compositions of tooth enamel from the main prey species found within the zooarchaeological assemblages from two cave sites, the Haua Fteah and Hagfet ed Dabba. The Haua Fteah (32.90˚N, 22.05˚E, ~50m asl, Fig. 1) is a large rock shelter situated ~1km from the coast on the northward facing lower escarpment of the Gebel Akhdar. The cave was first excavated by Charles McBurney during the 1950s and its re-excavation has been a central part of a renewed programme of archaeological investigation taking place in the region since 2007 (McBurney, 1967; Barker et al., 2007; 2008; 2009; 2010; 2012; Rabett et al., 2013; Farr et al., 2014). From the original excavations McBurney (1967) described an archaeological sequence containing (using his terminology) Middle Palaeolithic (Pre-Aurignacian and Levalloiso-Mousterian), Upper Palaeolithic (Dabban and Oranian), Mesolithic (Libyco-Capsian), Neolithic (of Capsian tradition), Graeco-Roman and post-Classical deposits.
In brief, the Pre-Aurignacian and Levalloiso-Mousterian phases are characterized by blades and burins, while chamfered blades and wide bladelets are typical of Dabban assemblages (McBurney, 1967; Barker et al., 2010; 2012). Use of the cave (or at least the area excavated) appears to have intensified during the Oranian phase, with evidence for in situ blade production and re-touching, trampling, and the year-round shellfish exploitation (Barker et al., 2010; 2012, Prendergast et al., accepted). The Capsian assemblage is characterized by backed bladelets, microliths and bone and shell artefacts, with evidence for an increase in shellfish and wild plant exploitation (McBurney, 1967; Barker et al., 2010). In the Neolithic phase there is evidence for further intensification in the exploitation and management of floral and faunal resources, with evidence of grinding implements, domestic caprids, and pottery, but no evidence for cereal cultivation (McBurney, 1967; Barker et al., 2012).

The 2007-onwards re-exca-vation and re-dating of the Haua Fteah sequence, combined with the reanalysis of the McBurney archive, are examining if these cultural divisions and terminologies remain appropriate, but as this work is ongoing, McBurney’s divisions and terminology are used in this paper. Chronological age estimates for McBurney’s cultural phases are displayed in Table 1 (Douka et al., 2014). These age brackets indicate the most probable upper and lower date for the phases; they do not imply that the phase lasted the duration of the age bracket, nor indicate whether single or multiple periods of occupation occurred within each phase.

The Hagfet ed Dabba (32.68°N, 21.56°E, ~360m asl, Fig. 1) is a smaller cave located ~60km from the Haua Fteah and ~15km from the present day coast. Situated on a dry tributary of Wadi Kuf (today the main watershed of the Gebel Akhdar), the cave was excavated in 1947 and 1948 by Charles McBurney, with an additional small test-pit made in 2008 (McBurney and Hey, 1955; Barker et al., 2008). The 1940s excavations revealed stratified deposits containing Dabban lithics (Layers VI to II) and a loose sub-surface layer
(Layer I) containing Roman pottery (McBurney and Hey, 1955). No absolute chronological age determinations are available for Hagfet ed Dabba.

2.3 Enamel isotopes in climate studies

This study analyses the oxygen isotope composition of the tooth enamel carbonate ($\delta^{18}$O$_{enamel}$) from samples from the Haua Fteah and Hagfet ed Dabba caves. The carbon isotope composition of the samples has also been measured and is submitted for publication elsewhere (Reade et al., submitted). In mammals, $\delta^{18}$O$_{enamel}$ is determined by the animal's body water $\delta^{18}$O$_{bw}$ during the period of mineralization; $\delta^{18}$O$_{bw}$ closely reflects ingested water $\delta^{18}$O ($\delta^{18}$O$_{iw}$) and is influenced by the animal's ecology and physiology (Longinelli, 1984; Luz et al., 1984; Luz and Kolodny, 1985; Bryant and Froelich, 1995; Kohn, 1996).

Enamel mineralization is a process that typically spans several months, and in medium and large ruminants a whole tooth forms over approximately a full year (Brown et al., 1960; Weinreb and Sharav, 1964; Suga, 1982; Aoba, 1996). $\delta^{18}$O$_{enamel}$ reflects an average of the $\delta^{18}$O$_{iw}$ over an equivalent period, although the exact temporal character of the signal will depend on sampling geometry and the species-specific pattern of mineralization (Passey and Cerling, 2002; Balasse, 2003; Zazzo et al., 2005).

