1 TITLE

2 **Gazelle seasonal mobility in the Jordanian Steppe: the use of dental isotopes and microwear as**

3 **environmental markers, applied to Epipalaeolithic Kharaneh IV**

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5 ABSTRACT

6 The Early/Middle Epipalaeolithic aggregation site of Kharaneh IV in the east Jordan steppe is one of the largest

7 of the period, showing repeated use, high degrees of site investment, and relatively prolonged periods of

8 occupation. Hunters relied heavily on the single prey species, *Gazella subgutturosa*. This paper reports on

9 isotopic analyses of gazelle teeth, drawn from the Kharaneh IV assemblage, to explore the seasonal and spatial

10 distribution of gazelle in life and examine models of long-distance seasonal gazelle migrations. Dental

11 microwear analysis is also employed to assess hunting seasons.

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13 Results from sequential isotope analyses of 11 Epipalaeolithic gazelle molars show that, with one exception,

14 gazelle did not move seasonally from the limestone steppe onto other geologies, nor did they seasonally relocate

15 to areas with different climate regimes. Rather, seasonal herd mobility seems to have been local, meaning

16 animals would have been available in the vicinity of Kharaneh IV year-round. Results from 19 microwear

17 analyses show some gazelle to have died in spring when grass graze was available, whilst others had been

18 browsing around their time of death, indicating non-spring hunting. Microwear evidence thus suggests gazelle

19 were hunted in more than one restricted season. The implications of these new datasets for hunter-gatherer use

20 of the steppe, and potential hunting methods, is highlighted.

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1   INTRODUCTION
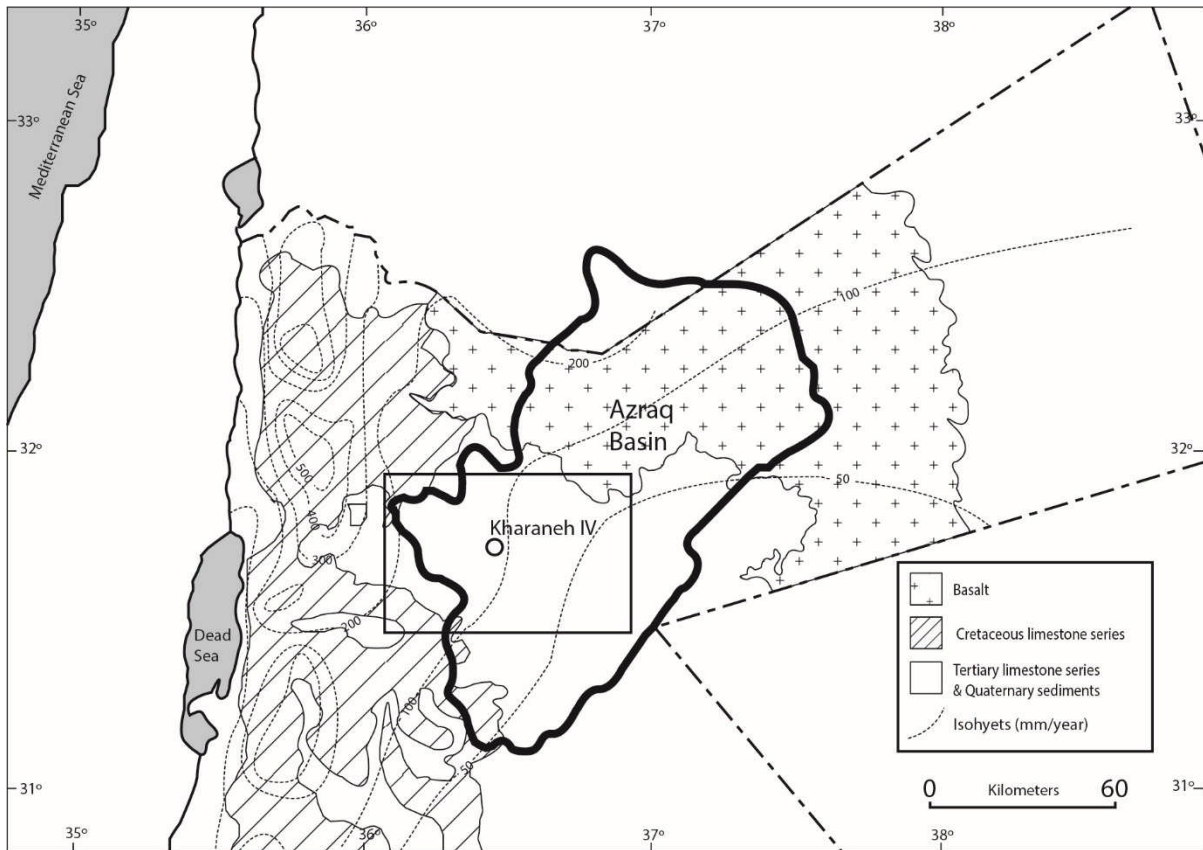
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3   *Fig.1 Map showing the Azraq Basin (black line), surrounding areas of Northeast Jordan (dash/dotted line) and*

4   *area shown in Fig. 2 (rectangle surrounding Kharaneh IV) (after Bender 1974; Jordan National Geographic*

5   *Centre 1984)*

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7   There are compelling reasons for archaeologists to attempt reconstruction of wildlife mobility in past

8   environments. Where zooarchaeological evidence shows hunter-gatherers have relied heavily on single prey

9   species, knowledge of herd seasonal movements is key for better understanding seasonal settlement organization

10   and hunting techniques (Frison 2004; Price et al 2015). The body chemistry of archaeological animal remains

11   can make aspects of the past visible (Feranec et al 2007), more so where multiple lines of evidence are studied

12   in combination (Lubinski 2012). For example, combined evidence from three isotope sequences retrieved from

13   bison dental enamel were employed to determine seasonal location patterns, and thus availability, to Palaeolithic

14   hunters (Julien et al 2012). Signatures of extended and confined seasons of death, determined from dental

15   microwear analysis (DMA) of extant ungulates, were applied to investigating mass cull and attritional hunting

16   techniques from DMA of archaeological assemblages (Rivals et al 2015). The current study utilises both

17   approaches in combination.

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19   This study focuses on the Early/Middle Epipalaeolithic of the Jordan steppe (*Fig. 1*) where evidence points to

20   reliance on goitered gazelle (*Gazella subgutturosa*) to the exclusion of other prey. Specifically, we focus on the

21   site of Kharaneh IV, one of the largest Levantine occupations of the period, in an attempt to understand how

22   gazelle herds may have underpinned large-scale, repeated occupations. The dominant model of Levantine

23   prehistoric *G. subgutturosa* mobility, proposed by Legge and Rowley-Conwy (1987; 2000), is based on

zooarchaeological analysis of late Epipalaeolithic gazelle remains from Abu Hureyra (Middle Euphrates), and draws on ethno-historic observations (18th - 20th C AD) of gazelle movements. Their study posits that the northern migration point of gazelle herds was near Abu Hureyra in spring for fresh graze, and their southernmost over-wintering point was the Jordanian steppe. This long-distance migration model has found widespread acceptance, particularly as an explanation for mass-capture 'kite' structures (e.g. Bar-Oz et al 2011), while some authors have also suggested that large Epipalaeolithic sites such as Kharaneh IV developed on gazelle migration routes (Goring-Morris 1995, 156).

Gazelles are extinct in the Jordanian steppe today, and historical accounts of recent mobility patterns cannot be assumed for the Epipalaeolithic before millennia of landscape degradation and livestock grazing (Martin 2000). Independent approaches are required for reconstructing the seasonal mobility of prehistoric gazelle herds (Julien et al 2012). We infer mobility and feeding seasonality from oxygen, carbon and strontium stable isotope sequences retrieved from Kharaneh IV gazelle teeth to ask whether, during the Epipalaeolithic, targeted herds undertook long-distance seasonal migrations in and out of the Jordan steppe area. Dental microwear analysis of the same tooth samples augment hunting seasonality evidence, providing indicators of diet, known to vary seasonally, at time of death. This study is the first use of archaeological isotopes to examine *Gazella subgutturosa* seasonal mobility in the Levantine Epipalaeolithic and the first regional application of a combined isotope/DMA approach.

KHARANEH IV

Kharaneh IV (hereafter Kharaneh) is within the Azraq Basin drainage system (*Fig. 2*), notable as one of the largest Epipalaeolithic sites (>21,000 m^2) of the region, with occupation radiocarbon dated between 19,830 and 18,600cal BP. Recent Epipalaeolithic Foragers in Azraq Project excavations have focused on two areas. Area B dates to the earliest millennium whilst Area A overlaps and continues later, 18,850-18,600cal BP (Maher et al 2016). Dates sit comfortably within a southern Levantine Early Epipalaeolithic chronology (Belfer-Cohen & Goring-Morris 2013 Table 3.3.1; Goring-Morris et al 2009, Table 10.1), although Area A lithics show clear typo-technological affinities with Middle Epipalaeolithic traditions (Maher & Macdonald 2013; Maher et al 2016; Richter et al 2013), thus suggesting an earlier Early-Middle division (Maher et al 2011) and confusing current classification. We use the broad term Early/Middle Epipalaeolithic for Area A, the focus of this study.

