The Diet and Management of Ancient Sheep and Goats: The Potential of Dental Microwear

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Abstract

Dental microwear analysis records and interprets the marks left on the enamel surface of a tooth, caused by hard abrasives in food or contaminants such as grit. The analysis provides evidence for short-term diet and has previously used Scanning Electron Microscopy (SEM) to photograph tooth surfaces at high magnification. In this thesis, a new low-magnification, digital method is developed, tested on modern teeth of known dietary history, and applied to archaeological sheep and goats from three Late and Final Neolithic sites in Greece: Toumba Kremastis-Koiladas (TKK), Makriyalos (MK), and Knossos (KN). The new, Digital Light Microscopy (DLM) method proved successful in recording and distinguishing microwear patterns associated with modern known-diet groups of sheep and goats, with results comparable to those produced by Ingrid Mainland using the SEM method on broadly the same samples.

Research questions addressed by investigating diet of archaeological sheep and goats at the three sites focussed on: the scale of animal husbandry and its degree of integration with crop husbandry; and the extent to which livestock were fattened prior to consumption within large-scale collective and/or small-scale domestic commensal events. The results revealed that foddering was common at all three sites and within contexts attributed to both large-scale feasting and 'domestic' habitation consumption, suggesting that it was a more prevalent aspect of Late Neolithic and Final Neolithic sheep and goat husbandry than previously suspected. Given the available evidence from dental eruption and wear for ages at death, it seems that the use of fodder was not limited to either winter or summer periods of scarce pasture, but was instead more likely a short-term method for fattening animals before slaughter, with significant implications for the reliability of agricultural subsistence ('through indirect storage') and for the cohesion and dynamism of Neolithic communities (through feasting and 'social storage').

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CHAPTER 1: INTRODUCTION

Over the last ten millennia, human communities across much of the world have widely and increasingly depended on the management of domestic animals. Although most of these communities were also, and often mainly, farmers of staple crops, their livestock also played various important roles: as sources of tillage and manure in crop husbandry; as providers of dairy produce, blood and fibre; as means of both local and long-distance transport; as repositories and symbols of wealth and prestige; and, eventually, as victims for slaughter or sacrifice and thus as the centrepieces of much domestic and collective commensality.

Despite their diverse and crucial contributions to human culture, however, the diet of domestic animals has attracted far less archaeological interest than has human subsistence. While this bias towards what our own species ate is perhaps no surprise, it is arguable to the detriment of our understanding of human history. What livestock ate obviously affected their physical condition, productivity, and sustainable numbers, and thus their potential contribution to human economy and culture. Moreover, even where human subsistence is overwhelmingly crop-based, more land is often devoted to pasture than to fields, so that livestock may exercise a disproportionate influence on the transformation of cultural landscapes. Pasture is also often more distant than cultivated land, such that neighbouring communities or polities often come into conflict over grazing lands located on their shared borders, while rights to scarce good pasture located close to a settlement may be a source of intra-communal conflict and developing inequality. More generally, cultivated land is widely acknowledged as private property or subject to long-term use rights, while pasture in the same historical contexts (including fields in fallow years and post-harvest seasons) is often regarded as collective or public property. The potentially complex boundaries between the sown and the grazed are thus often a source of conflict but equally of regulation, on both local and regional scales. Lastly, livestock may graze *sown* pasture or be fed hay or grain *crops*, whether these were sown for the benefit of livestock or were so used opportunistically in response to either crop failure (e.g. grazing a crop considered not worth harvesting) or surfeit (e.g. fattening livestock on grain considered surplus to human requirements). Such high-quality diets may be provided to livestock at the expense of human consumers of low entitlement and/or may also boost the status, influence and productivity of those with preferential access to land and labour. In either event, the foddering of livestock is a practice of considerable social as well as zootechnical significance.

Archaeological investigation of past livestock diet has expanded dramatically in the last 30 years, drawing on a wide range of techniques to analyse many different sources of evidence, including archaeobotanical and palynological study of plant inclusions in animal dung, palynological and anthracological investigation of changing cultural landscapes, stable isotope analysis of livestock bones and teeth, and – the focus of this dissertation – dental microwear examination of livestock teeth. As discussed below, each of these analytical techniques and datasets offers distinctive and complementary insights into past animal diet. In sum, however, stable isotope and dental microwear analysis offer relatively coarse insights into dietary composition but relatively precise identification of the consumer, while the former offers a longer- and the latter a shorter-term record. This thesis focusses on developing a rapid light-microscope method of investigating animal diet, which is tested on teeth of modern sheep and goats of known diet from northern Europe and Greece and then applied to three case studies from the Neolithic of Greece.

Chapter 2 reviews previous research into animal diet and, more generally, animal husbandry and crop farming practices of Late and Final Neolithic communities in Greece. The importance of animal diet is first explored in economic terms, addressing the practicalities of feeding animals within sedentary, small scale farming communities, and the interdependence of animal husbandry and crop cultivation. The socio-economic value and uses of meat is then explored and it is argued that, as humans and animals enter productive relations through domestication, they are incorporated into the household identity and are highly valuable gifts for commensal events. Chapter 2 then sets out the archaeological research questions to be tackled, the rationale for the choice of method (dental microwear analysis), and finally the archaeological background to the three sites investigated: Toumba Kremastis-Koiladas (TKK), Makriyalos (MK) and Knossos (KN).

Dental microwear analysis records and identifies dietary traits based on the microscopic marks left on the enamel surface of a tooth. Chapter 3 explores various methods used to record dental microwear analysis: a well tested but slow and costly method using Scanning Electron Microscopy (high-magnification typically 500x); and a recent light microscopy method using low-magnification (40x) stereomicroscopy. After reviewing the limitations of high- and low-magnification methods, a new method is developed – digital light microscopy – using high dynamic range imaging (HDRI).

In Chapter 4, the HDRI method is tested on ethnographic samples from groups of sheep and goats of known diet. These samples are broadly the same as those previously analysed by Ingrid Mainland in a series of landmark studies using SEM. In discriminating between modern known-diet samples, the HDRI method achieves a similar level of success, in large measure using similar variables, to the preceding SEM studies. Some limitations of this approach are also discussed, although these limitations also serve to highlight the greater weaknesses of alternative methods currently used by other scholars. It is concluded that the tested methodology is sufficiently robust to be applied to archaeological contexts.

In Chapter 5, the digital light microscopy method is then applied to the sheep and goat samples from the three archaeological sites, and their diet is investigated between contexts at TKK and MK, and between chronological time periods at KN. These results reveal both similarities and differences of diet within and between the three sites examined. They also reveal apparent contradictions between the results of dental microwear and stable isotope (principally $\delta^{15}N$ and $\delta^{13}C$) analyses at MK and KN, that are most plausibly understood in terms of a divergence between short-term *ante mortem* and long-term diet, respectively. The wider implications of these dietary insights are discussed in the concluding Chapter 6. Most striking is the evidence that most young sheep and goats, albeit to varying degrees at the three sites, were fattened on high-quality fodder in the days or weeks prior to their slaughter and consumption. Although such practices of indirect and social storage have been previously suggested for the Neolithic of Greece, their prevalence was wholly unexpected and their implications for our understanding of animal husbandry, for the integration of crop and livestock farming, and for the political economy in this region and period are profound.

CHAPTER 2: ANIMAL DIET

ARCHAEOLOGICAL BACKGROUND, RESEARCH QUESTIONS AND SAMPLE SELECTION

2.1 Introduction

The first part of this chapter explores two areas of interest for zooarchaeologists studying the Neolithic in Greece: farming and feasting. It draws out research questions in relation to animal diet in both of these fields, set within the context of the Greek Neolithic:

(1) farming: does evidence for diet shed light on the scale and mobility of livestock management, with wide-reaching implications for many aspects of human subsistence, land use and enculturation of the landscape?

(2) feasting: did domestic animals consumed in different commensal context have divergent dietary histories?

In both cases, ethnographic analogues drawn from studies of recent traditional husbandry play a central role in posing questions (and alternative answers) regarding past animal diet and its wider articulation with cultural landscapes, human subsistence and human social dynamics.

The second part of this chapter provides the archaeological background to, and details of sample selection from, three later Neolithic sites in Greece, Late Neolithic (LN) Toumba Kremastis-Koiladas, LN Makriyalos I and LN and FN (Final Neolithic) Knossos, and considers the particular questions related to animal diet to be addressed for each. The diet of sheep and goats from each of these sites is analysed later in Chapter 6.

2.2 Farming during the Neolithic in Greece

The Neolithic of Greece spans nearly 4000 years, from the early 7th mill BC to the beginning of the Bronze Age around 3000 BC, although this thesis is primarily concerned with the Late Neolithic (LN, mid-6th to mid-5th mill BC) and Final Neolithic (FN, later 5th and 4th mill BC). Throughout this period, surviving food remains on settlement sites are overwhelmingly dominated by charred grains and chaff of cereal and pulse crops (e.g. Halstead 1994) and by bones of domestic sheep, pigs, cattle, goats and dogs (e.g. Halstead 1996; Halstead and Isaakidou 2013), leaving little room for doubt that the inhabitants of these sites were essentially farmers. There is much less consensus regarding the methods, intensity, scale and mobility of both crop and livestock husbandry and thus also regarding the relative contribution of crops and livestock to the subsistence of these Neolithic farmers.

Intimately related with these questions regarding the nature of Neolithic farming in Greece is the diversity of settlement types encountered, which includes: (1) mounded tell sites formed by the rebuilding of houses vertically, creating 'monumental' structures (Kotsakis 1999); (2) flat extended sites with lateral rebuilding of settlements (Kotsakis 1999); (3) areally small, short-lived open sites; and (4) cave/rock-shelter sites. The tell mounds, on the basis of their long-term residential continuity and frequent association with substantial rectangular 'houses', have long been regarded as 'permanent' settlements, occupied year-round (e.g. Childe 1957). Although this interpretation of tells has been challenged (Whittle 1996), doubt regarding year-round habitation has been more frequent for the remaining three settlement types: flat extended sites, because houses tended to be of relatively flimsy construction and were not rebuilt *in situ*; small open-air sites, because occupation tended to be (in archaeological terms) short-lived; and both small open-air sites and caves/rock shelters, because thev are often located in agriculturally marginal areas apparently better suited to herding (Halstead 2005). This question of year-round sedentism versus seasonal mobility is integral to our understanding of (1) animal husbandry and cultivation, and (2) the socio-economic implications of these practices. The first of these points will be addressed in the following section 2.2 and the second in section 2.3.

2.2.1 Definitions

It is important to begin with a definition of terms used to describe two types of farming models and their typical characteristics:

Model 1: extensive, large-scale and often specialised production.

Model 2: intensive, small-scale and diversified production.

These two models, of course, do not represent the full and complex variety of farming strategies that have been documented, but have been chosen because evidence for each has been claimed in the archaeological and textual record for prehistoric Greece. Model 1 has been associated with the Late Bronze Age (later 2nd mill BC) palatial systems of southern Greece as documented in Linear B tablets (Halstead 2000; 2003), and it has been argued that Model 2 was prevalent in Neolithic Greece and continued into the Bronze Age for smaller sites and non-palatial production (Halstead 1987; 2000; 2003; Jones 1992; 2005; Bogaard 2004).

Model 1:

Extensive cultivation involves low inputs of labour per unit of land, exploiting natural fertility from regular fallow periods, silt deposition on floodplains or slash-and-burn use of temporary clearings, while plough animals enabled tillage of large areas of land (Sherratt 1980; 1981; Halstead 2000). In terms of animal husbandry, extensive refers to large-scale herding with the need to move across the landscape to secure pasture (Halstead 2000). Extensive farming tends to be associated with specialised surplus production, often for sale or exchange (Halstead 2000), as for example with the large-scale growing of 'wheat' (the conventional translation of the ideogram *120) and rearing of wool sheep, recorded in the Linear B tablets, to provide rations and raw fibre, respectively, for palatial textile workers (Halstead 2000).

Model 2:

Intensive cultivation involves high inputs of labour to smaller areas of land with cultivation typically for domestic use (Halstead 2000). Intensive farming is typically associated with the husbandry of mixed crop and livestock species, providing the variety of food and other resources needed for household consumption, enabling balanced use of available labour and land use, and minimising the risk of total subsistence failure (Halstead 2000). Typical practices to enrich the fertility of soils include manuring and crop rotation. Neolithic cultivation is often referred to in terms of 'garden plots', reflecting both the diversity and suspected small scale of crops grown (Halstead 1987; Jones 1992; 2005; Bogaard 2004). It is also argued that the investment of labour in these plots is likely to discourage mobility (Jones 2005). In terms of animal husbandry, intensive farming of small herds with low mobility offers the benefit of maximising the availability of manure to crops, but also the disadvantage of livestock numbers and condition being limited by pasture and fodder resources available locally (Halstead 1987; Jones 1992; 2005; Bogaard 2004).

2.2.2 Archaeological and ethnographic evidence: scale and mobility

A growing and increasingly diverse body of bioarchaeological data has been interpreted in terms of small-scale, intensive farming of garden plots (Halstead 1987; Jones 1992; 2005; Bogaard 2004), contrary to older arguments for extensive farming during the Neolithic (Boserup 1965; Sherratt 1980). The management of livestock within both models has been investigated by examining evidence for: (1) the mobility of herds and farmers and (2) the scale of farming.

Mobility

One recent argument for a farming system similar to Model 2 in Neolithic Greece is the limited evidence for mobility. Isotopic data from livestock and humans gathered from settlements in central and northern Europe has shown that some livestock and humans travelled large distances during the Neolithic (Knipper 2009; Viner et al. 2010; Sjögren et al. 2013; Gerling et al. 2017). Conversely, analysis of strontium isotope values in humans and livestock from sites in northern Greece (Vaiglova et al. 2018; Whelton et al. 2018) implies only limited mobility (or movements only between geologically similar regions) during the Neolithic. Furthermore, evidence for the season of slaughter of young sheep and goats from various settlement types across Greece offers no support for only seasonal habitation of sites (Halstead 2005). In light of these data, livestock were most likely reared mainly locally to settlements within Greece, although this does not preclude limited mobility (Halstead 2005, 39), as for example in the suggestion (based on $\delta^{13}C$ isotope values) that cattle from Makriyalos I grazed on coastal wetlands a few kilometres from the site (Vaiglova et al. 2018), and some exchange of animals between settlements to maintain viable breeding populations can probably be assumed (Halstead 1992a) even if not detectable isotopically.

The predominant domesticate found at earlier Neolithic sites in Greece is the sheep, better suited to grassland than wooded areas, which cattle, pigs and goats, found in higher proportions at *later* Neolithic sites, exploit more successfully (Halstead 2000; 2012). Large herds of sheep would have required significant opening up of the woodland that apparently dominated the Neolithic landscape, especially in northern Greece (Halstead 2000). Anthracological evidence from multiple Neolithic sites in northern Greece (and likewise Bulgaria), however, shows no indication of pronounced deforestation (Marinova and Ntinou 2017), as would be expected if land was continuously cleared for large mobile herds or other extensive agricultural practices. Indeed, comparison of two pollen cores from the Dikili Tash tell settlement and the nearby Tenaghi-Phillipon marsh (Greig and Turner 1974; Glais et al. 2016) identified the impact of initial clearances local to Dikili Tash during the Early Neolithic (6400 cal BC) but no impact on the wider regional landscape until the early 2nd mill. BC.

Scale

If farming was indeed largely sedentary, this will have restricted the scale of livestock husbandry during the Neolithic as pasture and fodder resources needed to maintain animals would have been limited to the local environment.

In lowland Greece, pasture is particularly scarce during the cold winters in the north of the country (as in Britain), when herbaceous vegetation grows only slowly and deciduous trees and shrubs are bare. Further south, the dry, hot summers tend to be the leanest season for grazing species (notably sheep, but also cattle), while the greater abundance of evergreen trees and shrubs means that pasture for browsers (notably goats) is relatively perennial in availability, although most nutritious in late spring-early summer. Conversely, in the mountains of both north and south Greece, winters are harsh, but summers provide rich pastures. In the recent past, large flocks (mainly sheep) and even whole communities took advantage of these seasonally complementary resources, 'transhuming' between winter pastures in the lowlands and summer pastures in the highlands (e.g. Campbell 1964). Shorter-distance movements in summer were also commonplace to seasonal wetlands, especially by herds of cattle and water-buffalo. A wealth of epigraphic evidence from Classical (mid-1st millennium BC) Greece documents grazing of, and sometimes conflict over, wetland and mountain pastures on the borders between polities, but not the large-scale use of high-altitude pastures as practised by recent transhumant herders (Chandezon 2003).

Contrary to much early academic writing on ancient Mediterranean pastoralism (e.g. Semple 1922; Skydsgaard 1988), the removal of lowland livestock in summer to upland or wetland pastures is not essential (and thus timeless), especially in the north of the country where summers are not rainless. Access to richer wetland or upland pasture does enable maintenance of larger numbers of livestock, however, and animals that are well fed, whether thanks to rich seasonal pasture or the provision of collected fodder supplements, tend to achieve larger and fatter carcasses, produce larger offspring and higher milk yields, and be capable of more or heavier work (Halstead 2012, 25). Again despite widespread assumptions to the contrary, the provision of collected fodder for livestock has a long history in temperate Europe (e.g. Hodgson et al. 1999; Rasmussen 1993), but also apparently in Greece (see below).

Small quantities of fresh fodder, to supplement the diet of a few stalled or penned animals, are often collected during the course of weeding or pruning or while herding (e.g. Forbes 1998; Halstead 2014, 238-9) and thus may not require much *additional* human labour. Chaff and straw have traditionally (e.g. Jones 1984; Halstead 2014, 55-56), and also in

Classical antiquity (Foxhall 1998), provided a major (but generally low-quality) contribution to stored fodder and, to some extent, represented 'free' by-products of processing grain crops for consumption, although they did entail some additional labour in reaping, transport of sheaves, threshing and winnowing (Halstead and Jones 1989). The bulk provision of other forms of fodder was even more demanding of human labour.

Halstead's (1998) ethnographic study of foddering in the village of Plikati in the Pindos mountains (1240m altitude) represents a rather extreme case, because the depth of snow cover enforced the stall-feeding of animals in winter for between three and six months (from November or January until April). For sheep and goats, fodder consisted primarily of grassy and leafy hay, the latter (comprised of dried oak and beech branches) being the more stable source as it was less dependent on summer rainfall than the former. Leafy fodder was also collected fresh for immediate use, mainly during spring/summer from deciduous trees but also in severe winters (when stored leafy hay ran scarce) from firs (Halstead 1998, 218). Grassy hay was more nutritious stored fodder than leafy hay and was fed to cattle and mules as well as sheep and goats, but was very scarce until the later 20th-century contraction in local grain growing allowed former fields to be converted to meadows. Oak and beech branches suitable for drying as leafy hay were much more abundant, albeit thanks to careful private management of trees surrounding fields and collective constraints on the use of community woodland, but their use was constrained by the considerable labour costs of their harvest, transport and drying for storage. The collection of leafy hay requires intensive labour within a short time period at the end of summer to enable branches to be dried for winter (Halstead 1998, 218). At Plikati 30-50 bundles of leafy hay were needed per sheep or goat, and 2-5 loads (6 bundles per load) could be collected per person per day (1998, 227), representing a need for 2-4 days of work per sheep or goat, using iron billhooks for lopping and mules for transport. Neolithic farmers with only stone tools and without pack animals would have needed even more labour to harvest and transport leafy or grassy hay and, although any period of necessary stall-feeding will have been of much shorter duration in the lowlands, and the use of leafy hay and grassy hay is likely to have been feasible for only modest numbers of livestock (Halstead 2000).

Dental microwear analysis of sheep and goats at the Late Neolithic site of Makriyalos I has identified the use of soft, fodder diets similar to leafy hay or cereal fodder (Mainland and Halstead 2005). Additionally, the archaeobotanical remains from Makriyalos and another Late Neolithic site in northern Greece, Makri, have provided evidence for glume-wheat chaff and fig in animal dung (Valamoti 2004; Valamoti and Charles 2005). These two lines of evidence have been interpreted as indicating the fattening of Neolithic livestock for feasts at Makriyalos, or to increase milk yields and the productivity of working animals (Mainland and Halstead 2005; Valamoti and Charles 2005). Foddering, given the labour commitment this entails, is certainly compatible with arguments for sedentary, small-scale animal husbandry, but both dental microwear and dung inclusions may represent livestock diet in only the short term.

The use of crop grain for animal consumption (inferred from inclusions in dung) during the Neolithic (Charles 1998; Mainland and Halstead 2005; Robinson and Rasmussen 1989; Valamoti 2004) further illustrates the close interdependence of livestock rearing and plant cultivation. Halstead (2000; 2006) argues that the predominance of sheep during the Neolithic may have allowed for a very closely integrated farming system. Neolithic farmers may have used their plots flexibly for human or animal consumption depending upon the variable needs of both and the availability of grain surplus to human requirements (Halstead 2006). Livestock may have grazed on crop stubble and sprouting cereals, thereby facilitating tillage, countering the risk of lodging (collapse of crop stems which makes harvesting difficult and reduces yield), and helping to maintain fertility (Halstead 2006). A study of crop nitrogen isotopes from Neolithic sites across Europe identified the selective manuring of wheat and pulses at Koufovouno (southern Greece) (Bogaard et al. 2013, 12591), suggesting that at least some animals were kept close enough to plots for dung to be collected or that plots were manured directly by small herds grazing on them (Isaakidou et al. 2011; Vaiglova et al. 2014). Furthermore, the implied long-term manuring of plots provides an insight into the investment of labour and resources into the same land area, tying crop growth and animal husbandry closely together (Bogaard et al. 2013; Isaakidou 2011; Halstead 2000; 2006; Jones 2005).

2.2.3 Summary of Neolithic farming and livestock management, and further archaeological questions

Overall, the available archaeological data arguably support a form of Neolithic land use that recalls recent sedentary, diverse, small-scale farming using intensive techniques, but current understanding is both patchy and tentative. Knowledge of Neolithic animal diet has the potential to enrich our understanding of livestock management, crop cultivation and the degree of integration between these.

First, although sheep are by preference grazers and goats browsers, each species is capable of exploiting the other's niche if necessary. Thus the balance between graze- and browse-dominated diets may shed light on the extent to which livestock mainly exploited cleared land, and were thus probably restricted in number, or also ranged in surrounding woodland, with the potential to support larger herds. Moreover, the ability of sheep and goats to exploit their preferred niches will have been somewhat limited, especially in mainland northern Greece where there was a range of large predators, by the availability of sufficient human labour to herd them separately. Thus dietary divergence between the two species, with sheep grazing and goats browsing, would be suggestive of greater livestock numbers, while the lack thereof would favour smaller numbers. Also, the greater the frequency of browsing, the more likely it is that livestock played an active role in opening up the wider landscape. Conversely, if grazing were dominant, consideration of season at death might clarify whether this involved seasonal removal to more distant, higher-quality pasture or reflected year-round use of local, perhaps poor-quality pasture. Alternatively, a combination of high-quality graze with year-round slaughter of animals might indicate grazing of sown pasture or failed grain crops (cf. Halstead 2006). The latter scenario would also probably reflect the closest integration of livestock with crop cultivation, although larger numbers of livestock browsing surrounding woodland by day and enclosed on arable land at night might have offered the highest inputs of manure.

Secondly, a recurring concern of recent Mediterranean farmers (e.g. Forbes 1989; Halstead and Jones 1989; Halstead 1990), also discussed in the literature on Neolithic farming (e.g. Halstead 1989), is the need to cope with inevitable variation between good and bad harvests. While overproduction of grain crops and storage of the resulting surplus was a fundamental buffering mechanism of traditional grain farmers, in Greece and elsewhere, grain has a fairly short 'shelf life' and unused surplus was often fed to livestock as a form of 'indirect storage' (Flannery 1969). If the resulting fattened carcasses were slaughtered for supra-household commensality, thereby creating prestige for the host but also obligations of reciprocation on the part of guests, they also served more particularly as a form of 'social storage' (Halstead and O'Shea 1982). These terms are discussed in further detail in the following section (2.3).

The key questions to emerge thus far, therefore, are:

- Were Neolithic livestock primarily grazers, browsers or fodder-fed and do different species exhibit consistent differences in diet?

