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THE USE OF OXYGEN ISOTOPES IN SHEEP MOLARS TO INVESTIGATE PAST HERDING PRACTICES AT THE NEOLITHIC SETTLEMENT OF ÇATALHÖYÜK, CENTRAL ANATOLIA*

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This paper presents a pilot study designed to test the use of oxygen isotopes for investigating aspects of early herding practices in the Neolithic of western Asia, using the site of Çatalhöyük in central Anatolia as a case study. Time-sequenced $\delta^{18}O$ values in dental enamel of archaeological sheep are assessed for post-depositional diagenetic effects and compared with seasonal $\delta^{18}O$ meteoric water values in the region today. The evidence is used to indicate the environmental conditions in which individual sheep spent their first year, enabling management of breeding and birthing seasons, and movement to seasonal pastures, to be investigated.

KEYWORDS: ANATOLIA, NEOLITHIC, OXYGEN ISOTOPES, TOOTH ENAMEL, SHEEP, HERDING INTENSIFICATION, SEASONAL PASTURING, HERD MOVEMENT

INTRODUCTION

The archaeological application of oxygen isotope analysis, often in combination with analyses of carbon, nitrogen or strontium isotopes, can provide evidence to establish the seasonality and locality of food or water intake of animals or humans. Such evidence has allowed annual herding mobility (Balasse *et al.* 2002), lambing seasonality (Balasse *et al.* 2003) and the manipulation of breeding seasons (Balasse and Tresset 2007) to be investigated. In addition, archaeologists have undertaken baseline studies in south-west Asia of oxygen isotope variability in modern transhumant herds (Mashkour *et al.* 2002) and in settlement-based herds (Wiedemann *et al.* 1996).

Methodological studies on the interpretive limits to archaeological evidence due to tooth enamel formation (Balasse 2002, 2003; Zazzo *et al.* 2005) and to weaning signatures (Kohn *et al.* 1998; Balasse and Tresset 2002) have contributed to the growing body of literature on the archaeological application of oxygen isotopes.

This paper builds on the previous work outlined above, and explores the use of oxygen isotopes in researching whether and how early domestic herd management intensified during the Neolithic of south-west Asia. The oxygen isotope values in archaeological sheep teeth are interpreted in terms of the region in which the animals were raised, the degree to which mating and birthing seasons were controlled, and the movement of herds to pasturing resources in the wider landscape.

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Regional and seasonal herding patterns would reflect underlying management decisions, where herd security and resource availability would be weighed against societal demands for easily accessible animal products and labour scheduling costs. Such decisions might indicate the manner and the extent to which herders and arable farmers co-operated; farmers might have needed crop protection from herd trampling but allowed herd access to fallow fields for manuring; herders might have needed the best graze for their herds in mating and birthing seasons with nutritional supplementary stubble or crop by-products to maintain herds kept near the settlement during winter.

THE RESEARCH CONTEXT

Research into the earliest herding of domesticated sheep and goats in Western Asia has tended to focus on the role large herds might have played in the environmental degradation and subsequent collapse of many long-occupied Neolithic settlements *c*.7500 cal. BC (Köhler-Rollefson and Rollefson 1990). Where settlement continued, theoretical models propose early specialization and separation of nomadic pastoral economies from settled arable farming (e.g. Köhler-Rollefson 1992). However, the likelihood and timing of this is widely debated (e.g. Sherratt 1983; Halstead 1996), and an alternative model proposes close integration of crop and livestock husbandry nearer the settlement (Halstead 2006).

Recently, zooarchaeological methods have included those that directly link individual animals to their environmental conditions outside the settlement; these allow innovations in herding economies to be explored in more detail. For example, dental microwear analysis of Neolithic herd animals in Greece showed that diets varied between animals destined for different uses after their slaughter (Mainland and Halstead 2002). Variety in Neolithic resource utilization has been explored using stable isotopes of carbon and nitrogen in bone tissue to identify the dietary breadth of central Anatolian herd animals (Richards *et al.* 2003; Pearson *et al.* 2007); the evidence suggests that diet was restricted at Aşıklı Höyük (8040–7490 cal. BC), possibly as herds were enclosed, but was broader later at Çatalhöyük (7400–6200 cal. BC), possibly as herders took their herds further afield to graze.

Direct evidence of seasonality and locality are useful additional tools for investigating how far away and at what times of year herders were pasturing animals that were not immediately of use (fallow herds), and whether breeding and lambing were tightly scheduled so that herds could be moved further afield before crop growth. The substance of this paper discusses how oxygen isotopes in sheep teeth might be used to address such questions, and to investigate whether and how early herding practices intensified and became more tightly scheduled to meet increasing pressures on local resources by long-term settlement.

THE CASE STUDY: NEOLITHIC SHEEP HERDING IN ÇATALHÖYÜK, CENTRAL ANATOLIA

Çatalhöyük, central Anatolia (Fig. 1), is a Neolithic tell site that has been extensively excavated and researched (Mellart 1967; Hodder 1999). It was settled during the later aceramic and early ceramic phases of the Neolithic between 7400 and 6200 cal. BC (Fig. 2) (Hodder 2005). The settlement was founded on a newly forming fertile alluvial fan which spilled out over infertile and impermeable marl plains and was surrounded by a sharp relief of karstic mountains rising 2000 m above the settlement and over 30 km distant (Roberts 1983). Between the mountains and the plains, 5–10 km distant, there were infertile but well-drained sand ridges and slightly more fertile Neogene limestone terraces (Roberts 1983). Geoarchaeological evidence suggests that there was

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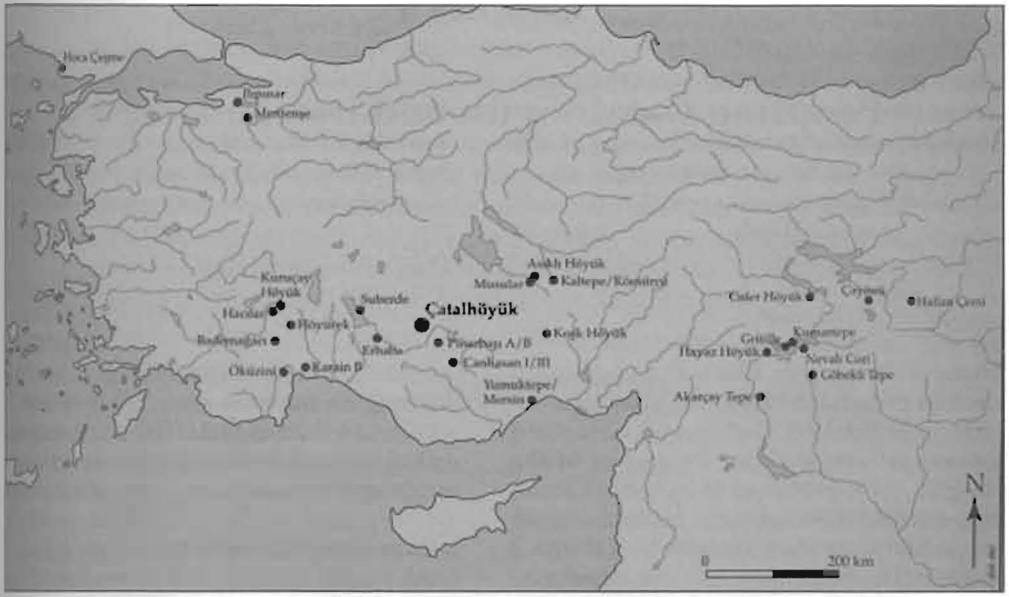

Figure 1 *Map showing Neolithic sites in central and eastern Antolia (Hodder 2005).*

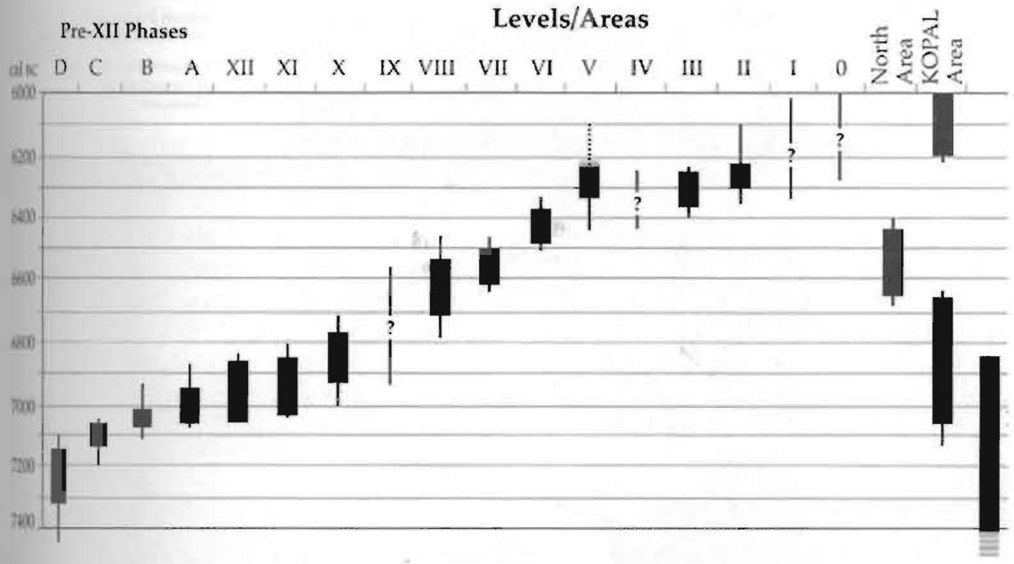

Figure 2 *Radiocarbon dating of Çatalhöyük occupation levels (Hodder 2005).*

a mosaic of well-drained and waterlogged locations in the immediate vicinity of the settlement (Boyer *et al.* 2006). It is possible that, during the late winter and early spring, flooding on the alluvial fan and marl plains became more extensive throughout the occupation of the settlement (Boyer *et al.* 2006).