Findings at Kharaneh raise questions about the nature of hunter-gatherer occupation in Levantine steppes. Site size, artefact density, investment in features and variety of lithic traditions (Maher & Macdonald 2013) attest to large aggregations of hunter-gatherer groups, gathering perhaps for social/economic events (Maher et al 2012a). Combined with palaeoenvironmental evidence for lusher, better-watered settings (see Palaeoenvironment), research argues that Kharaneh would have been "…an attractive locale for repeated and prolonged occupation" (Maher et al 2012a, 8). For Area A, >90% of animal remains represent locally hunted gazelle (*Gazella subgutturosa*) (Spyrou 2014, Table 2 & Fig. 7). This focus on gazelle hunting is typical of other Jordanian prehistoric steppic assemblages and of earlier zooarchaeological studies at Kharaneh (Martin et al 2010) and begs questions about the seasonal spatial distribution of this mainstay herd animal. Did gazelle seasonally
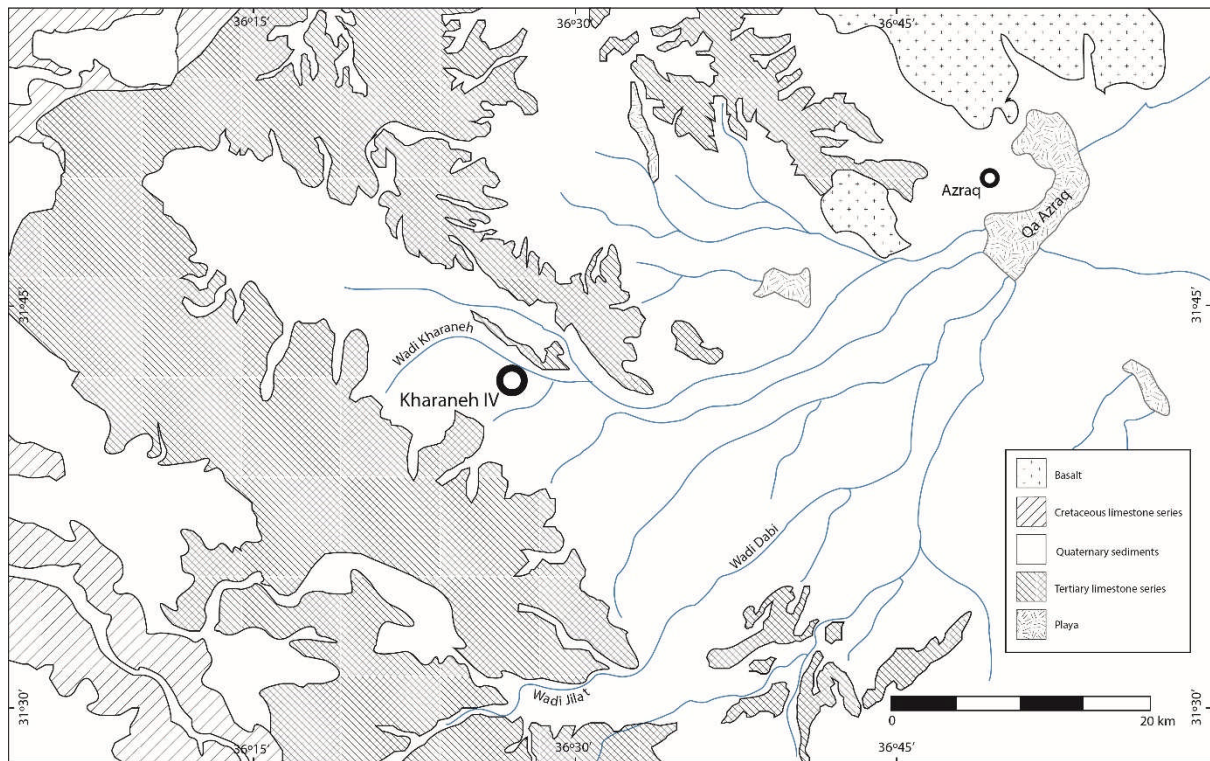
Fig. 2 Map showing the location of Kharaneh and the wadi system draining into the central Azraq Oasis

migrate in and out of the Jordan steppe or could they have maintained a more year-round presence? The latter could have aided the prolonged hunter-gatherer site residence proposed by Kharaneh excavators (Maher et al 2012a).

There are presently two sources of evidence for Kharaneh gazelle hunting seasonality. Fusion data shows targeted winter culling and slight evidence for spring culls (Martin et al 2010), and a tooth cementum pilot study (Jones 2012) finds evidence for both spring/summer and autumn/winter culls. Questions remain as to whether gazelle herds were on northerly migrations in spring (as Legge and Rowley-Conwy predict) and were present in the Jordan steppe mainly in winter, or whether other mobility patterns pertained. Animal behavioural plasticity is an adaptive response to environmental conditions, and Martin (2000) has argued that small-bodied gazelle may not have needed to move far in search of resources. Considering *G. subguttorosa* behavioural and forage requirements, and the environmental parameters of our study region, we propose four potential herd mobility patterns for Epipalaeolithic gazelle herds (*Fig. 3*). Gazelle herds might seasonally aggregate and disperse locally in the steppe (1), or might undergo longer seasonal migrations following better resources, westwards into the Jordanian Highlands in summer (2), northwards towards the Middle Euphrates in spring (3) or south-eastwards along the Wadi Sirhan corridor (4). In cases 2-4, animal presence in the Jordan steppe is predicted to be seasonal.

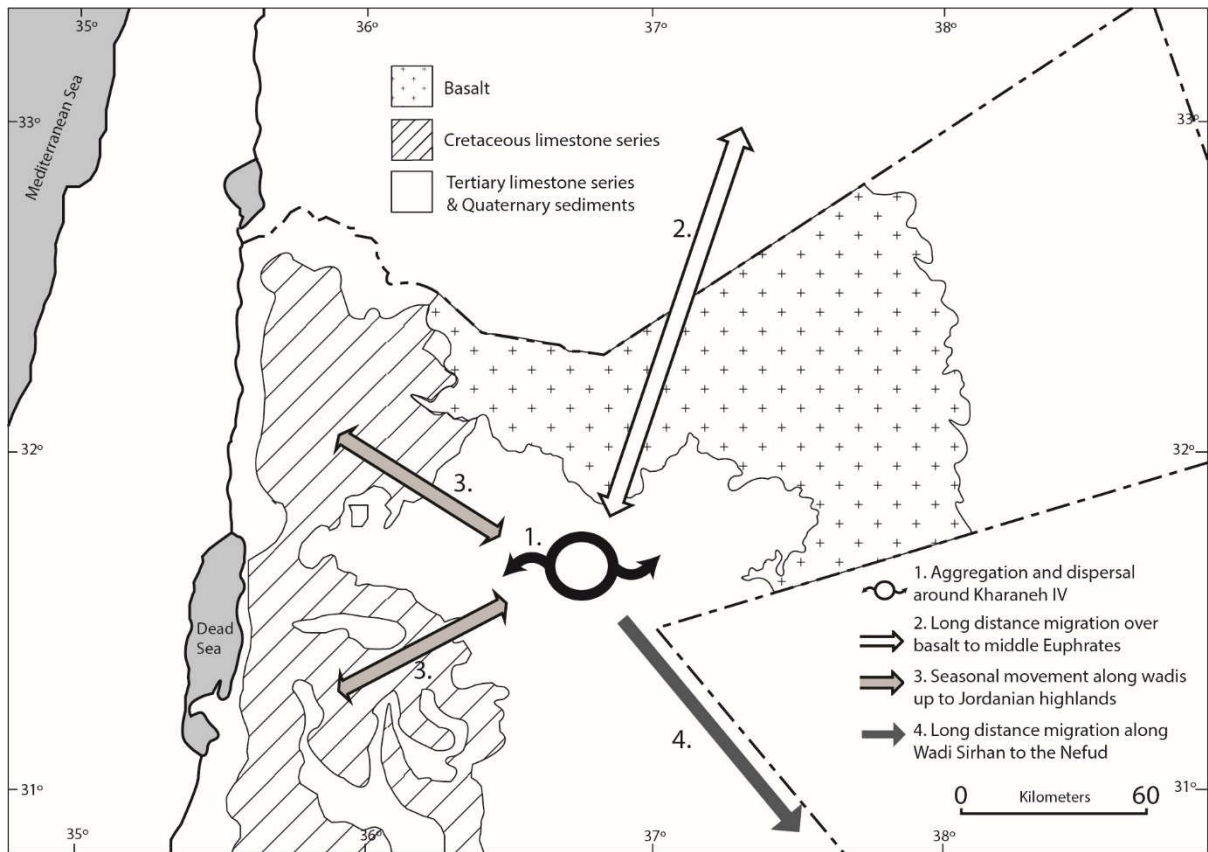AZRAQ BASIN PALAEOENVIRONMENT

Geology

Fig.3 Map showing the four proposed movement patterns of gazelle in the Early/Middle Epipalaeolithic (after Bender 1974; Jordan National Geographic Centre 1984)

The Azraq Basin is a 12,000km^2 endorheic drainage basin covering north-central Jordan (Garrard & Byrd 2013), with Early Tertiary (tt_1) chalky limestones and marls exposed along western and eastern flanks. In the north there is an extensive cover of Pliocene/Oligocene (B_4) and Pliocene/Miocene (B_5) basalts, whilst in the centre and southeast there is a spread of Quaternary gravels and silts (q_2). Further west, the Jordanian Highlands are composed of Cretaceous dolomitic limestones and marls (c_2) (Bender 1974). Wadi Kharaneh, in the Basin's central-western sector, drains from Early Tertiary uplands (c850m) to the central Qa Azraq (c500m). Kharaneh is situated in the broad wadi c640masl, c40km west of Azraq (*Fig. 2*). Where conditions allow, small pockets of rendzina soils have accumulated.