    - Answers to these questions may help to shed light on the scale and mobility of animal husbandry and thus on such issues as its relative contribution to human subsistence, degree of integration with arable farming, impact on cultural landscapes
- Were Neolithic livestock consuming high- or low-quality pasture/fodder?
    - Answers to this question are again relevant to the scale and mobility of stock husbandry, but also to the likely condition and productivity of domestic animals and, in the case of foddering, to the possible use of livestock as a means of indirect and/or social storage.

2.3 Neolithic feasting, commensal politics and hospitality

Halstead argues that 'the degree of permanence of residence exercises an equally powerful influence on the nature of social interaction' (2005, 38). On the one hand, seasonally mobile farmers can resolve conflict by physically distancing themselves, and have more opportunities to socialise with regional groups by travelling beyond the local area (Halstead 2005, 39). On the other hand, sedentary communities have to use strategies to reduce tensions between neighbours living in close proximity and to socialise with regional groups, essential for biological and social reproduction (Halstead 2005). In the case of Neolithic Greece, for which primary dietary dependence on staple grains has been argued on a range of empirical and circumstantial grounds (e.g. Isaakidou and Halstead 2018), sharing of meat from domestic animals may have had a particularly important role in these strategies, at a household, village and regional level.

2.3.1 'Households': problems of definition

It is acknowledged that the term 'household' used throughout the following sections is contentious among prehistorians, so it is important to provide a definition. Housing structures found at Neolithic sites in Greece are variable. For instance, at the flat-extended sites of Makriyalos I and Sesklo B, the dominant form of dwellings consists of small pit huts and horizontally drifting constructions typified by room clusters, respectively (Halstead 1999, 88). In contrast, residential structures at tell sites such as Sesklo A are predominantly formed of free-standing 'houses' (Halstead 1999, 88; Kotsakis 1999, 70). These structural differences may reflect very different social organisations and attitudes towards household versus communal identity (Kotsakis 1999; 2006).

A 'household' does not refer simply to the physical domain of a group of people cohabiting, as in many societies today, and it does not presume the co-residence of strictly biological family members. The household as used in this thesis refers to the socio-economic unit of production and domestic consumption. Bogucki (1993) describes the household perspective as 'making the assumption that the household, however constituted, was the significant unit of economic decision-making'. The household members are an economically cooperative group and are the focus of social interactions and obligations (Bogucki 1993, 493). As previously discussed, the scale of farming during the Neolithic was most likely small and diverse, suited towards a household unit. The walling off of food preparation or cooking spaces (e.g. hearths within indoor spaces), more or less progressive through the Neolithic of Greece, indicates that at least some consumption was limited to the physical household or controlled at a household level (Halstead 1999). Similarly, negotiations over private versus communal claims to resources are physically expressed through the continuous rebuilding of houses over the same spaces at tell sites like Sesklo A, implying ownership at a household level (Kotsakis 1999). It is in this socio-economic sense that the role of the household will be examined in the context of feasting and commensal politics.

2.3.2 Feasting

There are multiple definitions and understandings of what makes an act of 'feasting', including the type and quantity of food shared and the number of participants. Hayden (2001, 28) proposes that a feast includes 'any sharing between two or more people of special foods…in a meal for a special occasion', focussing upon the food items and the purpose of sharing food. Using this definition, feasting includes the sharing of food on a relatively small scale such as within and between Neolithic households, but is distinguished from everyday, domestic consumption by the use of 'special foods' for a 'special occasion'.

The consumption of meat is associated with feasting when consumed on a large scale but may also in itself be a special food item (Halstead 2007). Makriyalos I revealed vast quantities of faunal remains in two large pits, showing large-scale meat consumption that possibly lasted several months between a few dozen or few hundred individuals (Pappa et al. 2004). On a smaller scale, cattle bones found at nearby Early Neolithic Revenia-Korinou (also northern Greece) and Late Neolithic Knossos (Crete) represent the apparently simultaneous slaughter of several animals (Isaakidou 2004, 198; Halstead and Isaakidou 2011, 95). These animals are individually too large to be consumed *fresh* by a single household, and indeed the majority of domesticates found at Neolithic sites were slaughtered at ages too old (and thus with carcasses too large) for fresh household consumption (e.g. yearling and older pigs, sheep and goats) (Halstead 2007; Halstead and Isaakidou 2011, 95).

Ethnographic research suggests that a household in rural Greece could comfortably consume a suckling lamb or kid but that any larger carcass risks spoiling after 2-3 days, especially in the summer heat (Halstead 2007, 29). While consumption rates today may not be the same as they were in the Neolithic, they provide a useful guide to thinking about the quantity of meat available to be shared between households and among the wider community/ies. With these quantities in mind, it may be argued that domesticates during the Neolithic were reared with the purpose of being shared with social groups larger than a household (Halstead and Isaakidou 2011, 95). Halstead (2004, 156) also argues that the consumption of meat could have been a 'profoundly meaningful experience in the Neolithic' as it was almost certainly less regularly available than plants, lifting its status to be valued as a 'special food'. This is partly supported by analysis of $\delta^{13}C$ and $\delta^{15}N$ values found in human bone collagen, which show that the carcasses at least of these largest domesticates were not regular contributors to human diet at Makriyalos, suggesting that their consumption was episodic or rare (Triantaphyllou 2001; Vaiglova et al. 2018; Isaakidou and Halstead 2018).

Another definition for feasting provided by Dietler (2001, 67) places more emphasis upon the communal act of feasting: 'a form of public ritual activity centred around communal consumption of food'. Ritual activities can be difficult to infer from typical remains of food consumption such as bones, teeth and charred plants, but the importance of commensal activities can be inferred from ceramics associated with consumption, such as the fine 'tableware' prominent in Middle Neolithic and Late Neolithic material culture (Sherratt 1991). For example, highly decorated serving vessels at Makriyalos are large enough to contain a whole meal shared between a small (say, nuclear-family sized) group of people (Urem-Kotsou and Kotsakis 2007, 228; Lymperaki et al. 2016). Similarly, the homogeneity of cooking and serving vessels projects an ideal of communality and equality between households or groups (Urem-Kotsou and Kotsakis 2007, 242). Some decorative pottery styles are associated with particular areas of the settlement, outside of the communal feasting pits, and possibly represent smaller social groups or household identities (Urem-Kotsou and Kotsakis 2007, 228). In contrast to these finds, smaller drinking vessels found in both feasting and domestic contexts are highly variable in terms of formation and decoration, and seem to express individual rather than group identity (Urem-Kotsou and Kotsakis 2007, 230). This analysis of the ceramic assemblage demonstrates the multiplicity of social identities that were signalled by eating and drinking vessels and perhaps reflect a tension between a wider communal identity and smaller constituent identities.

Another important aspect of Dietler's definition of feasting is that they are 'public' activities. Huge feasting events such as those found at Makriyalos are assumed to have occurred in public spaces, but analysis of private and public preparation of food on a smaller scale has focused upon the location of hearths within or outside building structures. There is perhaps a general shift from the Early to the Late Neolithic in the location of cooking areas at Greek sites, with the progressive walling off of rectangular buildings and subdivisions of villages, while hearths were increasingly located within buildings (Halstead 1999, 80). During the Final Neolithic and Early Bronze Age, external cooking facilities are often contained within yard walls, arguably displaying a more private nature to food-related activities (Halstead 1999, 80). Flexible boundaries of private and public cooking areas are strategically used to balance household needs (private storage/consumption) against repaying and establishing debts through hospitality (i.e. feasting) (Halstead 2004, 154-156).

The above examples and observations highlight oppositions: private versus public; storing versus sharing; and provider versus receiver. They illustrate the inherently political dimensions of feasting, and will be further explored by examining commensal politics and hospitality (Dietler 2001, 73).

2.3.3 Commensal politics and hospitality

Commensal politics and hospitality define the relationship between host and guest or donor and receiver, and the social and economic strategy of creating and repaying debts (Dietler 2001, 73). These dynamics are explored in Mauss' (1954, 15) anthropological survey of gift exchange in which he explains that, once given, a gift imposes an obligation on the beneficiary to repay the benefactor with something of equal value, be it goods, labour or food. A key concept in this sense of obligation is ownership; the gift possesses a quality of the original owner and imposes a debt and hold over the beneficiary (on Maori law, Mauss 1954, 15). Mauss (1954, 17) also identifies the equally powerful obligation to receive gifts: 'to refuse to give, to fail to invite, just as to refuse to accept, is tantamount to declaring war; it is to reject the bond of alliance and commonality'. The fear of offending by refusing gifts or food recurs across many cultures and probably has deep historical roots. For example, gift exchange and commensal hospitality are themes that run throughout the Homeric poem, *The*

Odyssey and are perhaps summarised by the phrase ‘unrewarded generosity’ spoken by Alcinous while giving parting gifts to Odysseus:

> ‘Each of us now should add a mighty tripod
> and cauldron. I will make the people pay
> a levy; so that none of us will suffer
> from unrewarded generosity.’ (Book 13, lines 12-15)

This phrase reveals the expectation that in usual circumstances generosity should be rewarded in some form, exemplifying the obligation to reciprocate in Mauss’ discussion of gift exchange.

Dietler (2011, 183) argues that the embodiment of food makes feasting different to other forms of gift exchange because it is destroyed when ingested and cannot be recirculated in other gift-exchange relationships. New food must be produced and reciprocation may take the form of another feast. This aspect of feasting reveals the opportunity for economic competition and wealth accumulation, and the advantages of storage – all characteristics of transegalitarian feasts (Hayden 2001, 44-45). Commensality may well have promoted competition and inequality in the Neolithic of Greece (Halstead 2012, 30): for example, if a household was unable to uphold their social obligations to reciprocate in kind, they would become indebted to other households, risking subordinate social and economic relationships. These kind of risks may explain the role of storage for economic competition and wealth accumulation in farming communities.

It is argued that regular overproduction would have been a minimum requirement of survival for farmers during the Neolithic, and direct storage of surplus grain would have mitigated poor harvests (Halstead 1992b, 111). Grain has a limited storage life but, fed to livestock, it can be transformed into a more stable resource, meat and fat, representing a strategy of ‘indirect storage’ (Flannery 1969). Furthermore, if meat was valued as a special food item, fattening livestock intended for feasts could increase their value as gifts, thus also increasing the value of reciprocal obligations. This investment for future exchange has been termed ‘social storage’ by Halstead and O’Shea (1982, 93) who also propose that food items can be exchanged for non-food tokens or labour.

These types of storage strategies play an important role in hospitality. For example, in recent rural communities in Greece, the ability to provide food for unexpected guests, along with the appearance of work animals and clothing worn by household members, is a sign of economic standing (Halstead 2012, 24). Households often stored ground bulgur, pasta and *fullo* pastry specifically for these occasions, and in winter pigs were typically slaughtered and preserved with the intention of consumption at unexpected, commensal events (Halstead 2012, 24). This hospitality encourages kinship ties, marriage arrangements and commercial alliances, securing the future economic success of the household (Halstead 2012, 24). Evidence for fattening sheep and goats may demonstrate the use of indirect and social storage strategies during the Neolithic (Mainland and Halstead 2005; Valamoti and Charles 2005). Moreover, although analysis of animal diet has so far focussed on the fattening of domesticates in preparation for consumption of their carcasses, the feeding of domesticates may also have been important to enhance their output of secondary products (milk, labour) or demonstrate the prowess of herders during the animals' lifetime.

Campbell's (1974) study of the transhumant pastoralists, the Sarakatsani, emphasises the impact of livestock welfare on family reputation. For instance, Campbell explains: 'the condition of the family's flock is not only the basis of its physical existence but the source of pride and prestige. A man fears to meet the appraising eyes of another if his animals are in a meagre and spindle-shanked condition' (1974, 41). For the Sarakatsani, sheep and goats are not just a reflection of a family's economic prosperity but are arguably an important part of its status as a productive unit. Again, an important concept in this integration of domestic animals within the identity of a productive unit is *ownership*. Ingold (1980, 82) argues that the defining difference between hunters and pastoralists is not in the physical traits of the exploited animals (i.e. wild and hunted versus domesticated and farmed), but in the 'productive relations' between the humans and animals. It is through these productive relations that animals are incorporated into the household identity, such that pastoralists *own* livestock while hunters do not.

Du Boulay's (1974) description of livestock and households in the Greek mountain village, Ambéli, is an apt example of these productive relations and shared identity:

"These four walls…house an exclusive group of which everything, down to the last chicken, was a full member, bound together by mutual obligations according to which the animals were entitled to protection…the family then still lives, as in the older days, in close contact with the animals – the horse or mules, the household goats, and perhaps a sheep – which are in almost every case either below or opposite the rooms in which the family sleeps; and in most cases the plough-animals are capable, if their feed at 2 a.m. and again at 6 a.m. is forgotten, of waking up the family by banging against the manger and making sleep impossible. The house is still thought of as a unit enclosing a group which includes animals and inanimate property as well as the family in the centre…" (1974, 16-17).

Clay images of animals, in zoomorphic figurines and vessels with animal features, most of which seemingly represent domesticates rather than wild animals, provide an insight into the cultural significance of the former in the Neolithic of Greece (Toufexis 2003, 263). It is tempting to interpret three models of buildings adorned with animal heads as visual representations of the incorporation of domesticates into the household identity (one surface find from Thessaly – Toufexis 2003, 263; and two models from Promachon-Topolnica in Macedonia – Koukouli-Chrysanthaki et al. 2007). These models are relatively scarce, but finds of moulded *bucrania* at Promachon-Topolnica suggest that they do reflect the reality of household structures within the settlements (Toufexis 2003, 263; Koukouli-Chrysanthaki et al. 2007, 60). If domesticates were included within the household identity, then this probably reinforced the cultural significance of sharing meat, underlining the value of such gifts at commensal events (Halstead 2004).

2.3.4 Summary of feasting during the Neolithic and further archaeological questions

The discussion above has explored the role of feasting in household production and survival and in the reproduction of identity in Neolithic Greece. It has also questioned whether meat specifically from domesticated animals is identifiable as a 'special food item' during the Neolithic period. Further investigation into the short term diet of animals may identify fattening in preparation for commensal events. This may provide insight into the use of indirect and social storage strategies in commensal politics, but may also indicate whether such use is related to the scale of consumption events. Inferences regarding the quality of the diet (i.e. quality of pasture or fodder) may also reveal the importance of animal diet to Neolithic farmers in terms of both economic productivity and the social prestige or reputation of the household.

To our previous identified questions, therefore, we must now add:

- Does animal diet differ between depositional contexts on archaeological sites?
    - A positive answer to this question might indicate that livestock were reared or fed differentially with their eventual social contexts of consumption in mind.
- And, more particularly, is animal diet related to the scale of commensal events?

- A positive answer to this question, particularly involving consumption of grain fodder, might help to distinguish between indirect storage on a domestic scale and social storage in the context of large commensal events.

2.5 Choice of method

A number of methods for analysing the diet of animals have been previously mentioned including isotopic analysis, archaeobotanical analysis of dung, and dental microwear analysis. Inclusions in dung provide much the most precise identifications of what animals have eaten, but archaeological finds of dung are rather scarce, suffer from significant biases due to uneven preservation and identifiability, pose considerable risks of post-depositional contamination (Charles et al. 1998; Wallace and Charles 2013). Furthermore, modern experimental observations of botanical remains in dung have shown that macrobotanical remains do not survive digestion well (Wallace and Charles 2013). and offer limited information on the identity of the consumer. Conversely, stable isotope analysis of animal bones and teeth and dental microwear analysis of animal teeth provide less precise information on dietary components, but more precise and reliable identification of the consumer – to taxon (usually species), and perhaps to age, sex, domestic/wild status and even breed.

The use of stable isotope analysis, particularly $\delta^{13}C$ and $\delta^{15}N$, provides useful information on the type of environment an individual animal was feeding in or the type of foods it was consuming. For example, it may indicate whether, in the long term, animals browsed in open or closed woodland (e.g. Fraser et al. 2013), grazed manured or unmanured land (e.g. Vaiglova et al. 2014), and ate C_3 plants (including wheat or barley and most European natural pasture) or C_4 plants (including millet). Moreover, as in the case of isotopic analyses of *postcranial* bones, dietary data could potentially be integrated with biometric evidence for the plane of nutrition of livestock as a measure of the overall quality, as opposed to composition, of their diet (e.g. biometric studies: Albarella 1997; Albarella et al. 2008; Davis and Beckett 1999; Valenzuela-Lamas and Albarella 2017). Distinguishing between more specific types of dietary items, however, can be difficult: for instance, between fresh browse and leafy hay, between fresh graze and grassy hay (although associated beetle faunas *may* help to distinguish between fresh and stored plant food – Smith 1998), between millet and unsown C_4 pasture (such as coastal marsh), or between different C_3 grain crops. For the purposes of the research questions previously identified, the differences between fresh pasture and dried fodder, or between cultivated fodder crops and natural pasture, are important. Moreover, the fattening of animals, whether or not in the context of indirect and social storage strategies, has been identified as an important research issue and, is likely to have been undertaken in the short term, in preparation for slaughter, making isotopic analysis an unsuitable method for its identification. By contrast, dental microwear analysis records wear features on the enamel surface caused by the consumption of abrasives (e.g. food and exogenous particles) and so may reveal whether livestock consumed dried fodder or fresh pasture/browse (Mainland 1994; 1998a; 1998b; 2003a; 2003b). Microwear is also rapidly overwritten and so, unlike isotopes, may reflect short-term fattening before consumption (Mainland and Halstead 2005).

Whereas early dental microwear research used high-resolution, high-cost SEM images, more recent research with light-microscopy greatly reduces costs and increases sample size (e.g. Rivals et al. 2011 on Neolithic Koufovouno, southern Greece). Whereas Mainland (1994) tested the SEM method on modern domesticates of known and subtly different dietary histories, however, the interpretation of light-microscope data has hitherto extrapolated from coarse dietary distinctions between modern wild herbivore taxa (Solounias and Semprebon 2002), without recourse to modern analogues (viewed at the same level of magnification) for dried versus fresh diets as required to address this thesis' research questions. Therefore, the light-microscopy method needs to be tested on a wider range of modern known-diet analogues before it can be applied to archaeological samples. Chapters 3 and 4 concentrate first on the development of the methodology itself and secondly on testing it on the same sample of ethnographic sheep and goats as was previously analysed using SEM by Mainland (1994; 1998a; 1998b; 2003a; 2003b). Dental microwear is variable between species and teeth, due to the different masticatory mechanics of both, meaning that the archaeological samples will need to be of the same tooth and species as those in the ethnographic sample: the mandibular dP_4's of sheep and goats.

2.6 Site backgrounds

Discussion in the first part of this chapter identified research questions related to animal diet. To address these questions, the diet of sheep and goats from three sites, Toumba Kremastis-Koiladas, Makriyalos and Knossos, will be analysed using dental microwear analysis (by digital light microscopy, as explained in detail in Chapter 3). All three sites are located in Greece and the sheep and goats investigated date to the Late Neolithic and also, at Knossos, the Final Neolithic. The location of Toumba Kremastis-Koiladas and Makriyalos in northern Greece and Knossos on Crete (southern Greece) enables comparisons of northern mainland and southern island management practices. On the other hand, comparison of inland mid-altitude Toumba Kremastis-Koiladas with coastal lowland Makriyalos and Knossos offers some scope to explore the influence of seasonal climate on animal husbandry. In addition, Knossos provides the opportunity for diachronic analysis of animal diets through the Late Neolithic and Final Neolithic, while the clear definition of different types of depositional features at Toumba Kremastis-Koiladas and Makriyalos enables comparison of animal diet in relation to varying forms and scales of commensal events.

2.6.1 Site 1: Toumba Kremastis-Koiladas (TKK)

Background

TKK is located in northwestern Greece between the villages of Kremasti and Koilada, at 661m above sea level in the south-east of the raised Kitrini Limni basin (Figure 2.1). The basin experiences cold winters and cooler summers compared to lowland areas to the east, and is formed of lacustrine and alluvial deposits (Hondrogianni-Metoki 2009).

Overall the site measures 7.5-8ha (Hondrogianni-Metoki 2009, 637) (Figure 2.2) and comprises both a low mounded tell and a flat-extended component, initially discovered after a survey in 1986 (Karamitrou-Mentesidi 1986). First excavations of a small area of the tell started in 1996 due to the construction of the Egnatia Highway (Ziota 1996). After a change in the planned route of the highway, the second excavation campaign uncovered a 0.7 ha area outside the limits of the mound (Hondrogianni-Metoki 2009, 67). This part of the settlement closely resembles a flat extended settlement, revealing 462 pits and a system of ditches cut into bedrock. This excavated area on the periphery of the settlement represents 'non-domestic' use of space (Hondrogianni-Metoki 2009) and the analysis of sheep and goats from TKK will be restricted to this part of the excavation. The settlement has yielded a particularly large bone assemblage of over 30,000 recorded specimens (Tzevelekidi 2012) dating to the early part of the Late Neolithic, 5340-4930 BC (Hondrogianni-Metoki 2009). An important characteristic of the site is the structured deposition of faunal and human remains, artefacts and architectural remains (Hondrogianni-Metoki 2009). Three main depositional contexts have been identified at the site: pits and ditches, which were cut into the bedrock and so clearly defined spatially, and 'other' contexts, representing the upper parts of occupation levels for which pedogenesis had obscured distinctions between different depositional features.

Pits

The pits found at TKK vary in size, shape, depth, contents and function. A few of them have been interpreted as potential subterranean dwellings and a few others as borrow pits for the extraction of clay, but the majority are associated with the disposal of 'mundane waste'. Strikingly, a few pits were used for human burials and for the structured deposition of 'special material', including nine nearly complete animal skeletons of pigs, dogs, and sheep (Hondrogianni-Metoki 2009; Tzevelekidi 2012).

Ditches

A system of U- and V-section ditches, characterized by phases of cutting and re-cutting, does not seem to encircle the settlement (Hondrogianni-Metoki 2009; Tzevelekidi 2012). The archaeological contents of ditches are more homogenous than those found in pits but also sparser. It has been proposed that the ditches were dug for the extraction of clay or alternatively perhaps for ideological purposes due to their close proximity to human burials and resemblance to small rivers (Hondrogianni-Metoki 2009).

'Other' contexts

A third context type has been identified from levels overlying pit and ditch fills, and areas where pits or ditches were not found (Tzevelekidi 2012). Zooarchaeological analysis of the carcass management and the deposition of bones found in these contexts has highlighted several differences from the contents of pits and ditches (Tzevelekidi 2012).

Patterns of meat consumption

The most frequent domesticate identified at TKK is sheep, followed by pigs, then goats and cattle. Analysis of mortality patterns suggests meat-oriented husbandry and no significant differences in this respect were found between contexts (Tzevelekidi 2012). However, analysis of the macroscopic wear of teeth identified differences of diet, and thus by extension of herding or feeding strategies, between pit and 'other' contexts – particularly in sheep and pigs (Tzevelekidi 2012). The diet of sheep in pit contexts had a comparatively more abrasive diet than those found in 'other' contexts (Tzevelekidi 2012). 'Penning-elbow', a pathology that has been linked to rapid weight gain due to intentional fattening, is unusually high at TKK in both pit and 'other' contexts (Tzevelekidi 2012).

Variation has also been identified at TKK in the preparation of carcasses for consumption, based on analysis of cut marks. The higher frequency of cut marks in 'other' contexts suggests more intensive butchery practices than in pits and ditches, implying that meat in the latter contexts was prepared in larger parcels and probably for larger social groups (Tzevelekidi 2012; 2015; Tzevelekidi et al 2014). There is also a contrast in the frequency of cut marks between sheep and goats, with the former being less intensively butchered than the latter, indicating that sheep meat was prepared in larger carcass sections than goat meat (Tzevelekidi 2012; Tzevelekidi et al 2014). Additionally, variation in carcass processing methods can be seen in the frequencies of filleting marks, which are highest on cattle bones, then sheep/goat and then pigs (Tzevelekidi 2012). Interestingly, the slaughter of animals may have played a role in commensal politics at TKK without physical ingestion of their carcasses, as Tzevelekidi (2012; 2015) interprets the deposition of nearly whole animals as displaying wasteful or conspicuous consumption.

Further questions regarding animal diet at TKK

Zooarchaeological analysis of the TKK assemblage has demonstrated clear differences between domestic species and between archaeological context types in the preparation, consumption and deposition of carcasses, that are likely to have been linked to cooking preferences, the perceived value of species/body parts, and type of consumption event. Dental microwear analysis, which provides evidence for short-term feeding strategies, may shed further light on the preparation of domesticates for different consumption events.