For terrestrial mammals ingested water is largely acquired, either directly or indirectly, from meteoric water, which has a $\delta^{18}$O composition dependent on climatic (e.g. temperature, rainfall, and humidity) and geographical (e.g. distance from the ocean/precipitation source and altitude) factors (Dansgaard, 1964; Rozanski et al., 1992). If an animal migrates both climatic and geographical factors will be represented in the $\delta^{18}$O$_{enamel}$. Sources of ingested waters can include surface water, groundwater, water contained in the diet, and dew. Obligate drinkers typically consume water from surface sources, which have a $\delta^{18}$O similar to precipitation $\delta^{18}$O ($\delta^{18}$O$_{precip}$) in environments where evaporation is limited; in evaporative environments surface water is enriched in $^{18}$O relative to precipitation (Dansgaard, 1964; Longinelli, 1984; Luz and Kolodny, 1985; Rozanski et al., 1992).
1992). Non-obligate drinkers principally acquire water from dietary sources (i.e. plant water for herbivores) (Ayliffe and Chivas, 1990; Luz et al., 1990; Delgado Heurtas et al., 1995; Murphy et al., 2007). Plant water is derived from recent precipitation and/or groundwater and has a $\delta^{18}O$ signature indirectly linked to $\delta^{18}O_{\text{precip}}$, potentially being modified by input from other water pools, through evaporation at the surface, and transpiration from the leaves (which is mediated by water availability, temperature and humidity) (Dongmann et al., 1974; Ehleringer and Dawson, 1992; Barbour, 2007). A number of studies have shown a strong relationship between relative humidity and skeletal $\delta^{18}O$ from non-obligate drinking animals, with higher $\delta^{18}O$ values occurring in lower humidity environments (Ayliffe and Chivas, 1990; Delgado Huertas et al., 1995; Murphy et al., 2007). Skeletal $\delta^{18}O$ in obligate drinkers most commonly relates to $\delta^{18}O_{\text{precip}}$ and temperature (e.g. Longinelli, 1984; Hoppe et al., 2006).

3. Material and methods

79 Ammotragus lervia teeth from the Haua Fteah and 50 from Hagfet ed Dabba were sampled for oxygen isotope analysis. Additionally, 21 Bos sp. and 12 domestic caprid (Ovis sp. and Capra sp.) teeth from Haua Fteah were also analysed. All samples are from the McBurney excavations at the two sites. Samples from the Haua Fteah are curated in the Museum of Archaeology and Anthropology, University of Cambridge. Samples from the Hagfet ed Dabba are curated in the Natural History Museum, London. The teeth do not show direct evidence of human manipulation (e.g. cut marks, burning, fracturing), but examples of such modifications have been identified on other skeletal elements from the same species found within the same contexts at the sites, albeit at relatively low frequencies (Klein and Scott, 1986). This, combined with the large quantity of lithic and other archaeological material excavated from the same spits/layers as the samples, we judge to indicate that the samples are the result of human activity within the caves, and thus are temporally tied to periods when people were present within the Gebel Akhdar landscape.
The species analysed in this study are a mix of obligate (*Bos* sp.), non-obligate (*A. lervia*) and ‘intermediary’ drinkers (domestic caprids). Domestic caprids cannot survive without drinking water indefinitely but desert-adapted breeds can tolerate arid, water-stressed environments with little or no access to water over short time periods (El-Nouty et al., 1988). Bovids have higher water requirements, and while arid-adapted species/breeds can survive with less water than those from more humid environments, the required volume and frequency of access to drinking water is far greater than for caprids (King, 1983). *A. lervia* is a non-obligate drinker and can meet its water requirements solely through water contained in the diet (Ogren, 1965). Therefore, we predict that *Bos* sp. $\delta^{18}$O enamel will most likely reflect the $\delta^{18}$O of surface waters, potentially enriched relative to $\delta^{18}$Oprecip through evaporation, *A. lervia* $\delta^{18}$O enamel will most likely reflect $\delta^{18}$Oplant, and may be influenced by relative humidity, and domestic caprid $\delta^{18}$Oenamel may represent an intermediary signal. None of the wild species analysed in this study are thought to undertake long distance seasonal migrations in the context of the Gebel Akhdar’s geographical setting, thus the data presented here will reflect a signal local to the Gebel Akhdar. This also implies that year-round surface water must have been available within the region during the time periods where *Bos* sp. are present.