Climate and hydrology

Present-day Azraq Basin temperatures range from 45ºC to -10 ºC, and precipitation from 200mm (NW) to <50mm (SE). The Mediterranean controls rainfall distribution; westerly winds bring rain in the cold season but effectively none in the highly evaporative hot season (Enzel et al 2008) (*Fig. 4*). Winter run-off collects in playas and stream channels but evaporates as temperatures rise, becoming highly saline and drying within months; only spring-fed Azraq Oasis marshlands have perennial freshwater.
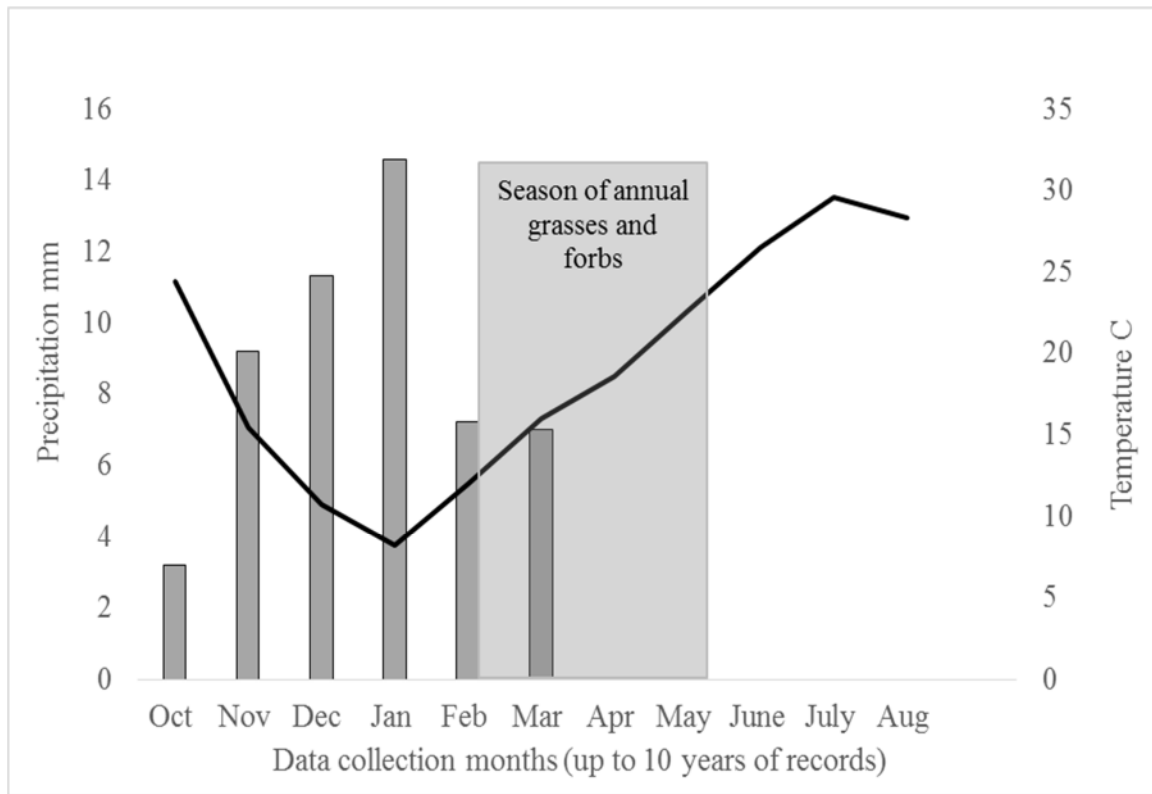
Fig. 4 Mean monthly GNIP temperature and precipitation data for Azraq (WMO/IAEA 2014) with the prime vegetation growth season

Regional and local evidence (Frumkin et al 1999; Hunt and Garrard 2013; Jones & Richter 2011; Jones et al 2016; Ramsey & Rosen 2016) suggest the Last Glacial Maximum (LGM) climate in the Mediterranean zone and regions due east was wetter than now, but with the same atmospheric circulation and seasonality (Enzel et al 2008). However, there is evidence for increasing dryness during the post-LGM period (Hunt and Garrard 2013; Jones et al 2016). Kharaneh was established on the marls of a receding wetland area, possibly 2km maximum, which appears to have dried out during occupation, later overlain by loess (Garrard et al 1985; Jones et al 2016).

<u>Vegetation</u>

Due to precipitation seasonality, opportunistic annual grasses and forbs germinate rapidly in moist, warming spring soils, outcompeting slower growing perennials but soon setting seed and withering as aridity increases, leaving only xeric shrubs and species tolerant of soil salinity (Batanouny 2001; Hillman 1996). Vegetation zones grade according to isohyets; the Highlands have higher rainfall and lower temperatures supporting oak woodland (>400mm) and park woodland/ woodland steppe (400-200mm). Within the Azraq Basin, this grades into the steppe plant community described above (200-100mm), and desert vegetation (<100mm) (Hillman 1996; Hillman in Moore et al 2000). Each zone extends further east along wadi edges than on interfluvial plains, and in the Oasis permanent springs support marshland plants. Today, Kharaneh is located on the Irano-Turanian steppe/desert 100mm isohyet boundary.

Modelled palaeovegetation distribution (Byrd et al 2016; Colledge 2001; Hillman 1996) shows an eastward shift and greater species abundance, such that xeric woody thickets encroached along wadis and perennial pools;

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1 annual grasses blanketed interfluvial areas for an extended season; halophytic species were less dominant in arid

2 seasons. The zooarchaeological spectrum offers support to this model with water dependent species by large

3 wadis and in the Oasis, numerous gazelle associated with dry steppic grasslands and an absence of woodland

4 habitat species such as deer (Edwards pers. comm; Martin et al 2010).

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6 PRINCIPLES UNDERLYING METHODS

7 Isotope analysis – tooth enamel

8 Gazelle tooth enamel apatite is chosen for isotope analyses because developmental morphology of hypsodont

9 mandibular molars allows bi-monthly sampling resolution along the growth axis (Balasse et al 2003; Fricke &

10 O'Neil, 1996; Henton 2012; Kohn et al 1998; Zazzo et al 2002) (*Fig. 5*). A sampling sequence spans an annual

11 cycle as enamel precipitation proceeds during the first year in the second molar and between nine and eighteen

12 months in the third (Davis 1980; Munro et al 2009). Intra-species developmental consistency pertains,

13 particularly in M_2s (Blaise & Balasse 2011; Tornero et al 2013). In this study, trajectories of change during the

14 gazelle's annual cycle are most pertinent to research questions. Each data point retrieved from the tooth growth

15 column is not considered in isolation but as a fixed-position contributor to an annual curve. The research goal

16 does not require precise conversions of stand-alone data-point values, diminishing problems arising from sample

17 resolution and enamel formation time-lags (Britton et al 2011; Hoppe et al 2005).

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19 Within the tooth enamel time capsule, where seasonality exists, the sequence of retrieved oxygen ($\delta^{18}O$) isotope

20 signatures identify (via ingested water) patterns of seasonal change (Bryant & Froelich 1995; Dansgaard 1964;

21 Fricke et al 1998; Iacumin & Longinelli 2002); where geological substrata variation allows, strontium ($^{87}Sr/^{86}Sr$)

22 isotope signatures identify (via ingested forage) changing location (Bentley 2006; Faure & Powell 1972;

23 Graustein 1989; Sillen et al 1998); and where plant species have varied morphological or physiological stress

24 responses, carbon ($\delta^{13}C$) isotope signatures identify (via ingested forage) changing feeding habits (Bender 1971;

25 Cerling & Harris 1999; Ehleringer et al 1997; Heaton 1999; de Niro & Epstein 1978; O'Leary 1988; Tieszen

26 1991; Vogel et al 1986). By analysing all three isotopes in the same sample, seasonality of carbon signatures can

27 be inferred from oxygen signatures, but strontium incorporates into enamel more slowly introducing an

28 unknown time-lag (Montgomery et al 2010).