Sample selection

72 sheep and goat mandibular 4th deciduous premolars (dP_4's) were originally sampled from pit and ditch contexts from TKK; material from 'other' contexts was not sampled, as some of this is probably derived from the upper parts of pits and ditches, rather than from a third surface form of depositional context. After initial inspection of the teeth under the microscope, 48 samples were deemed suitable for analysis in terms of the preservation of the enamel bands. Of these, 36 (26 sheep and 10 goats) come from pits and 12 (9 sheep and 3 goats) from ditches (Table 2.1). The former samples were found in 12 pits: nos. 4, 17, 27, 42, 76, 109, 151, 164, 199, 211, 222 and 247. It is likely that the use of these pits varied but for the scope of this thesis, and given the limitations of sample size, the pit samples are grouped

and compared to those from the ditches. Ideally, specimens would also have been chosen for analysis so as to ensure an even seasonal spread. In practice, however, this was not possible: sheep and goats retain their dP_4's through the first two years of life, but the age at death of second-year animals cannot be determined with sufficient precision for secure attribution to a season; and, anyway, all suitably preserved dP_4's from pits and ditches were selected for analysis for the sake of securing a sufficiently large sample. The first-year deaths can be aged more accurately, however, and specimens associated with a first or second molar (M1 or M2) in eruption or early wear imply deaths spread more or less throughout the first 12 months of life. This evidence is discussed in more detail below (section 5.4.1).

2.6.2 Site 2: Makriyalos I (MK)

Background

The archaeological site of Makriyalos is located in the Pieria area of northern Greece (Figure 2.3) and is situated on a natural hill covering 50ha, 6ha (12%) of which have been excavated (Pappa and Besios 1999). Motorway and railway construction work led to excavations in the area between 1992 and 1995, which revealed the Late Neolithic, flat extended settlement of Makriyalos (Pappa and Besios 1999). The low, heavily eroded hill on which the settlement is located consists of a succession of marls and palaeosols. Two ravines pass northeast and southwest of the site (Pappa and Besios 1999), while the sea is today less than 2km to the east and the Pieria mountains approximately 15km to the west (Pappa and Besios 1999).

The settlement consists of two habitation phases, MKI and MKII, which are distinct both chronologically and spatially (Pappa and Besios 1999) (Figure 2.4). The analysis and discussion within this thesis concentrates exclusively on the first of these phases (MKI), located on the south/southwest slope of the hill and dating to the early part of the Late Neolithic, 5500/5400-5000BC. The main structural features found at MKI are pits and ditches.

Ditches

Two ditches running in parallel surround an estimated area of 28ha, and a third ditch (gamma) was identified in the middle of the enclosure (Pappa and Besios 1999) (Figure 2.4). The two encircling ditches, Alpha and Beta, were systematically investigated over 230m but were also tracked for 470m through excavation and trial trenches; their maximum dimensions are 3.5m wide and 4.5m deep (Pappa and Besios 1999). These ditches have been interpreted as marking the boundary of the habitation area, and the considerable labour cost for their construction and maintenance highlight their social importance to the settlement (Pappa and Besios 1999).

Pits

The pit features found at the settlement have been categorised into two groups based on their contents and dimensions: (1) habitation and (2) feasting.

Habitation:

Clusters of pits within the area enclosed area by ditches A and B have been interpreted as the remains of semi-subterranean buildings, mainly used as dwellings. Small hearths inside and outside these pits, and associated outdoor features have been interpreted as servicing habitation and domestic consumption.

Feasting:

Two large borrow pits of up to 30m in diameter, pit 212 and pit 214 (Figure 2.4), originally dug to obtain marl bedrock and then subsequently filled with refuse, yielded huge quantities of animal remains and artefacts. Pit 212, the larger of these borrow pits, produced a faunal assemblage including remains of several hundred sheep, goats, pigs and cattle (Collins and Halstead 1999), even though half of the pit had been destroyed prior to archaeological excavation. Stratigraphic evidence from these pits suggests it was filled rapidly, probably over no more than a few months, and represented feasting on a scale potentially exceeding those sponsored by later Mycenaean palaces (Collins and Halstead 1999; Halstead and Isaakidou 2011).

Patterns of meat consumption

The commonest domesticates at MKI are pigs, followed by cattle and sheep, and then lastly goats, but the contents of pit 214 are atypical in that remains of cattle are most abundant, while those of goats and sheep were found in similar numbers (Tzevelekidi et al. 2014). The mortality patterns for these domesticates indicate predominantly meat-oriented husbandry, with sparse evidence of ‘traction pathologies’ perhaps indicating the use of cattle for draught (Pappa et al. 2013).

Anatomical frequencies (with all parts well represented, once allowance is made for partial recovery and preservation) imply on-site slaughter of domesticates (Tzevelekidi et al. 2014), while the age at death of the youngest animals (those which can be aged most accurately) suggests slaughter (and thus human presence) during most of the year (Halstead

2005). Stable isotope analyses ($\delta^{18}O$ and $\delta^{13}C$) of domesticates and dental microwear analysis of pigs also suggest restricted mobility of most livestock, apparently reared within the settlement or on cultivated land (Triantaphyllou 2001; Vanpouke et al. 2009), although cattle seem to have grazed a little further afield on coastal marsh (Vaiglova et al. 2018). While isotopic analyses have shed light on animal diet at MK more or less in the long term, dental microwear investigation of the short-term diet of sheep and goats consumed at the settlement may shed light on the extent to which strategies of indirect or social storage were pursued by foddering or use of high-quality pasture.

SEM-based dental microwear analysis of a small sample of sheep and goats found in feasting pit contexts revealed some dietary signatures suggestive of soft foods such as leafy hay and cereal fodder (Mainland and Halstead 2005). This was interpreted in terms of the fattening of kids and lambs in preparation for large feasting events, apparently in contrast with the preparation of animals for consumption in habitation contexts (Mainland and Halstead 2005). Therefore, previous research at Makriyalos has yielded evidence apparently compatible with indirect and social storage strategies, that can be investigated further by enlarging the sample size for dental microwear analysis.

Further questions regarding animal diet at Makriyalos

Evidence for both large-scale feasting and smaller-scale, 'domestic' consumption at Makriyalos provides a good opportunity to investigate further the use of grain in indirect or social storage at varying scales of consumption. Furthermore, evidence for rearing livestock close to or within the settlement with limited mobility provides the opportunity to investigate whether animals were restricted to overgrazed pasture or benefitted from foddering during lean seasons.

Sample selection

126 samples from MK were originally sampled, including all available sheep and goat mandibular dP_4's from the site. After examination of the teeth, 56 samples were deemed sufficiently well preserved for analysis from feasting pits (henceforth referred to as 'pits'), habitation pits (henceforth 'habitation'), and ditch contexts. A total of 29 samples (25 sheep and 4 goats) were found in pit (feasting) contexts, 17 samples (15 sheep and 2 goats) in habitation contexts, and 10 samples (8 sheep and 2 goats) in ditch contexts (Table 2.2). Samples from the 'pits' include 28 from Pit 212 and only one (a goat) from Pit 214. As at TKK, it was not possible to select samples so as to achieve an even seasonal distribution, but

deaths again seem to have been widely distributed through the first year of life (below, section 5.5.5).

2.6.3 Site 3: Knossos (KN)

Background

Knossos (KN), located near the north coast of Crete and the modern city of Heraklion (Figure 2.5), has produced an apparently continuous occupation sequence spanning from the Aceramic or Initial Neolithic, through the palatial later Bronze Age, to the Roman period. The periods of particular interest to this thesis are the Late Neolithic (LN, late 6th and early 5th millennia BC) and Final Neolithic (FN, late-5th and 4th millennia BC) (Tomkins 2008).

Sir Arthur Evans began excavations at KN in 1900 and a 1901 report described an extensive Neolithic site underlying the whole of the Kephala hill occupied by the later Bronze Age palace (Harden 1951). Subsequent excavation campaigns by John Evans during 1957-60 and 1969-70 included the collection of bioarchaeological remains (including sheep and goat teeth analysed in this thesis) and radiocarbon dating, setting new standards for stratigraphic and contextual excavation (Isaakidou and Tomkins 2008, 1).

Because of the overlying Bronze Age palace, excavation of the lower Neolithic levels at KN has been limited. A small part of the 'Central Court', soundings ABCD, and KLMN, was excavated in 1960, with KLMN further excavated in 1969-1970 (Evans 1971) (Figure 2.6). Areas: AA, BB, CC and DD; and EE, FF and GG, located in the 'West Court' of the settlement were also excavated in the 1969-1970 excavation campaigns. These areas only represent a fraction of the Neolithic settlement at KN and so offer much more restricted horizontal exposure than at TKK and MK. This, coupled with the much greater stratigraphic complexity of a 'tell' such as Knossos (compared to the flat extended sites of TKK and MK, with clearly defined features cut into bedrock), affords much less contextual precision in this case. However, the excavated trenches yielded a deep Neolithic stratigraphy with substantial associated faunal assemblages especially from the upper LN and FN levels (Evans 1964; 1971).

Patterns of production and meat consumption

The predominant domesticate at Knossos during the Aceramic to the LN was sheep, with cattle, pigs and goats also represented at the site, but cattle increased in frequency during the Neolithic (Jarman and Jarman 1968; Isaakidou 2008). Analysis of the age and sex of domesticates suggests a predominantly meat-oriented husbandry strategy (Isaakidou 2006, 101-103). Pathologies consistent with use for traction are found on female cattle bones throughout the Neolithic, although such evidence is sparse in the small EN and MN assemblages, when the proportion of cattle was also relatively low (Isaakidou 2006, 106; 2008, 96). Draught *cows* generally have a lower capacity for work than castrated male oxen and so their apparent presence at Knossos is compatible with intensive crop husbandry (Isaakidou 2008). The evidence for yoking of cattle is much stronger at Knossos than elsewhere in the Neolithic of Greece, possibly because the length and severity of the summer drought on Crete created much greater time stress during the autumn sowing period, and thus provided a much stronger incentive for the maintenance and use of draught animals, than in the central and northern mainland (Halstead 1992b, 108; Isaakidou 2008, 104). The use of draught animals would have facilitated prompt sowing, once the autumn rains came, thus lengthening the growing season and increasing the reliability of yields of staple grain crops. Any inequality in access to draught cattle may thus have led to variation between households in normal and surplus production (Isaakidou 2008, 105). The use of draught cattle was perhaps very restricted in the EN, when cattle made up a very small proportion of the faunal assemblage, and anyway does not seem to have triggered settlement expansion, as might be expected if plough animals had facilitated extensive cultivation (Isaakidou 2008, 104). Considerable settlement expansion is not proposed to have occurred until the LNI-II (Tomkins 2008, 32), followed by either a period of stability (Tomkins 2008, 32) or further expansion (Whitelaw 2012, 147-148) during the FN. Stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) of sheep and goat bones matches the expectations for the expansion of settlement through the Neolithic and commensurate increase in the distance over which livestock were herded, as animal diet moves away from its initially rather narrow focus (based on $\delta^{15}N$ values) on manured, presumably arable land (Isaakidou pers. comm.). By using dental microwear analysis, short-term feeding in preparation for consumption may provide further insight into the economic strategies used during these times of expansion or stability.

Diachronic change in the pattern of meat consumption has been identified between the Neolithic and Bronze Age palatial contexts (Isaakidou 2007), from sparse Neolithic butchery apparently producing large 'joints' or carcass sections, probably to be shared widely after cooking, to intensive dismembering and filleting in palatial contexts that was arguably associated with the development of diacritical 'haute cuisine', as inferred from several complementary lines of evidence (Isaakidou 2007). While the Bronze Age palaces are beyond the scope of this thesis, evidence for fattening of animals before consumption in the

Neolithic may provide insight into the earlier roots of competitive and diacritical commensality.

Further questions regarding animal diet at KN

Investigation of the short-term diet of sheep and goats will explore diachronic change or continuity in the preparation of sheep and goats for consumption. This may shed light on the availability of pasture/fodder resources as the settlement expanded in size and, other things being equal, as the radius over which animals were herded increased. It may also provide information about the economic and social use of indirect storage, particularly in light of the increasing use of draught cattle and potential availability of surplus production.

Sample selection

126 sheep and goat dP_4's from Late and Final Neolithic KN were sampled. After examining their enamel under the microscope, 76 samples were considered suitable for analysis. These samples have provisionally been assigned chronologically to eight time periods: LN1, LNII, LNII/FNIA, FNIA, FNIB, FNII, FNII/III, and FNIII (Table 2.3). All of these samples will be used when comparing data with the two other sites, TKK and MK.

To investigate diachronic change at KN, 6 samples from mixed contexts (i.e. not assigned to either the Late Neolithic or Final Neolithic) will be removed. Subgroups from the Late Neolithic (LNI and LNII) and the Final Neolithic (FNII and FNIII) are combined due to their small sample sizes. There are six goat samples in total, two from FNIA and four from FNIB (Table 2.4).

The majority of samples come from the area of the Central Court: 63 (LNI-FNII) from ABCD soundings in a small confined area in the northern part of the Central Court; and 11 (FNII-III) from KLMN, a building overlying the Central Court in the southeastern corner. Two samples (FNII) from FF come from the northern part of the West Court (Evans 1971, 95-98).

Because the Knossos assemblage is considerably more fragmented than those more recently excavated from TKK and MK, information on season of slaughter is coarser, but again there is no indication that young sheep were selectively culled in one season (below, section 5.6.4).

CHAPTER 3: DEVELOPMENT OF A METHODOLOGY

Chapter 2 outlined the research questions concerning animal diet and the choice of method to approach these questions: dental microwear analysis, which infers diet from the microscopic marks left on the enamel surface of teeth caused by abrasive foods and exogenous particles. This chapter provides a background to the different methods of dental microwear analysis and will detail the development of the method used in this thesis. It explores previous research into dental microwear and examines the advantages and limitations of Scanning Electron Microscopy (SEM) and low-magnification light microscopy analysis (using a stereomicroscope). It will then explore and test new advancements in digital microscopy and develop ways to tackle key limitations of microphotography. Sample descriptions of the modern control groups analysed and preliminary results are then provided, and a detailed guide describes the methodology used to analyse ethnographic and archaeological samples.

3.1 Can low-magnification methods provide comparable microwear patterns to SEM? Results from previous studies.

3.1.1 SEM Analysis of Modern Sheep and Goats (Mainland 1994; 1998a; 1998b; 2000a; 2000b; 2003a; 2003b)

Mainland used SEM to analyse the dental microwear of modern sheep and goats from controlled dietary backgrounds. Distinctions between the microwear of sheep and goats with different diets (fresh graze, grassy hay, and leafy hay) were identified by multivariate statistical analysis of feature type, frequency, size, dimensions and shape (Mainland 1994; 1998a, 58; 1998b, 1266; 2003b). The results differed from the previous dichotomous distinction between non-domesticated grazers (highly striated) and browsers (highly pitted) in displaying higher pit and striation frequencies in the leafy hay fed (dry browse) sample than the grazing specimens (Mainland 1998b, 1268).

Mainland's demonstration of the variability in microwear features of domesticated ovicaprids compared to non-domesticated ungulates highlighted the importance of testing methodologies on modern sample sets with known diets (Mainland 1994; 1998a, 60). It also highlighted the need to understand the immediate causes (e.g. acidity, phytolith size, fibrous content, and volume of grit ingested) of particular microwear features and to explore how these causal factors are related to different diets of domesticated ovicaprids (Mainland 1994; 1998a, 58). As Binford (1981) emphasised, such understanding of why different forms of behaviour (in this case ovicaprid dietary regimes) leave distinctive material traces (here, dental microwear) in the present is essential for the development of robust middle-range theory that can safely be applied to other past contexts.

The cause of varying abrasiveness in the diets of grazing sheep and goat populations was investigated by analysing the microwear of three groups of Greenlandic sheep: 1) summer/autumn upland grazers, 2) winter upland grazers and 3) wethers fed indoors on meadow hay (Mainland 2000a). The dental microwear results identified a seasonal difference in grazing diets, with increased abrasion in the winter grazing sheep compared to sheep grazed in the summer/autumn, while the hay-fed sheep exhibited variable levels of abrasion overlapping both grazing groups (Mainland 2000a). Analysis of dung samples from the three dietary groups revealed the levels of opal phytoliths and soil minerals ingested in each diet (Mainland 2000a). Significant differences were found between the summer and winter populations, indicating that sheep grazing in the winter ingested higher concentrations of abrasives (Mainland 2000a), including higher levels of phytoliths and soil minerals, probably due to the greater maturity and patchier distribution of pasture plants in winter (Mainland 2000a; 2003a).

The level of abrasives ingested by sheep fed with grassy hay fell between summer and winter populations, similar to the pattern observed in the microwear results (Mainland 2000a). This is an interesting observation as theoretically feeding fodder to animals indoors should remove some factors causing grit ingestion, such as contact with the soil on which pasture is growing. Evidently the collection and storage of hay incorporates dust and grit, leading to higher concentrations than in some grazing diets (Mainland 2000a). This again reinforces the dangers inherent in interpreting microwear results from domesticates, with diets that may include dry fodder, in the light of observations on non-domesticated ungulates consuming fresh browse or graze.

The relationship between the ingestion of grit and microwear features was further investigated by comparing microwear and dung data results for the Greenlandic upland grazers with data for Gotland sheep from Denmark grazed on heavily utilised, cropped grassland (Mainland 2003a, 1524). The dung analysis demonstrated that both populations had similar overall concentrations of abrasives (opal phytoliths and soil minerals), but higher proportions of soil mineral were found in the dung of Gotland sheep (Mainland 2000a; 2003a). Microwear results from both populations revealed higher numbers of striations also within the Gotland sheep, suggesting that grit particles rather than phytoliths (as was previously assumed) are responsible for the increased number of striations (Mainland 2000a;

2003a). This is an important distinction as it may enable archaeologists to use microwear analysis to differentiate between high and low stocking levels on pasture (Mainland 2003a, 1524).

In the same study the results from microwear and dung analysis of grazing sheep were compared to woodland browsing sheep from Denmark (Mainland 2003a). The microwear results revealed significant differences between the Gotland grazers and browsers, with the browsing specimens dominated by pitted features in comparison to the highly striated grazers (Mainland 2003a, 1523). Supporting dung analysis confirmed lower concentrations of grit and phytoliths in the diets of the browser group, probably caused by the height of browsed plants, reducing oral contact with soil particles (Mainland 2003a, 1523-25). The relatively low abrasion exhibited by some of the Greenlandic grazers, however, resulted in overlap with the browsing sheep from Denmark (Mainland 2003a), highlighting again the significant but subtle dietary distinctions that occur within domesticate diets. In this case, the microwear of sheep grazed on good-quality, low-abrasive pasture might be mistaken for that of browsers.

The detailed data collected in Mainland's analysis of modern sheep and goat diets provides considerable knowledge of the nature, and causes of the formation, of different microwear features. It has provided a scale of abrasion for a broad range of diets specific to domestic sheep and goats, including grazers from various seasons and on different pasture types, woodland browsers, seaweed grazers, and animals foddered with leafy hay and grassy hay (Mainland 1994; 1998a; 1998b; 2000a; 2000b; 2003a; 2003b). This has encouraged archaeologists to offer more accurate and detailed interpretations of ancient sheep and goat diets and farming practices, such as the running of ovicaprines on overgrazed pasture in Medieval Greenland, or the potential fattening of ovicaprines for feasts in Late Neolithic Makriyalos, Greece (Mainland 2006; Mainland and Halstead 2005). Furthermore, it has demonstrated the dangers in interpreting the dental microwear of domesticates on the basis of observations on wild or free-ranging, non-domesticates.

3.1.2 Low-magnification microwear analysis: Live Light Microscopy (LLM) and Digital Light Microscopy (DLM)

Dental microwear features are typically recorded at low magnification levels (c. 30-100x magnification) by either (1) counting features 'live' through the microscope (LLM) or (2) counting and recording other quantitative data, such as the lengths and width of features from digital micro-photographs (DLM). LLM was previously used to analyse dental microwear before SEM enabled depth of field difficulties to be overcome (Walker 1976). Solounias and Semprebon (2002) re-established an LLM methodology, creating a large database of microwear results from 809 individuals from 50 species of extant, free-range ungulates. Average pit and scratch counts showed frequencies of striated features increasing from typical browsers through ‘mixed feeders’ to grazers (Solounias et al. 2002, 21-22). These results mirror those encountered in SEM studies, with grazers and browsers discriminated on the basis of high and low frequencies, respectively, of scratches attributed to the ingestion of grass phytoliths (Solounias et al. 2000; 2002, 20-21) or exogenous grit particles, as Mainland has argued. The significant advantage of using this low-magnification method is the potential for rapid analysis of large sample sizes, as in Solounias and Semprebon’s (2002) study. Large samples, *inter alia*, increase the likelihood of obtaining statistically valid results. The low-magnification method is especially rapid when data are recorded ‘live’ through the microscope (see below), rather than from photographs as is the practice with the SEM method.

LLM has been adopted by many researchers who have compared and added data to those for extant and extinct species catalogued in Solounias and Semprebon’s database (2002; Asevedo et al. 2012; Bastl et al. 2012; Green 2009; Green et al. 2005; Rivals 2012; Rivals and Athanassiou 2008; Rivals and Semprebon 2006; 2011; Rivals et al. 2010; 2012; Semprebon et al. 2004; 2011; Townsend and Croft 2008a; 2008b). For example, it was recently used in archaeological research into Middle Palaeolithic hominid occupation and hunting strategies at the Arago Cave in France and into dietary variability among domestic and wild ungulates at Neolithic Koufovouno in southern Greece (Rivals et al. 2009; 2011).

In their study of Neolithic Koufovouno, Rivals et al. (2011) analysed both the mesowear and the microwear of teeth from wild (red deer, *Cervus elaphus*, and ‘wild’ [presumably feral] goat, *Capra* sp.), and domestic (pig, *Sus*, cattle, *Bos*, and sheep/goat *Ovis/Capra*) animals found at the site. They aimed to identify potential diachronic changes between the Middle and Late Neolithic, and interspecific variation in resource access between the different ungulates examined, in order to infer animal management practices at Koufovouno (Rivals et al. 2011, 528). The dental microwear results displayed clear differences between the wild and domestic animals, identifying the ‘wild’ goat and deer as typical browsers and assigning the domesticates to the grazer and mixed feeder diets proposed by Solounias and Semprebon (2002) (Figure 3.1). The microwear results demonstrate similar patterns for both the sheep and goats suggesting that they had access to similar food resources and were probably reared together (Rivals et al. 2011, 534-5). The variation exhibited by both the sheep and goats is interesting as it indicates diets with different concentrations of abrasives – whether phytoliths or minerals from soil ingestion as Mainland (2003a) suggested. Rivals et al. (2011, 534) interpreted this variance as related to zooarchaeological evidence (not presented) for seasonal slaughter. Factors interpreted as potentially influencing the microwear results include vegetation cover/ type, stocking levels, and increased levels of dust/grit due to dry or wet seasonal conditions (Rivals et al. 2011, 534). The interpretation of these data is problematic, however, due to the lack of available modern reference data for domestic sheep and goats *analysed at a similar level of magnification*. The data of wild ungulates that Rivals et al. have compared their results to are unsuitable and unlikely to provide a useful basis for interpretation. As found in previous SEM research of dental microwear, it is likely that microwear results from low-magnification studies will be heavily influenced by factors specific to domesticate diets. Therefore, it is necessary to test whether subtler dietary distinctions, such as between foddered and summer grazed sheep and goats, can be identified at low-magnification, and how the causal factors of microwear formation, discussed above, influence results at low-magnification.

3.1.3 Limitations of Low-Magnification Analysis and Alternative Methods: DLM and HDRI

Digital Light Microscopy

The analysis of dental microwear through live streaming does not produce microphotographs such as the previously established SEM method. This has been critiqued as a limitation of the method since the recording of features is subjective and thus prone to inter- and intra-observer inconsistency, causing problems of reproducibility (Mihlbachler et al. 2012; Scott et al. 2008; Teaford et al. 2008). Producing images is advantageous as they can be stored for re-analysis and shared between researchers and, in both cases, images clearly illustrate different types of feature and surface texture can then be used as reference tools in future research. It also standardizes the area of enamel that is to be examined, enabling observers to re-examine or compare microwear counts (Fraser et al. 2009, 818).