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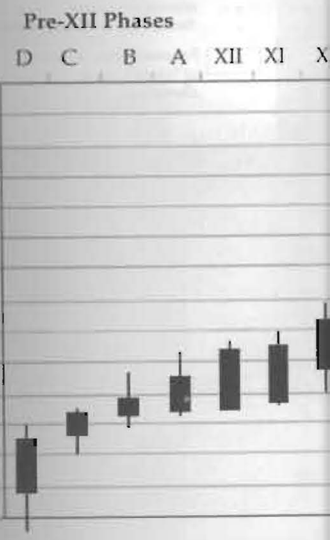

Figure 2 *Radiocarbon*

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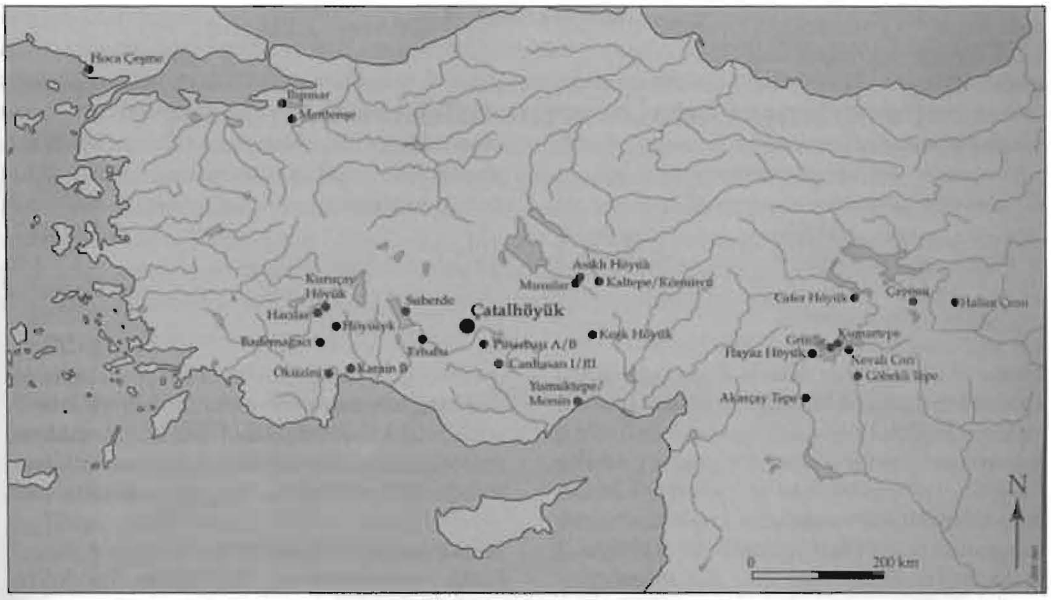

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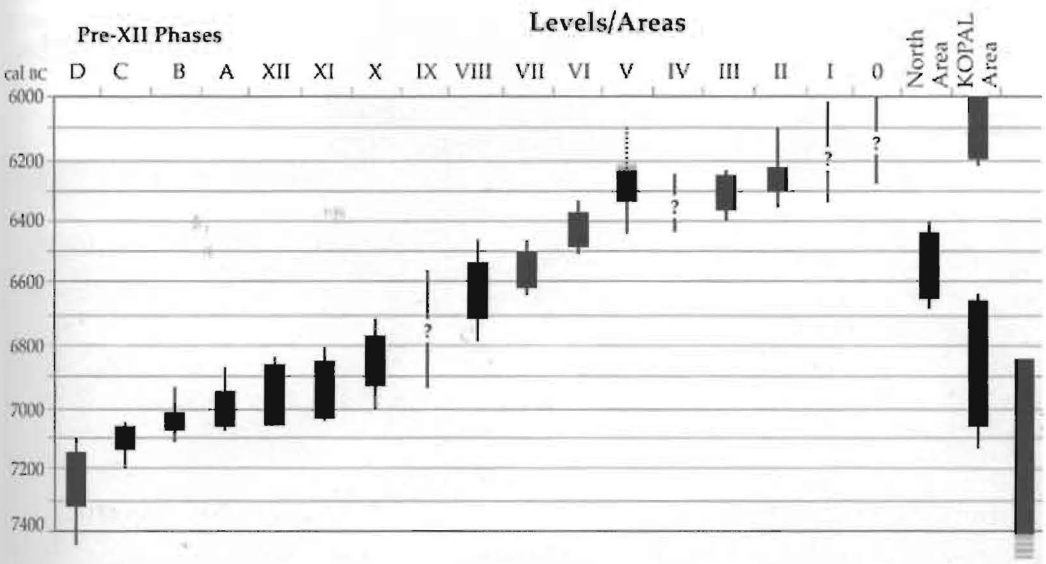

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The first settlers brought domestic crops (Fairbairn *et al.* 2005) and caprine herds (Russell and Martin 2005) with them. The most recent faunal analysis shows that meat and fat from sheep and goats were the main contributors, alongside cereals and pulses, to domestic meals, with little change throughout the occupation of the settlement (Russell and Martin 2005).There is some evidence in earlier phases of penning of sheep on the edge of the settlement (Matthews 2005), but modelled settlement density, with population figures rising to 6000 (Cessford 2005), would suggest that large herds were needed, and that fallow herds might have had to have been raised away from the settlement.

Archaeological and archaeobotanical evidence allows an environmental reconstruction to be proposed (Fig. 3), including the possible distribution of good pasture, of less nutritious, fall-back

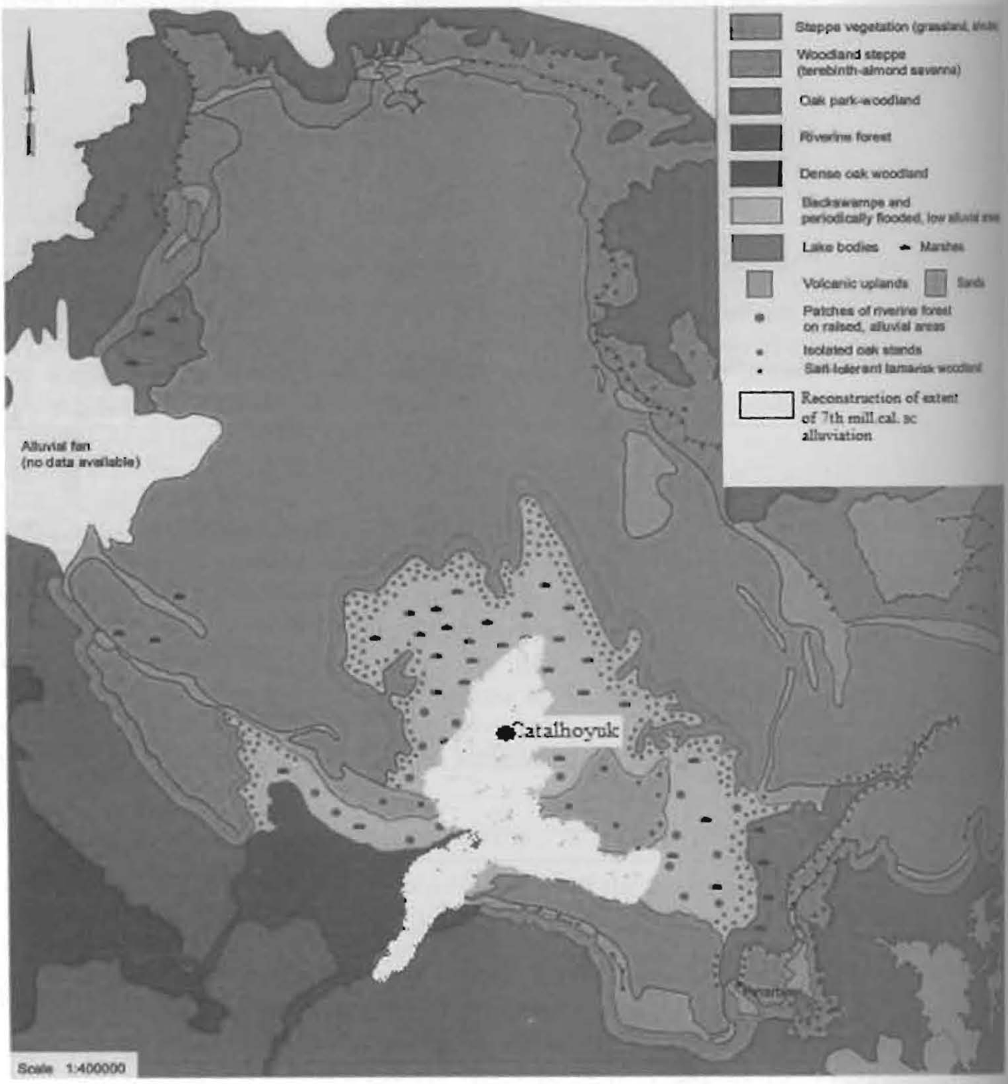

Figure 3 *Model of vegetation zones in the Çatalhöyük landscape (Asouti 2005).*

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Oxygen isotopes in precipitation