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30 Isotope analysis – the palaeoenvironment

31 The Azraq Basin palaeoenvironment is eminently suitable for investigation through these isotopic signatures, as

32 its climate, geology and vegetation can be related to modern environmental parameters, and as isotopic variation

33 potentially discriminates season, location and forage. Global Natural Isotopes in Precipitation records (*Fig. 6*)

34 show clear summer peaks and winter troughs in monthly $\delta^{18}O$; >0.57 to -6.32 for Azraq, and >-3.32 to -7.28 for

35 the Jordanian Highlands (IAEA/WMO 2014). Labile $^{87}Sr/^{86}Sr$ signatures retrieved from modern Jordanian

36 plants and animals (Shewan 2004) fall within accepted bedrock parameters (Bentley 2006; Hartman & Richards

37 2014), discriminating the Cretaceous limestone series in the Jordanian Highlands, the Tertiary limestone series

38 in the steppe, and the younger basalt shield. Short-lived spring annuals constitute 80% of Azraq Basin plant

39 species (Zohary 1973) and have C_3 photosynthetic pathways (Bocherens et al 2001; Ramsey & Rosen 2016), as

40 do slower growing woody shrubs and trees; these would return $\delta^{13}C$ that group around -27‰ (Bender 1971;
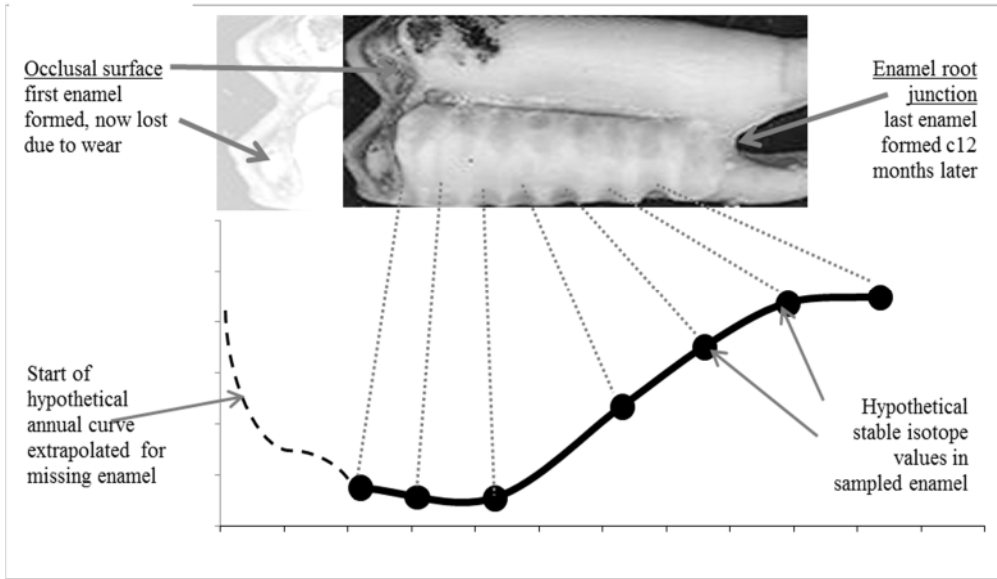
Fig. 5 Diagram showing a hypothetical annual graph retrieved from the sequential drilling of enamel apatite in an ungulate second mandibular molar formed over 12 months
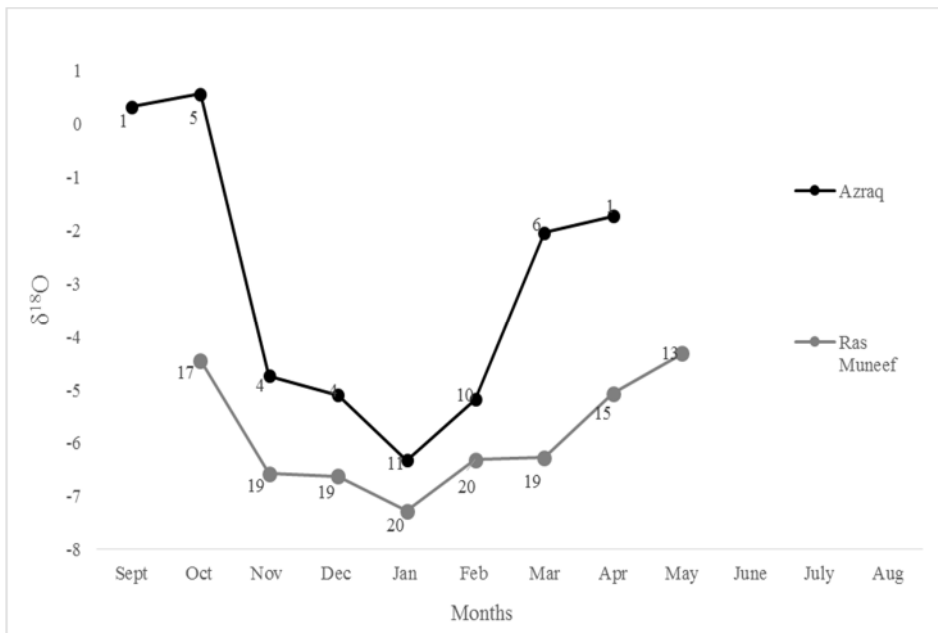
Fig 6. Mean monthly GNIP $\delta18O_{VSMOW}$ data (WMO/IAEA2014) comparing highland Ras Muneef to Azraq (number of modern records

Ehleringer et al 1997; O'Leary 1988). Whereas halophytic chenopods, more predominant throughout the arid season, have C_4 photosynthetic pathways that enrich $\delta^{13}C$ to c.-12‰ (Akhani et al 1997; Shomer-Ilan et al 1981).

Isotope analysis – gazelle ethology

This research focuses on seasonal changes experienced by gazelle, and their ethology constrains likely environmental situations. Gazelle are non-obligate drinkers with water needs met by plant tissues, where arid-

1 season $\delta^{18}O$ is considerably enriched by evapo-transpiration (Ayliff & Chivas 1990), enhancing, but not

2 masking, the summer/winter range in values (Kohn et al 1996, 1998). However, should gazelle migrate to

3 cooler, less-evaporative summer feeding grounds (Poage & Chamberlain 2001), the sinusoidal annual $\delta^{18}O$

4 curve would be disrupted due to loss of the extreme arid season signature.

5

6 Gazelle ingest strontium from plants which take up only the labile fraction. In more arid regimes, soils largely

7 derive from underlying bedrock (Bentley 2006), but where geologies intersect, where upland sediments are

8 washed downstream (Graustein 1989; Sillen et al 1998), or where windborne dust settles, the resulting soil

9 $^{87}Sr/^{86}Sr$ reflects the contributory mix. For this research, key location soil $^{87}Sr/^{86}Sr$ signatures are refined with

10 the aid of a small modern plant baseline; results for locations deep within major geologies conform to

11 established $^{87}Sr/^{86}Sr$ ranges; local to Kharaneh, Tertiary limestone series 0.70807-0.70819, Highlands

12 Cretaceous limestone series 0.70845-0.70854 and basalt lava flows 0.70764-0.70778 (*Supplement 1, Table 1 &*

13 *Fig. 1*; Henton et al submitted to Environmental Archaeology). Curves constructed from sequential $^{87}Sr/^{86}Sr$

14 sampling are predicted to be flat in gazelle remaining on a single bedrock type but where they might have

15 moved between different geologies within a yearly cycle, the curves would, respectively, progressively rise or

16 fall in gazelle progressing onto bedrock with higher or lower $^{87}Sr/^{86}Sr$ signatures. Climate-induced variation in

17 aeolian dust input (Hartman & Richards 2014; Stein et al 2007) would not register within an annual $^{87}Sr/^{86}Sr$

18 cycle in a gazelle tooth.

19

20 Gazelle primarily ingest carbon from forage; grazing or browsing as seasonal mixed feeders on many Irano-

21 Turanic species, but preferentially eating high-nutrient grasses, particularly during late gestation and lactation

22 (Kingswood & Blank 1996). Seasonal $\delta^{13}C$ change in archaeological gazelle enamel is predicted due to the

23 combined effects of seasonal availability of C_3 and C_4 plants and feeding preferences. In spring/early summer,

24 when water-stress is minimal, enamel $\delta^{13}C$ would be most depleted as gazelle graze C_3 grasses, whereas high

25 summer to mid-winter browsing on water-stressed C_3 shrubs might enrich $\delta^{13}C$ by as much as 6‰ (Farquhar et

26 al 1989), and the inclusion of C4 halophytes would further raise values. After accounting for a +14.1‰

27 fractionation factor between plant and animal tissue (Cerling & Harris 1999), $\delta^{13}C$ of -12‰ might be

28 approached in spring/early summer, becoming enriched by >-8‰ in the rest of the year.