This limitation has led to an alternative method for recording microwear at low magnification using digital photography - DLM (Merceron et al. 2004a; 2004b; 2005). Merceron et al. (2004a; 2004b; 2005) produced high-quality images with sharpness comparable to SEM images but at much lower magnification (30x magnification compared to 500x using SEM). The microwear results from these studies have also produced trends similar to those from SEM and live microscopy analysis, and have been adopted by researchers to investigate the microwear of extinct and extant ungulates, carnivores and primates (Goillot et al. 2009; Merceron et al. 2004a; 2004b; 2005; Oliver et al. 2014).

The present author's MSc dissertation project (Lawrence 2013) was a pilot study involving the analysis, using low-magnification (x40) microphotography, of modern sheep and goat samples analysed in Mainland's research (1994; 1998b; 2000a; 2003a; 2003b). Casting procedures, choice of tooth/enamel band and feature definitions followed procedures outlined in Mainland's original SEM analysis (1994). Microphotography broadly followed the protocol of Merceron et al. (2004a; 2004b), although make of camera and digital software were of the same standard but not identical. During this study a number of methodological difficulties were encountered and images of the same standard as previous DLM or SEM studies could not be obtained.

Factors that contribute to the difficulty of photographing dental microwear using a stereomicroscope include the curvature and slope of the dP_4 enamel bands, creating depth of field and focussing issues. The oblique lighting created over and under-exposed areas that effectively obscured microwear features and the resulting analysis from these images did not provide distinctive dietary microwear signatures. While abrasive patterns could be inferred/detected from the microwear results, no clear distinctions could be identified between grazer and browser specimens based on pit and scratch counts as reported in previous studies (Figure 3.9). Furthermore, the extreme contrast created by the oblique lighting and uneven surface distorted the shape of some features, limiting the observer's ability to record feature dimensions accurately.

One methodological discrepancy between this pilot study and the previous low-magnification research of Solounias and Semprebon (2002) was in the former's analysis of the mandibular fourth deciduous premolar (dP_4) from young sheep and goats instead of the maxillary or mandibular second molars. However, SEM analysis of the same sample groups, tooth type and area of enamel band has successfully discriminated between various dietary groups as previously discussed. Evaluation of the results from the pilot study, together with observations made throughout the application of the methodology, made clear that, in order for the low-magnification DLM method to produce dietary signatures comparable to SEM data, it was critical to increase the quality of microphotographs and thus to resolve the problems encountered with depth of field, exposure and focussing.

High Dynamic Range Imaging (HDRI)

Photography techniques in paleoecology have benefitted from 'high dynamic range imaging' as set out by Theodor and Furr (2008). The technique involves combining digital images of a subject at multiple exposure levels into one image file which stores more radiance light information than standard image files. The image files are 'tonemapped', meaning an image software programme runs an algorithm to create an image with optimum exposure balance, enabling observers to manipulate unwanted shadows or darken overly exposed areas (Theodor and Furr 2008). Researchers are now using this technique to increase the quality of low-magnification DLM images and to enhance the visibility of microwear features (Fraser and Theodor 2013; Fraser et al. 2009; Theodor and Furr 2008; Townsend and Croft 2011). Fraser et al. (2009) provide a detailed explanation and methodology for applying HDRI to low-magnification microwear analysis and have produced high-resolution and detailed images of microwear features. Their analysis of these images produced results that are consistent with trends displayed in Solounias and Semprebon's (2002) ungulate data, but arguably avoid some of the repeatability problems with LLM (Fraser et al. 2009).

A consistency study comparing previous LLM results for caviomorph rodents (Townsend and Croft 2008b) with HDRI DLM results for the same sample has also produced high-quality images, but highlighted differences in the types of features recorded (Townsend and Croft 2011). The HDRI DLM results showed an increase in features related to 'hard-object' feeding, including large pits and both large and small puncture pits, and a decrease in fine scratch features and small pits (Townsend and Croft 2011). These discrepancies have been attributed to divergent methods of feature description and definition (Townsend and Croft 2011). LLM classifies features based upon refractive qualities (e.g., small pits look bright and shiny under oblique lighting), whereas digital photographs are unlikely to capture the full range of refractive properties and these may also be removed during HDRI processing as it reduces the effects of glare and shadows. It seems necessary, therefore, to collect quantitative and qualitative microwear data from HDR images using a standardized method suited to these images, probably incorporating metrical ratios and feature definitions as used in SEM studies.

3.1.4 Choice of method: HDRI DLM

A variety of alternative methods have been discussed in this chapter. In order to create a reproducible, low-magnification method that provides microwear results consistent with SEM analysis of domestic sheep and goats, it is important to acquire high-quality images of enamel surfaces. The use of HDRI enables the researcher to observe microwear features that may previously have been hidden due to exposure problems, as well as sharpening feature boundaries which may allow further metrical data to be collected. Microwear analysis of modern sheep and goat samples in this thesis will use DLM analysis with image quality enhanced by HDRI. The success or failure of the methodology, in terms of its ability to replicate the results of Mainland's previous SEM analyses of the same samples, will determine whether archaeological material will be analysed in the same way.

3.1.5 Objectives for resolving methodological issues

There are specific challenges to developing and standardizing the DLM method for archaeological research. These were highlighted in the pilot study of DLM analysis of modern sheep and goat mandibular teeth (Lawrence 2013). Inter- and intra-observer testing has also identified problems with the repeatability and subjectivity of DLM and LLM (Mihlbachler et al. 2012; Scott et al. 2008; Teaford et al. 2008) including a) microscope and lighting set up, b) image processing, and c) quantitative/qualitative analysis. In order to resolve issues with the DLM method, therefore, this thesis has specific methodological objectives:

1) to evaluate the comparability of DLM results from sheep and goats with Mainland's SEM method.
2) microscope and lighting:

- to create a standard for microscopic and camera magnification and image pixel resolution (dpi).
- to experiment with types of lighting to find a standard, optimal position for digital photography.

3) image processing:

- to produce high-quality images that represent the range and frequency of microwear features present.
- to increase the visibility and definition of microwear features in digital images by using computer software and High Dynamic Range Imaging (HDRI) to combat light exposure problems.
- to select and adapt a standard 'tone-mapping' algorithm to process digital HDR images.

4) Quantitative and qualitative analysis

- To investigate potential problems with recording and statistical analysis of feature length and breadth data when using oblique lighting.
- To standardize feature shape definitions in terms of width/length ratios, and to establish the minimum size of recordable features.
- To define qualitative features and textures and establish a recording method.
- To identify statistically the best diagnostic (sets of) features for separating modern dietary groups and to determine how best to identify dietary signatures of archaeological specimens of unknown diet.

3.2 Ethnographic sample description

3.2.1 Sample groups

The modern samples analysed in this thesis are composed of contemporary sheep (*Ovis aries*) and goats (*Capra hircus*), with known and controlled pre-slaughter diets. Three broad dietary groups will be analysed using DLM, including 1) grazers, 2) browsers, and 3) fodder-fed sheep and goats. These are divided into sub-groups based on specific dietary information and subject to previous SEM analysis (Mainland 1994; 1998b; 2000a; 2003a; 2003b).

The grazers include four sub-groups:

a) Gotland sheep from Lejre, Denmark, that grazed heavily utilised and cropped pasture and have previously produced highly abraded microwear results under SEM.

b) Greenlandic sheep from Upernaviarsurk grazed on upland pasture in the winter season, exhibiting lighter abrasive microwear under SEM than the Lejre grazers.

c) Greenlandic sheep from Upernaviarsurk grazed on upland pasture in the summer/autumn season, exhibiting low abrasive microwear under SEM in comparison to other grazers ((a) and (b)).

d) Grazing sheep from the Scottish Borders again exhibiting relatively low microwear abrasion under SEM compared with other grazing diets ((a) and (b)).

The browsing sheep consist of one group:

a) Sheep from Lejre browsing in deciduous woodland and grazing open pasture.

Fodder-fed sheep and goats consist of three sub-groups:

a) Sheep and goats from upland Plikati in the mountains of northwest Greece, fed dried grassy hay and leafy hay (primarily dried branches of deciduous oak) with other supplements (below).

b) Grassy hay-fed sheep from Upernaviasurk, Greenland.

c) Sheep and goats from both a local sedentary and a transhumant flock from Assiros, lowland northern Greece, fed wheat straw with whole grains and grassy hay with milled cereal, respectively.

These samples were collected by Ingrid Mainland and Paul Halstead. All samples have been previously analysed for dental microwear by SEM (Mainland 1994; 1998b; 2000a; 2003a; 2003b).

3.2.2 Age and Dietary Information

High-quality graze: Upernaviarsuk summer/winter and Scottish border sheep

The grazing sample groups collected from the Upernaviarsuk research station were obtained through the Greenlandic Agricultural Advisory Service (Mainland 2000a). Wether lambs slaughtered in October 1996 at 5-6 months represent a summer/autumn seasonal diet, while others slaughtered in January 1997 at 8-9 months of age represent a winter diet; the diet was known throughout the lives of both seasonal groups (Mainland 2000a). The flocks were extensively grazed on upland uncultivated, indigenous vegetation including copse/dwarf shrub, heath grassland, herb slope and fell field (Mainland 2000a; 2003a). Stocking levels were relatively low and vegetation cover was good all year round although 'patchier' during winter months (Mainland 2003a, 1524).

Wethers from the Scottish borders were provided by the Macaulay Land Use Research Institute (MLURI) and were slaughtered around 16-21 months of age (Mainland 1994, 92; 1998, 1260). The diet of these yearlings was known for the last 3 months before death and consisted of two pasture types: 1) rough indigenous grassland dominated by *Nardus stricta* (with high levels of opal phytoliths and typically avoided by sheep if possible) with lesser quantities of *Agrostis* sp., *Festuca* sp. and *Deschampsia* sp.; and 2) semi-indigenous/cultivated pasture, reseeded with *Lolium* sp. rye grass (mixed rye-grass and *Agrostis* sp. sward) (Mainland 1994, 92; 1998b, 1260).

Low-quality graze: Gotland sheep from Lejre

Gotland sheep are a small, primitive breed originating from the Swedish island of Gotland. The sample was obtained from the Archaeological Research Centre in Lejre (Mainland 2003a, 1514). Female and male lambs were born in March/April of 1996 and 1997, and slaughtered in the following November at 9 months old (Mainland 2003a, 1515). The lambs grazed on open-grassland comprising unimproved and improved grasses and species such as nettles and thistles (Mainland 2003a, 1514-1515).

This group was clearly differentiated from the Upernaviarsuk grazers both by the abrasive content of their dung and by SEM microwear analysis (Mainland 2000a; 2003a). The higher mineral content found in their dung and relatively highly striated enamel surfaces indicate a more abrasive diet due to ingestion of soil and grit particles (Mainland 2000a; 2003a, 1513 and 1524). The different levels of soil ingestion may be related to stocking rates, land use and intensity of grazing. It is likely that the closely cropped, and heavily utilised grassland increased the quantity of soil ingested by the Gotland sheep, in comparison to the relatively good vegetation cover and low stocking rates of the Greenlandic flock (Mainland 2003a, 1524). Therefore, it is appropriate to analyse these grazing groups separately in order to test whether these pasture and management practices seen at high-resolution/magnification can be identified at low magnification.

Browsers: sheep from Lejre

The female and male browsing sheep from Lejre were also collected from the Archaeological Research Centre, and were likewise slaughtered in November and at the same age (9 months) as the grazers (Mainland 2003a, 1514). These Gotland sheep were pastured in areas created specifically to reconstruct prehistoric pasture systems and consisting of open grassland interspersed with deciduous woodland (Mainland 2003a, 1514). The vegetation comprised shrubs, trees and unimproved grasses including 'wild rose, hawthorn, stinging nettle, elder, beech, ash, willow, elm, birch, lime, hazel and couch grass' (Mainland 2003a, 1514). While their diets also consisted of graze, observations suggest that, as winter approached and grasses became less common, the lambs consumed more deciduous browse (Mainland 2003a, 1514). It was estimated that, by late October-November, 40% of the lambs' diets consisted of bark, twigs and deciduous browse and 60% of graze species (Mainland 2003a, 1515).

Fodder: Leafy Hay and Grassy Hay from Plikati and Upernaviarsuk

The sample of sheep and goats foddered with leafy hay was collected from the village of Plikati at 1200m altitude in northwest Greece, and consists of lambs and kids slaughtered at 3-7 months with the exception of two yearling sheep aged 12-16 months (Mainland 1994, 94; 2003b, 45). This leafy hay diet included a mixture of grassy hay (sown alfalfa or natural meadow grassland), leafy hay (*Quercus cerris*) and supplements of bran and grain (Mainland 1994, 94) (dietary specifications for each individual can be found in Table 3.1 after Mainland 1994). One escapee lamb (PK17) grazed on grass for several days before slaughter (Mainland 1994, 94) and will be considered when interpreting microwear patterns. It is acknowledged

that this sample set has a mixed diet of grassy and leafy hay, but as in previous studies (Mainland 1994, 95) the group will be referred to as 'leafy hay' for brevity.
The Greenland grassy hay-fed wether lambs were born at the Upernaviarsuk research centre, and are the same age as the winter grazers (8-9 months) (Mainland 2000a). The lambs were stall-fed indoors during the winter months with harvested hay from natural, non-cultivated grassland such as *Deschampsia flexuosa* and *Poa pratensis* (Mainland 2000a).

Fodder: diets including cereal grain from Assiros

The cereal-fed sheep and goats were obtained from two flocks: a small flock raised by a local resident from the village of Assiros and a large transhumant herd from Grevena based in Assiros during the winter months (Mainland 2003b, 46). All of the individuals were killed in late winter-spring and ranged in age between two and 12 months (Mainland 2003b, 45). The smaller, local set of animals was fed whole grains and wheat straw for at least 3-4 months, while the larger transhumant herd group was fed grassy hay and milled cereal (Mainland 2003b, 46). The types of cereal and grass consumed by the transhumant herd were unspecified, but are thought likely to have been a mixture of barley, wheat and sown alfalfa (Mainland 2003b, 46).

Summary of available specimens for each dietary group

The total sample numbers for each dietary group may differ from Mainland's original research, due to unavailability of some specimens. The sample totals and details are outlined in Table 3.2.

3.3 Choice of Tooth and Enamel Band

The choice of tooth examined for DLM research was unfortunately limited due to the young age of the samples, meaning that while previous LLM and DLM analysis has focussed on the upper and lower second molars of ungulates, the most common and most analogous tooth among the samples studied here is the lower deciduous fourth premolar (dP_4). This may complicate comparison with Solounias and Semprebon's database (2002), but has the major advantage of facilitating comparison with Mainland's SEM research by analysing the same tooth and area of enamel band and thus providing an opportunity to test whether low-magnification microscopy can produce microwear results comparable to SEM.

As previously stated, the same enamel band and similar area of the band analysed by Mainland will be photographed, namely the occlusal surface of the anterior-facing enamel band of the bucco-posterior cusp (Figure 3.2). Previous research has discovered that microwear of sheep and goats is variable between teeth, tooth facets and occasionally within different areas of the same band (Mainland 1994). This has had significant impact on the choice of facet and area of analysis. After qualitatively examining microwear variances between teeth and facets from different diets, the anterior-facing enamel band of the bucco-posterior cusp was considered to represent abrasion by food more than attrition by occluding teeth, and was found to produce microwear features that could distinguish between diets (Mainland 1994).

3.4 Cleaning and Casting Procedures

The specimens from samples previously analysed in Mainland's SEM studies (1994; 1998b; 2000a; 2003a; 2003b) had already been cleaned to remove surface material that would obscure microwear features during microphotography. Two negative casts were taken from these samples in order to remove dust and dirt that may have gathered during storage. Cleaning of the archaeological samples will follow a similar process, initially brushing off dirt accrued prior to excavation and then swabbing the enamel surface with acetone using cotton buds to remove any tougher residues.

Negative impressions were taken from the bucco-posterior cusp of the dP_4 using a high-resolution, dentistry polyvinylsiloxane material (President Jet Light) (Figure 3.3). This impression material is likely to show less detail than observing microwear on the tooth directly, but the low viscosity of President Jet Light has been tested and shown to provide high precision and accuracy (Goodall et al. 2015). Many of the impressions were taken in Orkney at the University of Highlands and Islands, where the majority of the mandibles were stored. This step is advantageous as it eliminates the need to travel with mandibles from different locations by transporting lighter and replaceable negative casts (Semprebon et al. 2004, 117). Two sets of negative impressions for each specimen were created and brought back to the University of Sheffield to be examined at the Department of Archaeology.

Due to time limitations, the positive casts were created in Sheffield, but for some specimens the positive casting did not work on either the first or the second negative, reducing the total sample size. The negative impressions were cut using a scalpel to leave only the enamel band to be examined, together with the tip of the cusp and a small portion of the bucco-posterior enamel band from the same cusp to assist orientation during microphotography. The negatives were also cut in an attempt to create a flat surface that would enable the microscope to focus on a full area, without distorting feature shapes (Mihlbachler et al. 2012, 6).

Coltène President fast setting putty was then moulded around the negative impressions and used as a supporting base when making the positive enamel replicas. The putty was also used to create a wall around the impressions in order to prevent the epoxy liquid from leaking over the edge, and to create a ‘well-like’ structure enabling the epoxy solution to be filled high (Solounias and Semprebon 2002, 6-7). This ensures that the basal surface of the replica cast does not interfere with the examined surface during microphotography and analysis (Merceron et al. 2004a, 146; Solounias and Semprebon 2002, 7).

The casting material included Araldite 2022 epoxy resin and hardener; 2g of resin were mixed with 0.6g of hardener by slowly stirring for 3 minutes to avoid creating bubbles. The epoxy mixture was then poured at a shallow angle into the putty ‘wells’ again to avoid bubbles forming within the corners and crevices of the enamel impression (Solounias and Semprebon 2002, 7). The mixture was then left to harden for 2-3 days and stored in small plastic bags, clearly labelled (including which side of the mandible the tooth came from, to assist orientation of the replicas during examination).

3.5 Lighting and Microphotography

The casts were examined at 40X magnification using a Leica MZ95 microscope connected to a CCD camera (QImaging Micropublisher 5.0 RTV). Microwear features were exposed by obliquely lighting the enamel surface using external optical lights. This method of lighting is used in LLM, DLM and HDRI studies alike, as the refractive properties of different features create contrasting shadows and highlights, enabling the observer to view and analyse the microwear on the enamel surface (Fraser et al. 2009; Merceron et al. 2004a; Solounias and Semprebon 2002). Initial difficulties were encountered when attempting to standardize the angle of lighting as each specimen needed adjustments in order to highlight successfully the full range of microwear features present, and for the digital image to represent these features. This issue seemed to be the result of two factors: 1) curved shape and slope of enamel bands; and 2) varying refractive properties of different features.

The convex curve of many of the enamel bands examined caused lighting and depth of field problems. These curved surfaces are difficult to light obliquely as the angle of the light typically causes overexposure of the highest point of the curve where the light directly hits, while casting dark shadows over other lower areas, concealing microwear features. This issue has been partly resolved by using a steel ergo ball to stage the casts while lighting and photographing them. This has two advantages: first, the cast can be rotated easily and securely in order to gain the flattest surface possible and to adjust the angle and area of the band that the light source illuminates; secondly, the steel material partly reflects the external light source, creating sharper contrasting images. This has a similar effect to the mirror placed underneath the specimen's stage in the methodology of Merceron et al. (2004a). The over/underexposure issues were resolved by adopting the HDRI methodology described by Fraser et al. (2009). The creation of HDR image files allows the photographer to manipulate lighting after photography, so that lighting requires minimal adjustments during photography (Fraser et al. 2009, 819), effectively speeding up the lighting and photography process.

Depth of field issues associated with the curvature and slope of enamel bands are problematic due to the inherent inability of stereomicroscopes to focus on different heights at the same time, resulting in images with areas out-of-focus and unrecognisable microwear features. Imaging software Image Pro Insight offers tools to acquire images with multiple depths by using a combination of 'EDF' and 'Live Tiling', which effectively stitches together an image as the observer changes the microscope's focus (examples can be found at http://www.mediacy.com/index.aspx?page=IP_Insight_capture [Sept 2014]). After experimenting with these tools, however, it was clear that they were not capturing the required microwear detail, perhaps due to the type of lighting or the subtle nature of the features. It is likely that future developments in digital imaging tools such as these will facilitate the acquisition of microwear images.

Similar issues are caused by the varying refractive properties of microwear features as finer, shallower features such as scratches visible to the human eye during LLM, are not captured in digital images due to the limited light information that image files contain. Moreover, these types of features need particular angles of light and rotation of casts in order to be seen. The enamel band must be perpendicular to the ocular lens for accurate measurement of the areas to be analysed and of feature dimensions, thus limiting the amount of detail captured in a digital image.

Both of the issues discussed above affect the detail and type of microwear features captured in digital images as well as the potential to standardize the angle of the enamel band during photography. The creation of HDRI files provides a solution for the lack of light detail captured in digital images, as it stores more pixel radiance information than standard files such as JPEGs and TIFFs, while the tonemapping process allows these details to be visible on computer screens and printed (Fraser et al. 2009; Theodor and Furr 2008). The images produced using this method were of high quality and captured details of small pits and fine scratches while the enamel bands were photographed in a flat position. It is likely that not all features are represented in the images, but it is arguably more important to standardize the angle of the enamel band during photography for accurate measurements and also to limit potential bias in the types of features captured.

For example, the frequencies of shallow and fine features are likely to be reduced in all samples using this technique, meaning the bias against those features will be similar, if not the same, for all enamel bands photographed. Conversely, if the bands were photographed at different angles in order to highlight particular features, the images produced would be affected by varying and unknown degrees of bias against other features subsequently hidden by the differing angles of lighting. The impact of this bias is likely to increase if photography and microwear analysis are not performed with an element of blindness. For example, if the observer is conscious of the diet or predicted diet of the specimen, it is tempting to look for 'expected' features and it is likely that more time and manipulation of the enamel band position and lighting will occur to highlight these features, creating observer bias.

Therefore, it is argued that HDR imaging of enamel bands positioned flat and perpendicular to the ocular lens is the best balance between acquiring feature detail and reducing or controlling bias in the observed frequency of different feature types. The potential decrease in fine scratches or shallow pits may limit the ability to identify particular diets based on pit versus scratch frequencies or qualitative descriptions of fine reflective features, but further statistical analysis of feature dimensions will be used in an attempt to identify potential diagnostic features.

3.6 High Dynamic Range Imaging and Image Processing

The method used for creating HDR images follows the procedures described in Fraser et al. (2009). The bands were photographed at multiple exposure values using equal intervals for each frame; 9 or 13 frames were taken depending upon the level of contrast between the over/underexposed areas. The exposure values were easily changed using Image Pro Insight by manually entering EV (exposure value) numbers into the capture properties. The images were then saved as uncompressed JPEG files and transferred to the Photomatix Pro software, where the frames were selected to create a single HDR file. The image generated is formatted as a Radiance file and cannot be directly used in basic software. It is therefore necessary to 'tonemap' the images using enhancement algorithms to create workable and printable images (Fraser et al. 2009, 825). This was also achieved using the Photomatix Pro software.

In an attempt to standardize the tonemapping step, experiments were conducted testing the optimal number of EV frames, and detail captured through various enhancement algorithms, in order to create a standard to apply to each image. This involved comparing HDRI's of three specimens exhibiting high abrasion, low abrasion, and fine features respectively with various detail enhancements and images produced from 5 and 9 frames. Observations from these comparisons found that 9 frames produced HDRI's with only slightly more detail than images produced from 5 frames (Figure 4.4), but it is useful to take at least 9 frames to compensate for images with particularly difficult lighting that require additional digital manipulation and to reduce visible grain (Fraser et al. 2009).

After comparing results from both pre-set and adjusted enhancements, an algorithm was decided upon which provided visible detail and did not distort microwear features. All images were set to 'monochrome' creating a greyscale image, 'detail contrast' was increased to 10.0, 'micro-smoothing' was set to 0 and light adjustments ranged between 'natural' to 'medium'. The 'tone compression' values were adapted according to the individual needs of each image as this increased luminescence of dark images or decreased the overly exposed areas of brighter images (Figure 3.4). As Fraser et al. (2009) have previously observed, additional sharpening varied according to the type of microwear features present, as finer features needed sharpening while coarse microwear did not always benefit from these enhancements. 'Strong' sharpening enhancements were not used on any of the images analysed as it caused a 'grainy' appearance to the image and may artificially create non-existent features (Figure 3.5). The Photomatix software allows the researcher to save a file detailing the embedded enhancements and this was found to be a good source for future reference and comparison.