### 3.1 Chronological association of the samples

Samples analysed in this study from the Haua Fteah come from layers that are associated with the McBurney-defined cultural phases of the Levalloiso-Mousterian, Dabban, Oranian, Capsian and Neolithic, covering a period from OIS 4 to the mid Holocene (McBurney, 1967; Douka et al., 2014). McBurney excavated the site in a series of overlapping spits, which often spanned multiple stratigraphic layers (McBurney, 1967). As such, a large proportion of the samples cannot be attributed to a stratigraphic context more resolved than the cultural phase from which they came. Where samples can be attributed to spits that were either entirely contained within a single stratigraphic layer, or that span 2-3 layers but do not overlap with other spits, narrower chronological estimations are made (Table 1).
Samples from Hagfet ed Dabba come from Layers VI to I. So far, the site is undated and its chronological context can only be inferred through correlation with the lithic assemblage at Haua Fteah, and the dates associated with these Layers. In particular, McBurney suggested that a change in lithic technology occurring between Layer VI and III at Hagfet ed Dabba was similar to a change that occurs within Layer XX at Haua Fteah (McBurney and Hey, 1955; McBurney, 1967). Layer XX at Haua Fteah has been dated to ~32 ka (Douka et al., 2014). The duration and frequency of occupation represented in the Hagfet ed Dabba archaeological sequence are unclear.

3.2 Enamel sampling and isotopic analysis

Sampling was restricted to third molars (M3s) in the caprid samples to ensure an in utero/pre-weaning signal was avoided. M2s and M3s were sampled for the bovids. Bulk-tooth samples were taken to infer average $\delta^{18}O_{iw}$ over the period of tooth formation. Each tooth sampled is predicted to have mineralized over approximately 1 year (Brown, 1960; Ogren, 1965) although the time represented in each sample may be less as the full enamel depth was not sampled (see Reade et al., 2015). Each tooth selected for analysis was thoroughly cleaned prior to sampling. Using a diamond coated drill bit mounted on a variable-speed handheld drill, powdered enamel was collected (10-15 mg) evenly along a transect that spanned the length of the tooth from the occlusal surface to the enamel-root junction. A 5-7mg sub-sample was then chemically pre-treated following the method described by Balasse et al. (2002) to remove organic and secondary carbonate material. The treated powder was isotopically analysed at the Godwin Laboratory, Department of Earth Sciences, University of Cambridge. The carbonate phase of the samples were analysed on an automated Gasbench interfaced with a Thermo Finnigan MAT253 isotope ratio mass spectrometer, being reacted with 100% orthophosphoric acid for 2 hours at 70°C in individual vessels. Each run was accompanied by 10 reference carbonates (Carrara Z, $\delta^{18}O = -1.27\%_o$), two control samples (Fletton Clay, $\delta^{18}O = -0.3\%_o$) and in-house enamel reference samples (STD1 ($\delta^{18}O = -4.3\%_o$) and STD4 ($\delta^{18}O =$...
which were pre-treated following the same method used for the archaeological samples (n=4 for every 20 archaeological samples analysed). Carrara Z has been calibrated to VPDB using the IAEA NBS19 standard. Results are reported on the delta scale in units of permil with reference to the international standard VPDB. The machine precision for $^{18}O/^{16}O$ is better than ±0.1‰ based on replicate analyses of laboratory standards. Reproducibility on the in-house enamel references is ±0.2‰. Reproducibility on the Fletton Clay control sample is ±0.8‰. Statistical analysis was performed using SPSS v.19 (Statistical Package for Social Sciences) and statistical significance was accepted at $p<0.05$.

4. Results

A summary of results from the Haua Fteah and Hagfet ed Dabba is displayed in Table 2. Full results are available in Appendix A.

4.1 Haua Fteah

Considered by cultural phase, $A. lervia$ mean $\delta^{18}O_{enamel}$ from the Haua Fteah is highest in the Dabban (1.2 ± 0.5‰, n=5, range=1.3‰) and lowest in the Neolithic (-0.9 ± 0.9‰, n=29, range=3.4‰) (Table 2, Fig. 2), varying significantly through the sequence (Kruskal Wallis, $H(4)=20.967, p<0.05$). Inter-individual variation within each cultural phase is higher (≥3.4‰) in the Levalloiso-Mousterian (n=8), Oranian (n=30) and Neolithic (n=29) than in the Dabban (n=5) and Capsian (n=7) (≤1.4‰). While this may partly be an effect of different sample sizes, the notable difference in the spread of the data between the Levalloiso-Mousterian and the Dabban and Capsian (Table 2, Fig. 2), despite relatively little difference in sample size, suggests that the reduced variation observed in the Dabban and Capsian samples may be a true reflection of $\delta^{18}O$ variability during these time periods.

