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 δ¹⁸O values in dental enamel of archaeological sheep are assessed for post-depositional diageneric effects and compared with seasonal δ¹⁸O 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.
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 to which herdsmen and arable farmers co-operated; farmers might have needed crop protection from herd trampling but allowed herd access to fallow fields for manuring; herdsmen might have needed the best grazing 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 herdsmen 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 herdsmen 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 (Methart 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
The use of oxygen isotopes in sheep molars

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

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

1 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).
Regional and seasonal herding patterns would reflect underlying management decisions, where herd security and resource availability would be weighed against societal demands for accessible animal products and labour scheduling costs. Such decisions might indicate the manner and the extent to which herdsmen and arable farmers co-operated; farmers might have needed crop protection from herd trampling but allowed herd access to fallow fields for mating; herdsmen might have needed the best pasture 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 near 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 herdsmen 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 herdsmen were pasturing animals that were not immediately useful (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 200 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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Growing goats in Western Asia has tended to environmental degradation and subsequent 7500 cal. BC (Köhler-Rollefson and models propose early specialization arable farming (e.g. Köhler-Rollefson debated (e.g. Sherratt 1983; Halstead of crop and livestock husbandry nearer that directly link individual animals; these allow innovations in herding mental microwear analysis of Neolithic animals destined for different uses after Neolithic resource utilization has been one tissue to identify the dietary breadth 3; Pearson et al. 2007); the evidence 7490 cal. BC), possibly as herds were 3 cal. BC), possibly as herders took their additional tools for investigating how far animals that were not immediately of use tightly scheduled so that herds could be of this paper discusses how oxygen isotope studies may allow values in herding, and to investigate whether and are tightly scheduled to meet increasing

CATALHÖYÜK, CENTRAL ANATOLIA

site that has been extensively excavated dated during the later aceramic and early 90 cal. BC (Fig. 2) (Hodder 2005). The alluvial fan which spilled out over infertile and relief of karstic mountains rising 2000 m (1983). Between the mountains and the sand ridges and slightly more fertile logical evidence suggests that there was 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).

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, fallow pasture, and woodland, and different environmental factors and productive areas of good pasture, of less nutritious, fallow pasture, and woodland. The use of arable resources, and of areas of great grazing potential, was extended by the use of arable by-products (Halstead 2006), indicating that all these options might be used in combination to meet the needs of the population. A widening area of lands on the higher hill slopes could have been used to grow crops on the alluvial fan and pasture for sheep and goats. The exploitation of these resources might have involved the use of arable by-products, which could have been used to supply the settlement with food, while awaiting slaughter. Initially there may have been a policy of herding or the use of arable by-products, with a year occupation of the Çatalhöyük changing in later phases.

Figure 3  Model of vegetation zones in the Çatalhöyük landscape (Asouti 2005).
and caprine herds (Russell and Martin 2005). There is some evidence that meat and fat from sheep and goats could have been available for domestic meals, with little or no larger mammalian meat. The settlement (Matthews 2005), and to 6000 (Cessford 2005), would have had to have been raised by environmental reconstruction to be sustainable, of less nutritious, fall-back 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 living 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. The 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 Çatalhöyük changing technologies and ideologies, possibly influenced by interaction with the wider south-west Asian region, might have led to changing practices (Hodder 2005).

The use of oxygen isotopes in sheep molars

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 $\delta^{18}$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 $\delta^{18}$O values and temperature (Rozanski et al. 1992) (equation (1)) as well as altitude (Poage and Chamberlain 2001) (equation (2)):
The use of oxygen isotopes in sheep molar

wild fodder resources, and of areas of greatest resource competition caused by the interplay of limiting environmental factors and population pressures (Asouti 2005; McCrorriston 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 penning 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).

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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, 16O and 18O; the ratio in which they are found is a reflection of specific environmental histories. The ratio of 18O:16O is expressed in relation to the international calibration standard V-SMOW (Vienna Standard Mean Ocean Water) as δ18O 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 18O is preferentially retained in the liquid phase (Gat 1996). Empirical research has established the relationship between δ18O values and temperature (Rozanski et al. 1992) (equation (1)) as well as altitude (Foges and Chamberfain 2001) (equation (2)).

The temperature of source oceanic water, and thus of its $\delta^{18}O$, 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 $\delta^{18}O$, particularly over mountain ranges, en route from oceanic sources to more continental locations, results in depleted $\delta^{18}O$ values of precipitation with distance from the ocean (Dansgaard 1964). In addition, seasons of lower temperatures and increased rainfall serve to deplete $\delta^{18}O$ values compared with dryer, warmer seasons.