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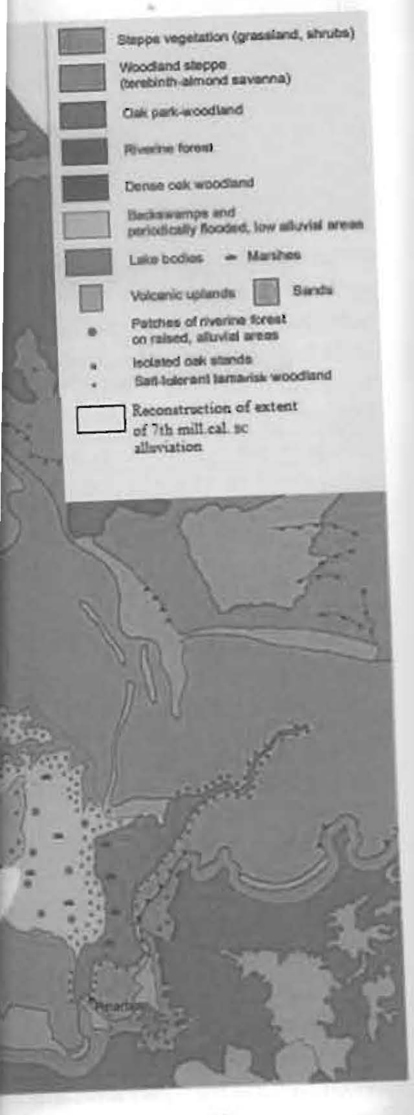

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wild fodder resources, and of areas of greatest resource competition caused by the interplay of limiting environmental factors and population pressures (Asouti 2005; McCorriston 1992). In addition to natural resources, evidence of arable crops raises the possibility of herds being grazed seasonally on nutritious weeds in fallow fields, on less-nutritious crop stubble, or foddered on stored arable by-products (Halstead 2006). The weed seed assemblage in the p[illegible]ing deposits possibly indicates that all these options might have been practised (Fairbairn *et al.* 2005). The local soils, susceptible to seasonal flooding and salinization, would only have been suitable for arable farming in a mosaic of raised areas. Limited crop weed evidence suggests that much of the grain crop might have been grown on dryer soils, such as those on the sand ridges and limestone terraces ((Fairbairn *et al.* 2005).

How did herders continue to supply sheep and goat products to the settlement for 1200 years, despite evidence of an expanding population and of increasingly restricted local grazing areas, and where longevity of settlement probably brought with it a degree of environmental degradation? A widening area of landscape exploitation that included grass parklands on the higher hill slopes could have extended seasonal pasture resources, kept herds away from growing crops on the alluvial fan, sand ridges and limestone terraces, reducing arable and pastoral competition for land nearer the settlement. Equally, tightly scheduled access to field stubble, fallow fields and arable by-products would have provided good nutritional fodder for herds kept near the settlement during the winter, when mating or lambing, or while awaiting slaughter. Initially there might have been conceptual limitations to distance herding or to the use of arable by-products and certain fodder resources, but during the 1200-year occupation of the Çatalhöyük changing technologies and ideologies, possibly influenced by interaction with the wider south-west Asian region, might have led to changing practices (Hodder 2005).

grazing pascolo

THE ARCHAEOLOGICAL APPLICATION OF OXYGEN ISOTOPES

At Çatalhöyük, carbon and nitrogen isotope evidence in animal and human bone suggests there was wider resource exploitation in later phases of occupation, but this evidence does not distinguish between fodder being brought to the herds, or herds being taken to distant pastures (Richards *et al.* 2003; Pearson *et al.* 2007). Oxygen isotope evidence can provide regional and seasonal evidence of where herds ingested their water, and might usefully approach the regional and seasonal schedule of herding at Çatalhöyük. The following section introduces oxygen isotopes and the variables contributing to the presence of each isotope, and then explores the uses and limitations of archaeological oxygen isotope evidence.

Oxygen isotopes in precipitation

There are two main stable isotopic forms of oxygen, ^{16}O and ^{18}O; the ratio in which they are found is a reflection of specific environmental histories. The ratio of ^{18}O:^{16}O is expressed in relation to the international calibration standard V-SMOW (Vienna Standard Mean Ocean Water) as δ^{18}O value. In water, the oxygen isotope ratio is influenced primarily by temperature acting on rates of precipitation and evaporation in the hydrology cycle, where the heavier ^{18}O is preferentially retained in the liquid phase (Gat 1996). Empirical research has established the relationship between δ^{18}O values and temperature (Rozanski *et al.* 1992) (equation (1)) as well as altitude (Poage and Chamberlain 2001) (equation (2)):

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puddles pozze

$$1^\circ\text{C rise in temperature} = 0.6‰ \text{ increase in } \delta^{18}\text{O} \quad (1)$$

$$100 \text{ m rise in altitude} = 0.3‰ \text{ decrease in } \delta^{18}\text{O} \quad (2)$$

The temperature of source oceanic water, and thus of its δ^{18}O, is a function of global insolation (the heat derived from the sun, subject to long-term variation due to solar activity and the proximity of the sun to the Earth), and serves to influence the seasonality of the weather trajectories taking the water inland. The progressive rain-out of ^{18}O, particularly over mountain ranges, en route from oceanic sources to more continental locations, results in depleted δ^{18}O values of precipitation with distance from the ocean (Dansgaard 1964). In addition, seasons of lower temperatures and increased rainfall serve to deplete δ^{18}O values compared with dryer, warmer seasons.

The δ^{18}O values in precipitation are reflected in seasonal surface waters such as puddles and perennial streams, and in plant leaf water. In hotter arid seasons the δ^{18}O values in longstanding lake waters and on leaf surfaces increase, as water molecules containing ^{16}O preferentially evaporate, leaving behind those containing ^{18}O isotopes (Gat and Gonfiatini 1981).

The many contributory factors to the oxygen isotopic composition of terrestrial water need to be understood before an interpretation of a sheep's drinking environment, let alone its herder's decisions, can be attempted. The present climate in the Çatalhöyük region is very cold to cold, semi-arid Mediterranean, with an annual rainfall of 245.6 mm on the plains, rising to 1000 mm in the uplands (Nahal 1981). Temperatures near the settlement range from –20°C in winter to +30°C in summer (Roberts 1983); the seasonality is a reflection of the weather system, bounded by the North Atlantic oscillation (NAO) to the north and the Inter-Tropical Convergence Zone (ITCZ) to the south (Roberts and Wright 1993).

The Global Network of Isotopes in Precipitation (GNIP) has surveyed the monthly content of oxygen isotopes in precipitation in Anatolia for 37 years; the annual weighted mean δ^{18}O is –8.4‰ and the mean seasonal δ^{18}O ranges from –12‰ in January to –4‰ in July (IAEA/WMO 2006). These values are considered to reflect the shallow, evaporative Mediterranean sources, with considerable enrichment in summer due to the net evaporative conditions inland (P. Blisniuk pers. comm. March 2008).

Turning to the mid-Holocene palaeoclimate of Neolithic Çatalhöyük, Rozanski *et al.* (1992) and Bowen and Wilkinson (2002) provide evidence of uniform air circulation and weather patterns within the mid and high latitudes throughout the past 35,000 years. In the Anatolian region the evidence shows no effects from the northerly shift of the ITCZ (bringing monsoonal rain from the Indian Ocean) (Gat 1996), nor from oscillations in the NAO (bringing weather in over the Alps) (P. Blisniuk pers. com. March 2008), suggesting that the Mediterranean was the main source of terrestrial precipitation in Anatolia during the Neolithic.

There are limitations to be taken into account when using modern data to model oxygen isotope values during the Neolithic. First, oceanic waters were approximately 2‰ isotopically lighter then than today due to the evaporative effects of greater global insolation (Rossignol-Strick 1999). Second, changes in the seasonal distribution of temperature and humidity are unclear, because of conflicting pollen, lake-core and sapropel evidence (e.g., Rossignol-Strick 1999; Roberts *et al.* 2001). Consequently seasonal evaporative effects on oxygen isotope values might differ between the present and the Neolithic, and while overall seasonal patterns can be expected to be similar, this is not so for absolute oxygen isotope values.

Oxygen isotopes in sheep tooth enamel

Oxygen in animal bone and teeth is deri
almost all their water needs can be met
rated within leaves (Silanikove 2000).
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no mixed, longer-residency water in th
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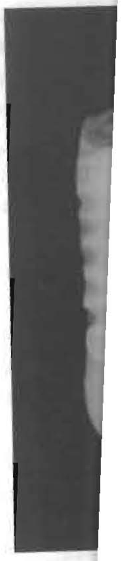

Figure 4 *Sheep second ma*

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ease in $\delta^{18}O$ (2)

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Neolithic Çatalhöyük, Rozanski *et al.*
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sapropel evidence (e.g., Rossignol-Strick
porative effects on oxygen isotope values
nd while overall seasonal patterns can be
gen isotope values.

Oxygen isotopes in sheep tooth enamel

Oxygen in animal bone and teeth is derived primarily from ingested water; in arid-region sheep, almost all their water needs can be met from seasonal precipitation on leaf surfaces or incorporated within leaves (Silanikove 2000). At the height of the Çatalhöyük arid season occasional drinking water would have been sourced from seasonal streams, puddles or marshes, as there was no mixed, longer-residency water in the area, such as that associated with deep lakes or man-made wells dug into aquifers. As there is a constant intra-species fractionation of oxygen isotopes on incorporation into body tissues of large, warm-blooded mammals such as sheep (Huertas Degardo *et al.* 1995; Fricke and O'Neil 1996), the $\delta^{18}O$ values in sheep tooth enamel may be calibrated to reflect those of the ingested water (Fricke and O'Neil 1996).

In sheep tooth enamel, oxygen is present in both the phosphate and carbonate components, and the $\delta^{18}O$ values in each may be converted into corresponding $\delta^{18}O$ values for ingested water using equations for domestic sheep proposed by D'Angela and Longinelli (1990) (equation (3)) and Iacumin *et al.* (1996) (equation (4));

$$\delta^{18}\text{O phosphate} = (1.48 \times \delta^{18}\text{O ingested water}) + 27.21 \tag{3}$$

$$\delta^{18}\text{O phosphate} = (0.98 \times \delta^{18}\text{O carbonate}) - 8.5 \tag{4}$$

Enamel formation in sheep molars proceeds down the crown in a sequential manner and is not later remodelled (Balasse 2002). In the sheep's second mandibular molar (M_2), the enamel forms over approximately 1 year, starting around birth (Weinreb and Sharav 1964) and calcification reaches its maximum (87%) very soon after eruption (Sakae and Hirai 1982). Thus a sequential series of enamel samples taken down the tooth column provides approximately a 1-year time capsule, in which the sequential $\delta^{18}O$ values may yield an annual curve (Fig. 4).