Mean $\delta^{18}O_{enamel}$ and inter-individual variation in the Neolithic domestic caprids (-0.7 ± 0.8‰, n=12, range=3.0‰) cannot be distinguished from the wild Neolithic $A. lervia$ samples (-0.9 ± 0.9‰, n=29, range=3.4‰) (Mann Whitney, $U=178, z=0.115, p>0.05$), indicating that the animals had isotopically similar sources of water. $Bos$ sp. mean $\delta^{18}O_{enamel}$ does not vary
between cultural phase (Kruskal Wallis, $H(2)=0.440, p>0.05$), and is indistinguishable from $A. lervia$ $\delta^{18}O_{\text{enamel}}$ in the Capsian (Mann Whitney, $U=6.0, z=-1.512, p>0.05$), but significantly different in the Oranian (Mann Whitney, $U=66.0, z=-3.828, p<0.05$). The two Dabban $Bos$ sp. samples are 2.1‰ and 2.4‰ lower than the mean Dabban $A. lervia$ $\delta^{18}O_{\text{enamel}}$ (1.2 ± 0.5 ‰, $n=5$). This suggests the two species were consuming isotopically different waters in the Oranian and Dabban. The highest within-phase inter-individual variation in the $Bos$ sp. data occurs in the Oranian (2.2‰), although this may be influenced by the relatively large sample size, in comparison to the Capsian and Dabban (Table 2).

When considering the subset of data for which more discrete stratigraphic provenances can be determined ($n=59$), and where $n\geq3$ (Fig. 3), the highest $\delta^{18}O_{\text{enamel}}$ for $A. lervia$ (1.5 ± 0.2‰, $n=3$) occurs in Dabban Layer XX, which is dated to ~32 ka (Douka et al., 2014). The Oranian Layers XIV, XV (~16.6-14.7 ka) display the widest intra-layer variability (3.4‰), being only 0.9‰ less than the total variation observed across the whole of the Haua Fteah sequence for $A. lervia$. $Bos$ sp. $\delta^{18}O_{\text{enamel}}$ shows lower values and higher variation within Oranian Layer XII (~15.0-13.5 ka) than in the preceding Oranian Layer XIII, XIV or subsequent Capsian Layer X (~12.6-7.9 ka), although differences are small in comparison to the $A. lervia$ data (Fig. 3).

4.2 Hagfet ed Dabba

Only $A. lervia$ samples were available for analysis from Hagfet ed Dabba. Mean $\delta^{18}O_{\text{enamel}}$ shows little variation between Layers IV and I (Fig. 4), ranging from 0.0 ± 0.4‰ (n=6, range=1.0‰) in Layer III to 0.3 ± 1.3‰ in Layer I (n=8, range=3.8‰) (Table 2). The lack of between-layer difference includes the samples from Layer I, from which Roman ceramic material was recovered. It is not clear whether teeth from Layer I are Dabban in age but have become mixed with Roman accumulations, or are contemporaneous with the Roman pottery, or date to an intervening period. Inter-individual variation is 3.8‰ in Layer I. This is similar to the variation observed within some layers in the Haua Fteah assemblage but is
greater than the range seen in the other Hagfet ed Dabba layers, which do not exceed 2.5‰.

Across the whole sequence (Layers VI-I, excluding Layer V) there is a significant inter-layer difference in mean $\delta^{18}O_{\text{enamel}}$ (Kruskal Wallis, $H(5) = 17.417$, $p < 0.05$), with lower values in Layer VI (-0.9 ± 0.7‰, $n=12$, range=1.9‰) than Layers IV-I (Table 2). Sample size for Layer V ($n=2$) is too small to facilitate statistical comparison to the other layers.

Although the $\delta^{18}O$ results from the Haua Fteah Dabban samples are within the range seen at Hagfet ed Dabba, there is a significant difference between the mean $\delta^{18}O$ from Hagfet ed Dabba ($n=50$) and that of the Dabban Haua Fteah samples ($n=5$) (Mann-Whitney, $U=228$, $z=3.016$, $p < 0.05$). This difference appears to be slightly reduced (Mann-Whitney, $U=142$, $z=2.579$, $p < 0.05$) when only the Haua Fteah samples from Layer XX ($n=3$) are considered, which is the layer thought to be most chronologically similar to the Hagfet ed Dabba assemblage (McBurney and Hey, 1955; McBurney, 1967). However, the very large discrepancy in sample size between the two sites should be noted.

5. Discussion

Data here are derived from non-obligate drinking $A. lervia$, obligate drinking $Bos$ sp., and domestic caprids. Domestic caprids and wild $A. lervia$ are isotopically indistinguishable. Lower $Bos$ sp. $\delta^{18}O_{\text{enamel}}$ values most probably reflect a larger intake of drinking water compared to the caprids, for whom plant water would have constituted a greater component.

