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Mobility and Herd Management Strategies of Early Pastoralists in South-Central Kenya, 3000-1200 BP

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MOBILITY AND HERD MANAGEMENT STRATEGIES OF EARLY PASTORALISTS IN SOUTH-CENTRAL KENYA, 3000-1200 BP

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by

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ABSTRACT

Anneke Janzen

Mobility and Herd Management Strategies of Early Pastoralists in South-Central Kenya, 3000-1200 BP

Specialized pastoralism emerged in Kenya around 3000 years ago and has evolved with changes in the social and ecological landscape to this day. Ethnographic research has documented significant changes in herding strategies among pastoral groups throughout colonial and post-colonial periods. Stable isotope analysis sheds light on how crucial mobility was in maintaining herds before the appearance of iron-using and –producing peoples in the region. This thesis explores the use of multiple stable isotopes to reconstruct mobility and herd management strategies of ancient pastoralists in south-central Kenya 3000 to 1200 years ago. Through intra-tooth sequential sampling of livestock tooth enamel, which presents an isotopic record of diet during tooth formation, movements across the landscape may be tracked. Further zooarchaeological analyses of livestock teeth include analysis of mortality profiles generated from age estimates based upon life histories. Combined with enamel hypoplasia data, these analyses inform on herd management strategies of early pastoralists.

Archaeological cattle and caprine teeth from seven Savanna Pastoral Neolithic sites in the Central Rift Valley and neighboring plains of Kenya were sequentially sampled and analyzed for their carbon, oxygen, and strontium stable isotopic composition. Consistently elevated carbon stable isotope ratios did not indicate any

herding at high elevations. Because the lack of altitudinal mobility does not preclude extensive herding and exchange of livestock long distances at low elevations, a strontium map of south-central Kenya was created by analyzing the stable strontium isotope composition of archaeological and modern microfauna collected from various locations throughout the Central Rift valley and adjacent mountain ranges and plains. $^{87}Sr/^{86}Sr$ ratios, which can reflect movement across geologically distinct soil complexes, also indicated low levels of seasonal or long-term mobility, with little evidence for exchange of livestock among far-flung herding groups, though some regional differences exist. In contrast to widespread seasonal mobility and exchange documented ethnographically, these data show that those patterns were not in place before agricultural populations moved into the region.

The mortality data presented for all definite pastoralist sites show that early herders kept cattle alive for somewhat longer than East African pastoralists do today, and that some variation in management techniques is apparent, perhaps due to environmental or cultural factors. Mortality profiles and hypoplasia data from livestock are quite similar between pastoralist sites and one with a mixed faunal assemblage, indicating that site with higher proportions of wild fauna was indeed occupied by pastoralists taking advantage of seasonally available migratory wild animals, suggesting some fluidity in subsistence strategies.

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CHAPTER 1: INTRODUCTION

The research presented here assesses mobility and herd management strategies of early pastoralists in Kenya. Pastoralists are people who primarily depend on products of domesticated herd animals. This mode of subsistence emerged in Kenya around 3000 years ago and has adapted to changes in the social and ecological landscape to this day. Specifically, this study examines the nature of early pastoralism in Kenya before the appearance of farming populations in the region, and explores interactions between herders and indigenous foragers.

The appearance of pastoralism is a critical development in the history of human subsistence, permitting more people to live in the earth's dry lands than does hunting and gathering. The earliest evidence for domesticates in Kenya appears at around 5000- 4500 BP in northwest Kenya in the Lake Turkana basin (Hildebrand and Grillo 2012; Marshall, et al. 1984). The spread of herding into Kenya's Central Rift Valley and its neighboring plains was slow, with fully pastoralist sites appearing around 3000 BP. Some sites, however, have mixed faunal assemblages, with substantial proportions of wild and domestic fauna. Such variations in subsistence, as well as material culture, suggest that the modern East African pattern of "mosaics" of interacting hunter-gatherers and pastoralists had emerged by 2000-3000 years ago (Marshall 2000). This work explores the diversity of mobility and land use strategies among pastoralists in south-central Kenya before the arrival of farming populations into the region. This human social landscape and ecology that differs from anything known in historically documented times, and therefore, in a broader sense, this project emphasizes a greater acknowledgement of the varying, historically contingent pathways toward food production in different parts of the world.

The project has significant implications for understanding the nature of early pastoralism before the encroachment of farming populations in two ways. First, ethnographic research has documented significant changes in herding strategies among pastoral groups in post-colonial periods (Gulliver 1955; McCabe 1994; McCabe 2004). These studies have highlighted the mutable nature of pastoralism as a lifeway, as well as the importance of mobility and extensive social networking not only within ethnic groups, but also across them (Sobania 1988, 1991). This work assesses the importance of seasonal mobility in maintaining herds from the time of entry of herding people into Kenya around 3000 years ago to the immigration of farming and iron-producing peoples into the region at the end of the 1st Millennium CE. Herders in Kenya in the present day frequently move livestock long distances and to higher altitudes on a seasonal basis (Nyariki, et al. 2009). However, this pervasive exchange of livestock among pastoralist groups has not been documented archaeologically, and a pioneering study has suggested less marked seasonal transhumance by the earliest herders in the region than in historic times, indicating a very dynamic history of herding strategies in the region's emergently integrating economies, even before colonialism (Balasse and Ambrose 2005b).

Second, my project sheds more light on the complexity of pastoral production and social interactions of East African pastoralists and indigenous hunter-gatherer populations. Ethnographic evidence highlights the relationships between herding and foraging groups (Cronk 2004; Sobania 1988, 1991). Furthermore, clear archaeological evidence exists that neither pastoral production nor farming was adopted wholesale as they spread into Kenya, but rather interdigitated with other subsistence strategies, forming which has been a “cultural mosaic” of ethnically and economically differentiated yet interdependent peoples (Gifford-Gonzalez 2003; Kusimba and Kusimba 2005; Robbins 1980). This project further elucidates the dynamics of these interactions.

In exploring the aspects of pastoral production outlined above, I focus specifically on pastoralist sites where Narosura ware comprises some part of the ceramic assemblage. Narosura is the widest-spread ceramic tradition associated with the Savanna Pastoral Neolithic (SPN), found from Kenya’s Central Rift Valley to western Kilimanjaro and the Serengeti Plains in northern Tanzania (Ambrose 1984c; Prendergast, et al. 2014; Wandibba 1977). SPN sites are found in open country settings. Fauna associated with most of these sites in the Central Rift are predominantly domesticates, with significantly more cattle than caprines. However, a few sites contain notable proportions of wild taxa, such as the site of Prolonged Drift (Gifford, et al. 1980). The common Narosura ceramic tradition among many SPN archaeological sites suggests some interaction between the occupants. However, not all of the sites in this study include SPN lithics: two sites contain lithic industries reflecting the adoption of pastoralism by Eburran hunter-gatherers, and one of those also contains Elmenteitan lithics, associated with another archaeological pastoral entity distinguished by differences in geographic range, lithic core reduction sequences, formal tools, shape and decoration of ceramic vessels, and use of obsidian sources (Ambrose 1984c; Merrick and Brown 1984; Robertshaw 1988, 1990b). These sites are included because they can provide further insight into the interactions and animal exchange relationships between different groups. The archaeological sites included in the study also differ with respect to environment. Several sites are situated in the steep-sided Central Rift Valley, while others are located on the neighboing Loita and Athi-Kapiti plains to the southwest and southeast of the Central Rift, respectively (Figure 1.1).

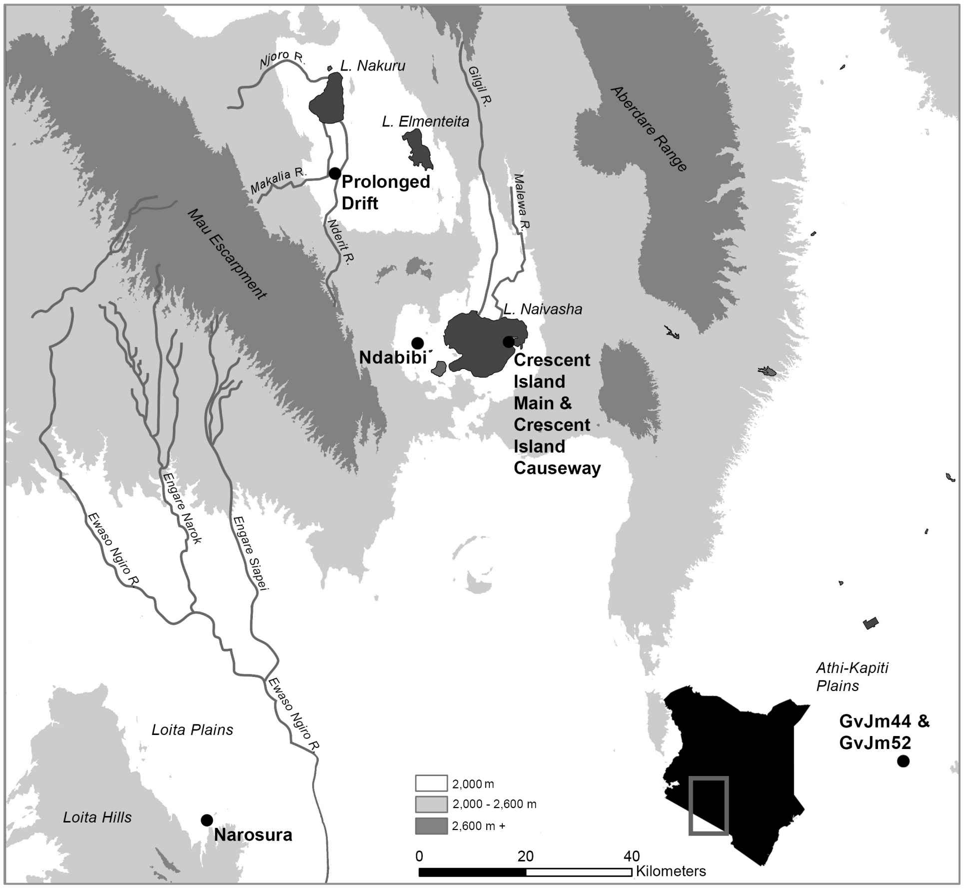


Figure 1.1: Map of study area with archaeological sites.

Four primary research questions guide this exploration of early pastoral mobility, exchange, and herd management strategies at these sites. These are outlined below, including the methods used to investigate each.