The $\delta^{18}O$ 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 $\delta^{18}O$ 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 $-20^\circ C$ in winter to $+30^\circ C$ 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 $\delta^{18}O$ is $-8.4\%e$ and the mean seasonal $\delta^{18}O$ ranges from $-12\%e$ in January to $-4\%e$ 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. comm. 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 $2\%e$ isotopically lighter 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.
H. F. Kemp

\text{Oxygen isotope values} 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 \text{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 Lacumin \text{et al.} (1996) (equation (4)):

\begin{align*}
\delta^{18}O_{\text{phosphate}} &= (1.48 \times \delta^{18}O \text{ ingested water}) + 27.21 \tag{3} \\
\delta^{18}O_{\text{phosphate}} &= (0.98 \times \delta^{18}O \text{ carbonate}) - 8.5 \tag{4}
\end{align*}

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 (M2), 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 intra-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 (Fröcke and O’Neill 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 $<0.5\%e$, 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 archaeological middens or as penning deposits (Table 1). Four teeth were from the early Pre-XIB IX/VIII phases (c. 6500–6800 cal. BC). It should be noted that some samples were also taken from two teeth otherwise stated, all chemicals used for sample preparation were purchased from Sigma-Aldrich (UK). The use of oxygen isotope evidence in this study is:

The carbonate component

Powdered enamel samples were first dissolved using a dental drill, wearing nitrile latex-free gloves between each sample. Sixty samples were also taken from two teeth otherwise stated, all chemicals used for sample preparation were purchased from Sigma-Aldrich (UK). The use of oxygen isotope evidence in this study is:

Sample preparation

Approximately 4 mg of tooth enamel was dissolved using an acetic acid for 4 h to remove diagenetic alteration. Samples were dried for 48 h at 45°C in an evacuated desiccator using P$_2$O$_5$, and subjected to the procedure sum:

$$\delta^{18}C_{\text{enam}} = +1.95\%e, \delta^{18}O_{\text{enam}} = -2.02\%e$$

$$\delta^{18}C_{\text{enam}} = +1.95\%e, \delta^{18}O_{\text{enam}} = -2.02\%e$$

Different isotopic composition (sodium bicarbonate B: $\delta^{18}C_{\text{enam}} = -4.5$)

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The use of oxygen isotopes in sheep molars

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-XII B 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 $\delta^{18}O$ value analysis and nine samples were also taken from two teeth to measure the enamel phosphate $\delta^{18}O$ 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 0.1 M 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 $\leq 45^\circ C$. Prior to analysis, samples were stored for 7 days in an evacuated desiccator using P₂O₅ as desiccant.

Table 1 Çatalhöyük archaeological tooth samples with spatial and chronological details

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<th>Tooth</th>
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<th>Site area</th>
<th>Context type</th>
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</tr>
<tr>
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<td>3740</td>
<td>F389</td>
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<td>Midden/infill</td>
<td>VIII</td>
</tr>
<tr>
<td>5</td>
<td>1873</td>
<td>F532</td>
<td>South</td>
<td>Domestic dump</td>
<td>IX</td>
</tr>
<tr>
<td>6</td>
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<td>F183</td>
<td>South</td>
<td>Domestic dump</td>
<td>IX</td>
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<tr>
<td>7</td>
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<td>South</td>
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<td>Pre-XII</td>
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</tbody>
</table>

procedure contemporaneously to anchor and quality control sample results. Exetainers were then flushed with N2:BIP, Air Products) for 10 min to remove all traces of atmospheric CO₂. Once flushed, 0.5 ml of absolute (water-free) sulphuric acid (99.99%) 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 CO₂ for δ¹³C and δ¹⁸O 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 centrifuged. 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 AgNO₃; 0.35M in NH₄NO₃ and 0.75M in concentrated NH₃·H₂O (~25% NH₃ 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 (Ag₅PO₄) was weighed into a silver capsule per individual analysis and dried in an evacuated desiccator using P₂O₅ as desiccant for 7 days prior to δ¹⁸O isotope analysis.

**Analysis**

**¹⁸O 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 δ¹⁸O isotope abundance analysis of CO₂ released by acid digestion. Each exetainer was sampled three times and each time an aliquot of the CO₂ 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 N₂ from CO₂, 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 (CO₂) 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 (δ¹⁸OᵥPHB = -2.20%) as well as two house standards (sodium bicarbonate A: δ¹⁸OᵥPHB = -12.38%, sodium bicarbonate B: δ¹⁸OᵥPHB = -10.60%). Reproducibility of δ¹⁸O isotope analysis as monitored by the reference sample measurement was typically ±0.5%o, indicating good accuracy and intra-sample variability.