It is interesting to note that the largest differences between $Bos$ sp. and $A. lervia$ occur in the late Pleistocene Dabban and Oranian samples. The Holocene Capsian $Bos$ sp. and $A. lervia$ samples follow a similar pattern to the Holocene Neolithic $A. lervia$ and domestic caprid samples, being statistically indistinguishable. This could suggest that there was less difference in $\delta^{18}O$ between surface waters and plant waters during the Holocene than the Pleistocene, an effect that would be produced under more humid conditions.

While the water sources vary, ultimately all originate from local precipitation, which is derived from the global oceans. As glacial ocean $\delta^{18}O$ was ~1‰ higher than today
(Shackleton, 1987; Schrag et al., 2002), some of the temporal variation that occurs in our data is likely the product of this change. However, accounting for this variation is not straightforward as glacial-interglacial ocean $\delta^{18}O$ change appears to have been geographically and temporally variable (Elderfield and Ganssen, 2000; Paul et al., 2001; Duplessy et al., 2002). Accounting for variations in the source composition is further complicated if the source area from which local precipitation is derived also changes. Comparison of modern $\delta^{18}O_{\text{precip}}$ to Saharan fossil groundwater suggests precipitation during the late Pleistocene and early Holocene was derived from mid-latitude climate systems, and particularly palaeo-westerlies of Atlantic origin (Sultan et al., 1997; Abouelmagd et al., 2012). However, these groundwaters are located to the south of the Gebel Akhdar, and may not reflect the situation in coastal locations. In comparison, precipitation along the Levantine coast to the northeast of the Gebel Akhdar, is heavily influence by Mediterranean cyclone activity (Alpert et al., 1990).

Given the Gebel Akhdar’s topography and promontory position jutting out into the eastern Mediterranean Sea it is probable that this region received rainfall from Mediterranean sources in addition to those from the Atlantic across the time period considered.

The highest $A. lervia$ $\delta^{18}O_{\text{enamel}}$ values in the Haua Fteah sequence occur in the Dabban, and in particular in Layer XX, which is dated to ~32 ka (Douka et al., 2014). We interpret this as representing the most arid environment of the time periods considered in this study. However, overall variation in aridity appears to be of a relatively small magnitude: the difference between the ‘most humid’ and ‘most arid’ cultural phase at the Haua Fteah is represented by a difference in mean $\delta^{18}O_{\text{enamel}}$ of only 2.1‰. High $\delta^{18}O$ values are also seen in terrestrial molluscs from Dabban layers in the Haua Fteah (Prendergast et al., submitted). At a more regional scale this arid episode could correlate chronologically with Heinrich event 3, which was marked by a widespread reduction of moisture availability (Bartov et al., 2003). Quantitative palaeoaridity estimates are currently beyond the scope of this study. The precise relationship between skeletal $\delta^{18}O$ and the external environment is determined by
species-specific physiological processes such as metabolism, respiration and water turnover rate (Luz et al., 1984; Bryant and Froelich, 1995; Kohn, 1996). No studies that characterize this relationship in modern A. lervia populations, or other in non-obligate drinking caprids, currently exist, and the protected status of the species (Cassinello et al., 2008) makes conducting such a study presently unfeasible. In the meantime, our results can be given some context by considering what is known of δ18O variation from comparable modern populations and environments.

Globally, wild goat (Capra ibex), mouflon (Ovis ammon musimon) and roe deer (Capreolus capreolus) display an average decrease of ~0.88‰ in bone phosphate δ18O (δ18O_{phos}) for every ~1‰ decrease in local δ18O_{precip} (Delgado Huertas et al., 1995). While A. lervia physiology may be similar to these species, ingested water for A. lervia is only indirectly linked to precipitation, through plant water (Ogren, 1965). The degree of enrichment in δ18O_{plant} relative to δ18O_{precip} is highly variable and depends on the exact sources of the plant’s water, the amount of evaporation that these sources have been subject to, plant physiology, and plant transpiration rates, which are strongly influenced by relative humidity (Ehleringer and Dawson, 1992; Barbour, 2007). Considering other herbivore species consuming water largely or solely from plants, a ~1‰ change in δ18O_{phos} has been observed to correspond to a ~3% change in mean annual relative humidity in macropods (Ayliffe and Chivas, 1990). White tailed and mule deer (Odocoileus sp.) δ18O_{phos} has been shown to vary by 9.65‰ between environments where δ18O_{precip} differs by 1.2‰, relative humidity by 44% and temperature by 14°C (Luz et al., 1990). More recently, the interactive effect of temperature and relative humidity on macropod tooth enamel carbonate δ18O has also been demonstrated (Murphy et al., 2007). It is not possible to estimate the effect of these different parameters on the archaeological A. lervia δ18O_{enamel} without comparative studies of modern populations and palaeotemperature estimates from additional independent proxies in the Gebel Akhdar.
However, with reference to the other studies discussed, a 2.1‰ change in *A. lervia* δ$^{18}$O$_{enamel}$ is likely to indicate a relative small climatic change, most likely in relative humidity.