1) How crucial were seasonal movements for early pastoralists to maintain herds? The variable landscape of Kenya, both in terms of geology and vegetation, allow for the movement of individuals to be tracked using isotopic methods. Carbon, oxygen, and strontium isotope analyses of sequentially sampled livestock teeth provide a record of seasonal changes in diet and feeding location.
2) Were livestock exchanged long distances among early pastoralists? Similar to the question above, the possible circulation of livestock may be explored using isotopic analyses. The presence of animals in sites with oxygen, carbon, or strontium isotope values differing markedly from those characteristic of the environment in which the site is located can indicate the movement of animals between far-flung pastoral groups.
3) Did early pastoralists manage livestock differently than modern pastoralists do today? This question is addressed through analyses of slaughter patterns and hypoplasia data, which provide insight into the products desired by herders and the health of livestock, respectively. Slaughter patterns and hypoplasia data can also indicate if harsher environmental conditions for herders resulted in different management techniques. The economic circumstances of site occupants may be elucidated through analysis of slaughter patterns as well as

hypoplasia data (Marshall 1990b; Prendergast and Mutundu 2010; Upex 2009). Isotopic analyses were also used to examine broad differences in herding patterns with respect to site environment and subsistence strategy.

4) How did pastoralism spread? What were the interactions between herders and hunter-gatherers? To explore these questions I compare zooarchaeological and isotopic evidence for herd management strategies from livestock from clearly pastoralist sites to the livestock from the mixed site of Prolonged Drift to assess the degree to which herding strategies diverge from those sites clearly occupied by herders and ascertain whether the livestock from Prolonged Drift were managed by experienced herders or inicpient pastoralists, and/or acquired by hunter-gatherers.

Results from these analyses show that early pastoralists in south-central Kenya did not rely on seasonal mobility to maintain livestock herds. Results also show little evidence for exchange of livestock among far-flung herding groups, though some regional differences exist, with evidence for increased mobility in the plains sites.

Slaughter patterns show that early herders kept cattle alive for somewhat longer than East African pastoralists do today, though there are some variations in management strategies, perhaps due to environmental or cultural factors. Mortality profiles and hypoplasia data from livestock are quite similar between pastoralist sites and Prolonged Drift, and thus indicate that Prolonged Drift livestock were managed by pastoralists.

Due to the nature of the research, the first portion of this work includes several background chapters that outline theoretical approaches in studies of African pastoralism, the history of archaeology in the region, as well as the environment of the study area. Chapters on the methods of analysis follow, including a review of stable isotope systematics and applications, as well as methods for assessing age and health status of ungulates based on dental remains. The latter third of the dissertation outlines the methods and results of the analyses and presents a discussion of herding practices of early pastoralists. Finally, the conclusion reviews the findings included here in the context of early pastoralism in East Africa, and suggests areas of further research.

The thesis is organized as follows: following this introductory chapter, I briefly review some theoretical approaches to studies of African pastoralists. Chapters 3 and 4 also focus on the study area. Chapter 3 offers a detailed review of relevant archaeological research. It begins with a review of archaeological research in North Africa, outlining and reviewing the origins and spread of pastoralism in East Africa: first tracking the appearance of domesticates in North Africa and then moving south into Kenya, tracking the timing and spread of domesticates and pastoralism through the study area. Chapter 4 outlines the geology, hydrology, and ecology of Kenya. Understanding the diversity of the environment is essential for interpreting results from the isotopic analyses.

In Chapter 5 I review the principles and systematics of stable isotopes in the biosphere, focusing in particular on the stable isotopes of those elements used in my archaeological investigations of animal diet and mobility: carbon, oxygen, and strontium. I also review the systematics of those isotopes in animal tissues, outlining how controlled feeding studies have allowed for paleodietary and paleoenvironmental reconstructions. Chapter 6 first offers a review of tooth growth and development. This chapter reviews the geometry and timing of growth of the various dental tissues, which has implications for recovery of the isotopic signal in those tissues. Chapter 7 then reviews earlier studies examining mobility and herding strategies using stable isotope analysis, which inform this study.

Chapter 8 turns to a review of pastoralist practices among modern herders in Africa, beginning with an overview of the livestock species analyzed in this study, and how their growth and reproduction has implications for slaughter patterns and herd structures among traditionally managed herds today. The chapter concludes with a brief discussion of pastoral mobility and exchange relationships between herding groups, as well as with foragers.

Chapter 9 lays out the methodologies used in the study. This chapter introduces the archaeological sites I analyzed, and how analysis of each one addresses the research questions presented here. Chapter 10 presents the results of the age-at-death estimates (and resulting mortality profiles) as well as the hypoplasia analyses. The latter half of the chapter turns to a discussion of the mortality and hypoplasia data as indicators of herd management strategies. Chapter 11 outlines the results of stable carbon and oxygen isotope analysis of both modern and archaeological livestock tooth enamel. The results as well as an interpretation isotopic data are presented with respect to the geographic region in which the sites are situated. Chapter 12 reviews results from the strontium stable isotope analyses of microfauna and presents the strontium isoscape created from those data. The chapter also reviews the strontium isotope composition of the archaeological livestock tooth enamel. It concludes with an interpretation of pastoral mobility and exchange for each site.

Chapter 13 presents a synthetic discussion of the mortality, hypoplasia, and isotopic data. This chapter examines the outcomes of the analyses in terms of the original research questions outlined here regarding herd management and mobility and exchange of livestock. I also discuss evidence for interactions of herders and foragers at Prolonged Drift. Finally, Chapter 14 reviews the conclusions and discusses some lingering questions put forward by the data presented here.

The research presented in this work contributes to a greater discussion of the diversity in food producing economies. The isotopic data presented here show that, unlike herding practices documented among modern pastoralists, early pastoralists in south-central Kenya relied relatively little on seasonal mobility to maintain their herds. Similarly, exchange of livestock among early herders is not as evident as described in ethnohistoric accounts. Livestock culling strategies of early pastoralists also differ to some degree from those of modern herders. This work thus also highlights the disconnect between historically documented accounts of pastoralism and the archaeological evidence.

CHAPTER 2: THEORETICAL APPROACHES TO PASTORALISM

In this chapter I provide an overview of theoretical approaches applied to pastoral societies. The long history of ethnographic research on African pastoralism has significant implications for how archaeologists have approached herding in the past. I also review how archaeological research on the development of food-production has influenced questions of the existence of pastoralist societies, as well as how Africanist archaeologists have viewed pastoralism in prehistory.

Ethnographic studies of African pastoralist societies have been structured around a few central questions: How do pastoralists survive in such marginal environments, and how does their environment, means of subsistence, and mobility affect their social structure? For over half a century ethnographies of African pastoralists aiming to address such issues have taken slightly different theoretical approaches, but due to the nature of those key questions outlined above, the predominant theoretical basis has been rather eco-functionalist or some variant of structural-functionalism (see Evans-Pritchard 1940; Gulliver 1955). In the 1960s and 1970s, however, social behavior began to be analyzed at the level of the individual, and there has been an increasing focus on social change, economic development, and the effects of colonial and national governments on these “traditional” societies (Dyson-Hudson and Dyson-Hudson 1980; McCabe 2004) (Dyson-Hudson and Dyson-Hudson 1980; McCabe 2004). Anthropological studies since the 1960s have seen more sophisticated applications of ecological theory to human behavior (Dyson-Hudson and Dyson-Hudson 1980).

Pastoralists are people who primarily depend on products of domesticated herd animals, but there is significant variation within this category, ranging from specialized nomadic pastoralists to those groups that also depend heavily on agriculture. Many scholars, therefore, argue that specialized pastoralism can only emerge through contact with sedentary groups.

Early theoretical perspectives on ecology and social organization

The earliest ethnographies of African pastoralists drew heavily from structural-functionalism, based on a Durkheimian theoretical perspective, that considers society and the relationships between institutions, which function together to maintain the society (Evans-Pritchard 1950, Trigger 1996). These early accounts described pastoral societies as egalitarian, and anthropologists concluded that this social structure was a direct consequence of their subsistence economy. This approach is evident in several ethnographies introduced below, including Evans-Pritchard's *The Nuer* (1940); Gulliver's *The Family Herds* (1955); and Spencer's *The Samburu: A Study of Gerontocracy* (1965).

A seminal ethnography of pastoralists, Evans-Pritchard's *The Nuer* presents a synchronic description of Nuer society (Evans-Pritchard 1940). Evans-Pritchard describes how the ecology of Sudan directly influences Nuer subsistence and social structure. Evans-Pritchard detailed how the segmentary lineage social structure operated in Nuer society: without any sort of centralized leadership, the segmentary system allowed tribal segments to band together when needed, but otherwise maintained sparsely populated settlements necessary for keeping large herds of livestock. The availability of water and adequate pasture for cattle dictated their movements across the landscape. To engage in several agricultural and pastoral activities, Nuer groups split up to the care for these different resources. For example, youths and girls cared for cattle during the dry season, while older people harvest millet. According to Evans-Pritchard, these strategies were in equilibrium with the environment: the cyclical movements of the Nuer occur in accordance with seasonality, and the organization of labor as well as timing of transhumance and harvesting influenced the organization of their society. Evans-Pritchard's structural-functionalist approach was quite appropriate in tackling questions about the survival of pastoralists in this harsh and unpredictable environment. His account of Nuer life was of a constant cycle of movements maintaining the equilibrium of society.

Gulliver's 1955 ethnography of the Turkana in northwestern Kenya is also characterized by a structural-functionalist approach, and describes the Turkana as largely reacting to the environment, exhibiting little initiative or agency. At the center of the Turkana social system was the extended family, which governs inheritance, ownership, and control of herds. The Turkana studied by Gulliver were nomadic, and this continual movement across the landscape was determined by the wet and dry seasons of the year. According to Gulliver, the overriding role of the environment and the pull of good grazing areas for livestock resulted in a very weak age-set system, lax territorial sections, fluid household organization, and no permanent accumulation of wealth. The structure of the society, by allowing for fluidity in family units to facilitate their own migrations with livestock, functioned to maintain the health of the herds and the continuation of pastoralists' livelihoods.

Finally, Spencer's 1965 ethnography details the lifeways of the Samburu, a group of nomadic cattle pastoralists that live near the southern end of Lake Turkana in northern Kenya. The society is described as a gerontocracy, where the power lies with the older men, achieved by both forbidding widows to remarry and preventing young men from marrying before they are old enough to have accrued enough stock. Delaying male age at marriage also functioned to prevent competition for herd animals between generations of family members. The *moran* (warrior age-set) spent most of their lives building up their herds in preparation for marriage. Though a man might accumulate many heads of livestock, these were eventually dispersed as bridewealth and among family members. Thus, although Spencer made much of psychological tensions between elders and warriors, in his view, pastoral production was the basis for the organization of the society, with men at the center.