3.6.1 Successes and Limitations of HDRI

The overall quality of the HDRI's is comparable to SEM micrographs, and the microwear features are more similar in appearance to those presented in SEM images than are feature descriptions from LLM analysis. For example, fine scratches and shallow pits are defined as highly refractive in LLM analysis and appear as white circles or lines (Solounias and Semprebon 2002). Conversely, the finer features identified in images produced by this work and those in Fraser et al. (2009) do not always have these reflective qualities, possibly due to the digital toning of these reflective properties. This has been taken into consideration during feature classification by defining pits and scratches on the basis of the width/length ratios used in SEM and DLM analyses (Mainland 1994; Merceron et al. 2005).

The HDRI method successfully resolves some of the problems inherent in DLM microwear analysis such as lighting and limited detail previously discussed in this chapter. However, the focussing issues pertaining to depth of field problems in digital photography cannot be resolved using HDRI. This problem was mitigated by trying to focus on the area of analysis during photography, with the aim of making sure an area of 0.4 x 0.4mm was in focus. This was not always possible, however, and in some samples portions of the area of analysis were out of focus and features could not be quantified. A similar problem occurred in the case of some enamel bands with widths below 0.4mm. Both of these issues are addressed during the quantification of microwear features by proportionately increasing results from these enamel bands (further discussed in 3.7).

3.7 Preliminary Analysis

Preliminary analysis of a sub-sample from the grazer and browser groups was undertaken to address two questions: 1) can the HDRI method produce dietary patterns comparable to SEM results? 2) Does the HDRI method improve the pit and scratch results compared to the results previously obtained using non-processed images (Lawrence 2013)?

3.7.1 Quantitative data selection for preliminary analysis

A 0.4 x 0.4 mm square was cropped from the HDRI using Windows Paint. The measurement for this square was obtained by referring to a scale bar from the original, calibrated image on Image Pro Insight. Cropping the areas to be analysed is advantageous as it prevents the observer from recognising the ‘taxonomic identity’ of the image (Mihlbachler et al. 2012). The image files can also be given coded names to keep the diet unknown in order to create observer blindness. The cropped areas were then saved as 24-bit Bitmaps in order to quantify features in Microware 4.02 (Ungar 2002). This software automatically classifies and quantifies pits and scratches by calculating the length to width ratios the observer has marked onto the features in the image. Pits are circular features and are classified by having a length to breadth ratio ≤4:1, while scratches are elongated features with a length to breadth ratio >4:1 (Grine 1986; Mainland 1994; 1998b; 2000a; 2003a; 2003b; Merceron 2004a; 2004b). These definitions differ from the refractive qualities used to classify pits and scratches in LLM analysis and previous HDRI studies (Fraser et al. 2009; Solounias and Semprebon 2002). The differences may influence the resulting frequencies of recorded pits versus scratches, potentially limiting comparability with the ungulate database produced by Solounias and Semprebon (2002), but previous microwear research has persuasively argued that use of quantitative classifications removes the subjectivity of qualitative feature categorisation (Mainland 1994). Accordingly, quantitative classification of feature types will be used in this thesis.

For images with significant areas out of focus and enamel bands smaller than 0.4mm, pit and scratch counts were proportionately increased by calculating the percentage of unanalysed areas using pixel graph on Windows Paint, and increasing the pit and scratch results accordingly. To take a hypothetical example, if an enamel band 0.3mm wide yielded 30 scratches and 120 pits, these results would be multiplied up by 4/3 to 40 and 160, respectively.

3.7.2 Preliminary results

Results from Figure 3.6 and comparison with SEM results

Figure 3.6 displays a pattern similar to previous SEM results from the same dietary groups (Mainland 2003a). The scratch counts increase with dietary abrasiveness; the Lejre high abrasion grazers have an overall scratch count higher than the Lejre browsers (Figure 3.7 and 3.8), while the low abrasive grazers from Upernaviarsurk fall between these dietary groups. A very similar relationship between dietary abrasiveness and microwear patterns was seen in Mainland's (2003a) research, which showed that the Lejre grazers ingested higher concentrations of soil minerals compared to the Upernaviarsurk sheep and Lejre browsers, causing higher levels of abrasion and scratches.

The results from Figure 3.6 have three obvious outliers, one from each dietary group. The outlying browser specimen is likely to have had an unusually abrasive diet compared to the other browsers, as the same specimen also produced higher scratch counts than the other browsers in the pilot study (see outlying browser in Figure 3.6). This may have been enabled by the known availability of both graze and browsing areas for this sample group.

The outlying summer grazer falls among the low-quality grazing sample, with a significantly higher scratch count compared to the rest of the sample. A causal factor may be that the enamel band was too small and so scratch counts were increased proportionately (Table 3.3). However, the pit counts were also increased and have not caused unusual results outside of the correlation. Arguably this is due to the nature of the scratch features as they are long and extend across the width of the enamel band in this specimen, whereas the pitted features are shorter. Therefore, increasing these results has created a disproportionate number of scratches due to their dimensions, while pitted features remain unaffected.

The low-quality grazing outlier produced lower scratch counts compared to the rest of the sample, falling among the high-quality grazers, while producing higher pit counts than all the other samples. This specimen should thus exhibit fewer abrasive features than the other grazers from Lejre, but it was particularly difficult to photograph due to its extremely pitted and gouged microwear surface, which implies a highly abrasive diet. It is likely that these pits and gouges mask scratches on the surface that would have been visible if there were fewer features. This specimen indicates the limited information that pit and scratch counts alone can provide, and highlights the need to record and analyse additional features.

Comparison with LLM data

In so far as the results in Figure 3.6 and the LLM data produced by Solounias and Semprebon (2002) can legitimately be compared, they seem to be similar, with the browsers and low-quality grazers exhibiting similar scratch ranges to the typical browsing and grazing ungulates. The scratch counts for our high-quality grazers would fall among the ‘mixed feeder’ ungulates, suggesting that quality of graze may affect the ability to identify grazers. The overall pit count for each sample group is higher than the results produced by Solounias and Semprebon (2002), perhaps due to methodological differences - for example, in the tooth examined, in feature classification or in quantification from images.

Comparison with Lawrence (2013)

Figures 3.6 and 3.9 present results from the same specimens, teeth, and enamel bands but using different methods of data capture. Comparing results from unprocessed images (Figure 3.9) with HDRI images demonstrates a clear improvement in separation of dietary microwear signatures using the HDRI methodology. Compared with the unprocessed images, the HDR images reveal significantly more scratches on the enamel surface (demonstrating HDRI’s ability to capture more detail) and are more comparable to SEM and LLM data.

3.7.3 Preliminary conclusions

The preliminary results and comparison with other methods of microwear analysis provide encouragement regarding the resolution and reproducibility of the HDRI methods and also useful pointers to areas of possible improvement in the digitization of dental microwear. Outlying specimens suggest that the quantification of additional feature types and perhaps qualitative variables might enhance discrimination between different diets. Comparing results from unprocessed images shows that HDRI provides superior diagnostic results. Care is also needed in the future when 'correcting' data to allow for images of reduced dimensions or partial 'visibility', and should be judged individually based on the type and nature of features present.

3.8 Recording and analysis of ethnographic samples

3.8.1 Quantitative data collection

The quantitative data was collected using Microware 4.02 (Ungar 2002) which automatically records the variables used in this analysis (except scratch and pit percentages). Features were identified as pits and scratches using length to breadth ratios ≤4:1 (pits) and >4:1 (scratches) as previously discussed (3.7.1). A total of 14 variables were recorded per photograph and can be categorised into 4 groups: (1) feature type, (2) average feature size and shape, (3) proportion of feature types, and (4) average orientation of features (Table 3.5). Feature lengths and widths were measured in microns, while the orientation data represents the average angle of features on a 0 to 180° scale, where 90° equates to features aligning vertically to an anterior-posterior orientation. Features between 0° and 90° have orientations directed to the buccal side of the jaw, while features with a 90° to 180° result are orientated towards the lingual side of the jaw. The data for orientation requires all samples to be aligned in the same way (i.e. same side of the jaw). However, six specimens (4 from the cereal-fed group and 2 from the leafy hay-fed group) out of the total modern sample are from the left hand-side jaw while all the remaining specimens are from the right. The data for these six specimens were therefore changed to reflect a 'mirrored' result.

3.8.2 Qualitative data collection

Collecting qualitative data, such as the texture of enamel surfaces (e.g. polish), is a fast method for recording distinguishing features that may not be captured in quantitative data

(Mainland 1994, 122). A total of 17 qualitative variables were recorded per photograph (Table 3.6), using Mainland's definitions and photographic key (1994, Vol. 2 7.1-7.20) in order to limit subjectivity. Variables were scored using a system of presence or absence (1 = present, 0 = absent) or similar to quantify the results in SPSS. The variables were chosen based on those used to differentiate between modern diet groups in Mainland's previous study (1994, 122-3), and are used to: (1) describe feature types, (2) provide descriptions of features and (3) describe surface textures/appearances.

3.9 Statistical analysis of ethnographic data

As in Mainland's SEM studies, discriminant analysis (DA) is used to explore the relationship between multiple variables describing the dental microwear features (see above sections 3.8) and the ethnographic dietary groups (see section 3.2.2) using SPSS (version 22).

DA provides the advantage of being able to use multiple variables, combining qualitative and quantitative, in a single analysis, so that finer distinctions between domesticated diets (e.g. dried leafy hay fodder and fresh browse) are more likely to be detected. DA uses multiple variables to create functions that best discriminate between groups - in this case ethnographic dietary groups. A series of DAs is undertaken to discriminate between: all five dietary groups (leafy hay, grassy hay, cereal fodder, fresh graze and fresh browse); two broad, combined groups, i.e. fodder (leafy hay, grassy hay, cereal fodder, fresh graze and fresh browse) versus fresh (browse and graze); fodder groups separately (leafy hay, grassy hay, cereal fodder); fresh groups separately (browse and graze); seasonal graze (winter versus summer); and pasture quality (high-quality graze versus low-quality graze).

DA may give unreliable results when the number of discriminating variables is similar to or in excess of the number of cases in the smallest group (Mainland 2000b; Perrins et al. 1992; Tabachnick and Fidell 1996). Due to the small size of some of the ethnographic dietary groups, a minimum number of the best discriminating variables was identified and used in the DA. These variables responsible for between group differences were identified using the correlation between the discriminating variables and the discriminant function (Mainland 2000b). Variables that correlated with each other such as, "smooth" and "polish", and "percentage of scratches" and "percentage of pits", were chosen or removed according to their contribution to the discriminant function, to ensure all variables were independent. The success of the discriminant functions was determined for each DA using a plot of the discriminant functions and reclassification tables (Mainland 2000b; Norušis 1990).

Each sample is given a predicted classification into a dietary group; both ‘pre-validated’ and ‘cross-validated’ results are provided for each analysis. The cross-validated results are of particular interest as the analysis leaves the discriminant scores of the sample being classified out of the group sample scores, thus providing a more reliable classification result. The classification phase of DA is particularly useful to explore diets of archaeological samples as cases with an unknown group membership can be classified. Any successful discrimination identified between ethnographic dietary groups can be applied directly to the dietary classification of archaeological samples (Mainland 2000b). This is, of course, dependent on the ethnographic dietary groups being representative of the archaeological diets under investigation (Mainland 2000b).

3.10 Archaeological samples: recording and statistical analysis

The selection of samples from archaeological sites TKK, MK and KN has been described in Chapter 2. The cleaning, casting, photography and recording of variables for the archaeological sample groups follow the same methods as used for the ethnographic samples. The archaeological samples are divided into contexts (TKK: pit and ditch; MK: pit (feasting), habitation and ditch) or chronological groups (KN: LNI-LNII, FNIA, FNIB, FNII-III). These samples were entered into the discriminant analyses as ‘unknown’ groups to explore their similarities to/distinctiveness from the ethnographic dietary groups using both plots and classification results (section 3.9).

CHAPTER 4: RESULTS 1

DENTAL MICROWEAR OF MODERN SHEEP AND GOATS

This chapter presents dental microwear results from discriminant analyses of modern, ethnographic groups of sheep and goats with more or less known and controlled diets, with the aim of evaluating the suitability of low-magnification, digital methods of dental microwear analysis for archaeological investigations of animal diet. To this end, it first explores microwear differences between the ethnographic dietary groups using low-magnification, digital light microscopy (DLM) and then compares these results with those from previous SEM work by Mainland.

4.1 The purpose of modern analyses

Discriminant analysis is used here to determine whether quantitative and qualitative dental microwear variables can successfully discriminate between ethnographic dietary groups of sheep and goats. The analyses undertaken will address this question in the following steps:

1) Can the selected variables discriminate between the following diets using a single analysis:

a) fresh graze vs fresh browse vs grassy-hay vs leafy-hay vs cereal-fodder?

2) Can dry fodder diets be distinguished from their fresh counterparts?

a) dried fodder (combined group of cereal, grassy-hay and leafy-hay) vs fresh diet (combined group of fresh browse and graze)

b) dried leafy hay vs fresh browse

c) dried grassy hay vs fresh graze

3) Can fresh graze be distinguished from fresh browse?

a) fresh graze vs fresh browse

4) Are there significant differences between summer and winter grazers?

a) summer-graze vs winter-graze (both fresh)

5) Can quality of grazed pasture be identified?

a) low-quality graze vs high-quality graze

6) Can different foddering groups be distinguished from each other?

a) Cereal vs leafy-hay vs grassy-hay.

4.2 Results

4.2.1 Distinguishing between grazing, browsing, leafy-hay, grassy-hay and cereal-foddering

Figure 4.1 is a plot of samples from five different dietary groups in relation to the first two discriminant functions extracted to distinguish these groups. These two functions account for 82.7% of the variation between groups; the third (unplotted) function accounts for only 12.3% of this variation.

Function 1 tends to distinguish the fresh graze and fresh browse (positively) from the cereal and grassy-hay groups (negatively), while the leafy-hay group plots neutrally (Figure 4.1). This is based largely on higher counts of pitted features and the presence of a porous surface, which load positively on the first function characterising the first two groups (Table 4.1). Function 2 tends to distinguish the fresh graze and cereal groups (positively) from the leafy-hay and fresh browse groups (negatively), while the grassy-hay group plots (neutrally) (Figure 4.1). This is based largely on deeper features loading positively on the second function characterising the fresh graze and cereal groups, and the presence of polished surfaces loading negatively, characterising the leafy-hay and fresh browse groups (Table 4.1). Function 3 (not plotted) distinguishes the grassy hay group using largely the variable "areas of empty enamel" (Table 4.1).

Figure 4.1 shows high overlap of samples from different groups and the overall percentage of samples correctly re-classified into their dietary groups is low (cross-validated: 56%) (Table 4.2), and is unlikely to be useful for identifying diets of archaeological samples. This modest success of discriminant analysis using the microwear features in re-classifying samples to their correct dietary group is somewhat expected due to the similarity of some of the diets. For example, it is unsurprising that the fresh browse and leafy-hay samples are grouped together in the analysis as they are essentially the same diet in fresh and dried states. It is likely that, in order to distinguish the dietary groups and identify the microwear signatures for each diet, further analysis with more broadly defined groups is initially needed.

4.2.2 Distinguishing between dried fodder and fresh graze/browse

Figure 4.2 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish these groups.

The function tends to distinguish the fresh dietary group (positively) from the fodder group (negatively) (Figure 4.2). This is based largely on the presence of surface porosity and higher feature counts loading positively that characterise the fresh dietary group, and the presence of smooth surfaces loading negatively that characterise the fodder dietary group (Table 4.3). These characteristics indicate that the fresh diet is more abrasive than the dried diet, perhaps due to hard, exogenous particles picked up through contact with soil particles in fresh diets.

Figure 4.2 shows some overlap between the two groups, but the overall percentage of samples correctly re-classified into their dietary groups is 77% (cross-validated) (Table 4.4). The grouping of the samples into two groups distinguished by whether the animals were fed on fresh or dried material has increased the percentage of samples correctly re-classified compared to the previous analysis (4.2.1) (Tables 4.2 and 4.4). However, 7 out of the 13 leafy hay samples were re-classified as “fresh”, meaning that the leafy-hay group could not be distinguished as a fodder diet from the fresh diets using this discriminant function.

4.2.3 Distinguishing between fresh browse and leafy hay

Figure 4.3 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish these groups.

The function tends to distinguish the fresh browse group (positively) from the leafy-hay group (negatively) (Figure 4.3). This is based largely on the orientation of features, with a more anterior-posterior direction loading negatively and characterising the leafy hay group, and the number of scratches, which load positively and characterise the fresh browse group (Table 4.5). The higher number of scratches found in the fresh browse samples may be caused by abrasive soil particles and grass phytoliths consumed during intermittent grazing. The difference in the orientation of the features may also indicate a difference in the mastication of dried and fresh browse.

Figure 4.3 shows a small amount of overlap and the overall percentage of samples correctly re-classified is 81% (cross-validated) (Table 4.6). By analysing the two dietary groups separately from the other fresh and foddered groups, the discriminant function can distinguish both groups and correctly re-classify most samples into their original dietary group (Table 4.6).

4.2.4 Distinguishing between dried grassy hay and fresh graze

Figure 4.4 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish these groups.

The function tends to distinguish the fresh graze group (positively) from the grassy-hay group (negatively) (Figure 4.4). This is based largely on the total number of features, presence of porous surfaces and presence of deep features which load positively and characterise the fresh graze group (Table 4.7). These variables represent more abrasive wear in comparison to the lower feature count, lower frequency of porous surfaces and presence of shallow features characterising the grassy hay group. The presence of rounded features and areas of enamel without features loading negatively, characterising the grassy-hay group, also indicate a less abraded enamel surface compared to the fresh grazers (Table 4.7). This is likely to reflect the differences in the quantity and types of abrasive particles ingested in outdoor and indoor diets.

The presence of porous surfaces has previously been associated with hay fed animals, with teeth described as having "acidic etching" (Mainland 1994; 1998a; 2001), although it has also been documented on a very small number of grazing sheep (Mainland 2001). The presence of these surfaces in the grazing group is therefore unexpected and may show that this feature is variable at different magnification levels (Mainland's SEM analysis uses 500x magnification) or is simply unreliable as an indicator of either dried or fresh diets.

Figure 4.4 shows some overlap, but the overall percentage of samples correctly re-classified is 81% (cross-validated) (Table 4.8). By analysing the two dietary groups separately from the other fresh and foddered groups, the discriminant function can distinguish both groups and correctly re-classify most samples into their original dietary group (Table 4.8).

4.2.5 Distinguishing between fresh browse and fresh graze

Figure 4.5 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish these groups.

The function tends to distinguish the fresh browse group (positively) from the fresh graze group (negatively) (Figure 4.5). This is based largely on the presence of polished surfaces loading positively, characterising the fresh browse group (Table 4.9). The polishing of enamel surfaces is likely to be caused by tooth-on-tooth attrition (Hillson 2005) as previous wear features are smoothed and the enamel surface becomes polished. The higher frequency of these surfaces within the fresh browse group is likely to be caused by a lower proportion of abrasive particles in the fresh browse diet (less contact with ground soil and grass phytoliths) compared to the fresh graze diet.

Figure 4.5 shows some overlap between the two groups but the overall percentage of samples correctly re-classified is 82% (cross-validated) (Table 4.10). The small sample size of the fresh browse group (n=8) must also be taken into consideration and caution should be exercised when using the re-classification results.

4.2.6 Distinguishing between summer and winter graze

Figure 4.6 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish between these groups.

The function tends to distinguish the summer-grazed group (positively) from the winter-grazed group (negatively) (Figure 4.6). This is based largely on the average length:width ratio of features loading positively, with the summer group characterised by longer/thinner and the winter group by shorter/wider features (Table 4.11). A higher percentage of scratches and the presence of uneven surfaces loading negatively also characterise the winter group (Table 4.11).

These latter variables suggest higher abrasion of the winter samples as has been previously found in Mainland's (2001) SEM analysis of microwear in the same samples, coupled with her analysis of abrasive inclusions in dung from the relevant pastures. The longer/thinner features recorded on the summer-graze samples are indicative of more scratch-like features compared to the short/wider pit-like features recorded on the winter-graze samples. These feature shapes are, at first sight, inconsistent with the higher percentage of scratches found in the *winter*-grazed group, since the long thin features characteristic of the summer-grazers, if they exhibit a length: width ratio higher than 4:1, will have been classified as scratches. Equally, one would expect a higher percentage of pit features in the winter-graze group given the higher ratio of short/wide features. This discrepancy, however, may be due to the cross-cutting of features, which is very common in well abraded enamel (such as that of winter grazers) containing many features. For example, a long scratch which runs across the width of the enamel band may be overlain by later pits and cross-scratches causing it to be recorded as two or three shorter scratches. Conversely, an enamel surface with less abrasion and fewer features will provide a clearer surface where the long scratch will be recorded as one feature and so yield an overall longer average feature length.

In either case, the observed differences in microwear feature shapes and frequency imply a seasonal contrast in the quantity and type of abrasives ingested, whether directly from the consumed plant material (e.g. because sheep are limited to more mature vegetation in the winter - Mainland 2001) or from associated soil particles. Figure 4.6, however, shows considerable overlap between the two groups and the overall percentage of samples correctly re-classified is lower than in previous analyses (cross-validated: 70%) (Table 4.12). The discriminant function showed limited differences between the two groups and is reflected in the contradictory nature of the two variables discussed. It should also be noted that, unlike all the other 'dietary' categories analysed here, winter and summer graze are defined in terms of time of year rather than type of food ingested. This is significant, because the two categories represent winter and summer pasture in *northern* Europe, whereas the season of scarce/low-quality pasture is summer in parts of southern Europe – from which the archaeological cases examined in this thesis are drawn.

4.2.7 Distinguishing between high- and low-quality graze

Figure 4.7 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish between these groups.

The function tends to distinguish the low-quality graze group (positively) from the high-quality graze group (negatively) (Figure 4.7). This is based largely on the number of scratches and the presence of uneven surfaces, loading positively and characterising the low-quality graze group, and the length of features, loading negatively and characterising the high-quality graze group (Table 4.13). The higher number of scratches and frequency of uneven surfaces exhibited in the low-quality graze group is indicative of a more abrasive diet. The longer average feature length seen in the high-quality grazed group may again, at first sight, seem inconsistent with the higher number of scratches found in the low-quality grazed group. This apparent contradiction should probably be interpreted in the manner proposed above for winter and summer grazers.

Figure 4.7 shows some overlap and the overall percentage of samples correctly re-classified is rather low (cross-validated: 73%) (Table 4.14), but the low-quality graze group is small (n=9) and so a negative conclusion should be drawn with caution. The discriminant function showed that there are some differences between the two groups, but the ability to reclassify samples successfully is limited.

4.2.8 Distinguishing between grassy-hay, leafy-hay and cereal-fodder

Figure 4.8 is a plot of samples from three dietary groups in relation to two discriminant functions extracted to distinguish between these groups.

Function 1 tends to distinguish the cereal group (positively) from the leafy-hay group (negatively) (Figure 4.8). This is based largely on the percentage of scratches, which loads positively characterising the cereal group, and the pit count, which loads negatively characterising the leafy-hay group (Table 4.15). Function 2 tends to distinguish the grassy-hay group (positively) from the cereal and leafy hay groups (negatively) (Figure 4.8). This is based largely on the presence of areas of enamel displaying no features, which loads positively characterising the grassy-hay group (Table 4.15).

High pit counts found on samples from the leafy hay group are a common feature associated with browse-based diets in previous SEM analyses (Mainland 1998b). The absence of microwear features on areas of enamel from samples in the grassy-hay group suggests occlusal "smoothening" of the enamel with an absence of particles hard enough to cause marks across the whole of the surface. The absence of abrasive features in the grassy-hay samples compared to the other fodder groups could be a consequence of how "cleanly" the fodder has been collected and stored (Mainland 2000a).

Figure 4.8 shows clear separation of the three groups, but the overall percentage of samples correctly re-classified is relatively low (cross-validated: 71%) (Table 4.16) compared to previous analyses in this chapter. This low percentage is largely caused by the poor distinction of the grassy-hay group, but leafy-hay samples are also incorrectly re-classified as grassy-hay (Table 4.16). To see whether this can be improved, the grassy-hay group will be analysed with each of the other two fodder groups separately in the following analyses.