Figure 4 *Sheep second mandibular molar showing sampling sequence of the enamel layer.*

Certain factors limit how $\delta^{18}O$ values from sheep tooth enamel may be used to elucidate the seasonal and regional environment of ingested water. First, the $\delta^{18}O$ values in the M_2 extend over approximately 1 year, and reflect the weather patterns of that year; therefore any differences between sampled sheep molars might be due solely to inter-annual fluctuations; however, the inter-annual variations seen in the 40-year GNIP record offer a model of expected fluctuations. Second, sheep molar enamel is deposited in overlapping sheaths, which has the effect of dampening (through time averaging) the seasonal signature of $\delta^{18}O$ values, such that, although they pattern the $\delta^{18}O$ values of ingested water, they do not exactly replicate them (Balasse 2002). Third, given that isolating the enamel sheaths during sampling is extremely difficult, each sample picks up enamel associated with a range of formation times; the effect of this on a sequential set of samples is to delay the temporal signature by a few months—6 months in cattle (Balasse and Tresset 2002). Thus, while inter-tooth variety in seasonality may be commented on, it is unsafe to determine the season of birth without reference to data from relevant modern comparators.

A fourth limitation in the use of oxygen isotope signatures in sheep tooth enamel is that tooth attrition removes enamel from the occlusal surface at an inexact rate and so the earliest $\delta^{18}O$ values (from around birth in the M_2) might be missing. However, the cervical-root junction of the tooth provides a constant point (approximately 1 year after birth in the M_2) which constrains the interpretation of the time sequence of $\delta^{18}O$ values (Fricke and O'Neil 1996). The fifth limitation, which is negligible in sheep, stems from the further fractionation of isotopes associated with milk suckling; this effect can be seen clearly in calves weaned quite abruptly at 7 months of age (Balasse and Tresset 2002). However, traditionally raised lambs start eating grass at 1 week and steadily replace the contribution of suckled milk to their diet by as early as 4 months (Dahl and Hjort 1976). In addition, modelling the physiological effects of both suckling and an increased juvenile metabolic rate in another arid-land, medium-sized bovid—the gazelle—Kohn *et al.* (1998) argue that suckling depletes $\delta^{18}O$ values by <0.5‰, and this is almost completely cancelled by the enrichment effects of the higher metabolic rate.

The potential applications of oxygen isotope evidence in this study are:

- The sharp relief and extreme seasonal climate variation in the Çatalhöyük region should allow good discrimination between $\delta^{18}O$ values in different seasons and varying altitudes.
- The $\delta^{18}O$ signatures from modern meteoric water from central Anatolia (GNIP data) may be broadly relied upon to give relevant regional and seasonal patterns, as well as inter-annual variability, and can be used to model the archaeological isotope evidence in this study.
- Tooth carbonate $\delta^{18}O$ values may be converted, using equations (3) and (4), into $\delta^{18}O$ values of ingested water. Given the insecure interpretation of the seasonal distribution of precipitation in Neolithic Anatolia, as well as the limitations arising from complex tooth enamel formation, a formal climate reconstruction cannot be attempted.
- Inter-tooth differences in $\delta^{18}O$ tooth carbonate values can be assessed within the range of inter-annual variation from the mean (±0.42‰) taken from modern GNIP Ankara data, and discussed in terms of possible temperature, altitude and continentality effects on $\delta^{18}O$ values.
- Intra-tooth sequences can be assessed starting from the cervical-root junction, taking the position of the highest and lowest $\delta^{18}O$ values to represent the warmest and coldest seasons of enamel formation, respectively, and the range of differences to represent the climatic extremes experienced by the sheep in its first year. The mean of the $\delta^{18}O$ values in the M_2 represent yearly means and can only be assessed in teeth with little wear.

Sample selection

Nine teeth were taken from archaeologic
middens or as penning deposits (Table 1)
four teeth were from the early Pre-XIIB
IX/VIII phases (*c.* 6500–6800 cal. BC). It
be renamed from the 2009 season onwar
VIII become 'South K' and 'South L', re

Sample preparation

Approximately 12 mg of tooth enamel
dental drill, wearing nitrile latex-free g
between each sample. Sixty samples w
samples were also taken from two teet
otherwise stated, all chemicals used for
and purchased from Sigma-Aldrich (U

Carbonate component

Powdered enamel samples were first
material, and then rinsed three times in
acetic acid for 4 h to remove diageneti
samples were dried for 48 h at <45°C
evacuated desiccator using P_2O_5 as de
Approximately 4 mg of sample wer
and subjected to the procedure sumr
($\delta^{13}C_{VPDB} = +1.95$‰; $\delta^{18}O_{VPDB} = -2.2$(
different isotopic composition (sodiur
sodium bicarbonate B: $\delta^{13}C_{VPDB} = -$(

Table 1 *Çatalhöyük archaeol*

Tooth	*Context*	*Faun specim*
8	4121	F1833
9	3740	F389
5	1873	F532
6	1889	F183
7	1889	F184
1	5290	F263
2	5290	F917
3	5290	F261
4	5290	F26(

h enamel may be used to elucidate the
irst, the δ^{18}O values in the M_2 extend
erns of that year; therefore any differ-
y to inter-annual fluctuations; however,
ecord offer a model of expected fluc-
erlapping sheaths, which has the effect
signature of δ^{18}O values, such that,
er, they do not exactly replicate them
sheaths during sampling is extremely
a range of formation times; the effect
emporal signature by a few months—6
le inter-tooth variety in seasonality may
of birth without reference to data from

e signatures in sheep tooth enamel is
l surface at an inexact rate and so the
it be missing. However, the cervical-root
oximately 1 year after birth in the M_2)
ence of δ^{18}O values (Fricke and O'Neil
eep, stems from the further fractionation
t can be seen clearly in calves weaned
sset 2002). However, traditionally raised
e the contribution of suckled milk to their
In addition, modelling the physiological
abolic rate in another arid-land, medium-
e that suckling depletes δ^{18}O values by
y the enrichment effects of the higher

nce in this study are:
tion in the Çatalhöyük region should allow
seasons and varying altitudes.
from central Anatolia (GNIP data) may be
seasonal patterns, as well as inter-annual
ical isotope evidence in this study.
ng equations (3) and (4), into δ^{18}O values of
the seasonal distribution of precipitation in
from complex tooth enamel formation, a

values can be assessed within the range
) taken from modern GNIP Ankara data,
ltitude and continentality effects on δ^{18}O

rom the cervical-root junction, taking the
present the warmest and coldest seasons of
fferences to represent the climatic extremes
of the δ^{18}O values in the M_2 represent yearly
wear.

PROCEDURE

Sample selection

Nine teeth were taken from archaeological contexts, the most secure being those identified as middens or as penning deposits (Table 1). In order to investigate possible chronological change, four teeth were from the early Pre-XIIB phase (*c.* 7000–7500 cal. BC) and five were from later IX/VIII phases (*c.* 6500–6800 cal. BC). It should be noted that these phases will, in all likelihood, be renamed from the 2009 season onwards: Pre-XII levels become 'South G' and levels IX and VIII become 'South K' and 'South L', respectively (Farid 2008, 20).

Sample preparation

Approximately 12 mg of tooth enamel was drilled in parallel bands from each tooth using a dental drill, wearing nitrile latex-free gloves, and cleaning thoroughly with de-ionized water between each sample. Sixty samples were taken for carbonate δ^{18}O value analysis and nine samples were also taken from two teeth to measure the enamel phosphate δ^{18}O values. Unless otherwise stated, all chemicals used for sample preparation were of the highest available purity and purchased from Sigma-Aldrich (UK).

Carbonate component

Powdered enamel samples were first immersed in 0.1M NaOCl for 24 h to remove organic material, and then rinsed three times in de-ionized water before further immersion in 5% glacial acetic acid for 4 h to remove diagenetic carbonates. After further rinsing in de-ionized water the samples were dried for 48 h at <45°C. Prior to analysis, samples were stored for 7 days in an evacuated desiccator using P_2O_5 as desiccant.

Approximately 4 mg of sample were weighed into an exetainer (Labco, High Wycombe, UK) and subjected to the procedure summarized below. Exetainers filled with 0.5 mg of NBS-19 ($\delta^{13}C_{VPDB} = +1.95‰$; $\delta^{18}O_{VPDB} = -2.20‰$) or either of two internal laboratory standards of known different isotopic composition (sodium bicarbonate A: $\delta^{13}C_{VPDB} = -4.43‰$; $\delta^{18}O_{VPDB} = -12.38‰$; sodium bicarbonate B: $\delta^{13}C_{VPDB} = -6.46‰$; $\delta^{18}O_{VPDB} = -10.60‰$) were put through the same

Table 1 *Çatalhöyük archaeological tooth samples with spatial and chronological details*

Tooth	*Context*	*Faunal specimen*	*Site area*	*Context type*	*Phase*
8	4121	F1833	South	Midden/dump	VIII
9	3740	F389	South	Midden/infill	VIII
5	1873	F532	South	Dump	IX
6	1889	F183	South	Domestic dump	IX
7	1889	F184	South	Domestic dump	IX
1	5290	F2635	South	Midden	Pre-XIIB
2	5290	F917	South	Midden	Pre-XIIB
3	5290	F2610	South	Midden	Pre-XIIB
4	5290	F2608	South	Midden	Pre-XIIB

procedure contemporaneously to anchor and quality control sample results. Exetainers were then flushed with N5.7 grade nitrogen (N2-BIP, Air Products) for 10 min to remove all traces of atmospheric CO_2. Once flushed, 0.5 ml of absolute (water-free) sulphuric acid (99.999%) was added by injection through the exetainer's septum. Acid digest was carried out by placing the prepared exetainers for 6 h into a thermostatically controlled heater block at 50°C. Samples were allowed to cool at room temperature for at least 6 h prior to stable isotope analysis of the evolved CO_2 for $\delta^{13}C$ and $\delta^{18}O$ isotopic composition.