Early ethnographers assumed that pastoralist society and culture was determined by their livelihood, and therefore would not change unless subsistence strategies did (Hodgson 2000). In later decades numerous ethnographic studies have shown that no cultural features or social structures are common to all pastoralist societies. Indeed, "the applied science of livestock raising cannot give us clues to the articulation and transformation of social systems" (Asad 1979:421; see also Dyson-Hudson and Dyson-Hudson 1980). While pastoralists were portrayed as keen decision-makers, they often were documented as merely responding to environmental and socio-political changes. This is an artifact of early functionalist studies that explicitly sought to explain social structures as direct products of ecological situations, and therefore viewed humans as only seeking to optimize returns from the environment.

In parallel, early ecological approaches in archaeology also linked culture and environment through the same functionalist paradigm. For example, Cambridge archaeologist Grahame Clark (1939) argued that all aspects of culture were constrained and influenced by the environment. Such ideas are clearly implicit in most studies of African pastoralist societies, many times by persons who also were strongly influenced by the Cambridge school emphasizing ecological-cultural relationships (Trigger 1996).

Such ethnographic descriptions of pastoralist communities as unchanging, acephalous, and egalitarian have certainly colored archaeological interpretations of pastoralist societies, contributing to the long-standing belief that African cultures were static and had only made progress towards complexity very recently (Stahl 1999; 2001). Early ethnographers assumed that time and history were irrelevant to understanding the function of such “simple” societies. This is best illustrated by how Evans-Pritchard described Nuer society: as an elegant, static, tightly integrated, functioning society, seemingly timeless. However, by the time these ethnographies were published, significant changes had occurred because of colonialism, yet the impacts of such contacts were usually never discussed (Stahl 2001, but see Stenning 1959).

McCabe (1994) notes that most studies, especially those in the 1960s and 1970s, described mobility as overly deterministic responses to environmental changes. Such interpretations were most likely vestiges from structural functionalist perspectives. In contrast, studies of Middle Eastern pastoralism emphasized the influence of political circumstances on mobility patterns (see the 1979 edition of *Pastoral Production and Society*). Studies carried out since the 1970s more carefully examined the ecological conditions in which pastoralist production takes place, dispelling notions of pastoral accumulation as irrational or dysfunctional (see Herskovits 1926). Dahl and Hjort's (1976) thorough examination of herd growth rates in Africa explains the strategy of East African pastoralists to maximize herd growth as a buffer against natural disasters, a strategy recorded in many subsequent studies (Fratkin and Roth 1990; Irons 1979; Khazanov 1994). The 1970s also saw an increasing focus on how individual herders dealt with the environmental and social issues, including the effects of colonialism, providing a more detailed understanding of pastoralist lifeways. Similarly, Western and Dunne's (1979) study of Maasai settlement patterns emphasized how the individual knowledge and experience of elders was crucial in determining new settlement locations. However, Borgerhoff Mulder and Sellen (1994) contend that these studies are too descriptive and anecdotal. In the past few decades research on pastoralism has also become increasingly interdisciplinary (Fratkin and Roth 1990), as well as focusing on development (Galaty and Bonte 1991), and the problems associated with economic and ecological change (Equipe Ecologie 1979; Monod 1975). Fratkin et al. (1994) argue that more recent volumes on pastoralism have lacked a serious attention to demographics, health, and human and livestock ecology, and call for a more holistic approach.

One particularly integrative and multidisciplinary study that focused in part on pastoralism was the South Turkana Ecosystem Project (STEP). McCabe's research on pastoralism among the Turkana is a clear departure from the earlier structural-functionalist and environmentally deterministic accounts of pastoralists (1994; 2004). Although his focus is primarily ecological, in contrast to Evans-Pritchard's analysis of Nuerland, the Turkana ecosystem is described as in a state of disequilibrium. According to this view, arid environments are inherently unstable, and therefore livestock numbers remain below carrying capacity. To maximize herd growth, pastoralists must continually move their herds to new environments. Aside from water and pasture availability, this emic approach shows that there are a number of factors that are considered when moving herds, such as raiding, predators, the presence of families or friends in a given area, and the individual strategy of the herd owner (1994; 2004). McCabe's data from the individual herders show that there was remarkable variability in mobility between the herd owners in any given year, as well as variability in one year to the next for individuals, this was partially a result of different life experiences as well as personalities. In line with other studies in the 1960s and 1970s, this approach most closely resembles the methodology employed as part of cognitive anthropology studies, where the individual is the unit of analysis (Dyson-Hudson and Dyson-Hudson 1980; Holland 1992, Linger 2005). It is evident through McCabe's long-term analysis that past individual experiences have helped shape their herding strategies, and continued to inform how they manage their livestock.

While behavioral ecology has provided a theoretical framework for many archaeologists studying forager and horticultural societies, this is a discussion that is not present in the literature of African pastoralism. Behavioral ecological analyses of pastoral production and decision-making have only emerged in the literature in the late 1980s (Borgerhoff Mulder and Sellen 1994). Such studies have used behavioral ecology examine the conditions under which specialized pastoralists may transition to agriculture (Mace et al. 1993), as well as to produce optimality models, which address long-term household persistence through herd-building strategies (Mace 1993; Mace and Houston 1989; Borgerhoff Mulder and Sellen 1994). However, these studies largely focus on agropastoralists involved in market economies, and in some cases researchers note that exchange for grain from agriculturalists is necessary for pastoralist survival (Upton 1986).

More recent research emerging from this field examines pastoralist mobility. Coppolillo’s (2000) study, for example, examines how labor availability, cultivation practices, herd size, water availability, and settlement density affected the distances herds traveled from home. However, such research is not explicitly framed within behavioral ecology. The lack of behavioral ecology in African pastoralist studies may also stem from the reluctance of scholars to view African herders as simply reacting to environmental cues. Rather, pastoralists are described as keen decision-makers and agents in determining herd migration routes, taking a multiplicity of factors into account, including vegetation and water distributions, but also social and political factors, such as the presence of friends or family members in specific areas, or the threat of raiding. McCabe (2004) even notes that the personalities and personal histories of the herders with whom he worked were significant factors in the level of risk-taking in their herd management strategies.

In the next part of this review, I will briefly discuss aspects of pastoral production that have become central to how anthropologists and archaeologists have theorized about them, including mobility, exchange, and accumulation of wealth.

Pastoral Production

Definitions of pastoralism have varied between scholars. While early works equated subsistence with social organization, studies carried out in the last few decades have clearly shown that pastoralist production encompasses a range of activities, from pure pastoralism to mixed herding and agriculture (Jacobs 1965; Khazanov 1994). Furthermore, shifts along the spectrum of pastoral production are not uncommon, and are usually facilitated by exchange relationships (see Jacobs 1965; Mutundu 2010; Sobania 1988, 1991).

Pastoral production is often characterized by a significant division of labor, often involving a segment of the population leaving to care for herds for part of the year. Fratkin and Smith (1994) note that among pastoralists such as the Turkana, extra labor is obtained by fostering children. Among stratified pastoralists, like the Tuareg or Fulani, slaves or dependent clients provide the labor force (Nicolaisen and

Nicolaisen 1997; Stenning 1959). Stenning (1959) notes that pastoral production requires maintaining a balance between the household labor force and the household's herd size.

Research on pastoralism has generally focused on men and male activities, but recent ethnographic studies have focused increasingly on the role of women in pastoralist societies. Most pastoralist societies are patriarchal, although Roth (1994) notes that senior wives can gain control of large herds when their husbands die. Nonetheless, most modern pastoralist women produce and manage all livestock products, including milk, hides, and dung (Buhl and Homewood 2000; Hodgson 2000), and may have ownership of some animals, although their husbands are in charge of organizing herding and migrations. For some pastoralist groups, selling milk today provides the bulk of the household income (Little 1994).

For most East African pastoralists, seasonal mobility is vital for maintaining herds, as shifts in water availability and vegetation quality require livestock to be herded at different areas during the year, particularly in areas with unpredictable rainfall patterns (Coughenour, et al. 1985; Nicholson 1996). Seasonal movements may be highly patterned or vary year to year, and can change significantly over time. Large scale migrations among pastoralists are also a common form of mobility (Stenning 1957). Mobility patterns among pastoralists are discussed in greater detail in Chapter 8.

One important aspect of pastoral production that seems to pervade ethnographic accounts is pastoralists' reliance upon other groups for exchange. Most pastoralists who focus solely on herding would have to rely on trade with agriculturalists to supply them with food resources in order to achieve a more balanced diet (Nicolaisen and Nicolaisen 1997). However, similar relationships between hunter-gatherer groups and pastoralists have also been documented, such as with the Elmolo and Samburu (Sobania 1988). Such networks can make up for shortfalls in livestock production, and are crucial in times of crisis, such as drought, extreme flooding, or disease epidemics (Waller and Sobania 1994). A greater discussion of pastoral exchange is outlined in Chapter 8.

Finally, we may consider the accumulation of wealth as part of pastoral production. While historical and ethnographic sources indicate large numbers of livestock could be acquired by certain individuals in traditional pastoralist societies (Evans-Pritchard 1940), these societies are usually described as “egalitarian”. The ethnographic examples listed above in part account for this apparent contradiction. All pastoralists desire large herds, even if this is not a sustainable goal. Livestock can be mobilized by lineages to obtain wives and necessary products not produced by the pastoralists themselves (Spencer 1965). Deng (1972) notes that the Dinka preferred to keep cattle “in circulation,” either loaned out among others or as bridewealth. Although livestock can be accumulated by individuals, Salzman (2004) argued that egalitarianism among pastoralists can be attributed to three factors: (1) no one can monopolize pastoral production, (2) resources like land and water are viewed as common, and (3) mobility allows for escape from an oppressor.

Among pastoralists, wealth and status are indexed by the types of herd animals owned by pastoralists; for example, large livestock such as cattle or camels are of significantly higher value than smaller species, although small species actually often contribute more to everyday nutrition (Dahl and Hjort 1976; Evans-Pritchard 1940; McCabe 2004). Animals that can be used in war or raiding were also highly valued among some groups.

However, wealth in the form of livestock can be fleeting, and the nature of pastoral production precludes its monopolization by any one individual. Numerous ethnographies and historical documentation describe the sudden and devastating loss of herd animals due to a variety of reasons, including droughts, disease, and raiding (Evans-Pritchard 1940; Fratkin and Roth 1990; McCabe 2004; Galaty and Bonte 1991; Nicolaisen and Nicolaisen 1997). While considerable wealth in livestock can be built up by one individual, it can be lost quite quickly. Many have argued that because of this inability to permanently accumulate wealth through livestock, pastoralist societies never develop social differentiation without contact with a sedentary society (Khazanov 1994; 2001; Kradin 2008). Paynter (1989) writes that inequalities fail to arise when members of the group lack the means to monopolize strategic resources in the face of substantial ecological and social leveling devices (see also Earle 1997). However, recent research by Borgerhoff-Mulder et al. (2010) has shown substantial intergenerational transmission of wealth among contemporary pastoralists.