In the Mediterranean environment, δ$^{18}$O$_{precip}$ is influenced by both temperature and rainfall amount (Gourcy, 2005). At the Soreq cave site (Israel, 31.45°N, 35.03°E) rainfall was found to be the dominant factor, with weighted annual average δ$^{18}$O$_{precip}$ being 1.02 ± 0.11‰ higher per 100mm decrease in annual precipitation amount (Bar-Matthews et al., 2003).

Rainfall amount was also found to be the dominant factor in northwest African gerbil δ$^{18}$O$_{enamel}$ when mean annual precipitation (MAP) is <600mm, with a 3.7‰ increase in δ$^{18}$O$_{enamel}$ corresponding to a MAP decrease from 600 to 200 mm (Jeffery et al., 2015).

However, small mammal’s body water may be subject to greater evaporative enriched than in large mammals, so direct comparison between the magnitude of change in gerbil and caprid/bovid δ$^{18}$O$_{enamel}$ cannot be made. It is therefore likely that our results indicate a change in environmental aridity/humidity, controlled largely by the amount of rainfall. However, the amount of variation observed in the data, compared to the magnitude a variation seen in other data sets, suggests this would not have resulted in major ecological changes in the local environment.

The samples from Hagfet ed Dabba are most likely of a similar age to the Dabban phase at Haua Fteah. The δ$^{18}$O$_{enamel}$ values from Layers IV-I, while lower than the corresponding Dabban samples from Haua Fteah, are still higher than elsewhere in the Haua Fteah sequence. The δ$^{18}$O$_{enamel}$ values from Layers VI and V are lower and fall within the ranges seen during the earlier and later cultural phases at the Haua Fteah. Differences between the two sites may in part relate to differences in sample size and/or chronological association, but could also in part be explained by altitudinal differences, which would produce both higher amounts of precipitation and lower δ$^{18}$O at the Hagfet ed Dabba (Dansgaard, 1964; Poage and Chamberlain, 2001).
In relation to the archaeological record, the increased aridity between the Levalloiso-Mousterian and Dabban samples recorded here broadly correlates with a notable decrease in the distribution of archaeological sites in the pre-desert regions immediately south of the Gebel Akhdar between the Middle Stone Age (MSA) and Later Stone Age (LSA) (which are roughly comparable to McBurney’s (1967) Levalloiso-Mousterian and Dabban phases), and a corresponding increase in sites between the MSA and LSA within Gebel Akhdar (Barker et al., 2010; 2009; Jones et al., 2011). These events also broadly correspond to a period of increased aridity and depopulation in the wider Saharan region (Castañeda et al., 2009; Cancellieri et al., 2013). The observed increase in population distribution/density within the Gebel Akhdar, and the corresponding decrease elsewhere, could have been in response to the climatic changes reported here, where the Gebel Akhdar, although following the regional trend towards more arid conditions, provided a relatively more humid environment than adjacent regions. Within the Gebel Akhdar, the persistence of more humid conditions is likely to have occurred particularly in more inland areas, such as in the Wadi Kuf and Hagfet ed Dabba region, where the higher elevation is likely to have resulted in higher rainfall amounts. This suggestion is consistent with archaeological site distribution patterns, which show sites dating to this time period were most common in higher elevation areas (Jones et al., 2011). Evidence for less arid conditions than in adjacent regions provides further support to the theory that the Gebel Akhdar may have served as a refugium for humans in North Africa during times of global climatic extremes (Barker et al. 2012; Prendergast et al. submitted; accepted; Reade et al., submitted).

The large variation in A. lervia and Bos sp. $\delta^{18}O_{\text{enamel}}$ that occurs during the late glacial Oranian likely reflects a variable climate during this time period, where relatively high-magnitude changes occurred on sub-millennial timescales across the Mediterranean basin (Bartov et al., 2003; Combourieu Nebout et al., 2009). At this time human activity at Haua Fteah appears to have intensified (at least in the area excavated) and potentially occurred
year round, with the density of lithic and faunal remains increasing, and evidence for in situ processing of lithics and an increase in marine and terrestrial mollusc exploitation (McBurney, 1967; Klein and Scott, 1986; Barker et al., 2010; 2012; Prendergast et al., accepted). Such activities have been suggested as possible indications of increased population density, changing landscape use, or increased resource pressure/dietary stress (Hunt et al., 2011; Prendergast et al., accepted). If the climate at this time was increasingly less stable it could have resulted in a more variable landscape with less predictable access to specific plant and animal resources on a year-to-year basis.