Phosphate component

Powdered enamel samples were agitated in a 2.5% sodium hypochlorite solution for 24 h. The solution was centrifuged for 5 min at 12 500 rpm. The supernatant was removed. The residue was washed five times to neutrality with doubly distilled water. Two millilitres of 2 M hydrofluoric acid (HF) was added and left for 24 h at room temperature. A 200 ml glass beaker was washed with ~30% nitric acid. The solution and residue resulting from the HF treatment were separated by centrifugation. The supernatant (apatite solution) was pipetted into the 200 ml beaker and 3 ml of 2 M potassium hydroxide added.

The residue was washed with 2 ml doubly distilled water, centrifuged and pipetted into the first aliquot of apatite solution. Doubly distilled water was added to make up to 200 ml of solution. Then 15 ml of buffered amine solution was added. The buffered amine solution used was an aqueous solution 0.2M in $AgNO_3$; 0.35M in NH_4NO_4 and 0.75M in concentrated NH_4OH (~25% NH_3 in water).The solution was gradually warmed up to 70°C and the temperature held for 3 h without adding water. After that period, the solution was slowly cooled down to room temperature. The pH values of the solution at the start and at the end of this procedure were 10 and 7, respectively.

The crystals were filtered on a weighed 0.2 μm filter and washed several times with distilled water and dried overnight at 50°C. Approximately 0.2 mg of the apatite precipitate (Ag_3PO_4) was weighed into a silver capsule per individual analysis and dried in an evacuated desiccator using P_2O_5 as desiccant for 7 days prior to ^{18}O isotope analysis.

Analysis

^{18}O isotope analysis of tooth carbonate Once removed from the heater block, exetainer tubes (Labco) were checked for dislodged screw tops, allowed to cool down to room temperature and then placed in the autosampler rack of an AP2003 gas isotope ratio mass spectrometer (Analytical Precision, UK) for ^{18}O isotope abundance analysis of CO_2 released by acid digest. Each exetainer was sampled three times and each time an aliquot of the CO_2 contained therein passed through a capillary, subsequently a tubular Nafion membrane water trap and finally into a gas sampling loop. From the loop the sample gas passed on to an isothermal chromatography column to separate out traces of atmospheric N_2 from CO_2, if at all present, to be ultimately admitted into the isotope ratio mass spectrometer (IRMS) for analysis. Once the IRMS had successfully received and analysed the sample, an aliquot of internal reference gas (CO_2) was automatically introduced to the mass spectrometer as part of the same analytical cycle.

Quality of the sample preparation procedure and analytical performance of the AP2003 IRMS were monitored by contemporaneously analysing acid digests of the international reference material NBS19 ($\delta^{18}O_{VPDB} = -2.20‰$) as well as two house standards (sodium bicarbonate A: $\delta^{18}O_{VPDB} = -12.38‰$; sodium bicarbonate B: $\delta^{18}O_{VPDB} = -10.60‰$). Reproducibility of ^{18}O

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isotope analysis as monitored by the ref
sample measurement was typically ±0.5
ducibility and intra-sample variability.

^{18}O isotope analysis of tooth phosphat
(TC/EA), coupled to a Delta^{Plus} XL isot
(Thermo-Fisher, Bremen, Germany), wa
phosphate samples prepared from tooth
sample was weighed into silver capsules
Zero-Blank autosampler (Pelican Scien
Alsint™ ceramic tube, a glassy carbon
(SerCon, Crewe, Cheshire), and was m
maintained at 85°C.

Data were processed using propriet
Measured $^{18}O/^{16}O$ isotope ratios are ex
mean ocean water (V-SMOW). The pre
different reference materials of know
Sigma-Aldrich, $\delta^{18}O_{V\text{-}SMOW} = 13.45‰$,
120C, $\delta^{18}O_{V\text{-}SMOW} = 21.33‰$) as referen
monitored by the reference materials w
surement was typically ±0.19‰.

Data evaluation

^{18}O isotope analysis of tooth carbonate
values were converted into correspond
(Friedman and O'Neil 1977) (Table 2):

$$\delta^{18}O_{V\text{-}SMO}$$

Archaeological tooth enamel samples,
sedimentary matrix and the fluctuatin
susceptible to diagenesis, particularly
enamel (Wang and Cerling 1994; Iacu
carbonate component is easily measu
therefore be a potentially useful and
assess any diagenetic influence, sampl
and $\delta^{18}O$ carbonate values (Table 3)
(Fig. 5). The solution for the linear re

$$\delta^{18}O \text{ phospha}$$

In addition to having a very high corre
of carbonate diagenesis, this linear r
et al. (1996) shown in equation (4).

Samples of all the other teeth were
of their carbonate fraction, and mea
calculated $\delta^{18}O$ water values (V-SM

trol sample results. Exetainers were then
cts) for 10 min to remove all traces of
ater-free) sulphuric acid (99.999%) was
id digest was carried out by placing the
olled heater block at 50°C. Samples were
r to stable isotope analysis of the evolved

dium hypochlorite solution for 24 h. The
upernatant was removed. The residue was
vater. Two millilitres of 2 M hydrofluoric
ature. A 200 ml glass beaker was washed
ng from the HF treatment were separated
is pipetted into the 200 ml beaker and 3 ml

vater, centrifuged and pipetted into the first
s added to make up to 200 ml of solution.
The buffered amine solution used was an
and 0.75M in concentrated NH_4OH (~25%
) to 70°C and the temperature held for 3 h
was slowly cooled down to room tempera-
t the end of this procedure were 10 and 7.

ter and washed several times with distilled
mg of the apatite precipitate (Ag_3PO_4) was
and dried in an evacuated desiccator using
lysis.

oved from the heater block, exetainer tubes
llowed to cool down to room temperature
2003 gas isotope ratio mass spectrometer
ce analysis of CO_2 released by acid digest.
h time an aliquot of the CO_2 contained
ular Nafion membrane water trap and finally
gas passed on to an isothermal chromatog-
, from CO_2, if at all present, to be ultimately
(IRMS) for analysis. Once the IRMS had
aliquot of internal reference gas (CO_2) was
s part of the same analytical cycle.
nalytical performance of the AP2003 IRMS
acid digests of the international reference
vo house standards (sodium bicarbonate A:
$)_{VPDB}$ = −10.60‰). Reproducibility of ^{18}O

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isotope analysis as monitored by the reference materials was typically ±0.18‰. Uncertainty of sample measurement was typically ±0.50‰, which is a composite of the aforementioned reproducibility and intra-sample variability.

^{18}O isotope analysis of tooth phosphate A high temperature conversion elemental analyser (TC/EA), coupled to a Delta^{Plus} XL isotope ratio mass spectrometer via a Conflow III Interface (Thermo-Fisher, Bremen, Germany), was used for oxygen isotope ratio measurement of silver phosphate samples prepared from tooth samples as described above. Approximately 0.2 mg of sample was weighed into silver capsules and introduced into the TC/EA by means of a Costech Zero-Blank autosampler (Pelican Scientific Ltd, Alford, UK). The reactor tube comprised an Alsint™ ceramic tube, a glassy carbon tube, glassy carbon granules and silver and quartz wool (SerCon, Crewe, Cheshire), and was maintained at 1450°C. The post-reactor GC column was maintained at 85°C.

Data were processed using proprietary software, Isodat NT version 2.0 (Thermo-Fisher). Measured $^{18}O/^{16}O$ isotope ratios are expressed as δ-values in [‰] relative to Vienna-standard mean ocean water (V-SMOW). The prepared apatite samples were analysed in a batch with two different reference materials of known $\delta^{18}O$ composition (commercial silver apatite from Sigma-Aldrich, $\delta^{18}O_{V\text{-}SMOW} = 13.45‰$, and the international hydroxyl apatite standard NBS 120C, $\delta^{18}O_{V\text{-}SMOW} = 21.33‰$) as reference materials. Reproducibility of $\delta^{18}O$ isotope analysis as monitored by the reference materials was typically ±0.24‰ while uncertainty of sample measurement was typically ±0.19‰.

Data evaluation

^{18}O isotope analysis of tooth carbonate yielded values on the V-PDB scale, therefore $\delta^{18}O_{VPDB}$ values were converted into corresponding $\delta^{18}O$ $_{V\text{-}SMOW}$ values using the following correlation (Friedman and O'Neil 1977) (Table 2):

$$\delta^{18}O_{V\text{-}SMOW} = (1.0309 \times \delta^{18}O_{VPDB}) + 30.9 \tag{5}$$

Archaeological tooth enamel samples, because of the length of time they have been resting in the sedimentary matrix and the fluctuating hydrology before excavation recovery, are potentially susceptible to diagenesis, particularly the carbonate component which comprises 4% of tooth enamel (Wang and Cerling 1994; Iacumin *et al.* 1996). However, the isotopic composition of the carbonate component is easily measured, requiring only minimal sample preparation, and can therefore be a potentially useful and convenient source of information. In order to exclude or assess any diagenetic influence, samples from two teeth were analysed for both $\delta^{18}O$ phosphate and $\delta^{18}O$ carbonate values (Table 3) and their correlation tested by linear regression analysis (Fig. 5). The solution for the linear regression of tooth 4 yielded;

$$\delta^{18}O \text{ phosphate} = (1.056 \times \delta^{18}O \text{ carbonate}) - 11.02 \tag{6}$$

In addition to having a very high correlation coefficient, $R^2 = 0.99$, which suggests a very low rate of carbonate diagenesis, this linear regression is in very good agreement with that of Iacumin *et al.* (1996) shown in equation (4).