While pastoralists seldom accumulate wealth in materials, it is often wealth in people that is sought. Pastoralists seek to maximize the size of their herds, but primarily as a means to expand their own families (McCabe 2004, see also Jacobs 1965; Spencer 1974). Although a pastoralist could accumulate vast amounts of livestock, it was distributed among his family members more or less equally. Among the Samburu cattle were allotted for each wife and there is substantial marriage between clans, ensuring that the herds were distributed more or less equally among families (Spencer 1965).

The concept of wealth-in-people is particularly useful for understanding this pattern of "accumulation" (Guyer 1995; Guyer and Belinga 1995). Wealthy pastoralists traditionally wanted to build up herds to convert into a following, much as the classic Oceanian "big-men" (Sahlins 1963). By accumulating a large number of dependents, whether wives, children, and/or laborers or other followers, an individual can broaden his social base, and through their wives' kinship ties have access to livestock, in case his herd collapses by natural disasters or raiding (Guyer and Belinga 1995). In this way, power is built through enlisting clients and followers, by consensus, rather than coercion, on the part of the leader. This is important in pastoralist groups, where land and livestock are abundant, but labor is necessary to maintain large herds (Dahl 1979; Fratkin and Smith 1994).

Although the mechanisms that acted to level pastoral wealth among lineages were probably very effective in the past to inhibit the development of hereditary economic inequality, evidence for long-term inequalities in modern contexts have been documented. This development, however, is a consequence of pastoralists encountering situations of restricted grazing, privatization of land, and unequal access to markets (Bradburd 1982; Fratkin and Roth 1990).

Emergence of pastoralism

The frequently documented interactions and exchange relationships between pastoralists and agriculturalists has led to some scholars to question whether the presence of sedentary agriculture is a precondition for pastoralism. Archaeological research in Eurasia, which began much earlier than it did in Africa, has contributed to the notion that agriculture is indeed a prerequisite. The sequence of events leading to specialized pastoralism in Southwest Asia has significantly affected how archaeologists viewed the African evidence, as well as discussions of complexity in pastoralist societies. In fact, specialized pastoralism in Southwest Asia and in East Africa, occurred, independently and in two very different contexts. More recent archaeological evidence from a wider region of Eurasia and Africa has produced new understandings of how pastoralism can emerge.

Lees and Bates (1974) argued that nomadic pastoralism emerged in a context of mixed farming and herding. The development of irrigation would have allowed people to populate dry areas farther from adequate pastures, encouraging mobility on the part of herders to seek better pastures. Eventually, Lees and Bates argue, this would have resulted in a specialized segment of herders breaking off from the group. Bar-Yosef and Meadow (1995) also contended that specialized pastoralism could only have emerged after sedentary agriculture. This pattern in Southwest Asia is supported by archaeological evidence, which indicates that plant domestication antedates archaeological evidence of domestic caprines in the Zagros at sites like Asiab and Ganj Dareh between 10,500 to 9900 cal BP (Zeder 2001).

Because agriculture appeared before pastoralism in Southwest Asia, and ethnographies of pastoralists recorded either some degree of agriculture or trade with sedentary groups for vegetable foods, (Barth 1961; Nicolaisen and Nicolaisen 1997) many theorists argue that specialized pastoralism could not develop or exist alone. This significantly colored how evidence for early pastoralism was interpreted in Africa.

In contrast with the typical Southwest Asian pattern, recent archaeological research farther east in Eurasia has provided evidence for early pastoralism without agriculture, reflecting a herding and hunting strategy, with no evidence for domestic crops (Frachetti and Mar'yashev 2007). Similarly, Rosen (2009) describes the presence of what he calls herder-gatherer sites in the early Timnian phase in the Negev dating to the sixth millennium BC, with little indication of exchange between nomadic pastoralists and sedentary agricultural communities. Interestingly, some of these sites are associated with megalithic shrines and tumulus burials. Betts (2008) also notes the presence of groups engaging in a range of economic activities involving herding, hunting, and gathering after the collapse of the PPNB in the Levant.

African archaeology began in a colonial setting, and archaeologists generally subscribed to the culture-historic interpretation of similarities as evidence of cultural connections resulting from migration and diffusion. Diffusion was used to explain away the evidence of cultural development in Africa, including iron-production, urbanism, monumental architecture, kingdoms, and art (Stahl 2005; Trigger 1990). Early studies assumed that all societies progressed through the same stages, and terms such as the "Mesolithic" and "Neolithic" were applied uncritically to African contexts based solely on technological evidence (Gifford-Gonzalez 2005; Stahl 2001a, b). Based on research in Southwest Asia, pastoralism was thought to have emerged after agriculture and sedentary settlement patterns. However, in Africa, ceramics appear very early, long before the appearance of domestic animals, and domestic morphology plants do not appear until much later (Khabir 1985; MacDonald 2000; Manning 2009; Neumann 2005). Marshall and Hildebrand (2002) argue that initial attempts to keep cattle in Africa were responses to resource unpredictability. Marshall and Hildebrand (2002) also posit that the adoption of herds may have been facilitated by early Holocene, delayed-return foraging strategies, which incorporated wild plant foods, possibly cultivated but not of domestic morphology allowing for ideas of ownership and making the transition to owning herds more fluid.

The fact that specialized pastoralism occurred in Africa before the advent of agriculture has been a vexing puzzle for some, but only when this evidence is viewed in the light of the Southwest Asian data (Gifford-Gonzalez 2005; Stahl 1999). This evidence has not yet been completely accepted by the archaeological community outside of Africa. Specialized pastoralism developed in Southwest Asia in a mixed farming context, and thus theories on how social complexity developed in pastoralist societies have generally been interpreted as occurring through contact with sedentary agricultural societies. The idea that specialized pastoralism cannot occur without the presence of agriculture is based on observations of nomadic pastoralists in increasingly marginalized areas, and these groups had all been affected by colonialism and state expansion (Irons 1979; Johnson 1991). Therefore many view pastoralists as dependent on the existence of sedentary agricultural groups.

African pastoralists' reliance on other groups for exchange is one important aspect of pastoral life that is described throughout ethnographic accounts of the latter part of the 20th century. Most pastoralists who focus solely on herding rely on exchange with agriculturalists to supplement their diets (Nicolaisen and Nicolaisen 1997). However, even in cases where exchange for food resources is necessary, this need not be with agriculturalists. Sobania (1988) highlights the importance of exchange between specialized pastoralists and hunter-fisher-foragers.

The effects of colonialism were disastrous for many pastoralist societies, partially because interactions between different groups were greatly hindered by forced settlement and the restructuring of territories. Colonial officials created "tribal grazing areas" for administrative order, but restrictions on movement led to hostility among locals, and separation between groups undercut previous social ties between populations like the Samburu and Rendille (Sobania 1991). The Nuer and Dinka found themselves in a similar situation when they were separated for security reasons in the early 20th century. Individuals could no longer form social networks across new political boundaries (Johnson 1991). Colonialism and the re-structuring of territories by colonial administrators were extremely harmful to pastoralists (Carr 1977). Restrictions on mobility impacted the level of exchange between groups and prevented necessary seasonal migrations to better pastures and to avoid flooded and disease-ridden areas.

How have archaeologists viewed African pastoralists?

Until recently, throughout the 1970s and 1980s archaeologists working in Africa have viewed past pastoralist societies through a culture-historic lens, however unconsciously, as a product of their scholastic pedigrees, and perhaps reinforced by colonial views on African "tribes" (Hall 1984). Archaeologists in East Africa continued to view ceramic traditions as representing distinct cultural entities. Archaeological groups were equated with specific artifacts, therefore Elmenteitan ceramics signaled an "Elmenteitan people", and/or these were also taken to represent divergent subsistence strategies, despite the development of processual archaeology in the USA and UK (Robertshaw 1990). Thus, Bower et al. (1977) linked Maringishu, Narosura, Elmenteitan, and Akira ceramic traditions with food production and the Kansyore tradition with hunting, foraging, and fishing peoples. Such culture-historic themes are evident in debates over whether Holocene changes in material culture and subsistence practices in East Africa were autochthonous developments or the products of diffusion or migration, e. g. Ambrose's (1984b) linking of the Elmenteitan with southern Nilotic-speaking peoples, based on earlier linguistic studies (Ehret 1967). In discussions of the spread of pastoralism, implicit progressivist assumptions about the adoption of herding and ceramics were still prevalent 20 years ago (cf. Bower 1988). In the last decade, however, there has been a theoretical shift, uncoupling cultures or ethnic groups from archaeological materials (Dale 2007; Dale and Ashley 2010; Lane et al. 2007; Prendergast 2010; Seitsonen 2010). Ethnoarchaeological work carried out in East Africa has also contributed to this shift (Dietler and Herbich 1989).

The interaction between groups with different subsistence strategies has been thoroughly discussed in the literature, stemming from ethnohistorical and ethnographic research (Mutundu 2010; Sobania 1988; Waller and Sobania 1994). Spencer (1974) also notes the occurrence of different groups and subsistence economies in East Africa, arguing that membership to “tribal groups” was not determined by birth, nor was it fixed. Kusimba et al. (2005) write on the “mosaic” of ethnic groups in East Africa. Similarly, in the ethnographic literature, as described above, pastoralists interact with hunter-gatherers, as well as agriculturalists, in relationships of exchange. In terms of archaeological investigations, recently an increased recognition of the fluidity of subsistence strategies has emerged. Rather than aligning groups with only one type of subsistence strategy, new work carried out by Mutundu (2010) presents criteria that archaeologists can use to distinguish different types of subsistence strategies. Marshall (1994) also argues for considerable variability in pastoralist subsistence strategies in the Pastoral Neolithic of East Africa (see also Gifford et al. 1980; Marean 1992; Marshall and Stewart 1995).

In sum, the study of pastoralist societies has shifted from emphasizing purely structural and ecological aspects to situating these groups within a broader political and historical context, focusing on social and political aspects of pastoral society. Archaeological studies of pastoralism are also crucial in understanding the development of pastoral production. Increasingly sophisticated and multidisciplinary examinations of pastoralists’ relationships with colonial and post-colonial governments as well as individual-focused studies of pastoral production hold great promise for the study of both contemporary and archaeological pastoralist groups. My project addresses some of these issues by exploring pastoral mobility and herd management in Kenya before the arrival of agricultural populations by highlighting the variation in pathways to food production. The next chapter delves into a review of the archaeology of the study region.