Capsian and Neolithic cultural phases in the Gebel Akhdar occurred in a more humid environment than earlier cultural phases. Little between-layer variation in mean $\delta^{18}$O enamel is apparent (Fig. 3), but an increase in intra-layer variation with time may indicate that after a period of relative stability in the early Holocene, the climate once again became less stable by the mid-Holocene. However, this change coincides with the first evidence of domestic animals in the region, as well as evidence of a change in local vegetation structure (McBurney, 1967; Klein and Scott, 1986; Reade et al., submitted), and it is possible that some variation may be caused by increased human influence on the local landscape and its local animal populations.

The increase in humidity is consistent with archives from elsewhere in North Africa which attest to increased fluvial activity in the early Holocene, related to an increase in Mediterranean precipitation and/or enhanced monsoonal circulation (Pachur and Rottinger, 1997; Kuper and Kröpelin, 2006). The later Neolithic samples from the Gebel Akhdar, which date to ~7-6 ka, may be contemporaneous with a period of short-term climatic instability seen elsewhere in the Mediterranean, as well as a trend towards more arid conditions in the Sahara (Cremaschi and di Lernia, 1999; De Rijk et al., 1999; Baioumy et al., 2011). In the Sahara this resulted in an increase in human mobility (Tafuri et al., 2006; Stojanowski and Knudson, 2014). In contrast, the appearance domesticated animals, pottery, and grinding implements in the Neolithic layers at Haua Fteah (McBurney, 1967), could be taken to indicate
a less mobile population, which presumably would indicate a favourable year-round
environment in the region.

*Bos* sp. samples were analysed for the Dabban, Oranian and Capsian periods. Bovids
are present in the Levalloiso-Mousterian and Neolithic faunal assemblages but no suitable
skeletal elements were available for inclusion in this study (McBurney, 1967; Klein and Scott,
1986). Given the variations in aridity inferred from the *A. lervia* samples across the Dabban-
Oranian-Capsian, the relatively stable *Bos* sp. $\delta^{18}O_{\text{enamel}}$ values are intriguing, particularly as
these samples span the time period when changes in global ocean $\delta^{18}O$ would have influenced
local $\delta^{18}O_{\text{precip}}$, irrespective of other climatic variation. For *Bos* sp. to be present in the
landscape there must have been year-round drinking water available, but the lack of variation
in the data would indicate that the source water $\delta^{18}O$ did not vary significantly. One possible
explanation is the contribution of groundwater to the bovid's drinking water. Today in the
Gebel Akhdar precipitation is highly seasonal and year-round surface water is relatively rare,
with no large river networks or other permanent large bodies of surface water being present
(Hamad, 2009). Natural springs occur in the region and these are supplied by highly localized,
relatively shallow groundwater, which is recharged from local precipitation (Hamad, 2009). It
is likely that these springs were also present during the last glacial, and it is possible that
these were an important source of drinking water for the local bovid population. As
groundwater $\delta^{18}O$ typically reflects a signal homogenized over many years to millennia
(Darling, 2004) the relative lack of variation in the *Bos* sp. data could be explained by at least
part of the animal's water being derived from such sources.

Using a conversion equation derived from modern bovid (*Bison bison*) tooth enamel
carbonate in North America the mean *Bos* sp. $\delta^{18}O_{\text{enamel}}$ from Haua Fteah produces a $\delta^{18}O_{\text{w}}$
estimate of $-0.6 \pm 2.0\%$ (n=21) (Hoppe et al., 2006; Pryor et al., 2014). No comparative
groundwater $\delta^{18}O$ data are available from the Gebel Akhdar, but the estimated value is higher
than present day local $\delta^{18}O_{\text{precip}}$ ($\sim-4.5\%$) (IAEA, 2015), suggesting that the ingested water
may have been enriched relative to its source through evaporative processes in the surface environment. The estimated $\delta^{18}O_{iw}$ is considerably higher than groundwater $\delta^{18}O$ from the Western Desert in Egypt (~-11‰), which likely indicates differing sources of precipitation between the two regions (Sultan et al., 1997). However, we have not tested modern samples to establish whether the Hoppe et al. (2006) correlation is valid for the bovid species analysed or environmental context considered here.

6. Conclusion

Overall, the data presented in this paper indicate that the Gebel Akhdar did not experience climatic variation of a magnitude comparable to more continental areas of North Africa. The region was more arid during the last glacial than during the early/mid Holocene, with the most arid phase identified dating to ~32ka, but no hyper-arid periods are evident in the data and the region was overall more humid than adjacent regions. This finding provides further support to the theory that the Gebel Akhdar may have served as a refugium for humans in North Africa during times of global climatic extremes (Barker et al. 2012; Prendergast et al. submitted; accepted; Reade et al submitted). The most humid phase identified in the record dates to ~9-5ka. Climate instability may have been greater in the late glacial, and to a lesser extent the mid-Holocene, than during other periods.