Samples of all the other teeth were therefore analysed for $\delta^{13}C$ and $\delta^{18}O$ isotopic composition of their carbonate fraction, and measured $\delta^{18}O$ carbonate values (VPDB) were converted into calculated $\delta^{18}O$ water values (V-SMOW) using equations (3)–(5).

Table 2 *$\delta^{18}O_{V\text{-}SMOW}$ values for archaeological tooth enamel carbonate samples, with calibrations for enamel phosphate and ingested water values*

Archaeological tooth	*Samples along tooth column (numbered from occlusal end)*	*Tooth carbonate*	*Tooth phosphate**	*Ingested water*
			$\delta^{18}O_{V\text{-}SMOW}$†	
1	1.1	29.19	20.11	−4.80
	1.2	25.05	16.05	−7.54
	1.3	26.45	17.42	−6.61
	1.4	28.25	19.19	−5.42
	1.5	33.19	24.03	−2.15
	1.6	34.17	24.99	−1.50
	1.7	34.08	24.90	−1.56
2	2.3	31.29	22.16	−3.41
	2.4	28.17	19.11	−5.48
	2.5	26.38	17.35	−6.66
	2.6	24.09	15.11	−8.18
	2.7	24.74	15.75	−7.75
3	3.1	34.38	25.19	−1.36
	3.2	36.84	27.60	0.27
	3.3	32.93	23.77	−2.32
	3.4	38.01	28.75	1.04
	3.5	38.29	29.02	1.23
	3.6	36.09	26.87	−0.23
	3.7	35.9	26.68	−0.36
4	4.1	25.99	16.97	−6.92
	4.2	27	17.96	−6.25
	4.3	28.59	19.52	−5.20
	4.4	32.34	23.19	−2.71
	4.5	34.54	25.35	−1.26
	4.6	34.99	25.79	−0.96
	4.7	31.73	22.60	−3.12
5	5.1	26.06	17.04	−6.87
	5.2	30.36	21.25	−4.03
	5.3	29.55	20.46	−4.56
	5.4	31.88	22.74	−3.02
	5.5	34.09	24.91	−1.56
	5.6	33.76	24.58	−1.77
	5.7	30.38	21.27	−4.01
6	6.1	30.15	21.05	−4.16
	6.2	27.23	18.19	−6.10
	6.3	25.96	16.94	−6.94
	6.4	27.44	18.39	−5.96
	6.5	26.94	17.90	−6.29
	6.6	35.53	26.32	−0.60
	6.7	35.42	26.21	−0.67
7	7.1	27.21	18.17	−6.11
	7.2	28	18.94	−5.59
	7.3	29.02	19.94	−4.91
	7.4	32.62	23.47	−2.53
	7.5	29.77	20.67	−4.42
	7.6	31.36	22.23	−3.36
	7.7	25.73	16.72	−7.09

Archaeological tooth	*Samples along tooth column (numbered from occlusal end)*
8	8.1
	8.2
	8.3
	8.4
	8.5
	8.6
	8.7
	8.8
	8.9
9	9.4
	9.5
	9.6
	9.7

*Iacumin *et al.* (1996) (equation 4).

†Friedman and O'Neil (1977) (equation 5).

‡D'Angela and Longinelli (1990) (equation 3).

Table 3 *Measured $\delta^{18}O$*

Sample
4.2P
4.3P
4.4P
4.5P
8.1P
8.2P
8.3P
8.4P

All the results from the isotope anal discussion in Figures 8–11. This sect of oxygen isotope analysis in Çata precludes any statistically secure int

Intra-tooth variation in $\delta^{18}O$ values

Figure 6 presents the seasonal curve modern GNIP data (IAEA/WMO 2

carbonate samples, with calibrations for enamel
water values

onate	Tooth phosphate*	Ingested water‡
	$\delta^{18}O_{V\text{-}SMOW}$†	
	20.11	−4.80
	16.05	−7.54
	17.42	−6.61
	19.19	−5.42
	24.03	−2.15
7	24.99	−1.50
8	24.90	−1.56
9	22.16	−3.41
7	19.11	−5.48
8	17.35	−6.66
9	15.11	−8.18
4	15.75	−7.75
8	25.19	−1.36
4	27.60	0.27
3	23.77	−2.32
1	28.75	1.04
29	29.02	1.23
99	26.87	−0.23
9	26.68	−0.36
99	16.97	−6.92
	17.96	−6.25
59	19.52	−5.20
34	23.19	−2.71
.54	25.35	−1.26
.99	25.79	−0.96
.73	22.60	−3.12
.06	17.04	−6.87
.36	21.25	−4.03
.55	20.46	−4.56
.88	22.74	−3.02
.09	24.91	−1.56
.76	24.58	−1.77
.38	21.27	−4.01
.15	21.05	−4.16
.23	18.19	−6.10
.96	16.94	−6.94
.44	18.39	−5.96
.94	17.90	−6.29
5.53	26.32	−0.60
5.42	26.21	−0.67
7.21	18.17	−6.11
8	18.94	−5.59
9.02	19.94	−4.91
2.62	23.47	−2.53
9.77	20.67	−4.42
1.36	22.23	−3.36
5.73	16.72	−7.09

Table 2 *Continued*

Archaeological tooth	*Samples along tooth column (numbered from occlusal end)*	*Tooth carbonate*	*Tooth phosphate**	*Ingested water‡*
		$\delta^{18}O_{V\text{-}SMOW}$†		
8	8.1	28.87	19.79	−5.01
	8.2	30.59	21.48	−3.87
	8.3	30.77	21.65	−3.75
	8.4	29.69	20.60	−4.47
	8.5	33.26	24.09	−2.10
	8.6	28.15	19.09	−5.49
	8.7	32.23	23.09	−2.79
	8.8	28.55	19.48	−5.22
	8.9	26.66	17.63	−6.48
9	9.4	34.54	25.35	−1.26
	9.5	33.4	24.23	−2.01
	9.6	30.86	21.74	−3.69
	9.7	29.02	19.94	−4.91

*Iacumin *et al.* (1996) (equation 4).
†Friedman and O'Neil (1977) (equation 5).
‡D'Angela and Longinelli (1990) (equation 3).

Table 3 *Measured $\delta^{18}O_{V\text{-}SMOW}$ values for archaeological tooth enamel phosphate samples*

Sample	*Tooth phosphate $\delta^{18}O_{V\text{-}SMOW}$*	
4.2P	16.22	17.1
4.3P	18.6	19.65
4.4P	22.09	23.15
4.5P	24.16	25.33
8.1P	17.25	18.02
8.2P	18.24	19.32
8.3P	20.56	21.44
8.4P	19.09	20.91

RESULTS

All the results from the isotope analyses are provided in Table 2 and presented graphically for discussion in Figures 8–11. This section should be seen as being illustrative of the potential use of oxygen isotope analysis in Çatalhöyük domestic herds; the extremely small sample size precludes any statistically secure interpretation.

Intra-tooth variation in $\delta^{18}O$ values

Figure 6 presents the seasonal curve of $\delta^{18}O$ water values for Ankara starting in September, using modern GNIP data (IAEA/WMO 2006); it is used to model the sequential curve of $\delta^{18}O$ values

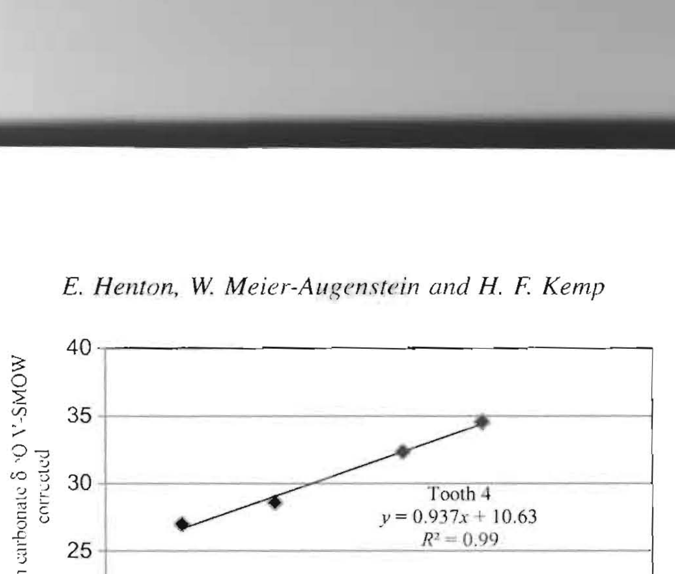

Figure 5 *Correlation of $\delta^{18}O$ values in the carbonate and phosphate fractions of tooth 4.*