CHAPTER 3: ARCHAEOLOGY OF PASTORALISM IN KENYA

The appearance of pastoralism is a critical development in the history of human subsistence, permitting more people to live in the earth's dry lands than does foraging. In northern Africa, pastoralism developed, around 8,000 years ago, and gradually spread throughout the continent over the next several millennia. Specialized pastoralism emerged in Kenya around 3000 years ago and has adapted with changes in the social and ecological landscape to this day. Ethnographic research has documented significant changes in herding strategies among pastoral groups throughout colonial and post-colonial periods (Gulliver 1955; McCabe 1994; McCabe 2004). These studies have highlighted the malleable nature of pastoralism, hinting that, as documented ethnographically, pastoralist practices in prehistoric times would have shifted and adapted to social and ecological changes. Furthermore, clear archaeological evidence exists that neither pastoral production nor farming was adopted wholesale as they spread into Kenya, but rather interdigitated with other subsistence strategies, forming a "cultural mosaic" of ethnically and economically differentiated yet interdependent peoples.

The development of food producing economies in Africa followed a trajectory very different from that in Southwest Asia and Europe, with pastoralism and ceramic production appearing long before sedentary agriculture. Before the advent of herding, hunter-gatherers with ceramics populated early Holocene northern Africa. Pastoralism first appeared around 7700-8000 years BP in the Nabta-Kiseiba area, while settled village life appeared over 5000 years later. The fact that specialized pastoralism occurred in Africa before the advent of agriculture has been a vexing puzzle for many, but it is only so when this evidence is viewed in the light of expectations about a universal sequence toward food production drawn from Southwest Asian models (Stahl 2005). The pastoralist period has often been called "Neolithic" by researchers in North and East Africa because of the presence of ceramics, polished stone, and domestic animals. In the classic, Eurocentric definition, the Neolithic is characterized by domestic plant and animal-based food production and permanent settlements. Ambrose (1997) argues for substituting the term "Ceramic Late Stone Age" for this period Africa, because pottery significantly predated settled agricultural societies.

To explore the emergence of domesticated animals and pastoralism in Africa, I first review research on the Holocene in northern Africa, briefly reviwing its climatic changes and the hunting, foraging, and fishing populations who lived in northern and eastern Africa. I then turn to East Africa in detail, beginning with a brief overview of archaeological research, then discussing first appearance of ceramics before the advent of food production, and finally the emergence and nature of herding economies there through the beginning of ironworking. In the process, I outline some lingering concerns and debates in the study of the history of pastoralism in East Africa.

A history of North African Holocene archaeology

Research on food production in North Africa began in the early 20th Century. Scholars working during this period assumed that the African record would parallel that of Eurasia (Robertshaw 1990a), and attempted to fit African sites into the European sequence, often attaching a geographical prefix, e.g. the Kenya Aurignacian (Leakey 1931). Overall models for the emergence of food production were progressivist and at least implicitly assumed that the Near Eastern and European archaeological sequences were universal, an idea reinforced by archaeologists working in Egypt, which was indeed significantly influenced by Southwest Asia (Wetterstrom 1993). Even after World War II, archaeologists working in North Africa were trained solely in the Southwest Asian sequence. Rather than considering the possibility of other, divergent sequences, they unconsciously held expectations that the African data did not meet, producing a "puzzle." The slow acceptance of the alternative sequence of food production in Africa stems from archaeologists' assumption that the Southwest Asian sequence of events was universal: pastoralism was thought to have emerged after agriculture and sedentary settlement patterns. Such ideas echo progressivist notions that all peoples eventually pass through the same series of developmental stages (Gifford-Gonzalez 2005; Stahl 2001a, b).

Archaeological research in East Africa was first carried out by L.S.B. Leakey. The "Neolithic" there was first defined by Leakey in 1931, but fully described by Mary Leakey in 1945. The stone bowls from these East African sites became the *fossil directeur* for the East African Neolithic, taken as evidence for processing plant material, and thus, food production. As might be expected for the times, the Leakeys' research involved a typical culture-historic approach. Such normative, culture-historic perspectives view artifactual traditions, or industries, as representing ethnically distinct peoples, and continued to prevail in East African research through much of the 20th Century, despite new developments in archaeological theory elsewhere (Robertshaw 1990a; Trigger 1990). Diffusion was often invoked to explain cultural developments such as iron production, monumental architecture, and urbanism in Africa (Trigger 1990). In its most extreme form, the "Hamitic hypothesis" was used during the colonial period to deny black "natives" any creativity, attributing all change to now-vanished, light-skinned immigrants (Robertshaw 1990a).

The prospect of early hominids pulled the Leakeys' interest towards paleoanthropology in the 1950s, and work on "Neolithic" sites virtually ceased until the 1960s (Conroy 2005). In the 1970s, research on Holocene sites intensified as archaeologists from the University of California at Berkeley, University of Chicago, and University of Massachusetts began work in the Central Rift (Bower, et al. 1977; Butzer, et al. 1972; Gifford, et al. 1980). Barthelme (1985) and Robbins (1972) carried out parallel research in the Lake Turkana Basin in the 1970s. The 1970s and 1980s also saw zooarchaeological research on "Neolithic" faunas, initially by students of Glynn Isaac of UC Berkeley (Gifford, et al. 1980; Gifford-Gonzalez and Kimengich 1984; Marshall, et al. 1984; Robertshaw and Marshall 1990). These reflect the encouragement by Cambridge-trained, Berkeley-based Africanists of Cambridge-style subsistence- and environment-focused research (Robertshaw 1990a;

Trigger 1990).

This work made clear that stone bowls, initially assumed to represent food production in East Africa, did not appear in every site with livestock. Rather, geometric microliths and ceramics were the common hallmarks of these sites. The name "Stone Bowl Culture" was abandoned for the term "Pastoral Neolithic" (PN), seen by some as an evolutionary stage between the Late Stone Age (LSA) and the Pastoral Iron Age (Bower 1988; Bower, et al. 1977). Ambrose (1984b) argues that archaeological research on Holocene East Africa into the early 1970s was hindered by insufficient descriptions of identified archaeological cultures. Identifications relied upon single traits (e.g. stone bowls) to define archaeological cultures, rather than a multivariate approach, and sites were often misclassified as researchers attempted to fit new data into frameworks based upon small initial samples.

Although in the US and Britain "New Archaeologies" developed as a reaction to normative archaeology and diffusionist arguments, archaeologists working in Africa in the 1970s and 1980s continued to subscribe to the culture-historic view, however unconsciously, as a product of their scholastic pedigrees. New techniques such as zooarchaeology and radiocarbon dating were adopted, but a culture-historic perspective persisted in African archaeology, perhaps reinforced by colonial views on African "tribes" (Hall 1984; Robertshaw 1990a). Archaeologists in East Africa continued to view ceramic traditions as representing distinct cultural entities, with divergent subsistence strategies. Thus, Bower, et al. (1977) linked the PN Maringishu, Narosura, Elmenteitan, and Akira ceramic traditions with food production and the

Kansyore with hunting, foraging, and fishing peoples. Culture-historic themes are evident in Holocene East African archaeology in debates over whether changes in material culture and subsistence practices were autochthonous developments or the products of diffusion or migration, as evident in cases outlined below. Implicit progressivist assumptions about the adoption of herding and ceramics were still prevalent 20 years ago in discussions of the spread of pastoralism (cf. Bower 1988). Processualism was not incorporated into African research largely because archaeologists working there were trained by older, Cambridge-trained mentors who were still teaching normative archaeology within an increasingly ecological paradigm (Robertshaw 1990a).

The 21st Century has seen more interest in early to middle Holocene East Africa and a more contemporary approach to archaeological theory, within a general Anglo-American paradigm. Recent work includes research on Kansyore sites on the eastern end of Lake Victoria. (Dale 2007; Dale and Ashley 2010; Lane, et al. 2007; Prendergast 2010; Prendergast and Lane 2010; Seitsonen 2010), as well as investigations of monumental sites with Nderit ceramics in the Lake Turkana basin (Grillo and Hildebrand 2013; Hildebrand, et al. 2011), and ethnoarchaeological investigations of transitions in subsistence strategies that present new criteria for distinguishing between hunter-gatherer and pastoralist sites (Mutundu 2010). This generation of archaeologists has also brought in a new set of theoretical perspectives in East African archaeology, including concepts such as “networks,” first introduced to Britain in the mid-1970s by Clarke (1976). In part influenced by more recent developments at Cambridge, Karega-Munene (1996) was the first to argue that ceramics found at some East African sites may not have been produced by the site occupants but obtained by exchange. Dale and Ashley (2010) stressed that, rather than a “Kansyore people,” it is preferable to refer to “Kansyore using people,” implying that not all who used this ceramic ware had to be of the same “culture.” Kusimba and Kusimba (e.g. 2005) have discussed so-called cultural mosaics as a more realistic model of Holocene social relations.

In East Africa the application of new analyses to archaeological materials has also been slow to reach standards developed elsewhere. Until the late 1990’s researchers working in this region took a typological approach to ceramic classification, even though attribute analysis was used to refine a priori categories (e.g. Collett and Robertshaw 1983; Wandibba 1980). Recently work includes technological analyses of ceramics and lithics, widely used elsewhere for decades (Dale 2007; Seitsonen 2010). New findings, applied within more contemporary theoretical paradigms, promise to shed much light on interactions among migrants and indigenous peoples. This review now turns to evidence for the emergence of pastoralism.

Archaeology of Northern Africa in the Early Holocene

The first human occupants of the “green Sahara” during the early Holocene humid phase were hunter-gatherers who exploited aquatic fauna and wild plants, and many sites appear to reflect at least seasonal sedentism (Hassan 2000). Early

Holocene sites in the Saharo-Sahelian zone that stretched from Nile Valley into West Africa are characterized by microliths, grinding stones, globular ceramics with wavy line and dotted wavy line decoration and other designs, barbed bone points, and wild aquatic fauna (Holl 2005; Khabir 1985; Mohammed-Ali and Khabir 2003; Sutton 1977).

North African ceramics are widely distributed by 9000-10,000 BP, in a diversity of designs. Honegger (2005) reports a site with ceramics near the Second Cataract of the Nile, dating to about 10,300 BP. Other early dates include wavy-line ceramics at around 9400 BP from Sarurab, in the Central Nile Valley in Sudan (Khabir 1985; Mohammed- Ali and Khabir 2003). These locally produced ceramics are distributed from as far west as Niger through the southern Sahara to the middle Nile in Southeast Egypt and up-river into the Kenyan Rift Valley, (Mohammed-Ali and Khabir 2003), and were likely used for processing aquatic food resources, as well as wild grains (Casey 2005; Holl 2005). The invention of ceramics and ability to boil foods enabled an increase in the exploitation of aquatic resources, evidenced by the presence of harpoons at early Holocene sites in the Nile Valley and lakeside sites in East Africa (Haaland 1992).