In relation to the archaeology of the Gebel Akhdar, differences in climates during different cultural units are observed. While Dabban populations inhabited a relatively arid landscape, the climatic conditions were likely to have been relatively stable. Data from the Hagfet ed Dabba suggest upland/inland areas within the Gebel Akhdar could have provided less arid environments than on the coast, which is consistent with the distribution of known archaeological sites across the region at this time period (Jones et al., 2011). Oranian populations living in the region during the late glacial would likely have experienced much greater climate instability than in other time periods, and this instability may have contributed to the increased intensity of human activity and possible change in resource
exploitation evident in the archaeological record (Barker et al., 2010; Prendergast et al.,
accepted). The Capsian and Neolithic phases occurred within a more humid environment,
which would have increased the potential to exploit a variety of floral, faunal and water
resources within the landscape.

The results of this study show that the environment of the Gebel Akhdar did not
remain stable and the landscape in which human populations operated was dynamic.
However, in the wider context of North Africa, the Gebel Akhdar most likely provided
relatively consistent opportunities for resource exploitation in comparison with adjacent
areas. The corollary of this finding is that it is unlikely that the technological and cultural
changes evident in the archaeological record occurred as a direct response to local climate
variations.

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Reviews.


Figure captions

Figure 1. Map of the Gebel Akhdar showing the position of the Haua Fteah and Hagfet ed Dabba caves. Grey areas represent areas of higher elevation (Drawing: D. Kemp).

Figure 2. Bulk-tooth $\delta^{18}$O results from all samples, displayed by species. Each circle (top graph) represents an individual animal. Boxplots (bottom graph) represent the median and interquartile ranges for each group. Haua Fteah samples are grouped by cultural attribution. Hagfet ed Dabba samples have an uncertain chronological association (both within site and with Haua Fteah), but are thought to be most likely associated with the Dabban at Haua Fteah. All samples from Hagfet ed Dabba are plotted as a single population.

Figure 3. Bulk-tooth $\delta^{18}$O from Haua Fteah A. lervia and Bos sp. for samples that can be attributed to specific stratigraphic layers/layer groupings, where $n\geq3$. Where possible, age estimates for each group are provided in table 1. Each circle (top graph) represents an individual animal. Boxplots (bottom graph) represent the median and interquartile ranges for each group.

Figure 4. Bulk-tooth $\delta^{18}$O from Hagfet ed Dabba, grouped by stratigraphic layer. Each circle (top graph) represents an individual animal. Boxplots (bottom graph) represent the median and interquartile ranges for each group.

Table captions

Table 1: The chronology of the Haua Fteah archaeological sequence according to McBurney (1967) and the Bayesian statistical model from Douka et al. (2014) at 68.2% and 95.4% confidence. Age estimations from specific layers/layer groupings from which samples analysed in this study come from are also provided. The listed age estimates presented are made using dates published in Douka et al. (2014) with correlations in site stratigraphy made between the McBurney excavations and the recent TRANS-NAP excavations. Dates with a * are based on a single sample, dates in italics are from Bayesian model estimates, all others are determinations from multiple radiocarbon samples.

Table 2: Summary of $\delta^{18}$O tooth enamel data from Haua Fteah and Hagfet ed Dabba, divided by cultural phase. A full list of results is available in Appendix A.
Figure 1

Mediterranean Sea

Haua Fteah

Hagfet ed Dabba

Gebel Akhdar
Figure 2

<table>
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<tr>
<th>Neolithic</th>
<th>Capsian</th>
<th>Oranian</th>
<th>Dabban</th>
<th>Hagfet ed Dabba</th>
<th>Levalloiso-Mousterian</th>
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<td>n=2</td>
<td>n=50</td>
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δ¹⁸O_VPDB (‰)

- 3.0
- 2.0
- 1.0
- 0.0
- -1.0
- -2.0

Legend:
- O. A. lervia
- A. lelevia
- Bovid
- Domestic caprid

n: Sample size
Figure 3

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<tr>
<th>Neolithic</th>
<th>Capsian</th>
<th>Oranian</th>
<th>Dabban</th>
<th>Levalloiso-Mousterian</th>
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A. lervia

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<td>VIII</td>
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<tr>
<td>X</td>
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Bos sp.

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<td>Phase</td>
<td>Layers (McBurney, 1967)</td>
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Table 1
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<th>Median</th>
<th>Max</th>
<th>Min</th>
<th>Range</th>
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<td>1.7</td>
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Table 2