**¹⁸O isotope analysis of tooth phosphate** The isotope ratio mass spectrometer (IRMS) (TC/EA), coupled to a DeltaPlus XL isotope ratio mass spectrometer (Thermo-Fisher, Bremen, Germany), was used for δ¹⁸O analysis of tooth phosphate samples prepared from tooth enamel. Each sample was weighed into silver capsules and weighed into silver capsules and then washed five times to neutrality with doubly distilled water. Two millilitres of 2 M hydrochloric acid 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 and dried overnight at 50°C. Approximately 0.2 mg of the apatite precipitate (Ag₅PO₄) was weighed into a silver capsule per individual analysis and dried in an evacuated desiccator using P₂O₅ as desiccant for 7 days prior to δ¹⁸O isotope analysis.

 Archaeological tooth enamel samples, being part of the sedimentary matrix and the fluctuating susceptible to diagenesis, particularly in certain environments (Wang and Cerling 1994; lacuna carbonate component is easily measured therefore to be potentially useful and assess any diagenetic influence, sample and δ¹⁸O carbonate values (Table 3) are given for each tooth (Fig. 5). The solution for the linear regression line was calculated: δ¹⁸O precipitate = -2.20%, δ¹⁸O water values (V-SMOW)
controlled sample results. Extrainers were then (cts) for 10 min to remove all traces of water-free sulphuric acid (99.999%) was added, and the acid digest was carried out by placing the sealed heater block at 50°C. Samples were then allowed to cool down to 20°C and the gas isotope ratio mass spectrometer (IRMS) for analysis. Once the IRMS analysis of the internal standard gas (CO₂) was completed part of the same analytical cycle. Analytical performance of the AP2003 IRMS acid digests of the international reference house standards (sodium bicarbonate A: δ₁₈O = −0.60‰). Reproducibility of δ₁₈O 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.

δ¹⁸O isotope analysis of tooth phosphate  A high temperature conversion elemental analyser (TC/EA), coupled to a DeltaSM 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 Alundum™ 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 δ¹⁸O δ¹⁸O 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 δ¹⁸O composition (commercial silver apatite from Sigma-Aldrich, δ¹⁸O = 13.45‰, and the international hydroxyl apatite standard NBS 19b, δ¹⁸O = 21.33‰) as reference materials. Reproducibility of δ¹⁸O isotope analysis as monitored by the reference materials was typically ±0.24‰ while uncertainty of sample measurement was typically ±0.19‰.

Data evaluation

δ¹⁸O isotope analysis of tooth carbonate yielded values on the V-PDB scale, therefore δ¹⁸O V-PDB values were converted into corresponding δ¹⁸O V-SMOW values using the following correlation (Friedman and O'Neil 1977) (Table 2):

\[
\delta^{18}O_{V\text{SMOW}} = (1.0309 \times \delta^{18}O_{V\text{PDB}}) + 30.9
\]  

(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 δ¹⁸O phosphate and δ¹⁸O carbonate values (Table 3) and their correlation tested by linear regression analysis (Fig 5). The solution for the linear regression of tooth 4 yielded:

\[
\delta^{18}O_{\text{phosphate}} = (1.056 \times \delta^{18}O_{\text{carbonate}}) - 11.02
\]  

(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 δ¹³C and δ¹⁸O isotopic composition of their carbonate fraction, and measured δ¹⁸O carbonate values (VPDB) were converted into calculated δ¹⁸O water values (V-SMOW) using equations (3)–(5).
Table 2  δ18Owater 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 δ18Owater
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*LezineK et al. (1996) (equation 4)
†Friedman and O'Neil (1977) (equation 5)
‡D'Angela and Longinelli (1990) (equation 3)

Table 3 Measured δ18O values

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<th>Sample</th>
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<th>4.4P</th>
<th>4.5P</th>
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All results from the isotope analysis are presented in Figures 8–11. This section of oxygen isotope analysis in Çatalhöyük precludes any statistically secure interpretative conclusions.