Sutton (1977) had earlier explained the wide distribution of a combination of locally produced wavy-line or dotted wavy-line pottery, fishing gear, and aquatic fauna in terms of diffusion, representing an “African Aqualithic” cultural complex that spanned the southern Sahara and Sahel, from the Upper Niger to the middle Nile, and southeast to the East African Rift. These traits, however, do not always occur together throughout northern Africa (Sutton 1974, 1977), and thus the pattern may be a result of parallel evolution, and convergence Holl (2005), since certain types of material culture, such as harpoons, are widespread across Africa, and not associated with a particular ethnic or linguistic group (Yellen 1998).

While Sutton (1977) may have gone too far in arguing that all of these groups exploiting aquatic resources belonged to one large cultural group, recent research in the Lake Victoria area hints at a possible connection between dotted-wavy line pottery and Kansyore wares (Dale 2007). Evidence for relatively large watercraft use during the early Holocene humid phase suggests that water-based transportation may explain the widespread distribution of early Holocene cultural traits across what is now the southern Sahara (Breunig 1996).

Origins of Domestic Livestock in Africa

Marshall and Hildebrand (2002) argue that herding was adopted in response to increased resource unpredictability as the Saharan savanna dried, facilitated by pre-existing concepts of ownership characteristic of delayed-return foraging strategies based upon wild plant foods. Because the earliest domestic cattle in Africa are found in the northern regions, overlapping with the range of wild African cattle, some researchers have suggested an independent domestication of African cattle, separate from that of Southwest Asia (Bradley, et al. 1996; Grigson 1991, 2000). Wendorf and colleagues argued that large bovid specimens from Bir Kiseiba (E-75-8) in the Nabta region, dating to about 9,000 BP, are domesticates (Gautier 1984; Wendorf and

Schild 1984, 1998), because without human management, these animals would not have survived in the harsh environment. Based on their size and morphology, Grigson (2000) argued that the bovids from Bir Kiseiba are wild, and Gautier later retracted his identification (Gautier 2002). Unequivocal evidence of domestic cattle in northern Africa is dated to 7700 – 6500 BP in the Nabta-Kiseiba area (Gautier 1984). The earliest African site with domestic cattle remains outside of the Nabta-Kiseiba area is in southwestern Libya in the Acacus at the site of Uan Muhuggiag, dated to about 7,440±220 years BP (Gautier 1987). However, that date is suspect, as most of the animal bones date to around 6000 BP, similar to other Middle Pastoral sites in the Central Sahara (Garcea 2004). Recent reports claim domestic cattle just south of the second cataract of the Nile, dating to about 8900 cal BP (Honegger 2005). No sheep or goat remains are associated with these very early cattle occurrences. A general trend exists for more recent dates for domestic cattle farther west from the northeastern Sahara, which is also supported by genetic evidence (Hanotte, et al. 2002).

Initial mtDNA evidence suggested an independent African origin for domestic cattle. The earliest domestic cattle in Africa were taurine, or straight-backed, and while morphological differences between Levantine and Egyptian cattle indicate that these two populations were separate from the fourth millennium BC (Grigson 2000), mtDNA dates the divergence between African and European cattle between 26,000 and 22,000 BP (Bradley, et al. 1996). However, more recent research presents a more complicated picture, suggesting that wild African aurochs may have contributed to the gene pool of domesticates through male introgression into stock of a Southwest Asian origin (Pérez-Pardal, et al. 2010).

Human genetic evidence supports archaeological dates for dairying with domestic herd animals. Alleles for lactase persistence are common in Nilo-Saharan speaking groups, the mutation estimated to have arisen around 6000-7000 years ago (Tishkoff, et al. 2007), corresponding with recent findings based on organic residues from Southwest Asian ceramics sites dating from about 9000 to 7000 BP (Evershed, et al. 2008).

Introduction of Small Stock

The introduction of small stock from Southwest Asia into Africa was likely not a single event. There are few sites in the Fertile Crescent with domestic caprines before 9000 BP, and domestication also probably occurred at more than one place (Legge 1996; Luikart, et al. 2006; Zeder and Hesse 2000), though a recent study suggests a single location (Naderi, et al. 2008). Phylogenetic analysis of sheep also indicates at least three different domestications in Southwest Asia (Bruford and Townsend 2006; Pedrosa, et al. 2005). Caprines first appear in Africa between 7500 and 7000 BP along the Mediterranean coast at Haua Fteah in northern Libya (Clutton-Brock 1993), Grotte Capeletti in northern Algeria, and in Egypt at Merimde Beni Salama. The North African populations may have been supplied from across the Mediterranean from Europe, while the Nile populations and would have come from the Sinai (Luikart et al. 2006). Another route into Africa may also have occurred along the Red Sea coast, as evidenced by caprines at Quessir at 7000 BP (Hassan 2000). With the increasing desiccation, pastoralist groups may have begun to focus on smaller stock. The greater water needs of cattle would have confined early pastoralists to locales with sufficient water. Caprines' ability to thrive in arid conditions and breed more quickly (Dahl and Hjort 1976) would have led to their rapid spread throughout Africa upon their introduction.

The earliest dated pastoral sites in the Egyptian and Sudanese Nile Valleys are around 6300 to 6000 BP (Haaland 1992; Wendorf and Schild 1998). The severe droughts that spanned about 7000 to 6000 BP likely led to the movement of Saharan herders into refuges such as the Nile Valley, already occupied by sedentary foragers (Hassan 1988, 2000; Kuper and Kröpelin 2006). These sites, like the 5900 BP Fayûm site Kom W, show a diversity of human food sources including domesticates and aquatic fauna (Hassan 1988).

Numerous examples of pastoralist monumental architecture exist in northern Africa, and these ceremonial sites permit another perspective on early herders. Monuments are found at Nabta Playa (Wendorf and Schild 1998), near the Middle Niger (MacDonald 1998), in southwestern Libya (di Lernia 2006), and other parts of the central Sahara. A circular alignment of sandstone slabs lies near to the Nabta Playa site E-75-8, which Wendorf and Schild (1998) hypothesize may have had been linked to solstice or other astronomical events. Such sites from northern Africa may be linked to later monumental sites in East Africa (Hildebrand and Grillo 2011; Lynch and Robbins 1979).

The symbolic importance of domestic cattle is evidenced in Saharan cattle burials, which are common throughout northern Africa in the mid-Holocene, where they are found as far apart as in Nabta, Egypt, Adrar Bous, Niger, the Acacus of southern Libya, and the Tilemsi River Valley in Mali (Clark, et al. 2008; di Lernia 2006; Wendorf and Schild 1998). Di Lernia (2006) argues that these burials and widespread Saharan megalithic monuments may have been a social response to cope with increasing aridity. Marshall and Hildebrand (2002) hypothesize that seasonal gatherings of pastoralist groups at such sites may have incorporated cattle-based rituals, and further aided in consolidating social and political networks.

Changes in mobility patterns are evidenced through isotopic research from the Acacus in southwestern Libya (di Lernia and Tafuri 2013; Tafuri, et al. 2006). Data from early Holocene (9800 to 7000 BP) hunter-gatherer skeletal material show a range of strontium isotope ratios, indicating considerable, perhaps transhumant, mobility, while data from pastoral groups in the same area dating from 7000-5000 BP show more homogeneity in their strontium isotope ratios, reflecting restricted mobility, though evidence exists for increased mobility as the climate became drier.

During the desiccation of the Sahara, pastoralists moved into river valleys and lake basins in several regions across the Sahel and farther south, sometimes bringing them into contact with hunter-gatherers or incipient cultivators residing in those areas. (Haaland 1992) hypothesizes that, at about 5300 BP, Nilo-Saharan-speaking fisher-foragers in the Khartoum area were largely replaced by Cushitic-speaking specialized pastoralists. These Nilo-Saharan-speaking people then migrated to areas undesirable for specialized herding, like the Sudd, allowing them to maintain their “multiresource adaptation,” (1992:59).

Hunters, Fishers, and Foragers with Ceramics in East Africa

Ceramics appear in hunter-gatherer sites in East Africa well before domesticated livestock. Haaland (1992) argues that Nile Valley ceramic technology was carried to East Africa by demic diffusion between 9500-8500 BP, during the humid phase of the Holocene. Pottery similar to the globular wavy-line and dotted wavy-line ceramics of early Holocene northern Africa appears just west of Lothagam, in the Lake Turkana basin, dated to 9173-8467 cal BP, associated with bone harpoons as well as aquatic and terrestrial fauna (Robbins 1972). These ceramics are confined to the early Holocene of the Lake Turkana basin, the southern-most point of eastern links with the White Nile.

On the western arm of White Nile linkages, another ceramic tradition, the Kansyore of the Lake Victoria basin, also dates to the early Holocene in East Africa, and is not associated with domestic animals or plants. Kansyore-making hunter-gatherers lived near Lake Victoria and as far southeast as Eyasi. These sites are characterized by a quartz-based lithic industry and heavy reliance on wild terrestrial and aquatic resources (Dale and Ashley 2010; Lane, et al. 2007; Prendergast and Lane 2010; Seitsonen 2010). Whether Kansyore, because of its similarity to Early Khartoum wavy-line and dotted wavy-line ceramics, reflects a connection between the two is still under debate. Dale (2007) argues that a shared design concept exists between the Nilotic and Kansyore ceramics, possibly indicating long distance contacts, though other scholars remain skeptical (Prendergast and Lane 2010; Robertshaw 1991).

Kenyan Kansyore sites are found both along the shores of Lake Victoria and at rapids of tributary rivers, such as the Kuja and Sondu-Miriu (Prendergast 2008). Researchers have identified an Early Kansyore phase with only wild animals 8000-7000 BP and a Late Kansyore phase (c. 3000 BP – 1500 BP, with a late date from Mumba), characterized by more terrestrial mammals than fish and some caprines (Dale and Ashley 2010; Prendergast 2008). Sites like Siror span both early and late phases. Early Kansyore sites, like the shell midden site of Pundo, reflect specialized fish and shellfish exploitation plus some hunting, with relatively rare ceramics bearing a fairly limited set of decorative techniques and styles (Prendergast and Lane 2010). Robertshaw (1993) notes that shell middens may only represent one segment of mobility and subsistence (Robertshaw, et al. 1983). Faunal evidence indicates Pundo was occupied during the dry season. It is possible such middens were more common in the earlier Kansyore span, although this may be an artifact of a small sample size.

Later Kansyore sites such as Usenge 3, Siror, and Gogo Falls, have significantly higher concentrations of mammalian taxa and some domesticates (Dale and Ashley 2010; Robertshaw 1993). Wadh Lang'o has domestic caprines present in its earliest levels, dating to 4408-3982 cal BP (Prendergast 2010). The differences between these sites may be due to differential use of landscape. While fauna at Pundo indicate a dry season occupation, the high proportion of anadromous fish in riverside open-air Kansyore sites, including Gogo Falls, Siror and Wadh Lang'o, suggests a rainy season occupation (Collett and Robertshaw 1980; Prendergast 2010; Prendergast and Lane 2010). The presence of domesticates at some Late Kanysore sites probably results from Kansyore-using foragers' interactions with Rift Valley pastoralists (Prendergast 2008).