29

30 Dental microwear analysis (DMA)

31 Isotope analyses reveal the seasonal forage landscape experienced by gazelle throughout a year of life as a sub-

32 adult, whereas DMA elucidates forage conditions in the final weeks before death. Microwear describes marks

33 on the enamel surface that last only a few weeks. Their interpretation draws on correlation with diets in modern

34 animals (Teaford & Walker 1984). A 2-feature discrimination of pits (length:breadth <4:1) and striations

35 (length:breadth >4:1) usefully identifies grazers, with more striations, from browsers, with more pits (Solounias

36 & Hayek 1993; Solounias & Moelleken 1992). This holds true across mammalian orders and between

37 geographical zones (Mainland 1998; Merceron et al 2005; Wilkie et al 2007), however tooth type introduces

38 DMA variation, where pit percentage increases towards the third molar (Gordon 1982).The rapidity of turnover

39 allows a bimodial distribution of features in seasonal mixed feeders such as gazelle (Merceron et al 2007; Rivals

40 et al 2011; Solounias and Hayek 1993; Solounias & Moelleken 1992).

As Jordanian steppe gazelle are seasonal mixed feeders on seasonally available food types, a strong seasonal signature might be revealed through DMA. Striation-rich microwear can be associated with spring/early summer as the only time when fibrous grasses flourish, pits with later summer, autumn and early winter when soft dicotyledonous plants are the sole dietary contributors, and an intermediate signal with the brief transitional periods where one diet replaces the other.

Summary

This research asks simple questions of each dataset; the strength of the approach becomes apparent in their combined interpretation constrained by gazelle ethology and palaeoenvironmental reconstruction. In considering the seasonal mobility represented by each gazelle tooth sample throughout a year of early life, the $\delta^{18}O$ sequence enables identification of four seasons, $^{87}Sr/^{86}Sr$ identifies movement over different geologies, and the $\delta^{13}C$ sequence identifies dietary shifts between spring/early summer and other seasons. Seasonal mobility patterns for sampled individuals are assumed to be representative of those of whole herds; sub-herds of *G. subgutturosa* may briefly form throughout the year, but unite for long-distance movements (Blank et al 2012). We also assume that patterns are likely to represent annually repeated movements if environmental pressures are largely unchanged (Cunningham & Wronski 2011). Microwear data provide insights on forage conditions around the time of death, when the gazelle's lifecycle was intercepted by hunters; a single tightly clustered pattern can be associated with a short, single hunting season, a bimodal pattern with two hunting seasons, and a non-modal, diffuse pattern with year-round hunting.

MATERIALS, PREPARATION PROTOCOLS AND ANALYSES

Fully developed third mandibular molars (M_3), just in wear and with closed roots, are most identifiable in the fragmented Kharaneh assemblage, but some securely identifiable second molars (M_2) were also sampled, meeting recommended sample sizes of nine teeth for isotope analyses (Hoppe et al 2005; Pearson & Grove 2013) and fourteen for microwear analyses (Mainland pers. comm.). *Table 1* provides the context and description of fourteen M_3 and eight M_2 archaeological specimens suitable for analyses; these represent twenty gazelle as two individuals had both M_2 and M_3 sampled.

After taking morphometric and photographic records, impression and resin casts were made following Mainland (1998) protocols. Four images of the infundibular enamel of the paraconid cusp were captured under a Hitachi S–3400N scanning electron microscope (SEM) at x500 magnification. The clearest and most representative was imported into Ungar's (2002) image analysis software (Microware 4.02) where the dimensions and orientation of each microwear feature in a surface area of $0.0404mm^2$ were quantified and categorised.

For isotope analyses, the mesial tooth-column buccal surface of each specimen was cleaned and six sequential samples of >20mg drilled at measured distances from the enamel:root junction (see *Fig. 5*); contamination and diagenetic carbonates were removed following established protocols (Balasse 2002). The carbonate fraction from 10mg of each was analysed for $\delta^{13}C$ and $\delta^{18}O$ by Isotope Ratio Mass Spectrometry at UCL Bloomsbury Environment Isotope Facility (BEIF). Each remaining 10mg was processed for $^{87}Sr/^{86}Sr$ analysis under clean

1 laboratory conditions in the Isotope Geochemistry Laboratories at Royal Holloway College, UL. The sample

2 was digested in concentrated HNO_3 and the soluble residue passed through columns that collected the strontium

3 on Sr-resin. This was eluted with triple-reduced water, evaporated, and mounted on Rhenium filaments for

4 analysis in a VG354 Thermal Ionisation Mass Spectrometer.

5

6 RESULTS

7 The Kharaneh depositional environment resulted in gazelle tooth specimens being considerably abraded,

8 concreted and fractured; of the 22 originally sampled, 11 yielded strontium data, 10 carbonate data and 19 DMA

9 data (*Table 1*). Each dataset sample size is adequate for robust analysis although variation due to tooth type

10 requires discussion.

11

12 <u>Isotope results</u>

13 Looking first at the isotope results (*Table 2*), external reproducibility of laboratory analyses is ±0.04‰ and

14 ±0.08‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively, and ±0.000014 (2σ) for $^{87}Sr/^{86}Sr$. Measured on the PDB scale,

15 maximum $\delta^{18}O$ is 6.54‰ and -4.24‰ minimum. These values fall within the modern range for Azraq $\delta^{18}O$ in

16 precipitation, although dampened due to sample resolution (Britton et al 2011). The $^{87}Sr/^{86}Sr$ (0.70822 to

17 0.70766‰) also fall within parameters established for the geology. Finally, $\delta^{13}C$ (-4.76 to -10.79‰), after

18 making a +1.5‰ adjustment to allow for the pre-industrial absence of the fossil fuel effect (Cerling & Harris

19 1999), convincingly equates to varying contributions of C_3 and C_4 plants typical of gazelle feeding ethology.

Kharanah IV Area A. context details			M_3			M_3 DMA CO$_3$ Sr (sample number)			M_2 Wear stage			M_2 DMA CO$_3$ Sr (sample number		
			Wear stage	Side	GH	DMA	CO$_3$	Sr	Wear stage	Side	GH	DMA	CO$_3$	Sr
AR36	100		adult	right	22.2	2	2	2						
AR35	1100	FN871174	9	left	20.7	4	4	4						
AS36	100	FN871150	10	left	10.5	5	x	x						
AT35	34	FN871032	x	left	x	8	x	x						
AP35	034 or 035		10	left	10	17	x	x						
AS42	115		9	right	10	20	x	x						
AQ36	80	FN871628	x	left	20.5	21	x	x						
AT36	34		10	right	11.6	22	x	x						
AT35	100		9	right	20.4	26	26	26						
AR36	34		adult	left	23.2	30	30	x						
AR36	34		young adult	right	13.6	31	31	x						
AV71	176	545075/1	9	left	9	78	x	x						
AS42	99	FN871101	x	left	15.6	35	35	35	5	x	11.2	x	x	38
AW73	158	545200/1	7	left	24.2	79	79	79	5	left	15.8	99	x	x
AS35	34	FN871094							4	left	23.3	49	49	49
AQ35	80								5	left	19.2	51	51	51
AR35	100								x	left	x	59	x	x
AY72	43	545193/1-2							x	x	26.4	x	74	74
AX74	88								5	left	17.7	76	x	76
AU73	178	545035/27							5	left	17.5	x	x	89
22 teeth from 20 individuals			**14 M3s**			**14**	**7**	**5**	**8 M2s**			**5**	**3**	**6**

21 *Table 1. Analysed specimens with contextual and zooarchaeological information and details of analyses*

22 *undertaken*

The results for each gazelle tooth are displayed in Figure 7. Sp38 (M_2 with grey border) and Sp35 (M_3 with white border) are from the same individual (top row *Fig. 7*) and, considered together, provide insight into how enamel precipitation timing, and therefore generated isotopic curves, relate sequentially between tooth-types. Consequently, all specimens (*Fig. 7* M_3s in rows 2 & 3 and M_2s, with grey borders, in rows 4 & 5) can be discussed in relation to each other.

In addition to tooth specimens with missing data sets, it is clear that not all time capsules span a whole year of life; this is to be expected as M_2s have <1 year formation period and toothwear has truncated M_3 records. Nevertheless, M_3 specimens 2, 4, 30 and 79 show clear seasonal variation in $\delta^{18}O$ with seasonally linked variation in $\delta^{13}C$. The $^{87}Sr/^{86}Sr$ sequences span the same length of time although without seasonal linkage. Although spanning a more limited period, a seasonal link between $\delta^{18}O$ and $\delta^{13}C$ can be observed in M_2 specimens 51, 74 and 49.

DMA

Turning to the DMA results (*Table 2*) fourteen M_3s (black) and five M_2s (open circles) are analysed using the simplest DMA, 2-feature pit to striation discrimination, and displayed in *Figure 8* with pit percentages for each on the x-axis and striation percentages on the y-axis. In this research we confine ourselves to this analysis as we do not have a modern comparator on which to base more nuanced DMA, and as recorders using this semi-quantitative recording method tends to miscount but not misidentify features (Grine et al 2002; Henton 2010 p328).

The results show the gazelle died having eaten a range of diets. The highest striation percentage was 79.5% and the lowest was 27.6%. Eight M_3s had more striations (>50%) than pits, and six had less; of the M_2s, three had more and two had less. The bar chart, inset on the left of *Figure 8*, clearly shows a relatively even distribution of results, only slightly higher than the 50% mark, with no evidence of any single or bimodal clustering. Whilst some adjustment should be made for the known increase in M_2s striation numbers compared to M_3s in the same tooth row, this might be offset by gazelle feeding behaviour; as ground feeders in more arid environments, gazelle species ingest grit and have higher pit numbers than many ungulates (Rivals et al 2011; Schulz et al 2013; Solounias & Semprebon 2002).