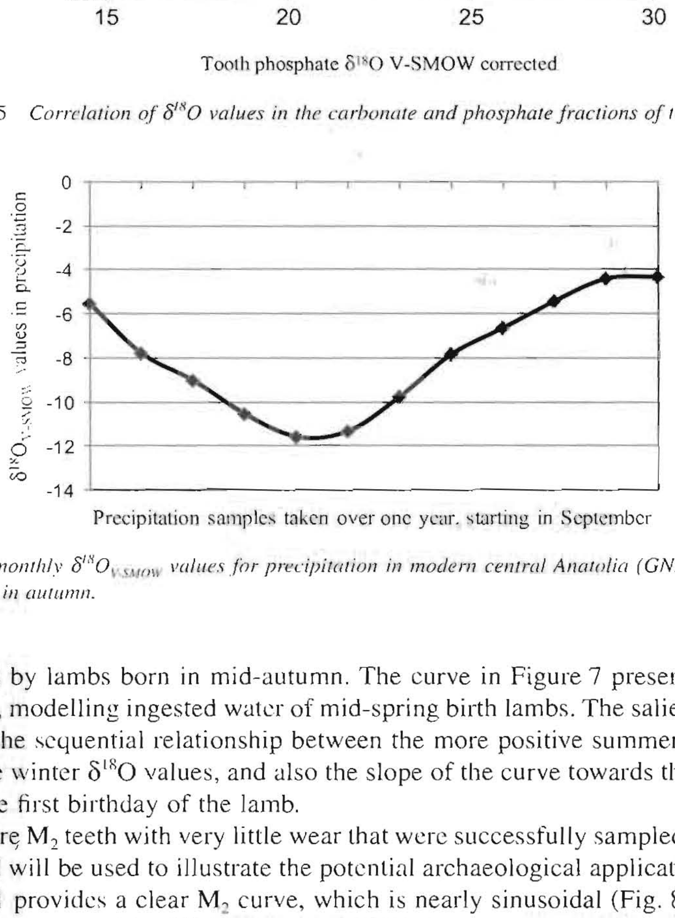

Figure 6 *Weighted monthly $\delta^{18}O_{V\text{-}SMOW}$ values for precipitation in modern central Anatolia (GNIP data), showing an annual cycle starting in autumn.*

of water ingested by lambs born in mid-autumn. The curve in Figure 7 presents the same data starting in March, modelling ingested water of mid-spring birth lambs. The salient distinguishing features include the sequential relationship between the more positive summer $\delta^{18}O$ values and the more negative winter $\delta^{18}O$ values, and also the slope of the curve towards the 12th month, or approximately the first birthday of the lamb.

Teeth 1 and 4 are M_2 teeth with very little wear that were successfully sampled up the complete tooth column and will be used to illustrate the potential archaeological application of intra-tooth variation. Tooth 1 provides a clear M_2 curve, which is nearly sinusoidal (Fig. 8). It finishes just before a period of more positive $\delta^{18}O$ values typical of summer precipitation and greater aridity. The heaviest depletion of $\delta^{18}O$ values in winter can be seen much earlier in the year of enamel formation and the drop in values that might be associated with late autumn are present even earlier in its formation. This sequence of $\delta^{18}O$ values suggests this lamb was born in late summer/early autumn. Tooth 4 (Fig. 9) appears to be from a sheep born much later in autumn as demonstrated by the last $\delta^{18}O$ values dropping towards more negative $\delta^{18}O$ winter values (Fig. 4). However, remembering the possible 6-month delay in signal due to the complexity of enamel formation, it is possible that the two teeth in fact demonstrate late winter and late spring births. Preliminary modern data (unpublished) from a sheep born in February and raised traditionally in

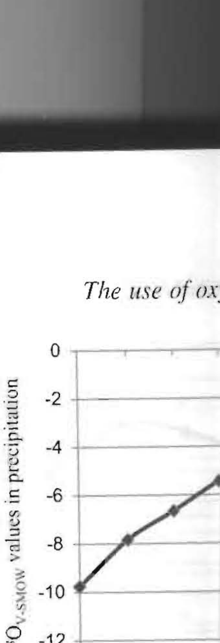

Figure 7 *Weighted monthly $\delta^{18}O_{V\text{-}SMOW}$ values f*
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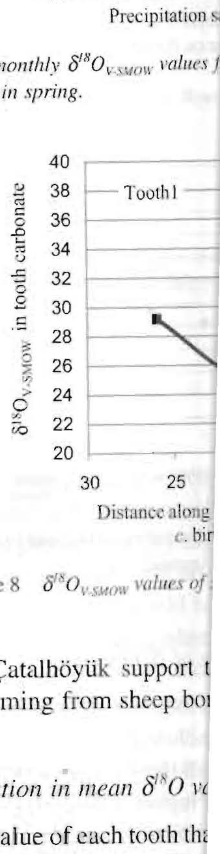

Figure 8 *$\delta^{18}O_{V\text{-}SMOW}$ values of*

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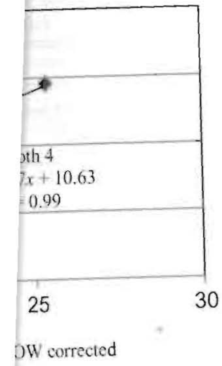

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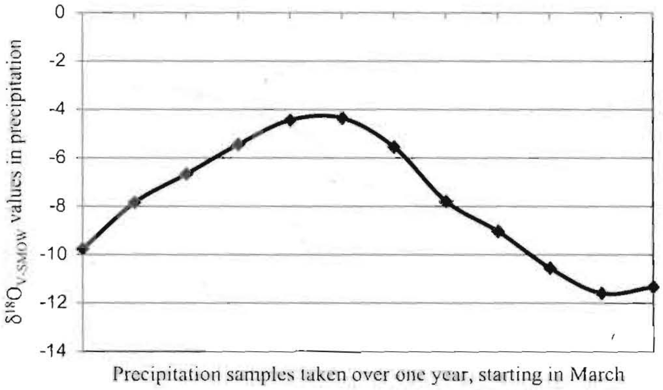

Figure 7 *Weighted monthly $\delta^{18}O_{V\text{-}SMOW}$ values for precipitation in modern central Anatolia (GNIP data), showing an annual cycle starting in spring.*

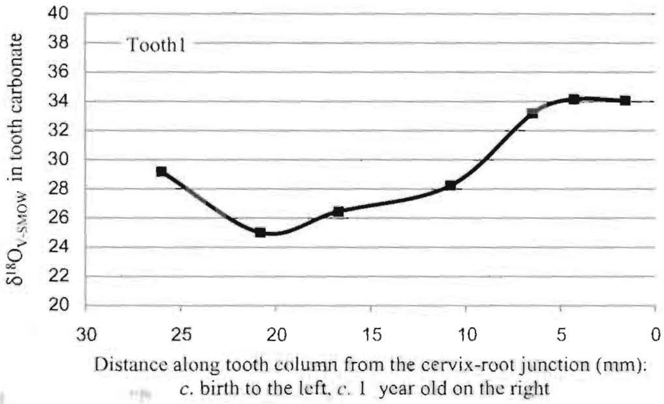

Figure 8 *$\delta^{18}O_{V\text{-}SMOW}$ values of sequential enamel carbonate samples taken from tooth 1.*

the locality of Çatalhöyük support the latter interpretation; the two archaeological teeth are interpreted as coming from sheep born at different times during the spring.

Inter-tooth variation in mean $\delta^{18}O$ values

The mean δ^{18}O value of each tooth that has not been excessively worn is plotted in Figure 10. The clustering of most mean values suggests that the enamel was formed in similar environmental conditions, and the most parsimonious explanation is that teeth are all from local sheep raised in the central Anatolian region. The exception is tooth 3. This tooth is in occlusion and already in wear and so enamelization is at least 87% equally complete throughout the tooth (Sakae and Hirai 1982); immaturity is therefore not the cause of exceptional diagenesis. Unusual diagenesis is unlikely for two further reasons. First, three other teeth from the same archaeological context fall neatly into the larger cluster. Second, tooth 4, the subject of the high carbonate–phosphate correlation discussed previously, is from the same context. An alternative explanation is that this lamb was raised throughout its first year in another region, and then brought to Çatalhöyük.

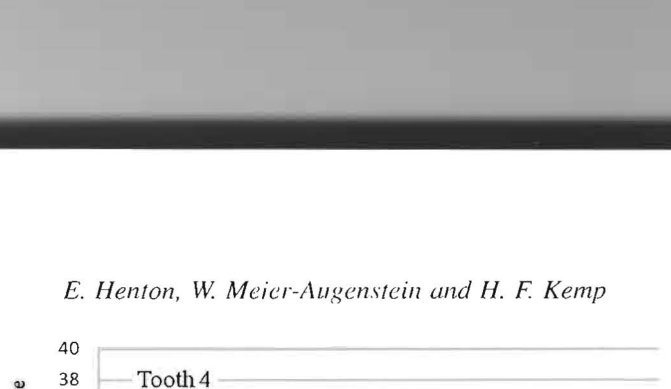

Figure 9 *$\delta^{18}O_{V\text{-}SMOW}$ values of sequential enamel carbonate samples taken from tooth 4.*

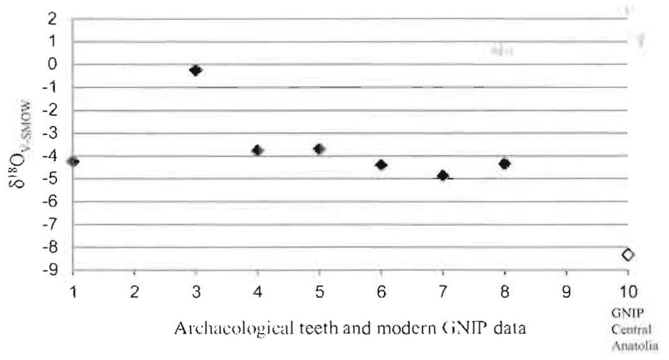

Figure 10 *Mean $\delta^{18}O$ values of samples taken from archaeological teeth (excluding teeth 2 and 9) calibrated to ingested water values and the yearly mean of weighted GNIP values for central Anatolia.*

Inter-tooth variation in the maximum, minimum and range of $\delta^{18}O$ values

The maximum, minimum and range of $\delta^{18}O$ values for each tooth are plotted in Figure 11. Again the teeth with greater wear or incomplete sampling are not included. In a preliminary analysis this shows that teeth 7 and 8 differ from teeth 1, 4, 5 and 6 in all three criteria, and in excess of the inter-annual variations shown in modern GNIP data for the region. The range in teeth 7 and 8 is some 2‰ lower and results mainly from *c.* 1.5‰ depletion in $\delta^{18}O$ summer values.