Timing of and mechanisms for the spread of pastoralism in East Africa

Nderit Ceramics

The earliest securely dated livestock in East Africa are found in the Lake Turkana basin. These sites contain Nderit pottery, characterized by decorations covering its outer surface and scoring on the interior (Bower 1973; Leakey 1931). Nderit ware, originally named Gumban A (from the type site Stable's Drift on the Nderit River, Leakey 1931) is found at early pastoral sites in the Lake Turkana basin such as Dongodien (GaJi4) and is associated with low densities of material culture and relatively high numbers of wild animals, relative to later Savanna Pastoral Neolithic (SPN) sites (Bower 1991). The earliest secure dates for Nderit pottery come from west of Lake Turkana, at Kangatotha and Site Bb-14, near Lothagam, and date to around 5000 BP (Robbins 1972). How various researchers classify these traditions differs, and I follow Ambrose, Gifford-Gonzalez, and Robertshaw in their treatment of the Pastoral Neolithic (PN) as comprising distinct cultural-technological entities, rather than Bower (1991) unitary grouping which combines combined the Nderit, Elmenteitan, and pottery associated with Savanna Pastoral Neolithic lithics into a "Pastoral Neolithic" category.

Nderit ware is the only ceramic tradition that extends from the Lake Turkana basin, through the Central Rift, the Athi Plains, to the Serengeti Plains in northern Tanzania (Barthelme 1977; Bower 1973; Bower, et al. 1977; Gramly 1975). These ceramics are associated with pastoralism in the Lake Turkana basin, but less securely connected with domesticates in the Central Rift, Athi and Serengeti Plains. Nderit sites south of the Turkana basin also lack monumental architecture. Gifford-Gonzalez (1998) argues that Nderit ware should be considered separate from the SPN grouping, due to its antiquity, widespread distribution, and occasional association with domestic fauna. For example, at Enkapune Ya Muto in the Central Rift, Nderit ceramics occur in association with the local Eburran 5 lithic tradition, in levels dated to 5597 cal BP, long before the first appearance of domesticates (Ambrose 1998).

The antiquity of Nderit ceramics is of some debate. An early date of 7255±55 BP for a few caprine elements and Nderit ware at the Central Rift rockshelter of Salasun (Bower, et al. 1977) is dubious given extensive rodent burrowing in the site (Gifford-Gonzalez 1998). Serengeti sites also have sparse but early evidence: Gol Kopjes (HcJe 1) in northern Tanzania has very early dates (~7000 BP) for Nderit ware, though faunal evidence rules out its association with pastoralists (Bower and Chadderdon 1986; Gifford-Gonzalez 2011). Nderit ceramics are also found under sparsely distributed Kansyore pottery at Seronera. Another early date for Nderit ceramics on the Serengeti is 5000 BP at Nasera (Mehlman 1977). While the dating of far southern Nderit sites has not fully been nailed down, sites where the pottery is found seem to be primarily of foragers, with or without some small domesticates (Gifford-Gonzalez 2011).

Lake Turkana also uniquely possesses megalithic monuments dating to 5000-4200 cal BP, possibly representing a continuation of the Sahelo-Saharan monumental tradition. The Jarigole Site (GbJj1), on the east side of Lake Turkana, is the best known example of such monumental architecture associated with the ceramic LSA in East Africa, featuring a prepared oval platform and mound, and at least twenty-eight columnar basalt pillars. It yielded the only ceramic figurines of animals in East Africa, Nderit ceramics, and very fragmented human remains (Robbins 2006). Namoratunga (pillar sites) on the west side of the lake bear striking resemblances to Jarigole, most of which also contain Nderit ceramics (Hildebrand and Grillo 2011; Nelson 1993). These sites, all dating to the fifth millennium cal BP, were probably not used much after 4100 BP (Hildebrand and Grillo 2011). Their purpose has been interpreted as calendrical systems (Robbins 2006). Several researchers (di Lernia 2006; Marshall and Hildebrand 2002) suggest that the use of such specialized sites for strengthening social ties would have been important for somewhat isolated pastoralist groups moving into a new area.

The indigenous Eburran industry and food production

The Eburran lithic industry, formerly called the Kenya Capsian (previously the Upper Kenya Aurignacian) (Leakey 1931), was renamed for Kenya's Mt. Eburru

(Ambrose, et al. 1980). Eburran sites are restricted to the Central Rift Valley around the Nakuru-Naivasha basin. Material culture associated with the Eburran industry includes burins, microliths, and long, narrow blades and flakes (Ambrose 1984b; Bower and Nelson 1978; Bower et al. 1977). The Eburran industry is linked with an indigenous transition from a broad-spectrum hunting and gathering adaptation to use of ceramics and introduced domestic herd animals. The Eburran lithic industry, with a distinctive core-reduction technology, is divided into five phases, the first four spanning from 12,000 BP to about 6000 BP, though later occurrences of Eburran 4 are present at Enkapune Ya Muto, while phases 5A and 5B occur much later, from around 3000 BP to 2000 BP (Ambrose 1984b, c, 1998). Phase 5A sites are dominated by hunter-gatherer activity with some incipient pastoralism and trade with pastoralists, while Phase 5B is characterized by pastoralism with hunting. They are also located in open savanna grassland habitats rather than at the savanna-montane transition ecotone, as is the case with Phase 5A. Eburran 5 occurrences include Enkapune ya Muto (GtJi12, EYM), a rock-shelter located on Kenya's Mau Escarpment. Ceramics appear sparsely in Eburran 5 levels, as early as 4860 BP. Some resemble Nderit/Ileret ceramics, while others are similar to Suswa/Salasun "wares" (Ambrose 1998). Caprines do not appear in association with the Eburran 5A until around 3990 BP, and then quite rarely, and domestic fauna are not prevalent in Eburran 5B until about 700 years later.

This gradual shift likely indicates the adoption of pastoralism by Eburran hunter-gatherers, and interaction with pastoralists is supported by the presence of

Nderit ceramics at the site. Thus, by 4000 BP, the climate was dry enough, and the Rift Valley open enough, that pastoralists and hunter-gatherers probably had regular contact. By 3,280 BP there is a transition to specialized caprine pastoralism continuing with the Eburran tradition, evidencing that Eburran hunter-gatherers and pastoralist groups coexisted, rather than the Eburran industry representing an evolutionary stage preceding pastoralism (Ambrose 1984c).

Pastoralism consolidates in East Africa

By c. 3000 BP fully pastoralist sites appear in East Africa, and two distinct archaeological pastoralist entities can be seen: the Elmenteitan and the so-called Savanna Pastoral Neolithic (Bower 1991; Leakey 1931; Marshall 1990c; Robertshaw 1988). While Bower (1991) combined the Nderit, Elmenteitan, and pottery associated with Savanna Pastoral Neolithic lithics into a “Pastoral Neolithic” category, other researchers prefer to treat them as distinct archaeological traditions, a practice I follow in this review. I have already discussed the conceptual problems of the term “Neolithic”, although this term is still in use as a convenient classificatory category in East Africa

Savanna Pastoral Neolithic (SPN)

As noted above, the Pastoral Neolithic (PN) was originally referred to as “Stone Bowl Culture” (Cohen 1970; Leakey 1931; Leakey and Leakey 1950), named after the ground stone bowls found in association with this variant of ceramics and lithics. In the 1970s, the association of domesticated fauna with such assemblages prompted a new terminology, emphasizing pastoralism (Bower 1991; Bower, et al. 1977; Bower and Nelson 1978). Dates for the PN range from about 3000 BP to 1200 BP. Ambrose (1984c) grouped some of these sites into the Savanna Pastoral Neolithic tradition, found from Kenya's Central Rift Valley to western Kilimanjaro and the Serengeti Plains in northern Tanzania. The SPN lithic industry is defined on a purely typological basis, although is highly variable, due in part to the differences in availability of raw materials. It is primarily an obsidian-based industry, dominated by microliths and endscrapers; stone bowls and ground-stone axes are also present at some sites. Continuities with Late Stone Age lithics exist in different regions (Mehlman 1989).

The SPN is associated with several ceramic decorative traditions. The earliest and perhaps most widespread is Narosura. The Akira tradition is more recent but found in association with Narosura, and, finally, the Maringishu is associated with the SPN. Scholars have grouped these ceramic traditions differently (Ambrose 1984c; Bower 1991; Robertshaw and Collett 1983b; Wandibba 1977). Despite differences in typology, it is clear that considerable temporal overlap exists among these different ceramics, and research is needed to date and distinguish the technological styles involved.

In contrast to Nderit ware, the Savanna Pastoral Neolithic pottery traditions are much more consistently associated with cattle-based pastoralism in East Africa. Narosura ceramics are found from Lake Naivasha to Lake Eyasi in Tanzania and from the Mara River to 50 km east of Nairobi. Elmenteitan ceramics, on the other hand, are found in a limited area between Mt. Eburru, Lake Nakuru, and Lake Victoria's eastern margin. The typology of lithics associated with these wares is under debate, although scholars generally argue that the Elmenteitan industry is distinct (Ambrose 1984c; Bower 1991). SPN sites are found in open country settings. Fauna associated with most of these sites in the Central Rift are predominantly domesticates, with significantly more cattle than caprines. However, a few sites contain notable proportions of wild taxa, such as the site of Prolonged Drift (Gifford, et al. 1980).

Akira ware, formerly called Thin Incised Pottery (Bower, et al. 1977), dating from 1900 to 1300 BP, is attributed to the "late Pastoral Neolithic." Akira pottery sites occupy a wide geographic range from Kenya's Central Rift Valley to the Serengeti of Tanzania (Mehlman 1989) and are predominantly associated with wild fauna and relatively few ground stone objects and very little archaeological material. Akira vessels do not appear to be made from local clays, and these may have been produced for exchange or had often become items of exchange and broken in transit (Langdon and Robertshaw 1985). Bower (1991) notes strong affinities between Akira and what he terms late or "evolved" PN, including Narosura and Marignishu. Maringishu ceramics are tentatively assigned to the "late Pastoral Neolithic" on the basis of the date of 1695±105 BP from one sample. In contrast, widespread Narosura ceramics have early dates in both Kenya and Tanzania, including 3075–2878 cal BP at Gileodabeshta 2 in the Eyasi Basin (Prendergast, et al. 2014).