Table 2 – Results of analyses.

Specimen M_3 white M_2 grey	Dental Microwear results			Isotope results										
	Total feature Number	Pit Number	Striation Number	a. Distance of sampling bands (1 to 6) from root/enamel junction mm; b. $\delta^{18}O_{(VPDB)}$; c. $\delta^{13}C_{(VPDB)}$; d. $^{87}Sr/^{86}Sr$	6	5	4	3	2	1	Mean	Maximum	Minimum	Range
2	70	43	27	a	19.5	19.8	15.9	12	8.9	5.3				
				b	-3.74	-3.71	-2.50	-0.95	-0.14	-1.73	-2.13	-0.14	-3.74	3.60
				c	-5.92	-5.57	-7.03	-8.42	-9.11	-9.20	-7.54	-5.57	-9.20	3.64
				d	0.70808	0.70808	0.70812	0.70814	0.70813	0.70810	0.70811	0.70814	0.70808	0.00006
4	82	48	34	a	18.4	15	11.4	8.1	6	3				
				b	-3.02	-0.41	3.32	5.27	4.92	3.85	2.32	5.27	-3.02	8.28
				c	-4.72	-6.20	-9.74	-10.75	-10.79	-10.50	-8.78	-4.72	-10.79	6.07
				d	0.70814	0.70816	0.70815	0.70815	0.70809	0.70814	0.70814	0.70816	0.70809	0.00007
5	38	13	25											
8	127	26	101											
17	90	50	40											
20	46	31	15											
21	79	49	30											
22	118	51	67											
26	138	56	82	a	19.2	12.8	10	7.4	4.9	1.4				
				b	-0.86	0.16					-0.35	0.16	-0.86	1.02
				c	-5.50	-7.09					-6.29	-5.50	-7.09	1.60
				d	0.70811		0.70822		0.70818		0.70817	0.70822	0.70811	0.00011
30	176	46	90	a	18.3	14.9	11.6	5.2	3.4	1.5				
				b	-3.99	-4.24	-4.11	-0.02	1.24	0.41	-1.78	1.24	-4.24	5.48
				c	-5.65	-5.85	-6.49	-8.77	-9.85	-9.64	-7.71	-5.65	-9.85	4.20
				d										
31	89	44	45	a	13.2	10.3	8.2	5.5	3.1	1.8				
				b	-0.50	0.96	1.61	1.82	1.08	-1.48	0.58	1.82	-1.48	3.30
				c	-8.82	-10.12	-9.76	-9.72	-9.50	-8.19	-9.35	-8.19	-10.12	1.94
				d										
35 (the M2 is 38)	134	60	74	a		12.3	10.3	8.2	6.2	4.1				
				b		-0.72	1.71	3.64	4.54	5.44	2.92	5.44	-0.72	6.16
				c		-5.97	-8.21	-9.68	-8.3		-8.29	-5.97	-9.68	3.71
				d		0.70815	0.70816	0.70814	0.70811	0.70805	0.70812	0.70816	0.70805	0.00011
38 (the M3 is 35)				a				9.4	6.5	3.5				
				b										
				c										
				d				0.70822	0.70817	0.70814	0.70818	0.70822	0.70814	0.00008
49	87	63	24	a	19.2	17.2	15	12.2	9.3	6.1				
				b	3.7	1.91	1.07	-1.16	-2.56	-4.24	-0.21	3.70	-4.24	7.94
				c	-8.08	-7.69	-7.41	-6.62	-6.23	-5.3	-6.89	-5.30	-8.08	2.78
				d	0.70814	0.70812	0.70812	0.70815	0.70816	0.70815	0.70814	0.70816	0.70812	0.00003
51	72	44	28	a		16.3	13	10.4	7.3	5.2				
				b		-0.39	-2.51	-3.45	-3.27	-2.93	-2.51	-0.39	-3.45	3.06
				c		-7.66	-6.72	-5.67	-5.08	-4.76	-5.98	-4.76	-7.66	2.90
				d		0.70766		0.70777		0.70796	0.70779	0.70796	0.70766	0.00031
59	204	93	111											
74				a		20.5	16.7	13.1	9.9	6.5				
				b		6.54	4.96	3.55	2.17	-0.21	3.40	6.54	-0.21	6.75
				c		-7.87	-7.79	-8.19	-8.07	-7.49	-7.88	-7.49	-8.19	0.70
				d		0.70811		0.70810		0.70811	0.70811	0.70811	0.70810	0.00001
76	96	36	60	a		15.1		9.1		3.2				
				b										
				c										
				d		0.70812		0.70809		0.70812	0.70811	0.70812	0.70809	0.00003
78	93	50	43	a										
				b										
				c										
				d										
79	148	59	89	a	20.9	17.7	14.2	11.5	9.5	6.1				
				b	-3.98	-4.03	-0.81	1.68	3.54	4.88	1.05	4.88	-4.03	8.91
				c	-5.56	-6.02	-9.14	-10.48	-10.62	-10.30	-9.31	-6.02	-10.62	4.60
				d	0.70821	0.70820	0.70821	0.70819	0.70818	0.70812	0.70818	0.70821	0.70812	0.00009
89				a		16		10.7	7.2	5.4				
				b										
				c										
				d		0.70810		0.70812	0.70812		0.70812	0.70812	0.70810	0.00002
99	66	29	37											