A year spent in one location would produce a certain range between maximum and minimum in $\delta^{18}O$ values, and altitudinal movement would affect that range. In other words, the seasonal signature will be distorted by altitudinal effects on $\delta^{18}O$ values. For example, long-distance summer pasturing in the hills would dampen the range as the sheep would not have ingested water with enriched $\delta^{18}O$ values associated with summer lowland temperature extremes, nor water with depleted $\delta^{18}O$ values associated with winter upland temperature extremes. If the larger cluster (teeth 1, 4, 5 and 6) is taken to have the true one-region range belonging to a herd that was not moved throughout the year, then the dampened range in the smaller cluster (teeth 7 and 8) might be associated with herd movement into the hills in summer.

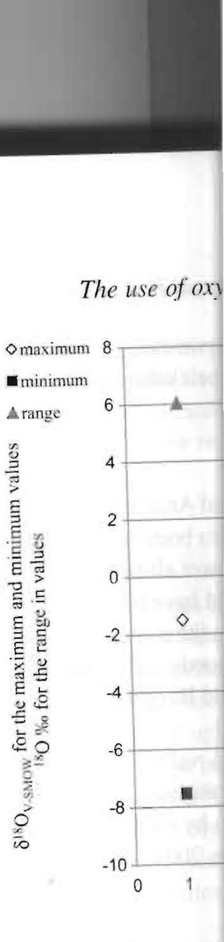

Figure 11 *Maximum, minimum and range of δ*
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Lamb birth season

If the results are interpreted correctly
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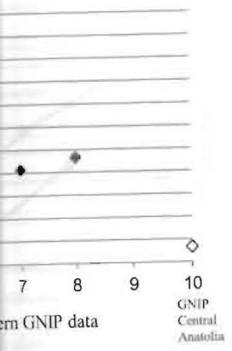

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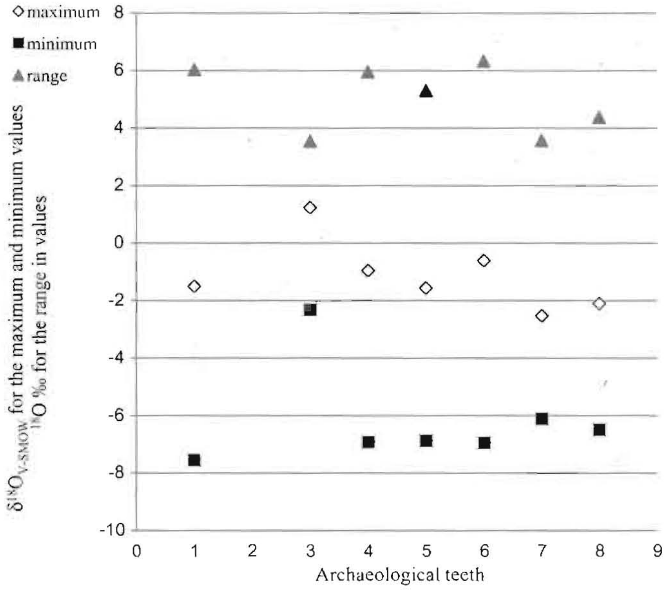

Figure 11 *Maximum, minimum and range of δ^{18}O values in samples taken from archaeological teeth (excluding teeth 2 and 9) calibrated to ingested water values.*

DISCUSSION

Lamb birth season

If the results are interpreted correctly, both examples (teeth 1 and 4) are from sheep born in spring. At these latitudes, sheep usually give birth in spring (M. Sivaş, local farmer, pers. comm. July 2006) but are physiologically capable of autumn births (Dahl and Hjort 1976); both wild and domestic sheep occasionally still do so in the Çatalhöyük locality (M. Sivaş pers. comm. July 2006). Autumn birth lambs would have had to have been raised during winter when resources were scarcer and the weather harsher. While herders would have had the time-consuming task of fodder collection, penning lambs close to the settlement would have offered protection from the weather and from predators. Spring birth lambs, such as the ones illustrated by teeth 1 and 4, would have had the advantages of warm weather while they grew, and fresh graze in early summer at least. However, at this time, while crops were still in the fields, it is less likely that they would have been herded in the closer locality and, unless they were born away from the settlement, the timing of their movement further afield would have had to have been finely judged; they would have needed to be old enough to make the >30 km transhumance, after any uphill snows had cleared but before the crops had started growing.

The disparity between the finer timing of the spring births is less likely to be due to the approximate timing of the completion of enamel formation as zooarchaeological evidence indicates that all sheep were from the same stock (Russell and Martin 2005). Instead it possibly reflects either that the herders had quite some flexibility in their scheduling, or that they were not yet fully in control of the mating. Certainly, controlled breeding would have required a labour investment in dividing herds to manage scheduled ram access to ewes, and also in providing nutritious feed to bring the breeding stock into full condition to mate, carry the lambs to gestation and then to suckle them. The choices made by the herders would provide insights into how they were constrained by graze or fodder availability or by their other seasonal tasks.

The sheep rearing region

The results suggest that most sheep were raised in central Anatolia as might be expected, but it is interesting that one sheep (tooth 3) appears to have been born in a very different environment. The consistently high δ^{18}O values are associated with lower altitudes, higher temperatures, less rainfall and greater continentality. Such conditions would have been found some distance from Çatalhöyük, for example south of the Toros Mountains on the more arid Mesopotamian plains. If so, long-distance networking and exchange of material goods and cultural practices in evidence throughout south-west Asia at this time (e.g., Özdöğan and Başgelen 1999) might have included livestock exchange.

An alternative explanation is that this sheep's δ^{18}O values signal water ingestion from unhealthy sources. One possibility is that it was raised on highly saline water and plants; for example at the contemporaneous site of Pınarbaşı which is by saline springs on the plains and has evidence of some year-round satellite herding (Carruthers 2004).

Herding mobility

Despite the small sample size, the interpretation of the range, maximum and minimum δ^{18}O values might identify most sheep (teeth 1, 4, 5 and 6) as having spent their first year near the settlement. They would probably have been pastured around the edges of arable fields or on collected fodder; however, both practices are labour intensive and provide less nutritious food for sheep consumption.

Two sheep (teeth 7 and 8) have dampened summer δ^{18}O values, approximately two per mill lower than sheep 1, 4, 5 and 6. Using equation (2), this might equate to *c*. 600 m rise in altitude. At Çatalhöyük this is consistent with the mid-slopes of the open oak-grass parkland mountainsides some 30 km distant; the grass-rich slopes would have provided good nutrition and easy herding during the spring and summer and into the early autumn. It is possible that fallow herds, at least, were herded in summer camps while crops were growing nearer the settlement and while arid conditions on the surrounding plains had arrested grass growth.

Chronology

The small sample size of suitable teeth—only two from the earlier phase and three from the latter—precludes any chronologically patterning to be realistically discerned. The young 'exotic' sheep (tooth 3) is from an earlier level of occupation; it might provide some indication of a continuing relationship with an ancestral settlement antecedent to Çatalhöyük, where lambs were brought in to contribute to founder flocks. Two sheep from the earlier phase (teeth 1 and 4) showed differences in the timing of their births but were both possibly raised near the settlement. This might indicate that there was no pressure on land for crops and that there was still ample, non-degraded, un-flooded pasture available; close control of mating might have been an unnecessary skill for the herders to have acquired.

The sheep that might have been pastured uphill from Çatalhöyük in summer (teeth 7 and 8) are both from the later phase of occupation. It is possible that after 1000 years of continuous occupation of the settlement, population increase, intensification of arable farming, larger flocks

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The sheep teeth sampled in this study
Project. Elizabeth Henton thanks AHR
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isotope analyses. Professor Ken Thom
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or shortage of fodder to supplement graze contributed to more controlled and more uniform herding practices, including uphill summer pasturing beyond increasingly extensive arable farming on the sand ridges and terraces. If this is so, then the Çatalhöyük settlers were able to incorporate new strategies into their repertoire and successfully meet social and environmental pressures.

CONCLUSION

This small study of oxygen isotopes in archaeological sheep tooth enamel has shown that the evidence has the potential to contribute to the elucidation of the regional and seasonal decisions taken by herders in the Neolithic settlement of Çatalhöyük at different phases of its chronology. Preliminary indications of varied breeding seasonality, of off-site provenancing of some of the stock, and of wider exploitation of uphill pastures later in the chronology are suggested.

There is an excellent correlation between $\delta^{18}O$ values in both enamel carbonates and phosphates, which validate the use of $\delta^{18}O$ in the carbonate component to be used as a proxy for meteoric water intake. In the Çatalhöyük region, where there is sharp relief and seasonality, the sequential enamel carbonate $\delta^{18}O$ values in each tooth, and their mean, maximum, minimum and range, give good discrimination, allowing inference of birth seasonality, region of rearing and seasonal herd movements.

This study is the first stage in a wider examination of relevant evidence. When considered alongside further evidence that investigates short-term and long-term feeding regimes, such as dental microwear or carbon stable isotopes in the same teeth, it is possible to constrain the seasonal and regional evidence offered by the oxygen isotopes. Interpreted through data from relevant modern comparators, a more detailed and nuanced life history of each sheep and thus of the yearly schedule of its herders might thus be reached. Any chronological changes in patterning, when compared with other evidence from the material culture of Çatalhöyük, could then contribute to the body of knowledge on emerging agricultural communities in the south-west Asian Neolithic.

ACKNOWLEDGEMENTS

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