4.2.9 Distinguishing between grassy-hay and leafy-hay

Figure 4.9 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish between these groups.

The function tends to separate the grassy hay group (positively) from the leafy hay group (negatively) (Figure 4.9). This is based largely on the presence of areas of enamel displaying no features, loading positively and characterising the grassy hay group (Table 4.17).

Figure 4.9 shows a good separation between the two groups and the percentage of samples correctly re-classified is 91% (cross-validated) (Table 4.18). By analysing the two dietary groups separately from the cereal group, the discriminant function distinguishes both groups and re-classifies most samples into their correct dietary group (Table 4.18).

4.2.10 Distinguishing between grassy-hay and cereal fodder

Figure 4.10 is a plot of samples from two dietary groups in relation to one discriminant function extracted to distinguish between these groups.

The function tends to separate the cereal group (positively) from the grassy-hay group (negatively) (Figure 4.10). This is based largely on the presence of deep features loading positively and characterising the cereal group, and the presence of areas of enamel displaying no features loading negatively and characterising the grassy-hay group (Table 4.19). The discriminating features show that the grassy-hay diet caused less abrasion than the cereal diet.

Figure 4.10 shows clear separation between the two groups and the percentage of samples correctly re-classified is 83% (cross-validated) (Table 4.20). By analysing the two dietary groups separately from the leafy hay group, the discriminant function distinguishes both groups and re-classifies most samples into their correct dietary group (Table 4.20).

4.3 Summary and evaluation of results

4.3.1 Fresh vs dried diets

The outdoor (fresh browse and graze) diets are characterised by more abrasive wear patterns, such as higher counts of features and deep features, compared to the dried diets, which display features such as smooth surfaces. This distinction was demonstrated in the analysis comparing broad dietary groups (e.g. ‘dried foddered’ versus ‘fresh’) as well as in analyses of narrower dietary groups comparing fresh and dried counterparts (e.g. graze versus grassy hay). The differences in abrasion are likely to be caused by the fresh diets involving increased contact with soil particles compared to the “cleaner”, indoor dried diet, either because fresh browse and graze were both contaminated by air-or water-borne dust particles or, perhaps more parsimoniously, because browsers also grazed (and thus ingested soil particles at ground level) to some extent. This supports Mainland’s (2001) argument that grit particles rather than grassy phytoliths are the main abrasive agents.

4.3.2 Fresh browse and graze

The main distinction between the fresh graze and fresh browse groups was the presence of polished enamel surfaces found within the fresh browse group. This feature indicates that tooth-on-tooth attrition has smoothed the surface of the enamel, creating a polished effect. It is therefore indicative of a lower proportion of abrasive particles hard enough to mark the enamel compared to the graze group. This is again likely to be a consequence of grazing animals having increased dental contact with soil particles compared to browsers because the former feed closer to the ground most of the time and the latter more occasionally.

The limited difference in microwear between summer-graze and winter-graze was predominantly in the shape of features, with the former characterised by narrow more scratch-like shapes and the latter by fatter pit-like features. Likely reasons for this contrast are differences in the shape or size either of exogenous particles (e.g. finer summer dust compared to larger winter grit) or of abrasive phytoliths (e.g. between young summer and mature winter parts of grasses). The former explanation is most likely given the argument previously discussed for grit particles rather than phytoliths being the main abrasive agents.

The distinction between pasture qualities was likewise mainly due to higher numbers of scratches in the low-quality and longer features in the high-quality group. A higher number of scratches is to be expected within the low quality pasture as the “patchier” graze would increase contact with soil particles. The longer features seen within the higher-quality graze group may again be a consequence of the shape/size of the abrasive, but are likely to be a consequence of features overlapping, creating shorter dimensions, in the low-quality group. The results show a pattern where poorer and patchier pastures produce a higher number of abrasive features, again supporting previous arguments that grit is the main abrasive agent (Mainland 2001).

4.3.3 Dried fodder diets

The high number of pits distinguishing the leafy hay group is a common feature amongst the browse diets and, when compared to the fresh browse, the distinguishing feature was a difference in the direction of the features. This suggests a difference in the masticatory mechanisms for the two diets, possibly a consequence of different types of leaf and the addition of intermittent graze in the fresh browse group, or different masticatory actions needed for dried and fresh material. Further research would be needed to distinguish between these alternatives.

Interestingly, the cereal-fodder and leafy hay groups show higher levels of abrasion than the grassy hay group. The grassy hay group was consistently characterised as having areas of the enamel displaying no microwear features. This is caused by tooth attrition with no abrasive particles between the teeth that are hard enough to cause marks on the enamel, indicating a “clean” diet with low proportions of abrasives. Again this is consistent with Mainland’s argument that grass phytoliths play a far smaller role in the formation of enamel microwear than do ingested dirt or dust particles. Why cereal and leafy hay should cause more abrasion than grassy hay, however, is not clear. In the former case, some attrition may be due to the impact of the hard seeds on enamel surfaces, but some cereal was fed in milled form. Alternatively, grain destined for fodder may not have been cleaned of dust particles thrown up during harvest with heavy machinery; prior to mechanisation, manually harvested pulses required additional cleaning for human consumption precisely to avoid the risk of broken teeth (Halstead 2014, 80, 156). In the latter case, whereas grassy hay is mown close to the ground, leafy hay is mostly lopped a few metres higher up and there is no obvious reason why it should be more exposed to dirt during drying, storage or feeding. Since the leafy hay samples were collected in different locations from the cereal and grassy hay samples, the observed differences in abrasion may conceivably be related to contrasting stalling arrangements (old dry-stone barns/byres in the former case and modern brick/concrete structures in the latter).

4.4 Understanding animal diet and the cause of microwear patterns

One area of contention in debate surrounding the causes of microwear features has been the relative impact of exogenous mineral particles (dust, grit) and dietary silica phytoliths (Mainland 2003a; Sanson et al. 2007; Lucas et al. 2013; Hedberg et al. 2016). It is likely that both biotic and abiotic matter contributes to the formation of microwear features (e.g grass phytoliths causing scratches and exogenous particles causing enamel abrasion). A recent study has argued that dust particles do not cause enough abrasion to distort the distinction between browse and graze diets caused by biotic matter (Merceron et al. 2016). Merceron et al. (2016) found that dust replicating that of Harmattan windblown dust applied to clover (browse) and grass (graze) fodder did not affect the dietary signals using textural analysis, meaning the predominant cause of variability in browse and graze tooth wear was caused by the foodstuff itself and not the exogenous particles. The results from this chapter, however, support previous arguments that the leading cause of heavy tooth abrasion is the ingestion of grit particles seen in the fresh graze diet (Mainland 2003a). The occurrence of pitted features in both fresh browse and dried leafy hay also suggests that these are caused by the food itself rather than “contamination”.

The discrepancies between these two studies may be due to differences in methodology (e.g. recording and analysis of tooth surface texture vs. dental microwear) and/or in the size and abrasiveness of the exogenous particles (the fine “Harmattan” windblown dust vs. the grit particles consumed due to contact with ground soil).

The shape, size and orientation of microwear features recorded in this chapter, as well as their number, are also important discriminating factors between dietary groups, but the immediate causes of these differences need to be explored further before they can be reliably associated with seasonal or quality differences in pasture.

4.5 Comparisons with Mainland’s SEM analyses

All of the samples analysed in this chapter have previously been analysed using SEM by Ingrid Mainland. Although the groups examined in this chapter and in the previous SEM analyses do differ slightly (some samples were included/excluded for methodological reasons or issues of access), the same tooth and enamel band were examined in both studies. The microwear features recorded will also be different as the SEM examines teeth at high-magnification (500-640x) while the present study has used low magnification (40x). The variables recorded in Mainland’s study also differ to those used here as qualitative features were not recorded and two types of pits were recorded (ovoid and rounded) in Mainland’s study. However, the frequency of feature types (excluding the ovoid/rounded pit dichotomy), and their lengths and breadths were recorded in both analyses. While these issues complicate a direct comparison between the two sets of analyses, a comparison will help to clarify whether 1) low-magnification digital light microscopy (DLM) can replicate dietary discriminations seen at high-magnification (SEM), and 2) discriminations are based on similar microwear differences.

4.5.1 Browse vs graze (Mainland 2003a)

Distinctions between browse and graze groups are seen in both the present study and Mainland’s SEM analysis (2003a). Mainland presents three sets of discriminant analyses, using different combinations of variables and sheep and goat specimens to those used in this chapter.

The first analysis discriminates between a grazing group (only including the sheep from Lejre) and the browse group and achieved better discrimination (with 95% of samples correctly re-classified) than the present study (with 82%, cross-validated) (Mainland 2003a, Table 3). The additional grazers included in the present study may be a contributing factor to the lower re-classification rate, as the Greenlandic sheep in particular grazed on higher-quality pastures with low stocking levels.

The second analysis discriminates between four groups of grazers: Greenland, Orkney (not analysed here), Lejre and Scottish borders, and one browse group from Lejre. The overall percentage of samples correctly re-classified was 50%, reflecting the similarity of the various grazing diets (Mainland 2003a, Table 4).

The third analysis discriminates between three groups: a combined group of grazers (including the Orkney samples not analysed here), a browse group, and a leafy hay group. The overall percentage of samples correctly re-classified into their groups was 68%, the low percentage again probably reflecting the similarity between the browse diet and the added leafy hay group (Mainland 2003a, Table 6).

Overall, it is difficult to compare the results of the two studies directly due to the differences in the analyses undertaken. Comparison with the present study is most useful in the case of Mainland's first analysis, for which the overall percentage of correctly re-classified samples is 95%. The 82% of correctly re-classified samples in the present study is, given the inclusion of additional grazer groups, relatively high and suggests that the DLM method can produce results similar to those using SEM.

The variables that caused the most discrimination between the grazers and browsers in Mainland's analysis were the ratio of pits to scratches and the ratio of ovoid to rounded pits. The characterisation of grazers as having a higher proportion of scratches and browsers a higher proportion of pits has also been reported in previous low-magnification analysis of microwear from wild animals (Solounias and Semprebon 2002). However, the variable causing the most discrimination in the present study was the presence of polished surfaces, predominantly found in samples from the browse group. While the presence of polished surfaces was not recorded in the SEM study and the ratio of ovoid to rounded pits was not recorded in the present study, the ratio of pits to scratches was recorded in both. The low impact of the variable "pits to scratches ratio" in the present study may be caused by the additional graze groups analysed here, as these demonstrated a lower scratch count compared to other grazing groups ("high quality" grazers, table 4.13).

4.5.2 Seasonal pastures

The seasonal groups from Upernaviasurk, Greenland were analysed as winter and summer grazers in Mainland's SEM analyses (2001) and in this study, which also included grazers from the Scottish borders and Lejre. The overall percentage of samples re-classified into their correct groups was 84% (cross-validated) in Mainland's (2001, Table 2) study and 70% (cross-validated) in the present study, meaning the SEM method discriminated between the two groups better than the low-magnification method but again this may be due to the inclusion of additional grazing groups in the latter analyses.

The most discriminating variables selected by the SEM analysis were the length and breadths of ovoid pits and ratio of ovoid to rounded pits (Mainland 2001). These variables indicate a difference in pit shapes much as does the variable length:width ratio, which best discriminates between the two groups in the present study.

4.5.3 Pasture quality

Mainland's (2006) study included low-quality grazers from Orkney and Lejre and high-quality grazers from the Scottish borders and Greenland, while the present study included the groups from Lejre, Scottish borders and Greenland, but not the Orkney sheep. Moreover, Mainland's analysis compares three diets, including leafy hay/cereal fodder as well as the two grazer groups. The overall percentage of samples correctly re-classified into their groups is 75% in Mainland's (2006, Figure 2) and 73% (cross-validated) in the present study. These results are very similar, but the additional fodder group in Mainland's analysis complicates comparison.

The most discriminating variables selected by Mainland's analysis were the ratio of pits to scratches and the frequency of rounded pits, with a higher ratio of pits and higher frequency of rounded pits in the high-quality graze than in the leafy hay/cereal and low-quality graze groups. In the present analysis, the low-quality graze group was characterised by higher counts of scratches and frequency of uneven surfaces. Two of the variables (uneven surfaces and rounded pits) were only recorded in one of the analyses, but contrasting frequencies of pits and scratches were found in both analyses, indicating that low-quality pasture causes higher proportions of scratches to pits and high-quality pasture the reverse at both high and low magnifications.

4.5.4 Fresh and dried diets

Grassy hay and fresh graze:

Mainland's doctoral thesis (1994) compared the microwear of two dietary groups from Scotland: grazers and grassy hay (small sample size n=5) using the same qualitative variables as the ones recorded in this study, but the two dietary groups are different from those analysed here (grazers and grassy hay sheep from Greenland). Mainland's analysis re-classified 100% of the grazers and 60% of the grassy hay samples into their correct groups. These groups were analysed multiple times using quantitative variables, with the best results showing 78% of the grazers and 80% of the grassy hay samples correctly reclassified, but the visual separation of the two groups is described as "poor" (Mainland 1998b, 1262).

In 2001 (Table 2), Mainland compared the grazer and grassy hay groups from Greenland using quantitative variables, but found poor separation between the groups with an overall 66% of samples correctly re-classified. These two groups are also analysed in this study, but with the addition of the Scottish border sheep to the grazer group, resulting in a higher overall percentage of samples correctly re-classified (cross-validated: 81%), which may be attributable to the combined analysis of both qualitative and quantitative variables as well as the different groups of grazing and grassy hay samples analysed.

The qualitative variables selected in Mainland's analyses characterise the grassy hay group as having porous surfaces, while the grazers were characterised by presence of abraded surfaces, deep features, an absence of enamel surfaces devoid of features, and features with an anterior-posterior orientation (Mainland 1994, 290). No differences were found using the quantitative variables in either analyses of the grassy hay and grazer groups (Mainland 1998b, 1264; 2001, Table 2). The presence of deep features was also selected by the present analysis to characterise the grazer group, but the presence of porous surfaces was associated with grazers. Porous surfaces have also been seen on a very small number of grazing samples from Greenland (Mainland 2001) and grassy hay samples from Scotland (Mainland 1994), suggesting that it may not be a reliable indicator of a grassy hay or fresh graze diet.

Fresh browse vs dried leafy hay:

The leafy hay dietary group from Plikati was compared to fresh graze and fresh browse groups in Mainland's (2003a, Table 6) analysis. The leafy hay group demonstrated a good separation from the other two groups with 77% of the samples correctly re-classified, but the percentage of all groups correctly reclassified was lower (69%) due to overlapping of the grazer and browser groups. The overall percentage of samples correctly re-classified in this study was higher at 81% (cross-validated), but again the additional group of grazers in Mainland's analysis makes direct comparison difficult.

The variables selected by Mainland's analysis characterised the leafy hay group as having higher feature counts and smaller feature dimensions (2003a, 1520), while those selected by this study characterise the leafy hay group as having a lower number of scratches and different orientation of features. Number of scratches and dimension of features are potentially related variables, in that shorter features are more likely (depending on the length:width ratio) to be classified as pits instead of scratches, but it must be noted that, given recording at very different magnifications, absolute feature dimensions are much smaller in Mainland's analysis than in the present study.

4.5.5 Fodder

Mainland's (2003b) article compares three groups: the cereal dietary group (from Assiros, Greece) with the leafy hay group (Plikati, Greece) and a grazer group (Scottish borders). The analysis shows a good distinction between the groups with an overall re-classification percentage of 82 % (69% leafy hay and 79% cereal correctly re-classified) (Mainland 2003b, Table 3.2). In the present study, comparison of the leafy hay, cereal and grassy hay groups produced a lower overall percentage of samples correctly re-classified (cross-validated: 71%) with 62% of leafy hay and 82% of cereal samples correctly re-classified, but perhaps because of the addition of grassy hay samples in place of fresh grazers since the grassy hay group could not be distinguished successfully from the leafy hay group.

The variables selected by Mainland's analysis as characterising the leafy hay group were a higher number of features and scratches with anterior-posterior orientation. The variables selected by the analysis in this study included a higher pit count in the leafy hay dietary group. These variables are to some extent similar with more features being recorded from the leafy hay group, but orientation was not selected as a useful discriminating variable in this chapter's analysis.

Mainland's PhD thesis (1994) also explores the differences between a grassy hay dietary group from Scotland (not studied in this thesis) and the leafy hay group from Plikati, using qualitative and quantitative variables in two separate analyses. The qualitative analysis successfully re-classified 100% of the samples into their correct group, while the quantitative analysis successfully re-classified 95%. Similarly, the analysis of the grassy hay group (Greenlandic) and the leafy hay group in this study successfully reclassified 91% of the samples into their correct group.

The qualitative variables selected by the analysis in Mainland's thesis were presence of porous features, polish and the partial exposure of underlying enamel structure, characterising the grassy hay group, and the presence of deep features, characterising the leafy hay group (1994, 242). The main quantitative variable distinguishing the two groups from each other was the higher number of 'medium' scratches present in the leafy hay group (Mainland 1994), while the variables selected by the analysis in this study characterised the grassy hay group as having areas of enamel without microwear features present. There may be a relationship between this variable and qualitative variable "presence of polish" in Mainland's study because both may result from tooth-on-tooth attrition erasing previous features and causing a polished surface. The grassy hay groups used in the two studies are not the same, however, so the comparison must again be treated with caution.

4.6 Conclusions: Can low-magnification, digital light microscopy replicate SEM analysis?

While direct comparisons were difficult due to differences of method and sample composition between this study and Mainland's SEM analyses, the digital light microscopy method identified dietary signatures of most dietary groups and the discriminant analyses correctly re-classified them with similar percentages to previous SEM analysis.

4.7 Is the digital light microscopy method suitable for analysing archaeological samples?

The results have shown that dietary groups can be distinguished, on the basis of microwear patterns that are in many cases similar to those found in previous SEM studies. That the discriminating variables are often similar between the two levels of magnification, and also can often be related plausibly to known functional characteristics of the diets under comparison, supports the view that dental microwear analysis, and more particularly the digital light microscopy method, can reliably be deployed in exploring the diets of sheep and goats found in archaeological contexts. Some apparent contradictions between the SEM and light microscope methods of analysis can plausibly be attributed to differences in the sample groups included in some analyses, but other discrepancies are probably due to contrasts in what is observed at such different scales of magnification. This highlights the need for dental microwear patterns captured by light microscopy to be interpreted in the light of similar analyses on modern teeth of known diet rather than by extrapolating from the results of SEM-based analyses of data captured at much higher magnification.

The difficulty in separating all the modern diets examined within one comparative analysis (4.2.1) means that, a sequence of discriminant functions distinguishing first more broadly and then more narrowly defined dietary groups is needed to classify the archaeological samples (of unknown dietary history). This provides potential complications when identifying ancient diets as the performance of multiple analyses comparing progressively narrower dietary ranges may erroneously exclude 'minority' diets. In exploring archaeological samples, therefore, the potential pitfalls of such multiple analyses must be borne firmly in mind.

CHAPTER 5: RESULTS 2

DENTAL MICROWEAR OF ARCHAEOLOGICAL SHEEP AND GOATS FROM TOUMBA KREMASTIS-KOILADAS, MAKRIYALOS AND KNOSSOS

This chapter presents dental microwear results from sheep and goats found in Late Neolithic contexts at Toumba Kremastis-Koiladas (TKK), Makriyalos (MK) and Knossos (KN). The archaeological results are compared to modern sheep and goats of known and controlled diets (see Chapter 4) using discriminant analysis (DA). The aim of these analyses is to investigate inter- and intra-site variation in diet and livestock management. This chapter firstly explores differences between sites by comparing results from all samples. It then explores results from each site individually, investigating contextual variation at TKK and MK, and diachronic variation at KN. Due to the limited sample sizes of goats, inter-species variation is only explored at TKK.

5.1 Background: comparing archaeological samples to ethnographic results

Chapter 4 concluded that the low-magnification, digital light microscopy (DLM) method was robust enough for application to archaeological material, although multiple analyses would be needed to separate diets most similar to each other (e.g. fresh browse and dried leafy fodder). It is, therefore, important to bear in mind the following limitations and resulting strategies for exploring the dental microwear results of archaeological samples:

1) DA of ethnographic diets including fresh graze, fresh browse, dried leafy hay, cereal fodder and dried grassy hay has a low reclassification rate (56% see chapter 4.2.1), as fresh and dried browse, and cereal and grassy hay could not be separated when all five ethnographic diets were compared in one analysis. The archaeological samples will instead be compared to the DA of two broad ethnographic dietary groups (dried fodder and fresh graze/browse), as this had a higher reclassification rate (Table 4.4).
2) In DA of dried fodder (cereal fodder, leafy hay and grassy hay combined) and fresh diets (fresh graze and browse combined) (see chapter 4.2.2), a high number of leafy hay samples were reclassified as 'fresh' meaning a separate analysis of fresh browse and dried leafy hay is needed to distinguish these two diets.
3) DA of fresh graze, comparing summer and winter (see chapter 4.2.6) or high-quality and low-quality pasture (see chapter 4.2.7), has relatively low success at

reclassifying samples (70% and 73% respectively). It is, however, useful to compare archaeological material to these four ethnographic sample groups as a guide to how abrasive is the material consumed and thus to pasture cover/quality.

5.2 Results: inter-site comparisons of TKK, MK and KN

5.2.1 Comparing all sites to all ethnographic dietary groups

Figure 5.1 is a plot of archaeological samples from all three sites compared to the DA of two ethnographic dietary groups 'fresh' (including fresh browse and fresh graze) and 'fodder' (including dried grassy hay, dried leafy hay and cereal fodder). The results presented in this plot show differences and similarities between the sites:

TKK: samples from TKK are distinct from the other two sites, with the majority of samples plotting among the ethnographic fodder group and very few samples falling clearly among the ethnographic fresh diets (Figure 5.1). Only a small number of samples have been classified as having a diet most similar to the ethnographic fresh diets with the large majority being classified as fodder (Table 5.1).

MK: samples from MK plot (Figure 5.1), and are classified (Table 5.1), relatively evenly between both ethnographic dietary groups with Figure 5.1 showing more clustering around the ethnographic fodder group.

KN: similar to MK, samples from KN plot (Figure 5.1), and are classified (Table 5.1), relatively evenly across both ethnographic dietary groups. Eight samples from KN plot beyond the range of modern fresh samples among the outlying samples from modern fodder groups. These samples may represent a type of diet not represented by the ethnographic diets in the analysis.

To summarise the results from comparing archaeological samples to fresh and fodder diets:

- Both the plots and classification results indicate that the sheep and goats from TKK were mostly foddered, distinguishing the site from KN and MK where more fresh graze/browse was also identified.

5.2.2 Comparing archaeological 'fodder' samples from all sites to ethnographic fodder groups

Figure 5.2 is a plot of archaeological samples previously classified as fodder (Table 5.1) from three sites, TKK, MK and KN, compared to the DA results of three ethnographic dietary groups: cereal fodder, dried leafy hay and dried grassy hay. The results show similarities between the three sites:

TKK + MK + KN: the majority of samples from all three sites fall among the grassy hay and cereal groups. Few samples from TKK and KN, and none from MK, plot close to the leafy hay centroid. The samples clustering on the positive end of function 2 (between 2 and 3 on the y axis) plot beyond the ethnographic grassy hay samples, indicating a dietary group or mixed diet not represented by the ethnographic foddered groups. The archaeological samples plotting towards the negative end of function 2 and neutrally on function 1 may also indicate an unknown diet or, as is likely to be the case with foddered animals, these ancient animals had a mixed diet. The similarity between the three sites is also shown in the classification results (Table 5.2) as the majority of samples from all three sites are classified as having diets most similar to grassy hay and cereal fodder, with only a minority attributed to dried leafy hay.

To summarise the results of comparing the archaeological 'fodder' samples to three ethnographic fodder groups:

- all sites have low percentages of leafy hay diets, suggesting that dried leaves were not commonly used at these sites.
- plots of some of the archaeological samples suggest that some ancient sheep and goats had diets diverging from the fodder diets represented in the ethnographic groups.

5.2.3 Comparing archaeological 'fresh' samples from all sites to ethnographic fresh graze and fresh browse groups

Figure 5.3 is a plot of archaeological samples previously classified as fresh pasture (Table 5.1) from three sites, TKK, MK and KN, compared to the DA results of two ethnographic dietary groups: fresh graze and fresh browse. The results show similarities and differences between the three sites:

TKK + MK: the majority of archaeological samples plot among the ethnographic fresh graze samples with very few samples from TKK and MK plotting among the ethnographic browse samples.