Table 2. Results of analyses for dental microwear and isotopes of oxygen, carbon and strontium in all specimens (M_2s are shaded grey)
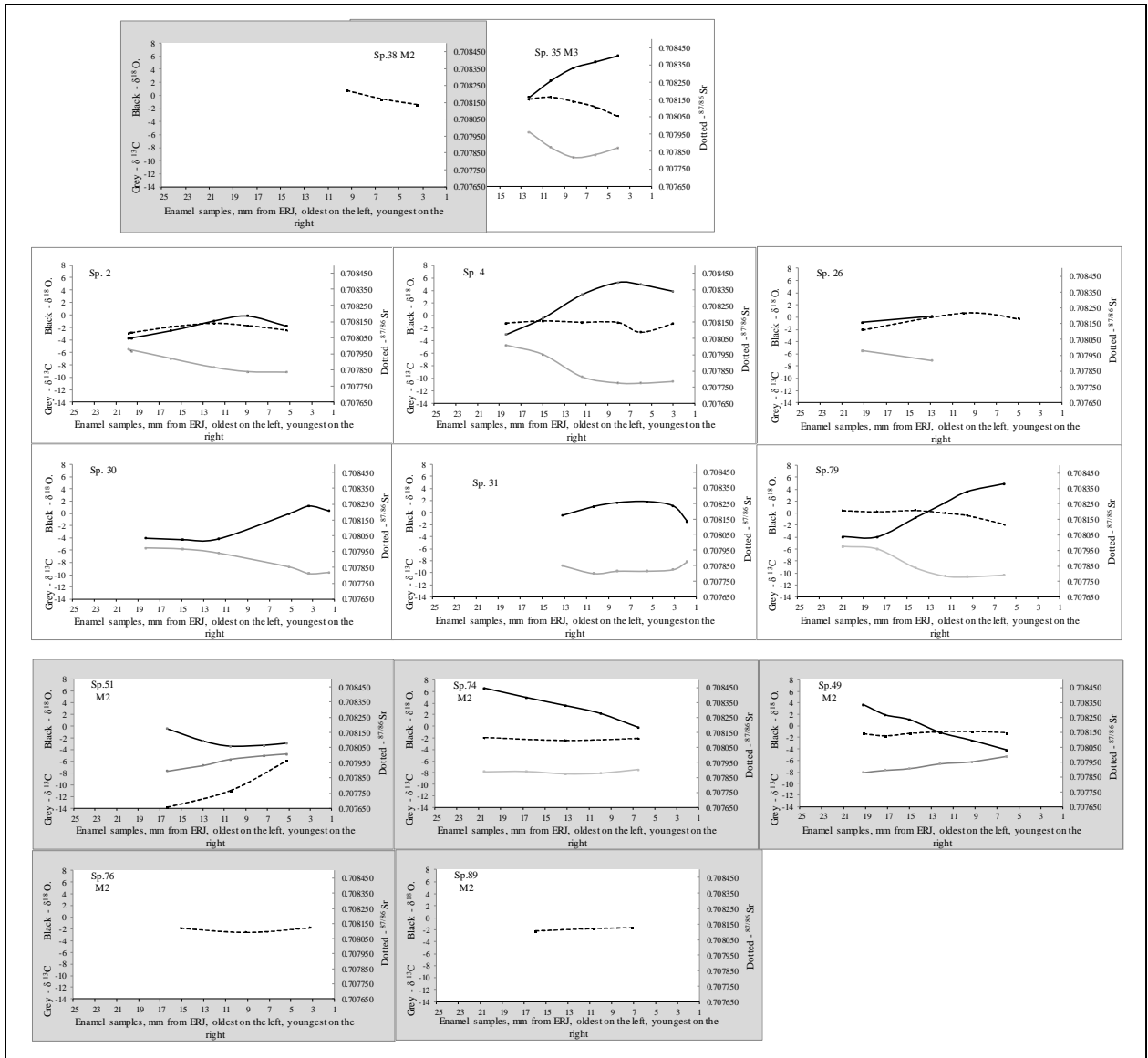
Fig 7. Plots of all isotope sequences for individual gazelle specimens. Top row: M_2 and M_3 from the same specimen. Rows 2 & 3: all other M_3s. Rows 4 & 5: all other M_2s (grey borders)
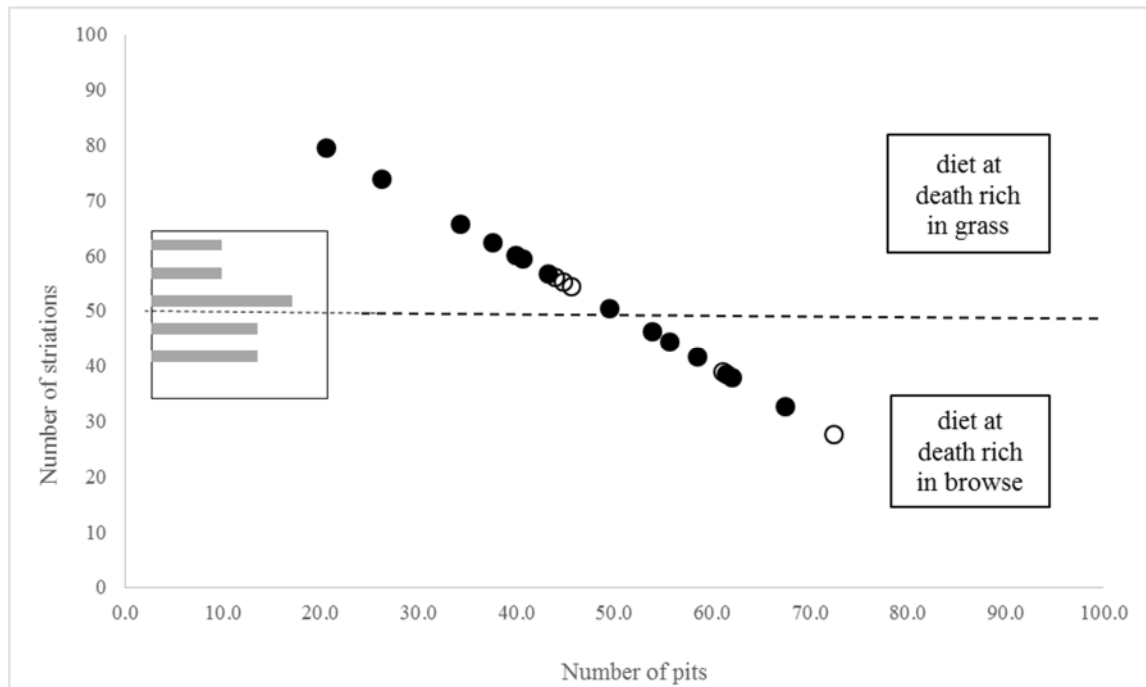
Fig 8. Chart of DMA results for all specimens, plotting percentage of pits against percentage of striations. M₃s are black circles and M₂s are open circles. The inset horizontal bar chart shows distribution in 10% ranges either side of 50%

DISCUSSION

<u>One sub-adult year</u>

To discuss seasonal mobility of Epipalaeolithic gazelle herds, specimen sequences are re-grouped by isotopic dataset (*Fig. 9*, $\delta^{18}O$ top row, $^{87}Sr/^{86}Sr$ middle row, $\delta^{13}C$ bottom row). The M_2 charts are to the left of M_3 charts suggestive of their developmental sequence. The two tooth-types (M_2 and M_3) together provide data that span an annual cycle, as can be seen from the fully sinusoidal $\delta^{18}O$ curves.

Starting with the $\delta^{18}O$ curves, it is tentatively argued that the specimens cluster, albeit loosely, to reflect animals living year-round in one climate regime in one location. Firstly, there are sharp seasonal differences between summer peaks and winter troughs mirroring those for local precipitation (*Fig. 6*) which markedly contrast cold, wet winters and hot, arid summers; inter-specimen differences reflect inter-annual weather differences but each maintain strong seasonal differences. Had herds avoiding the hot, arid summers of the steppe by moving into cooler Jordanian Highland the highly seasonal summer signature would be lost and the resultant peak reduced. the M3 specimen 'two' might fall into this category, but, secondly, differences proceed smoothly along all curve, more in keeping with seasonal change than with the halting process of migration across climate zones.

The data also show, with greater certainty that these gazelle were born in the same season, as the curves show enamel formation proceeding at approximately the same time in all teeth (highest values all towards the final section of the curve).
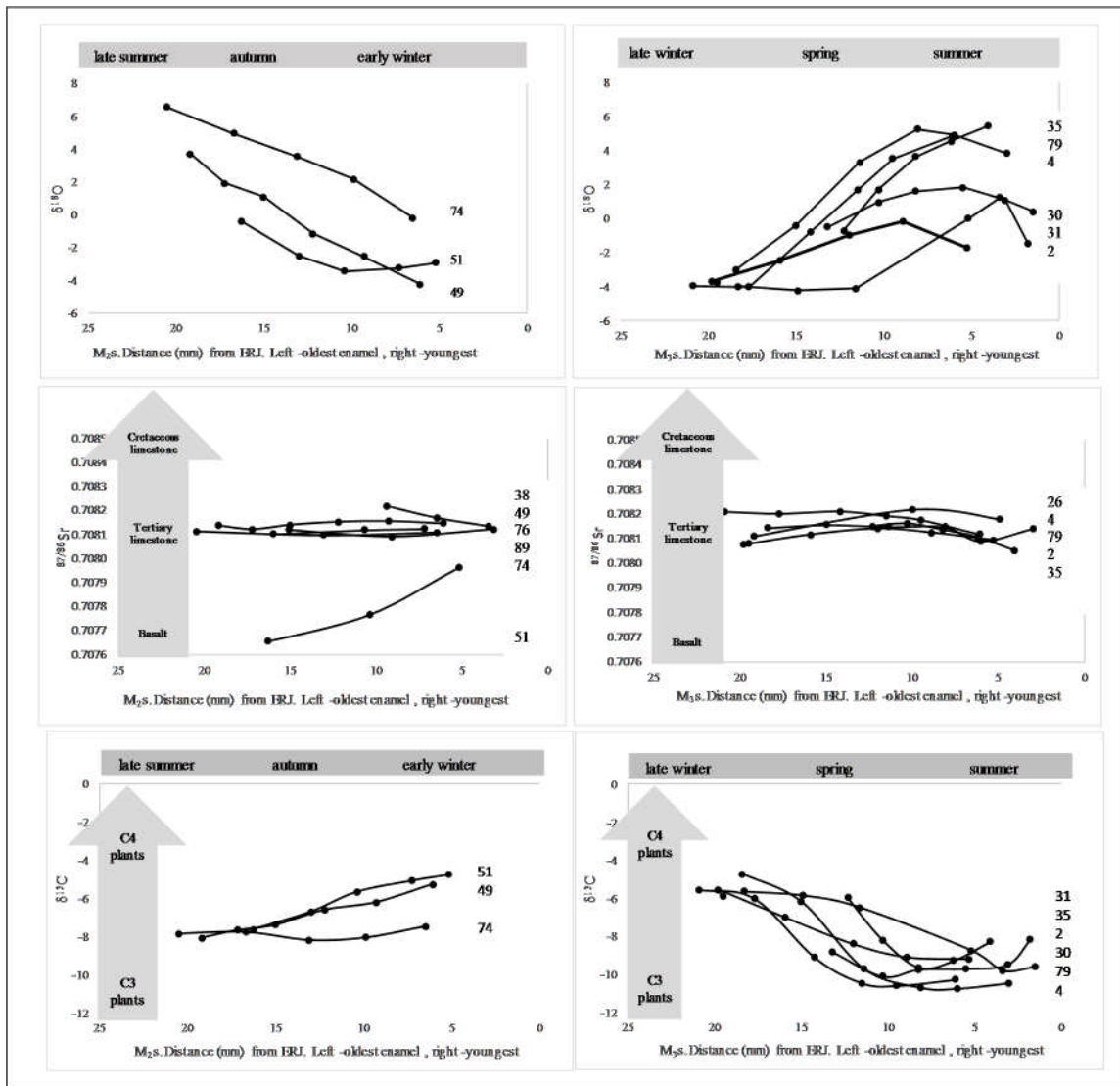
Fig 9. Charts showing all specimens on one chart for each isotope dataset, all M₂s on the left and M₃s on the right

Turning to $^{87}Sr/^{86}Sr$ curves, it is apparent that, with one exception later revisited, these animals lived on the Tertiary limestone series and did not travel long distances either westwards into the Cretaceous limestone hills or north-east over the basalt lava flows. This evidence strongly corroborates the more tentative $\delta^{18}O$ interpretation. Strontium results alone do not allow us to determine how far animals moved over the limestone steppe however we argue that the likelihood is that the $^{87}Sr/^{86}Sr$ results, strongly clustered throughout the annual cycle, represent the local Tertiary limestone location. Firstly, zooarchaeological analysis of body-part representation suggests hunting was local to the site (Martin et al 2010 p123, Fig.7) and therefore herds were nearby at some point in the annual cycle; and secondly, where no advantage would be gained from extensive movement within a similarly resourced landscape, gazelle movement would be limited to minimal dispersal in order to conserve energy and resources.