Intra-tooth variation in δ18O values

Figure 6 presents the seasonal curve derived from modern GNIP data (IAEA/WMO 2007)
The use of oxygen isotopes in sheep molars

Table 2 Continued

<table>
<thead>
<tr>
<th>Archological unit</th>
<th>Samples along tooth column (numbered from occlusal end)</th>
<th>Tooth carbonate</th>
<th>Tooth phosphate</th>
<th>Ingested water</th>
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*δ18O* values for archaeological tooth enamel samples

<table>
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<tr>
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<th>Tooth phosphate <em>δ18O</em></th>
<th>Ingested water</th>
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</thead>
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RESULTS

All of 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 Catalhöyük domestic herds; the extremely small sample size precludes any statistically secure interpretation.

Intra-tooth variation in *δ18O* values

Figure 6 presents the seasonal curve of *δ18O* water values for Ankara starting in September, using modern GNIP data (IAEA/WMO 2006); it is used to model the sequential curve of *δ18O* values...
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 the locality of Çatalhöyük support this interpretation as coming from sheep born in late spring/early summer. The mean $\delta^{18}O$ value of each tooth the clustering of most mean values suggests conditions, and the most parsimonious interpretation comes from the central Anatolian region. The exact age and so enamelization is at least (1982); immaturity is therefore not unlikely for two further reasons. First, neonatal data neatly into the larger cluster. Second, correlation discussed previously, is likely for the first two teeth, and so enamelization is at least (1982); immaturity is therefore not unlikely for two further reasons.
The use of oxygen isotopes in sheep molars

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

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

The curve in Figure 7 presents the same data for birth lambs. The salient distinguishing feature is more positive summer $\delta^{18}O$ values and a shift of the curve towards the 12th month, or winter, suggesting this lamb was born in late May, June, or July.

Precipitation samples taken over one year, starting in March

Distance along tooth column from the cervix-root junction (mm): c. birth to the left, c. 1 year old on the right

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 incomplete and already in wear, and enamelization is at least 87% complete throughout the tooth (Sakae and Hirai 1982); immaturity is therefore not the cause of exceptional diageneis. Unusual diageneis is unlikely for two further reasons. First, three other teeth from the same archaeological context fall neatly into the larger cluster. Second, tooth 1 from the same context shows a 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.

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

The mean $\delta^{18}O$ 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 incomplete and already in wear, and enamelization is at least 87% complete throughout the tooth (Sakae and Hirai 1982); immaturity is therefore not the cause of exceptional diageneis. Unusual diageneis is unlikely for two further reasons. First, three other teeth from the same archaeological context fall neatly into the larger cluster. Second, tooth 1 from the same context shows a 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.
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 a 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.

Lamb birth season

If the results are interpreted correctly for spring. At these latitudes, sheep usually gave birth in July 2006 but are physiologically capable of domestic sheeps occasionally still do so. Autumn birth lambs would have been scarcer and the weather harsher, with fodder collection, penning lambs close to the weather and from predators. Spring birth would have had the advantages of a summer at least. However, at this time, the herds would have been herded in the colder settlers, the timing of their move judged; they would have needed to be up the rope sheep had cleared but before the uphill snows had cleared.

The disparity between the finer temporal approximate timing of the completion indicates that all sheep were from the same flock and reflects either that the herders had quite yet fully in control of the mating. Continued investment in dividing herds to maintain nutritious feed to bring the breeding stock.
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 δ18O 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., Özdögan and Başgelen 1999) might have included livestock exchange.

An alternative explanation is that this sheep’s δ18O 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 δ18O 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 δ18O values, approximately two per mil 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 or shortage of fodder to supplement grazing practices, including uphill summer farming on the sand ridges and terraces, incorporate new strategies into their repertoires.

This small study of oxygen isotopes in sheep shows that the evidence has the potential to contribute to taken by herders in the Neolithic settlement Preliminary indications of varied breeding and, of wider exploitation of stock.

There is an excellent correlation between phases, which validate the use of δ18O in meteoric water intake. In the Çatalhöyük sequential enamel carbonate δ18O values range, giving good discrimination, allow seasonal herd movements.

This study is the first stage in a wider alongside further evidence that investigates dendritic microwear or carbon stable isotopes and sequential and regional evidence offered relevant modern comparators, a more detailed the yearly schedule of its herders might herders, when compared with other evidence, contribute to the body of knowledge on Asian Neolithic.

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The sheep teeth sampled in this study were from Project. Elizabeth Henton thanks AHRC London Graduate School and the Institute of Archaeology, Oxford, for their reviews of this paper.


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 δ¹⁸O values in both enamel carbonates and phosphates, which validate the use of δ¹⁸O 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 δ¹⁸O 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 pattern formation, 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.

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