KN: A higher proportion of samples from KN plot among the ethnographic browse samples compared to the other sites, but the majority of samples from KN also plot among the ethnographic graze samples. The sample size at TKK is too small for reliable comparison of the classification results (Table 5.3) with KN and MK, but there is an evident contrast between the latter two sites, with a larger proportion of samples classified as fresh browse at KN.

To summarise the results of comparing the archaeological 'fresh' samples to ethnographic fresh (browse/graze) dietary groups:

- KN is the only site with many samples similar to the ethnographic fresh browsers;
- the majority of samples from MK were similar to the ethnographic fresh grazers; and
- the TKK sample size is very small but is tentatively similar to MK with the majority of samples also matching the ethnographic grazers.

5.3 Summary and discussion: inter-site comparisons of TKK, MK and KN

TKK presented the most distinctive results with the diet of young sheep and goats being overwhelmingly most similar to dried fodder, whereas KN and MK showed a mixture of both fresh and foddered diets. For the predominance of foddering of young animals at TKK, two obvious explanations present themselves. First, the site is located in a land-locked inland basin at an altitude of 660 m above sea-level and so is exposed to much harsher winters than Makriyalos or Knossos, which are both close to the coast and sea-level. The prevalence of foddering might thus reflect slaughter and consumption of these animals during winter when fresh browse or graze was scarce (but see below). The higher proportions of fresh diets at MK and KN might then reflect the milder winters and lesser need for foddering at these sites, or the sampling of animals slaughtered and consumed over a longer period of the year, or a combination of both factors.

Secondly, much of the TKK faunal assemblage is derived from evident structured depositions, which may have been associated with formal feasting events (Tzevelekidi 2012), while macroscopic dental analysis has shown contextual differences in the speed of tooth wear, that suggest dietary differences between animals deposited in different types of contexts (Tzevelekidi 2012). The prevalence of foddered diets at TKK might thus alternatively be related to the fattening of livestock for slaughter at ceremonial occasions. In this case, the greater representation of fresh graze/browse at KN and MK might indicate that the samples analysed from these two sites were drawn from a wider range of less ceremonial consumption episodes or that fattening of livestock prior to ceremonial slaughter was less routine.

The majority of foddered sheep and goats at all three sites, however, have diets similar to grassy hay and cereal, suggesting that the use of soft/non-abrasive fodder for young sheep and goats was widespread and common during the Late Neolithic period. While these diets might represent the overwintering of animals, this is arguably a little implausible for KN, given the mildness of coastal Cretan winters, favouring fattening for consumption as previously argued on the basis of (SEM-derived) dental microwear data for MK (Mainland and Halstead 2005). In fact, macroscopic zooarchaeological evidence for the preparation of large carcass portions and deposition of animal bones in very large quantities provide evidence of large-scale sharing of meat at all three sites (Isaakidou 2004; Tzevelikidi et al 2014; Pappa et al. 2004). Meat with high fat content – such as young sheep and goats fattened on cereal – would have been a highly valuable resource to Neolithic farmers intensively labouring (Halstead 2007, 27). The fattening of these animals, if confirmed, across all three sites in different regions would also indicate management strategies or cultural values shared over great distances.

There is an absence of leafy browse diets at TKK and MK but a number of samples were classified as fresh browse or leafy hay at KN. The collection of leafy fodder (dried and fresh) to feed sheep and goats was an important management technique in Greece in the recent past (Halstead 1998) and is referred to in classical literature:

"…Daphnis was not with his flock: for he had gone up to the wood to cut some green branches to serve as fodder for the kids during the winter" (Daphnis and Chloe by Longus, 2nd Century AD).

If the browse diets at KN do reflect the collection of leafy hay, this would imply the availability of labour to cut and manage trees suitable for hay (Halstead 1998), while conversely lack of sufficient labour might account for the absence of this diet at MK and TKK. Due to the intensive labour needed to collect leafy hay, however, it is usually restricted to higher altitudes in northern Greece where, unlike Crete, harsh winters may make fresh graze and browse unavailable or inaccessible for long periods (Halstead 1998). It is therefore more likely that the sheep at KN consumed fresh browse.

The identification of some browse-like diets at KN reflects the overall greater breadth of diets at the site compared to TKK and MK, which in turn may mean that livestock ranged further afield or at least in more diverse pastures at KN than at the other two sites. One important consideration here, that would certainly have facilitated the mobility of livestock on Crete, will have been the absence of predators (Isaakidou 2004), in contrast with the northern Greek mainland where wolf, bear and lynx roamed. Another possibly significant dietary difference will have been the greater abundance of evergreen trees and bushes in the vicinity of Knossos on southerly Crete (Badal and Ntinou 2013) than around north Greek MK and TKK (Marinova and Ntinou 2018). Moreover, because summer drought is both more severe and of much longer duration on Crete than in the northern mainland (Isaakidou 2008, 100 Figure 6.3), livestock from Knossos are more likely to have browsed evergreens in the summer months, when grassy pasture dried up.

5.4 Results: comparing contexts and species at TKK

5.4.1 Comparing TKK pit and ditch contexts to all ethnographic groups

Figure 5.4 is a plot of the same samples from TKK compared to the discriminant analysis results of two modern dietary groups: fresh diets (combining fresh graze and fresh browse) and dried fodder (combining cereal fodder, leafy hay and grassy hay). There is a contrast between the two context types as the majority of samples from pits and ditches plot among the fodder group, but a few samples from ditch contexts also plot among the fresh dietary group. Table 5.4 shows the classification results from the analysis presented in Figure 5.4. The results from ditch contexts are classified almost evenly between ethnographic fresh and fodder diets, while samples from pit contexts are overwhelmingly attributed to fodder with only one sample classified as fresh. Table 5.5 presents the classification results of sheep and goats separately. There is no dietary contrast between species within the pit contexts. In the ditches, the cases attributed to fresh pasture are all sheep (outnumbering fodder-fed sheep), but small sample size again dictates caution in interpreting these results.

Although the small size of the ditch sample demands caution, the contrasting proportions of fresh diets between pits and ditches are worth considering in the light of dental evidence for the seasons of slaughter represented. Because age of tooth eruption is less variable than speed of tooth wear (e.g. Jones 2006), age and thus season of slaughter is most reliably estimated for these young animals on the basis of the eruption and early wear stages of the permanent molars (M1 and M2) rather than the advanced wear stages of the deciduous dP_4. At least in the case of sheep M1, there is a contrast between pits, with wear concentrated at Payne's (1987) stages 2A and 7A with relatively few cases between, and ditches, with cases well represented in stages 5A and 7A (Tzevelekidi 2011, 170 Figure 5.20). Adopting Jones' (2006) figures for the relationship between wear and age in modern British sheep on a variety of pastures, this implies that first-year deaths (the most precisely ageable) were numerous at 3-5 (wear stage 2A) and 8-11 (stage 7A) months in the case of pits and at 6-10 (stage 5A) and 8-11 months in the case of ditches. If lambing took place in January-February, as in the recent past in northern Greece (Halstead 2005), then ‘pit lambs’ were mainly slaughtered in spring-early summer and autumn-winter, while ‘ditch lambs’ were slaughtered from mid-summer or autumn onwards. Thus, the larger pit sample (certainly) and the smaller ditch sample (probably) include a significant proportion of first-year deaths *outside* winter, confirming that the predominance of foddered diets at TKK cannot plausibly be attributed to the animals studied having been slaughtered only in winter.

To summarise the comparison of TKK samples with ethnographic dietary groups:

- There is some evidence for contextual variation, with samples from ditch contexts showing a broader range of diets, including fresh browse/graze, while samples from pit contexts have overwhelmingly foddered diets.
- Consideration of macroscopic dental evidence for seasons(s) of death indicates that the lambs deposited in pits and perhaps ditches were not killed only or even mainly in winter, ruling out the need to overwinter livestock as the only reason for the predominance of foddered diets.
- There is no evidence for dietary variation between species in pit contexts.

5.4.2 Comparing archaeological ‘fodder’ samples from different TKK contexts and species to ethnographic fodder groups

Figure 5.5 is a plot of TKK samples from pit and ditch contexts, previously classified as fodder (Table 5.4), compared to the discriminant analysis results of three ethnographic dietary groups: cereal fodder, dried leafy hay and dried grassy hay. The results show no clear differences between the two contexts with the majority of samples plotting neutrally and among the grassy hay and cereal fodder samples.

Table 5.6 shows the classification results from the analysis presented in Figure 5.5. While the majority of samples from pit contexts have been classified as having microwear patterns most similar to the ethnographic grassy hay and cereal fodder diets, the few samples from ditch contexts (pit n=35, ditch n=7) have been classified almost evenly across the three fodder types.

Table 5.7 presents the classification results of sheep and goats separately. The results show no clear dietary difference between species with the majority of sheep and goats classified as grassy hay and cereal fodder consumers. The only samples attributed to leafy hay were sheep but the sample size for goats is small and especially in ditch contexts (pits: sheep n=25, goats n=10; ditches: sheep n=4, goats n=3).

5.4.3 Comparing archaeological 'fresh' samples from different TKK contexts and species to ethnographic fresh graze and fresh browse groups

The number of samples previously classified as 'fresh' (Table 5.4 is too small (n=6) to explore dietary variation between contexts and all samples previously classified as having a fresh diet are sheep.

5.4.4 Comparing archaeological 'fresh graze' samples from different TKK contexts and species to ethnographic grazers: winter graze and summer graze; and high- and low-quality pasture

Figure 5.6 is a plot of TKK samples from pit and ditch contexts, previously classified as grazers (Table 5.3), compared to the discriminant analysis results of two ethnographic dietary groups: winter graze and summer graze. While the overall sample size is too small to explore contextual variation (ditch n=5, pit n=1), a comparison between the archaeological and ethnographic samples shows that the majority of TKK samples plot closer to the winter grazing group. Table 5.8 presents the classification results from the analysis presented in Figure 5.6, and shows that all of the samples have been classified as having microwear patterns most similar to the ethnographic samples grazed in winter. Although the modern winter samples from northern Europe may be a better match for a different season in the Mediterranean lowlands, they may be more relevant comparanda for Neolithic TKK, given its upland and land-locked location, than for KN or MK

Figure 5.7 is a plot of the same samples from TKK previously classified as grazers (Table 5.3), compared to the discriminant analysis results of two ethnographic dietary groups: high- and low-quality graze. Again, the overall sample size is too small to compare dietary variation between contexts, but the comparison of archaeological and ethnographic samples shows that the majority of those from TKK are most similar to sheep grazing on high-quality pasture. Table 5.9 presents the classification results from the analysis presented in Figure 5.7. The majority of samples have been classified as having microwear patterns most similar to ethnographic samples grazed on high-quality pasture. The only sample plotting among, and classified as having a diet of, low-quality graze is the single sample from a pit context.

To summarise the results of TKK fresh graze samples compared to ethnographic grazer groups:

- the TKK samples demonstrate wear similar to ethnographic sheep grazed in winter.
- the majority of samples were similar to ethnographic sheep grazed on high-quality pasture.
- the only sample demonstrating heavily abraded wear similar to the ethnographic sheep grazed on poor and highly utilised pasture was from a pit context.

5.4.5 TKK summary of results and discussion: dietary variation between contexts and species

Due to the small sample size of goats, dietary variation between species can only really be explored for pit contexts, where no differences in diet were detected between sheep and goats. More specifically, foddered diets predominate, particularly in pit contexts. The results suggest that fodder similar to grassy hay and cereal grain (soft, low abrasive foods) was used to feed young sheep and goats at TKK, probably to fatten them before consumption rather for overwintering. This is supported by a high frequency of sheep and goats at TKK having 'penning elbow' pathologies potentially indicative of rapid weight-gain as a result of fattening (Tzevelikidi et al. 2014). The use of fodder suggests that these young animals were kept in small groups close to or within the site, and the low-abrasion microwear suggests they were not also feeding heavily off fresh grass. Keeping young livestock within the site and possibly indoors has the added advantage of providing protection against predators.

The small sample size from the ditch contexts makes it difficult to compare contexts but the results show a possible contrast between pits and ditches with a higher proportion of fresh browse/graze found in the latter. This contrast, if valid, again reflects the greater tendency for the young sheep/goats found in pit contexts to have been fattened on softer foods prior to slaughter. The sheep from ditch contexts classified as having grazing diets, however, were apparently fed on high-quality pasture compared to the over-grazed, heavily utilised pasture available to some of the ethnographic samples. In other words, both the mainly fodder-fed animals from the pits and those from the ditches that spent their last days grazing seem to have been fattened for consumption.

Previous analysis of the faunal remains at TKK has highlighted contextual variation between pits and 'other' contexts, including in macroscopically assessed rates of tooth wear, with sheep in pit contexts having a more abrasive diet than those found in 'other' units

(Tzevelekidi 2012). Pit contexts also display more intensive carcass dressing than ‘other’ units (Tzevelekidi 2015), indicating differences not only in how livestock were reared, but also in how their carcasses were prepared for consumption in the commensal events represented by the two types of depositional context. These differences, together with the evidence for structured deposition in pit contexts, have been associated with contrasting degrees of formality between consumption events (Tzevelekidi 2015). The ‘other’ contextual units are not explored in this thesis, but the contrasting management practices evidenced here between pits and ditches by dental microwear data are paralleled by the dietary differences between pits and ‘other’ contexts indicated by macroscopic rates of tooth wear.

5.5 Results: comparing contexts and species at MK

5.5.1 Comparing MK pit, ditch and habitation contexts to all ethnographic groups

Figure 5.8 is a plot of all MK samples from pit (i.e. the large borrow pits 212 and 214 filled with large quantities of ‘feasting’ debris), habitation and ditch contexts compared to the discriminant analysis of two ethnographic dietary groups; fodder (including leafy hay, grassy hay and cereal) and fresh (including browse and graze). The pit and habitation samples fall across the full range of both fodder and fresh ethnographic groups, with a slightly higher proportion of samples from habitation contexts plotting among the fodder group and, more tentatively, the opposite trend among pits. In contrast, the majority of ditch samples fall among the ethnographic fodder group with few falling neutrally and one outlying sample plotting on the positive axis beyond the modern fresh samples.

Table 5.10 provides the classification results from the discriminant analysis presented in Figure 5.8. Slightly more samples from pit contexts have been classified as having diets most similar to fresh pasture rather than dried fodder, while habitation contexts again exhibit the reverse pattern. The majority of samples from ditch contexts have been classified as fodder with a small number classified as fresh.

Table 5.11 show the dietary classifications of sheep and goats from pit contexts. The sample size of goats is too small in ditch and habitation contexts (both n=2) for interspecies comparisons. While also having a small sample size, the goats found in pit contexts (n=4) show no variation in diet compared to the sheep found in the same contexts.

To summarise the comparison of MK samples to all ethnographic dietary groups:

- there is some variation between the three context types with samples from ditch contexts exhibiting fewer examples of fresh diet than do samples from pit and habitation contexts.
- pit and habitation contexts showed similar dietary variation, but slightly more pit samples were classified as fresh graze/browse and slightly more habitation samples as fodder.

5.5.2 Comparing archaeological 'fodder' samples from different MK contexts and species to ethnographic fodder groups

Figure 5.9 is a plot of archaeological samples from MK previously classified as fodder (Table 5.8) compared to the DA results of three modern dietary groups: cereal fodder, dried leafy hay and dried grassy hay. The results show some contextual variation with samples from pit contexts plotting differently to the samples from habitation and ditch contexts. The majority of the samples from the habitation and ditch contexts plot among the grassy hay and cereal samples. The samples from pit contexts plot among the grassy hay and cereal group but also neutrally, towards the leafy hay group. Two samples from the pit contexts also plot outside the range of leafy hay and cereal samples, perhaps showing a diet (mixture) not represented by the ethnographic groups used in the analysis.

Table 5.12 shows the classification results from the analysis presented in Figure 5.9. The classification results show no contextual variation. The majority of samples from all three contexts have been classified as cereal and grassy hay, in fairly balanced numbers, and only one sample from a pit context is classified as leafy hay.

The slight discrepancy between the variation seen in Figure 5.9 and the classification results in Table 5.12 is probably due to some samples from pit contexts plotting neutrally between, and outside the range of, the ethnographic groups, implying a mixed diet or one not represented by the modern samples.

The sample size of goats from MK classified as fodder is too small (total across all contexts n=5) to explore variation between species.

5.5.3 Comparing archaeological 'fresh' pasture samples from different MK contexts and species to ethnographic groups: fresh graze and fresh browse

Figure 5.10 is a plot of MK archaeological samples previously classified as fresh feeders (Table 5.10), compared to the DA results of two modern dietary groups: fresh graze and fresh browse. There is limited variation between the three context types as the majority of samples from all contexts plot negatively among the ethnographic fresh graze group, and only two samples from habitation contexts plot positively among the ethnographic fresh browse samples.

Table 5.13 shows the classification results from the analysis presented in Figure 5.10. The results match the patterns detected visually in Figure 5.10 with no clear variation between contexts apart from the two habitation samples classified as fresh browse.

The sample size of goats in this analysis is too small to explore variation between species (total across contexts n=3), but it is noteworthy that the two samples classified as having diets most similar to fresh browse are sheep and not, as might be expected, goats.

5.5.4 Comparing archaeological 'fresh graze' samples from different MK contexts and species to ethnographic grazer groups: winter graze and summer graze; and high-quality and low-quality pasture

Figure 5.11 is a plot of archaeological samples from MK previously classified as having a diet most similar to fresh graze (Table 5.13) compared to the DA results of two ethnographic dietary groups: winter graze and summer graze. The results show no clear contextual variation. The majority of samples from all contexts fall among the winter graze samples. Two samples from pit and habitation contexts plot negatively beyond the range of the ethnographic samples, indicating a comparatively abrasive diet. Five samples from pit and habitation contexts plot neutrally between the two modern graze groups.

Table 5.14 shows the classification results from the analysis presented in Figure 5.11. The results reflect those discerned visually in Figure 5.12 with no clear variation seen between contexts. The majority of samples from all contexts have been classified as having diets most similar to the winter grazer group, with only three samples from pit and habitation contexts classified as summer grazers. As noted for TKK, it is uncertain how these seasonal categories should be 'translated' in the context of coastal north Greek MK.

Figure 5.12 is a plot of the same samples from MK previously classified as having a diet most similar to fresh graze (Table 5.13) compared to the DA results of two further modern dietary groups: high- and low-quality graze. The sample sizes for the three contexts within this analysis are uneven, with habitation and ditch contexts having smaller sample sizes than the pit contexts (n=5, n=3, n=16 respectively) making it difficult clearly to detect variation. Samples from pit contexts, however, tend to plot towards the positive end of the axis among the ethnographic low-quality graze samples with four samples plotting beyond the low-quality range suggesting heavily abraded wear. Samples from habitation contexts plot neutrally between both ethnographic group centroids. The only sample plotting negatively among the high-quality graze is from a ditch context, while the two other samples from this context group fall positively, again beyond the range of modern low-quality graze samples.

Table 5.15 shows the classification results from the analysis presented in Figure 5.12. All except four of the MK samples have been classified as having diets most similar to the low-quality graze. The habitation and ditch contexts have the highest proportions of samples classified as high-quality graze but the sample sizes for both are very small (n=5, n=3).

The sample sizes of goats within these analyses are too small to explore dietary variation between species (n=3).

To summarise the results of comparing MK 'fresh graze' samples to ethnographic grazer groups:

- The majority of samples from MK show heavily abraded wear patterns, implying animals that grazed on poor-quality pasture, possibly representing overstocking or grazing in a season unfavourable to plant growth (presumably mid-winter or mid-summer).
- Abrasion was particularly heavy on samples from pit and ditch contexts, while the small sample from habitation contexts perhaps shows less abraded wear.

5.5.5 MK summary of results and discussion: dietary variation between contexts and species

The results from microwear analysis of MK samples showed both similarities and differences between the three context types: pit, ditch and habitation. Overall, the sample from MK included very few with diets similar to the ethnographic fresh and dried browse, suggesting that leafy foddering and browsing in the surrounding woodlands were not common strategies for feeding young sheep/goats at MK. In all contexts, the foddered samples were most similar to the ethnographic cereal and grassy hay dietary groups, and the samples likely to have been grazed on fresh pasture were most similar to the ethnographic group grazed on patchy grassland in 'winter'.

The apparent use of cereal fodder within all contexts suggests fattening may have been more common at MK than previously thought. Dental microwear analysis on a smaller sample had associated the use of cereal fodder with pit contexts (Mainland and Halstead 2005), but the results from this thesis have identified this type of diet in all context types. The fattening of young animals in both smaller-scale 'domestic' and large-scale commensal events suggests that fattened animals were important at both. The conversion of grain to a more stable meat resource was coined by Flannery (1969) as indirect storage. This management strategy may also have considerable social significance if fattened animals are shared at or donated to commensal events (see definition of *social storage* in Halstead and O'Shea 1982, 92). The public distribution of these animals could have helped a farmer to acquire social prestige (through demonstration of skill in the production of fattened livestock); fulfil/create reciprocal debts and obligations (Mauss 1954, 15; Dietler 2011, 181-183); and would have been highly valuable in mitigating agricultural risk (e.g. crop failure, labour shortage) and reinforcing relationships of solidarity within and between farming communities (Halstead and O'Shea 1982; Halstead 1999, 82-84).

While the microwear results have shown similarities between contexts in the types of food consumed by sheep and goats at MK, they have also produced some evidence for variation. The ditch contexts differed from the pit and habitation contexts in having a comparatively higher proportion of foddered diets to fresh ones. It is possible that season of slaughter/consumption differs between contexts, with animals found in ditch units being slaughtered predominantly at times of scarce pasture (requiring supplementary foddering), but the small sample size from ditch contexts must also be noted.

The question of seasonal livestock mobility at MK was raised previously due to a lack of archaeobotanical evidence in dung for summer grazing, interpreted as indicating that animals were grazed away from the site during the summer months (Valamoti 2007). At first sight, this interpretation is supported by the prevalence, among the teeth attributed on the basis of dental microwear to grazers, of 'winter' grazers – if the relevant microwear patterns can be translated directly from north European to Mediterranean vegetation contexts. On the other hand, the absence of archaeobotanical evidence for summer grazing could equally reflect seasonal variation in the penning/stalling of livestock and thus in the deposition of dung (Pappa et al. 2013, 79). Moreover, zooarchaeological evidence for the ages at which animals were killed imply on-site slaughter during most of the year, suggesting that animals were kept locally to the site (Pappa et al. 2013, 79). Analysis of $\delta^{13}C$ and $\delta^{18}O$ isotope values from sheep teeth at Makriyalos has also provided evidence that sheep were annually grazed within a relatively narrow local environment (Vaiglova et al. 2018). Furthermore, the mudbrick wall on the outer edges of the ditch enclosing MK has been compared to medieval deer parks by Mainland and Halstead (2005), with the proposed purpose of keeping livestock within the site. The microwear results from this chapter are compatible with young sheep and goats at MK being kept within the site to be foddered or grazed on patchy pasture within the settlement instead of being moved around the landscape to better pastures or browse. These results support previous arguments for close interdependence between livestock and arable farming, with the former grazing and manuring arable plots potentially within the site (Mainland and Halstead 2005, 111; Halstead 2011, 141-142).

Finally, the young sheep dP_4's analysed here include several specimens with preserved information on eruption and wear of M1 (pits n=16, habitation n=8, ditch n=5) and M2 (pits n=12, habitation n=8, ditch n=3). These associated molars indicate for each context type a more or less continuous sequence of dental development from initial wear to Payne's stage 9A in M1 and including eruption/initial wear of M2. With due allowance for small sample sizes, therefore, all three context types seem to include young sheep slaughtered more or less throughout their first year of life, implying that contextual differences in diet are not determined simply by season of death.

The sample size of goats at MK I was mostly too small for separate analysis, but exploration of dietary variations between sheep and goats found in pit contexts (see 6.5.1) found no differences in diet between the two species, perhaps indicating that they were raised together, a view largely supported by analyses of $\delta^{13}C$ and $\delta^{15}N$ values (Styring et al. 2015, Figure 3; Vaiglova et al 2018).

5.6 Results: comparing time periods at KN

Due to the small sample size of goats from KN, dietary variation between species will not be explored.