Finally, the consistent link between $\delta^{13}C$ and $\delta^{18}O$ curves (*Fig.7*) show unstressed C₃ plants dominating food intake through late winter, into spring, and on into early summer, followed by increasing amounts of arid-

1   stressed C_3 plants, possibly including some C_4 plants in high summer and autumn. The modelled

2   palaeovegetation proposes a longer growing season for annual grasses than today, explaining why C_3 species

3   remain available through the earlier summer. The $^{87}Sr/^{86}Sr$ data interpretation establishes that dietary changes

4   were not due to animal seasonal movement to more mesic vegetation zones, so it is argued that variation is due

5   to seasonal forage availability or to seasonal feeding preference; it is unnecessary to disentangle which as

6   feeding ethology and food seasonality are interrelated. In addition, for gazelle herds local to Kharaneh, gazelle

7   ethology allows us to assume a spring birth season when nutritious grasses flourished.

8

9   <u>The weeks before death</u>

10   If the above interpretations are correct, and these sampled specimens are representative of wider herd behaviour,

11   it appears that gazelle herds in the vicinity of Kharaneh gave birth in spring and did not undertake long distance

12   seasonal movements or migrations. We now turn to the evidence from DMA to assess hunting seasonality.

13

14   DMA evidence (*Fig. 8*) points to some of the sampled herd being hunted (local to Kharaneh) between late

15   winter and early summer when grasses flourished and had not yet died back, and when feeding preference for

16   lactating females in particular meant grasses were essential. Others were hunted when grasses had died off and

17   the most palatable, and only available, food was browse which persists into arid periods (tree leaves, soft growth

18   on woody shrubs, perennials and annuals such as chenopods). Yet others died on a mixed diet, possibly in early

19   summer when sparse grasses had to be supplemented with browse, or in late winter when the first grass shoots

20   were appearing and supplement the browse diet. The important point is that dental microwear evidence shows

21   no indication of clustering in either one or two seasons, which might be expected if hunting had been seasonal

22   or if gazelle presence had been seasonal; rather, DMA clearly points to hunting at Kharaneh being practiced in

23   more than one season.

24

25   We have shown that gazelle remained on the limestone steppe year-round and were hunted in multiple seasons.

26   The microwear gives a stronger signature for spring hunting than fusion data which noted a peak in winter

27   culling, and helps define the broader spring/summer category identified by the cementum study. Each

28   zooarchaeological method for determining cull seasonality has limitations, only allowing assessment of

29   particular seasons rather than the whole annual cycle. The current study lends support, however, to other site

30   evidence (Maher et al 2012a) indicating multi-seasonal and prolonged occupation of Kharaneh.

31

32   CONCLUSION

33   Discussion of hunter-gatherer mobility and seasonality in the Levantine Epipalaeolithic often relies on

34   assumptions about underlying animal and plant resource availability. Some researchers draw on traditional

35   models of radiating and circulating mobility around resource patches (Bar-Yosef & Belfer-Cohen 1989;

36   Lieberman 1993), others look to recently observed pastoralist (Bedouin) seasonal movements in interpreting

37   prehistoric hunter-gatherer mobility (Henry 1989). Maher and colleagues (2012b) question the validity of

38   applying uniform mobility models across the Levant, where high degrees of ecological heterogeneity define the

39   region. Indeed, the large-scale, multi-phase, repeatedly revisited site of Kharaneh (and nearby Wadi Jilat 6,

Garrard & Byrd 2013) attests to settlement organization quite different to the small campsites characterising the Early/Middle Epipalaeolithic elsewhere.

This study makes an important contribution to the debate on settlement dynamics in the Epipalaeolithic Azraq basin. Isotopic evidence suggests these gazelle herds were sustained year-round in the eastern Jordan limestone steppe without recourse to long-distance seasonal migrations. An alternative model to that predicting large migrating herds crossing the steppe might be one supporting localised seasonal aggregation and dispersal consistent with seasonal variation in social groupings following vegetation availability and herd reproductive cycles, similar to that seen amongst goitered gazelle in Saudi Arabia (Cunningham & Wronski 2011). This scenario offers a different picture of wildlife availability in the Early/Middle Epipalaeolithic. Hunter-gatherers could potentially have inhabited the steppes year-round, possibly aggregating and dispersing with herds.

Wadi Kharaneh may well have been an attractive winter location for hunting or mass-trapping large mixed herds. But spring gazelle hunting probably targeted smaller herd groupings requiring different hunting techniques such as stalking. We do not assume an ecologically deterministic relationship between hunters and prey, the research presented here merely shows possibilities of how hunting practices may have varied seasonally following wildlife behaviour. This study cautions against using recent and historical animal migration patterns uncritically, especially where landscapes have been heavily impacted by humans and livestock.

Finally, we return briefly to Specimen 51, the M_2 outlier with a strontium sequence indicating movement from the basalt towards the Tertiary limestone series during the year (*Fig. 9*). This specimen (with no special depositional conditions) serves as a reminder of the complexity of attempting reconstruction of past animal mobility, and that regional (and indeed temporal) variation is to be expected. Future research, following the methods used here, aims to include other Azraq Basin prehistoric sites, in order to explore spatial and temporal variation of the animal behaviour that underpinned human use of the steppe in prehistory.

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6 SUPPLEMENTARY MATERIAL

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8 Supp 1. – ^{87}Sr/^{86}Sr in modern plants from three locations

9 This supplement provides a little background information on the strontium isotope baseline that is referred to in

10 this paper and used to contribute to the identification of key geological locations. The supplement forms a

11 preliminary report on a small part of a more comprehensive isotopic baseline using modern plant collections,

12 which is currently in publication preparation. The ^{87}Sr/^{86}Sr results reported here are those collected from key

13 geological endmembers within and around the Azraq Basin: the Cretaceous limestone series of the Highlands to

14 the west, the Basalt lava flow to the northeast and the Early Tertiary limestone series near Kharaneh IV.

15

16 The leaves and soft shoots of moderately rooted plants were collected in one season (April) and used to measure

17 labile strontium. Each sampling aliquot included material from three individual plants and duplicates were run

18 to test intra-species variation at one location. Plants were exported to UCL Institute of Archaeology with the

19 permission of the Department of Antiquities of Jordan. Samples were first washed in milli-Q water then, in the

20 Earth Sciences Department at Royal Holloway University of London, labile strontium was extracted from

21 homogenised material followed standard protocols, and analyses were made in a VG354 thermal ionisation mass

22 spectrometer. Typical external reproducibility for ^{87}Sr/^{86}Sr is ±0.000014 (2sd).

23

24 Results are displayed below in Supplementary 1, Figure 1. It is immediately clear that the plant labile ^{87}Sr/^{86}Sr

25 values cluster into three groups that discriminate between the three locations and convincingly reflect

26 underlying geologies (Bentley 2006; Hartman & Richards 2014). The averaged ^{87}Sr/^{86}Sr readings for the

27 Cretaceous Highland location is 0.708941‰, the Early Tertiary limestone steppe 0.708087‰, and the basalt

28 steppe is 0.707720‰.

Taxa * duplicate analyses from one plant	Location UTM (north hemisphere)	^{87}Sr/^{86}Sr average of 3 plants	Bedrock geology
Phlomis fruticosa *Salvia heirosolymitana* *Anthemis sp.*	Upper Wadi Yabis 36: 7.597 E x 35.881 N	0.708479 0.708453 0.708543	Cretaceous limestone series (c2)
Hordeum glaucum *Achillea fragrantissima* *Malva parviflora*	Kharaneh IV 37. 37: 2.587 E x 35.128 N	0.708115 0.708069 0.708078	Early Tertiary limestone series (tt1)
Achillea fragrantissima* *Achillea fragrantissima**	Shubayqa 1 37: 3.334 E x 35.868 N	0.707731 0.707737	Pliocene/Oligocene basalt (B4)

*Hordeum glaucum**		0.707775	
*Hordeum glaucum**		0.707780	
*Malva parviflora**		0.707642	
*Malva parviflora**		0.707656	

Supp. 1, Table 1. Labile $^{87}Sr/^{86}Sr$ in plants collected from 3 locations on different geologies

Supp. 1, Fig. 1. Chart showing results of modern plant $^{87}Sr/^{86}Sr$ analyses at 3 geological locations in the Azraq Basin and the Jordanian Highlands