5.6.1 Comparing KN time periods (LNI-II, FNIA, FNIB and FNII-III) with all ethnographic groups

Figure 5.13 is a plot of KN samples from four time periods (LNI-II, FNIA, FNIB and FNII-III) compared to the discriminant analysis of two ethnographic dietary groups: fodder (including leafy hay, grassy hay and cereal) and fresh pasture (including browse and graze). Samples from all four periods plot both negatively, among the modern fodder group, and positively, among the modern fresh pasture group, in each case with a few more or less extreme outliers at the positive end of the axis, beyond the range of modern fresh diets. In common with the previous analysis, however, some dietary variation can be seen between the four periods. While the samples from LNI-II and FNIB are distributed fairly evenly between the ethnographic fresh and fodder groups, samples from FNIA are concentrated positively among the ethnographic fresh pasture samples and those from FNII-III mostly plot negatively towards the modern fodder samples.

Table 5.6, showing the classification results from the analysis presented in Figure 5.13, confirms the visual impression:

LNI-II: foddered diets with a slightly lower proportion classified as fresh.
FNIA: fresh diets with very few samples classified as fodder.
FNIB: both fresh and foddered diets with the latter slightly more frequent.
FNII-III: foddered diets with fewer classified as fresh.

5.6.2 Comparing archaeological 'fodder' samples from different KN time periods (LNI-II, FNIA, FNIB and FNII-III) to ethnographic fodder groups

Figure 5.14 is a plot of KN samples previously classified as fodder (Table 5.16) from four time periods (LNI-II, FNIA, FNIB and FNII-III) compared to the discriminant analysis results of three modern dietary groups (cereal fodder, dried leafy hay and dried grassy hay). For each period (excluding FNIA represented by only two samples), the majority of samples plots among the ethnographic grassy hay and cereal fodder groups, perhaps with a bias to grassy hay in FNII-III.

Table 5.17 shows the classification results from the analysis presented in Figure 5.14 and confirms the visual observations noted above.

5.6.3 Comparing archaeological fresh pasture samples from different KN time periods (LNI-II, FNIA, FNIB and FNII-III) to ethnographic fresh graze and fresh browse

Figure 5.15 is a plot of KN samples previously classified as fresh pasture (Table 5.16) compared to the discriminant analysis results of two modern dietary groups: fresh graze and fresh browse. There is no clear variation between the four time periods, with the majority of samples plotting among the ethnographic fresh graze group.

Table 5.18 shows the classification results from the analysis presented in Figure 5.15. The majority of samples from each time period have been classified as having microwear most similar to the ethnographic fresh graze diet.

5.6.4 Comparing archaeological fresh graze samples from different KN time periods (LNI-II, FNIA, FNIB and FNII-III) to ethnographic grazers: winter graze and summer graze; and high- and low-quality pasture

Figure 5.16 is a plot of KN samples from four time periods (LNI-II, FNIA, FNIB and FNII-III), previously classified as having a diet most similar to fresh graze (Table 5.18), compared to the discriminant analysis results of two ethnographic dietary groups (winter graze and summer graze). There is no diachronic variation in the season of grazing as the majority of samples from all time periods falls among the modern 'winter' grazed samples, with just one sample from LNI-II plotting among the modern 'summer' grazed samples.

Table 5.19 shows the classification results from the analysis presented in Figure 5.16. All except one sample from LNI-II have been classified as having microwear most similar to the ethnographic winter graze group. Particularly in the semi-arid case of central Crete, the apparent similarity with north European winter grazing microwear may be misleading and, if it reflects sparse pasture, might equally reflect archaeological specimens from summer grazers. Unfortunately the Knossos assemblage is heavily fragmented, in large measure due to post-excavation damage (Isaakidou 2004), but seven of the younger FN sheep specimens, that could be aged relatively accurately, are again distributed more or less throughout the first year of life and so offer no hint that seasonally selective slaughter has significantly shaped the dietary signals reflected in dental microwear records.

Figure 5.17 is a plot of the same KN samples from four time periods (LNI-II, FNIA, FNIB and FNII-III) previously classified as having a diet most similar to fresh graze (Table 5.18), compared to the discriminant analysis results of two ethnographic dietary groups: high-quality and low-quality graze. There is no diachronic variation in pasture quality for grazers as the majority of samples from all time periods plot among the ethnographic low-quality grazers, with some samples from FNIA, FNIB and FNII-III also plotting beyond the range of this modern group indicating comparatively heavy abrasive wear on these archaeological samples.

Table 5.20 shows the classification results from the analysis presented in Figure 5.17. The majority of all samples have been classified as low-quality graze with no variation between time periods.

5.6.5 KN summary of results and discussion: diachronic dietary variation

The results from the microwear analysis showed similarities and some differences between the four time periods. The results showed no changes in the types of fodder consumed, with the majority of samples being most similar to cereal and grassy hay fodder, and the quality of fresh pasture remained poor throughout the Late and Final Neolithic at KN. There is evidence for chronological variation, however, in the proportion of fodder and fresh pasture diets, with the former more common throughout except in FNIA, when fresh diets were heavily predominant. More tentatively (given the reduced sample sizes), graze is roughly twice as common as browse *among fresh diets* in all periods, except FNII-III when graze is very heavily predominant.

Several alternative interpretations may be considered for the distinctive nature of the diets of young FNIA and perhaps FNII-III sheep/goats. First, the phasing of FN contexts at Knossos is currently under review (V. Isaakidou, pers. comm.) and so the diachronic differences in microwear results reported here must be considered provisional, although it seems unlikely that any mis-dating should have selectively affected deposits containing teeth with dental microwear characteristic of fresh pasture. Secondly, it is conceivable that excavation fortuitously uncovered a part of the FNIA settlement that was functionally or socially different from its counterparts of LNI-II, FNIB and FNII-III date. For all four periods, however, the analysed samples are drawn overwhelmingly from the 'Central Court' area of the site and Neolithic occupation seems to have been concentrated on the core of the settlement mound (Whitelaw 2012, 134), so there is no reason to anticipate marked diachronic differences of functional or social context. Thirdly, the results under discussion include a combination of sheep and goats, which have rather different feeding *preferences*, and $\delta^{13}C$ analyses of sheep and goat bones (mostly fused distal humeri, from animals in their late first year or older and so potentially overlapping in age with the dental samples) at Knossos imply increasing dietary divergence between the two species through the Neolithic (V. Isaakidou pers. comm.). The breakdown of sheep and goat dental microwear samples by period is: LNI-II 15 sheep + 0 goats; FNIA 13 sheep + 2 goats, the latter including one browser and one grazer; FNIB 18 sheep + 4 goats, the latter including one grazer, two cereal-and one grassy hay-fed; and FNII-III 18 sheep + 0 goats. Thus, although the chronological distribution of goat dental microwear samples is indeed uneven, it has not obviously distorted the results reported here. Fourthly, during the course of the Neolithic, the Knossos settlement expanded greatly in size and, *if* the number of livestock per inhabitant remained stable, then domestic animals will over time have grazed increasingly distant pastures among which browse and poor-quality graze are likely, for reasons of terrain and soil cover, to have been more prominent than in the fertile Knossos valley itself (cf. Isaakidou 2008). There is disagreement, however, on the timing of settlement expansion, with Tomkins favouring significant growth during LNI-II followed by stability through FN (Tomkins 2008, 32 table 3.2), while Whitelaw is more open to the possibility of significant further expansion during FN (Whitelaw 2012, 147-148). In broad chronological terms, $\delta^{13}C$ and $\delta^{15}N$ values for sheep and goat bones match the expectations of expanding settlement size and livestock numbers, with decreasing $\delta^{15}N$ values through the Neolithic, implying declining use of manured land (whether as pasture or as source of fodder grain), and rising $\delta^{13}C$ values, hinting at increasing browsing especially among goats (Isaakidou pers. comm.). The dental microwear data, however, regardless of the date accepted for settlement expansion, do not match the expectations of increasing numbers of livestock exploiting increasingly distant and diverse pasture. Here it must be recalled that the $\delta^{13}C$ and $\delta^{15}N$ values reflect long-term diet (potentially of mature adults), while dental microwear offers a record of diet of animals up to two years of age in the days or weeks prior to death. The clear implication is that, while settlement expansion at Neolithic Knossos was accompanied by the herding of sheep and goats over increasing distances and on increasingly diverse pastures, a high proportion of these animals were then fattened on fodder prior to consumption, resulting in superficially contradictory bone isotope and dental microwear results.

By default it seems that diachronic variation in the relative frequency of fresh and foddered diets at Knossos may reflect socio-political as much as agricultural imperatives, although why it should have been less desirable, or perhaps less feasible, to fatten young sheep and goats for consumption in FNIA is for now unclear. The more tentative suggestion that, in FNII-III, graze was particularly common among animals not selected for fattening with fodder is even more difficult to interpret, not least because this could in principle reflect not a decline in browsing but a tendency to select browsers more than grazers for fattening, thus overwriting their dental record of long-term diet.

5.7 Summary of archaeological results

Dental microwear analysis of sheep and goats from TKK, MK and KN reveals dietary similarities and difference between sites, contexts and time periods. The most striking differences between sites were the overwhelming predominance of foddered diets at TKK and the broader range of diets including browse at KN, with MK occupying an intermediate position between these extremes. The large and expanding size of the settlement at Knossos, coupled with its location in a topographically confined valley, perhaps dictated the herding of livestock at a greater distance and may thus account for the observed dietary diversity at this site. The long and severe summer drought on Crete, that will have both limited the availability of summer graze and favoured the development of evergreen arboreal vegetation, may account for the greater evidence for browsing than at the two northern mainland sites of TKK and MK. Conversely, TKK and MK were less topographically confined and will have had access to extensive fertile land that, if cleared for cultivation, would have offered a relative abundance of pasture suitable for grazing. In addition, a wealth of evidence for ceremonial structured depositions at TKK and for apparently large-scale commensal events at MK provide cultural contexts in which fattening with fodder in advance of slaughter is not surprising and indeed had already been proposed (Mainland and Halstead 2005) – albeit not with such a high frequency as is implied by the present study.

Dietary differences were also found between context types at TKK and MK, suggesting that pits and ditches at TKK and ditches, 'feasting pits' and habitation features at MK represent different types of commensal events with some contrasting dietary preparation of animals selected for slaughter and consumption. Variation is likewise observed at KN between different LN and FN chronological periods, with no evidence that the material from successive periods was dominated by different types of depositional context, but nor does diachronic dietary variation appear to be related to increasing settlement size and the expanding range of herding that might be expected to accompany it.

Arguably the most striking outcome of this study, however, is that, albeit to varying degrees between sites and contexts, foddered diets predominate over fresh graze and (less common) browse. The best ethnographic match for these foddered diets is overwhelmingly cereal grain or grassy hay, rather than leafy fodder, and thus they seem to represent the provision of a high-quality diet. In the recent past, sheep and goats were often fodder-fed over winter at higher altitudes in Greece, albeit with the intention of maintenance more than fattening (whence the suitability of leafy hay), but this interpretation is rather implausible for KN and MK, given their low-lying coastal locations, and is contradicted for TKK and MK, at least, by available evidence for age of slaughter and thus season of death. In traditional sheep and goat husbandry, higher quality fodder (i.e. grassy hay or grain) was given sparingly and usually to pregnant and suckling females, but the first- and second-year Neolithic animals analysed here were slaughtered before their likely first lambing/kidding at around two years of age and, anyway, lack of evidence for seasonal slaughter runs counter also to this interpretation. By default, therefore, and particularly for such young animals, fodder was arguably given to fatten them in preparation for consumption. The mismatch between dental-microwear and isotopic evidence for short-term end-of-life and long-term diet, respectively, at KN also favours the suggestion of fattening for consumption. A similar argument may be advanced for MK, where both $\delta^{13}C$ and $\delta^{15}N$ values for sheep and goats overlap only partially, implying that in the long term the two species were able to pursue their divergent food preferences, which is in turn more compatible with grazing/browsing than pen-feeding (Vaiglova et al. 2018).

If the 'fattening for consumption' interpretation of foddering is correct, then the samples classified as fresh feeders may be a misleading guide to longer-term diets. Nevertheless, it is worthwhile to consider the relative proportions of fresh grazers and fresh browsers at the three sites. The relative abundance of browsers at KN has already been noted and tentatively attributed to the negative impact of severe drought on the availability of summer graze on Crete, to which arboreal (perhaps especially evergreen) vegetation would have offered a ready alternative. At northerly MK and TKK, however, evidence for browsing is extremely scarce and, in an apparently wooded landscape (Marinova and Ntinou 2018), this lends support to earlier arguments (Halstead 1981) that livestock were concentrated on cleared land devoted to crops and perhaps short-term fallow. That this interpretation is also compatible with the slight dietary divergence between sheep and goats at MK, implied by and $\delta^{13}C$ and $\delta^{15}N$ isotopic analyses, is confirmed by the author's own observations around the modern village of Makriyalos in July 2016: as mixed herds of sheep and goats were driven slowly across harvested cereal fields, the sheep grazed on weeds and fallen ears among the stubble, while the goats mainly browsed on ruderal plants and brambles in the bordering hedgerows (Figures 5.18 and 5.19).

The implications of these insights into sheep and goat diet at these three Neolithic settlements are discussed further in their wider cultural and social context in the following chapter.

CHAPTER 6: CONCLUSIONS

6.1 Insights into dental microwear analysis: methods and resolution

The Digital Light Microscopy (DLM) method, using High Dynamic Range Imaging (HDRI), proved successful in recording and distinguishing microwear patterns associated with ethnographic known-diet groups, producing results comparable to those produced by Ingrid Mainland using the Scanning Electron Microscopy (SEM) method on broadly the same samples. Limitations of the method include: a) the restriction to only young (up to ca. 2 years of age, when the dP_4 is replaced by the permanent fourth premolar) sheep and goats; and b) the inevitably incomplete nature of the available range of ethnographic dietary analogues.

The first of these issues needs further investigation. Mainland (1994) demonstrated that, at high-magnification, dental microwear varied between both tooth types and enamel bands. The difference in magnification (500x SEM versus 40x DLM) means that the actual size of features and area being observed under the microscope are different, but, if the cause of the variation is the function of the tooth and enamel band during mastication, logically this should have an effect at whatever magnification is used. A study analysing inter-tooth and intra-tooth variation using the DLM method could provide further insight to this issue, but this may require collection and analysis of an ethnographic sample of teeth from *older* domestic sheep and goats of known diet. Work to date by both Mainland and the present author has focussed on *young* sheep and goats, precisely because modern specimens of known diet are easier to acquire from young than adult animals for the following practical reasons. First, under experimental conditions (the source of most of Mainland's modern known-diet specimens), it is much cheaper to rear a young animal on a controlled diet for 1-2 years than an adult for 2+ years. Secondly, under non-experimental conditions (the source of modern specimens reared on diets not represented at north European experimental stations), and especially in the Mediterranean where sheep and goats are usually herded across the landscape rather than enclosed, young animals are more likely to be stall-fed or penned, while the diet of adults is likely to be more or less uncontrolled for much of the year. An alternative strategy, more feasible if less ideal, is to compare microwear patterns on dP_4 and first and second molars from the *same* archaeological mandibles (i.e. not from animals of known diet), to establish whether there is a consistent relationship between microwear patterns on different teeth. A pilot study was undertaken (Beswick 2017), as far as possible using protocols identical to those used in this thesis, but without unequivocal outcomes. Further such work is needed, but, pending a (hopefully) successful outcome, it is unsafe to compare the results of the present study with the low-magnification analysis of dental microwear based on mixed mandibular and maxillary M2s at MN and LN Kouphovouno in southern mainland Greece, let alone to compare the latter with Mainland's SEM based modern analogues as do Rivals et al. (2011, 534-35).

The second issue highlighted is difficult to address fully as it is not possible to capture every possible archaeological diet within the ethnographic sample. As discussed in Chapter 3, however, a functional understanding of the *causes* of different microwear signatures greatly enhances the potential and reliability of extrapolating recent ethnographic analogue data to the distant past. For example, heavy microwear abrasion seems to be due to the ingestion of grit particles during grazing at ground level rather than just consumption of mature grasses rich in phytoliths (Mainland 2000a). In this light, differences observed in ethnographic analogues between browse and graze, or between high- and low-quality graze can plausibly be extrapolated to archaeological microwear data. Likewise, it is unsurprising that fresh browse and dried leafy hay leave similar microwear signatures. Conversely, the distinction between summer and winter graze, based on north European analogues, may be unsafe to apply to the Mediterranean where summer rather than winter is often the season of sparsest and poorest-quality pasture. The collection of a wider range of modern seasonal grazer (and likewise browser) specimens from the Mediterranean would clearly be valuable, although ethnographic samples from summer grazers on Mediterranean stubble fields are missing from the present study because adult rather than young sheep and goats tends to be killed in this season.

6.2 Insights into animal husbandry and meat consumption: TKK, MK and KN

Chapter 2 set out the research questions to be addressed by investigating animal diet at the archaeological sites of TKK, MK and KN. These focussed in particular on the scale of animal husbandry and its degree of integration with crop husbandry (for example, traces of browsing implying use of pasture beyond the confines of arable land) and the extent to which livestock were fattened prior to consumption within large-scale collective and/or small-scale domestic commensal events. The results from the analysis of sheep and goat teeth in Chapter 5 provided insights into the short-term diet and management of these animals.

Foddering was found to be common at all three sites and within contexts attributed to both large-scale feasting and 'domestic' habitation consumption, suggesting it was a more prevalent aspect of LN and FN sheep and goat husbandry than previously suspected. This was particularly striking at TKK where the most common diet was overwhelmingly cereal or grassy hay fodder. Given the available evidence from dental eruption and wear for ages at death, it seems that the use of fodder was not limited to either winter or summer periods of scarce pasture, but was instead more likely a short-term method for fattening animals before slaughter. As discussed in Chapter 2, foddering has implications for the scale of animal husbandry due to the considerable labour costs of collecting natural grassy/leafy hay or of producing surplus grain (i.e. grain in excess of human needs). Foddering also has more indirect implications for livestock mobility, in that large herds are more likely to be considered worth moving over significant distance, while animals that have benefitted from rich seasonal pasture are less likely to be selected for fattening before consumption.

The majority of archaeological sheep and goats classified as having a foddered diet, had microwear features similar to the grassy hay and cereal groups, that is soft diets with low-microwear abrasion, perhaps indicating that these animals ended their days penned or even housed with fodder. Of these two potential fodder categories, cereal grain or sown cereal hay is much more likely than 'natural' hay in this landscape and this period. First, *un-sown* herbaceous stands akin to north European meadows are uncommon in lowland Greece, other than on the margins of lakes (irrelevant at least in the case of MK and KN). Secondly, the harvesting of natural meadow, for example on weedy fallow fields, is prohibitively difficult and slow without modern scythes – even with modern iron sickles (Halstead 1998) – and, consistent with this, the harvesting of grassy hay seems not to have assumed importance in lowland southern England until the Iron Age (Hodgson et al. 1999). For both reasons, in the recent past in Greece, un-sown fodder was usually collected from trees and bushes, while potential grassy hay was usually consumed directly by grazing animals. At MK, evidence was found, in addition to foddering, of fresh graze with heavily abraded wear, perhaps indicating that animals were variously kept in over-grazed pens or fattened before slaughter within, or close to, the settlement. Furthermore, the distinctive lack of evidence for browsing at TKK and MK suggests that young sheep and goats were not herded in local woodland, at least in the final weeks before their slaughter.

Conversely, the broad range of diets identified at KN, including browse, suggests that here young livestock ranged further afield, outside of the local cultivated landscape, perhaps taking advantage of the absence of predators on Crete (Isaakidou 2004) and the abundance of arboreal vegetation during times of drought and limited graze characteristic of lowland southern Greece. Interestingly, the use of fodder prior to consumption remains common at Neolithic KN, even as isotopic analysis identifies changes to the longer-term (i.e. lifetime) management of sheep and goats during the expansion of the site, moving further from manured arable land on to the wider landscape (Isaakidou pers. comm.).

The prominent use of fodder across all three sites supports previous arguments for the close interdependence of animal husbandry and crop cultivation. The labour cost for the collection of fodder for the archaeological sheep and goats may not be as high as collection for over-wintering discussed in Chapter 2 because, as previously mentioned, the evidence arguably represents short-term fattening rather than foddering to combat seasonal shortages of fresh graze or browse. However, if the diet of these young animals consisted of grain fodder, as indicated by the dental microwear results, the frequency of this practice across all sites would suggest that *indirect storage* (Flannery 1968) was an important strategy for farmers in Late and Final Neolithic Greece. It would also support the argument that small, household farmers produced surplus grain, arguably as part of a strategy aimed at ensuring sufficiency in bad years, on a scale at least large enough to justify its regular conversion into meat (Halstead 1989; 2004).

Evidence for fattening animals is not entirely surprising at TKK which has a wealth of evidence for ceremonial structured depositions, nor within large-scale feasting contexts at MK, as at both sites the importance of sharing food and *social storage* has been previously argued (cf. Halstead and O'Shea 1982, 92). However, similar foddered diets were also seen within contexts associated with smaller, domestic consumption events (MK habitation) and across all three sites in different geographical regions. This suggests that fattening animals for consumption was not dependent upon the scale of the commensal event, supporting previous arguments that meat consumption was particularly important to commensal politics at a household, settlement and perhaps regional scale (e.g. Halstead and Isaakidou 2011; Halstead 2012). Dietary differences between context types at TKK (e.g. fattening on fodder in pits and on high-quality pasture in ditches) and MK (e.g. prevalence of fodder in ditches and equal representation of fresh graze in pits) also suggest animals were prepared differently, depending upon the type of commensal events associated with pit and ditch features. Expanding the applicability of the DLM method to older sheep, goats, and other domestic species would clarify whether the dietary preparations observed within this thesis were limited to young and small animals, or if these methods were also used to prepare older sheep and goats and larger species for consumption events.

Only young sheep and goats have been examined in this thesis and many of these were fattened before slaughter, potentially overwriting previous microwear traces of grazing or browsing, so the results presented here can shed only limited light on the husbandry of livestock. Nonetheless, for the reasons outlined above, the high frequency of foddering is more suggestive of small- than large-scale animal husbandry and this in turn, coupled with evidence for slaughter of young sheep more or less throughout the year at TKK, MK and (more tentatively) KN argues against seasonal removal to distant pastures. Moreover, among those animals for which microwear does not register fattening in the period leading up to slaughter, grazing (on high-quality pasture at TKK, but on low-quality at MK and KN) is indicated far more frequently than browsing, especially at TKK and MK. *If* these animals are representative of the earlier diet of fattened animals (i.e. if browsers were not selected over grazers for fattening), then relatively small and stationary herds of sheep and goat probably were largely restricted to the cleared arable landscape, as has previously been argued on other grounds (Halstead 1981; 2006) and now receives some support from $\delta^{15}N$ analyses.

As to why fattening of livestock destined for consumption was so widespread, two rationales discussed above (indirect storage and social storage) are not mutually exclusive. Subsistence dependence on staple grain crops requires strategies for mitigating poor harvests, of which the routine over-production of 'normal surplus' is one of the most effective and reliable (e.g. Halstead 1989). Continued investment of significant amounts of human labour in such over-production will have been difficult to maintain, however, through the inevitable runs of good years unless surplus grain could be put to good use, for example in brewing beer (Allan 1965) or fattening livestock (Flannery 1969). Fat meat (and likewise beer) can be enjoyed by the producer, but are also frequently used to host a party that recruits labour, earns prestige or creates social debts. That livestock in Neolithic Greece played this dual role of vehicles for both indirect and social storage has been discussed extensively (e.g. Halstead 2004; 2012), but on the basis of relatively slender empirical support. The results of this thesis dramatically strengthen this argument and highlight the central role, both economic and social, that livestock played in Neolithic political economy.

Finally, fattening of livestock for feasts sponsored by the Late Bronze Age palaces of southern Greece is recorded in Linear B texts (Killen 1999), but has not yet been investigated by dental microwear analysis. The application of this method to Bronze Age (and indeed later) contexts would shed light on the extent to which the use of fodder and indirect storage was or was not particularly characteristic of Neolithic household economies. It is already apparent, however, that large-scale feasting and the fattening of livestock for this purpose, which have attracted considerable attention as focal activities of the later palaces (e.g. Killen 1992; Wright 2004), were also of central significance to Neolithic communities in Greece.

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