The taxonomy of Pastoral Neolithic ceramics has been the subject of considerable debate. Wandibba (1977) provides an initial taxonomy of ceramic styles. However, any one of the lithic industries dating to this time period can be associated with several different ceramic styles (Ambrose 1984c; Bower 1988), and the styles classified by Wandibba fail to cluster with respect to geography/ecozones. Through further attribute analyses on PN pottery based on decoration, decorative technique, and form, Robertshaw and Collett (1983b) identified four distinct groups, to which they assigned Maa names: Elmenteitan, Olmalenge, Oltome, and Oldishi. However, other scholars argued that the analysis did not significantly re-aggregate Wandibba's original taxonomy, and that adopting these new terms simply created confusion by departing from the practice of naming according to type-site (Bower 1988; Gifford-Gonzalez 1998).

Ambrose (1984c) proposed a new taxonomy for food-producing traditions, based primarily upon lithic material, and grouped Bower's PN sites into the Eburran, the SPN, and the Elmenteitan. He further incorporated ecological factors in his analysis, noting that Eburran, SPN, and Elmenteitan industries are differentially distributed with respect to elevation. Bower, et al. (1977) also noted differences between settlement patterns: LSA open sites are usually single component, while PN sites are reused. This may partly result from the fact that livestock cannot tolerate certain soil types, such as black cotton soil and other clayey soils. Savanna Pastoral Neolithic sites are located in prime grazing areas, specifically, in open-country settings such as the Rift Valley floor, the Lemek-Mara area, and the Serengeti.

Elmenteitan

The Elmenteitan industry, identified by Leakey in 1931 from Gamble's Cave, is confined to the Central Rift and southwestern Kenya. Although Bower (1991) groups the Elmenteitan with Narosura as part of the "evolved PN", most researchers consider the Elmenteitan as distinct. It is present at sites including Enkapune ya Muto, Gogo Falls (the most western Elmenteitan locality), Ngamuriak, and Lemek, (Ambrose 1998; Marshall and Robertshaw 1982; Robertshaw 1988) and is consistently associated with pastoralism. Radiocarbon dates place this industry between 2500 and 1300 BP, though an earlier date for the industry at 3100 BP occurs at Njoro River Cave (Merrick and Monaghan 1984). This industry is characterized by large, punch-struck obsidian blades and long, broad blades and flakes made from a variety of materials (Ambrose 1984c, 1998), contrasting with the more microlithic SPN. Elmenteitan occupations often overlie Eburran ones in stratified sites, e.g. Enkapune ya Muto (Ambrose 1998; Marean 1992) and Maasai Gorge Rockshelter (Ambrose 1985; Gifford-Gonzalez 1985).

Obsidian for Elmenteitan lithics comes from sources in or near Mt. Eburru in the Central Rift Valley, and was often transported long distances. Some SPN sites located north of the Lake Naivasha and Mt. Eburru area, including Maringishu, are also dominated by obsidian by upper Eburru sources. However, most sites in the southern reaches of the area occupied by SPN groups are dominated by obsidian from Naivasha sources, but not from Eburru, despite the fact that the two sources are located no more than 20 km from one another (Merrick and Brown 1984).

Elmenteitan ceramics have also been found to overlie Kansyore ceramics in the eastern Lake Victoria basin at sites including Wadh Lang'o and Gogo Falls (Lane, et al. 2007). Only one ceramic tradition is associated with this lithic industry, termed Elmenteitan by Collett and Robertshaw (1983) and Remnant, after the Remnant Site, by Bower, et al. (1977). It is usually undecorated with spouts and lugs (Langdon and Robertshaw 1985; Wandibba 1977), although Robertshaw (1988) argues that different forms of Elmenteitan ceramics may occur according to the activities carried out at a particular site. Petrographic and XRF analyses by Langdon and Robertshaw (1985) indicate these were produced from local clays. Thus, while Elmenteitan lithic raw materials were procured over a distance, Elmenteitan ceramics are made and discarded locally.

The distinctiveness of Elmenteitan from SPN traditions is also evident in stable isotope analysis of human skeletal remains from SPN and Elmenteitan sites. The results indicate that the diet of Elmenteitan-using people was similar to that of the historic Kalenjin of highland western Kenya, who ate a diet of C_4 grains, mixed with animal products obtained through cattle and caprine pastoralism. In contrast, SPN peoples had diets high in animal foods, and likely did not practice agriculture, favoring a more meat- and milk-based diet (Ambrose and DeNiro 1986b).

In contrast to SPN sites, Central Rift Valley Elmenteitan sites at high elevations are mostly open settlements, while low elevation sites are small rockshelters with mostly caprines (see Ambrose 1984b), possibly owing to seasonal goat-herding in this region (Robertshaw 1988). In the Lemek-Mara area there is also variation in Elmenteitan site structure: some sites have large livestock enclosures, indicated by dung deposits, with surrounding smaller middens, while others have several middens associated with smaller patches of dung, but no evidence for a central enclosure. This may be due to varying degrees of pastoralist specialization, or a settlement pattern where livestock were kept farther away from more permanent settlements. Robertshaw (1988) notes that Elmenteitan settlements are located in areas with characteristics similar to those documented among Maasai herders, who consider factors such as slope, soil color, and proximity to resources when choosing settlement locations (Western and Dunne 1979). In contrast, SPN settlements seem to be primarily located on savanna grasslands. Ambrose (1984c) argues that their different habitat preferences may have facilitated coexistence between Elmenteitan and SPN groups. Despite isotopic suggestions of significant grain in the diet, the faunal assemblages from Elmenteitan sites often suggest committed pastoralism, as is the case in Elmenteitan levels of sites including Wadh Lang'o, Ngamuriak, Enkapune Ya Muto, and Maasai Gorge (Gifford-Gonzalez 1985; Marean 1992; Prendergast 2010; Robertshaw and Marshall 1990). They may herd predominantly cattle in open habitats (e.g. Ngamuriak) or caprines in more closed or higher altitude contexts, as found on the Mau Escarpment (e.g. Maasai Gorge Rockshelter).

In sum, multiple, independent lines of evidence including lithic technology, obsidian sourcing, stable isotope analysis of diet, settlement patterns and ceramics (both style and through petrographic analysis) point to Elmenteitan and SPN as two distinct cultural groups which maintained their boundaries long enough to produce an archaeological signature. Ambrose (1984c) notes that there seems to be more interaction between Eburran and SPN groups than between Elmenteitan and SPN groups, as SPN ceramics are found in Eburran 5 contexts.

Linguistic Correlations

The culture-historic approach that dominated East African archaeology for so long presumed that language, culture, and material culture were correlated, usually within defined cultural boundaries (Ambrose 1982). Ehret (1967) used loan words to trace the antiquity of cattle pastoralism and dairying in Africa, and argued that Southern Cushitic and Nilo-Saharan speakers were the earliest to herd and milk cattle, with Bantu speakers likely adopting herding from Cushites in East Africa. Ambrose (1982, 1984c), using Ehret's (1967) ideas, linked the SPN with Southern Cushitic speakers, and the Elmenteitan with a slightly later Nilotic immigration. Kusimba and Kusimba (2005) cautioned against assuming that ceramic differences reflect ethnic ones: variation may be a product of other social situations (Herbich 1987; Karega-Munene 1996). Nurse (1997) argues that lexicostatistics, which Ehret used to date migrations into East Africa, takes an oversimplified view of language change.

Examining East African subsistence and ecology archaeologically

The emergence of mosaics of differentiated economic specializations in East Africa may be illuminated through paleoecological, contextual, and archaeological evidence. Archaeological evidence documents a significant lag in the appearance of domesticates in Kenya south of the Lake Turkana basin, where they had been present from c. 5000 years BP. Only sparse evidence exists for caprines in the Central Rift Valley c. 4000, about 4220 cal BP at EYM (Ambrose 1998; Marean 1992), and cattle appear nearly 1000 years later. The delayed appearance of livestock south of Lake Turkana has been attributed to a number of factors. First, climate and vegetation would have presented significant barriers to pastoralists moving south. The early to mid-Holocene was characterized by high rainfall, lake high stands, and forest vegetation at lower altitudes (Ambrose and DeNiro 1989; Richardson and Richardson 1972). Such environments are unsuitable for herding livestock, which require savanna or savanna-woodlands. The expansion of domesticates into the Central Rift was delayed until the middle Holocene dry phase, beginning as early as 5600 BP, which opened more savanna grasslands (Ambrose and DeNiro 1989).

Second, endemic wildlife diseases may also have significantly hindered the spread of livestock, especially cattle, into eastern Africa (Gifford-Gonzalez 2000). Tsetse flies inhabit brushy environments and spread trypanosomiasis in humans and animals. Until the climate became drier and grasslands replaced forest and bush, the vegetation barrier that prevented southward migration from the Turkana basin into south-central Kenya would have been reinforced by a tsetse zone (Ambrose 1998). In the savanna several novel diseases would have resulted in a significant delay in the expansion of cattle, including wildebeest-derived malignant catarrhal fever (WD-MCF), which, transmitted to cattle from neonatal wildebeest, but nearly 100% fatal to cattle. Wildebeest only inhabit savannas south of Lake Turkana, and such disease challenges, also including East Coast fever (ECF) and corridor disease (CD), may thus have made East Africa savannas an inhospitable environment to cattle for some time (Gifford-Gonzalez 2000).

Finally, by around 2,500 BP a bimodal rainfall pattern, with ICTZ movements producing spring and autumn rains, emerged. Marshall (1990c) argues that only then could specialized, milk-based pastoralism develop, as before the onset of bimodal rainfall, pastoralists would have had to supplement milk with either wild animals or meat from their herds. Late Kansyore and Nderit sites dating from 4000 – 2500 BP show a mix of herding and foraging, as at Dongodien (GaJi4). Dated to c. 4500 cal BP, on the northeastern side of Lake Turkana, GaJi4 has domestic cattle and caprines, as well as a significant proportion of fish or wild terrestrial animals (Barthelme 1985; Hildebrand and Grillo 2012). Barthelme (1985) posits that Dongodien may have been occupied either by pastoralists with a diversified subsistence strategy, by pastoralists who had lost their herds, or by hunter-gatherers who had obtained domestic animals (see also Robbins 2006). After the advent of the bimodal rainfall pattern, wild ungulates, which were plentiful in the region and could have been a key food source, became underrepresented at large Elmenteitan and SPN sites, indicating that both groups concentrated on their herd animals for their subsistence (Marshall 1990).

The question of whether incoming pastoralists introduced African domestic plants such as pearl millet and sorghum into East Africa has not been fully investigated. Despite isotopic data suggesting a greater reliance crop plants in the Elmenteitan (Ambrose and DeNiro 1986b), few excavators have made the effort to search for remains such as phytoliths to assess the presence of domesticates in East Africa soils. Robertshaw and Collet (1983a) argued that SPN sites in the Nakuru basin and on the edges of highlands in the Rift Valley would have been suitable for crops. Although grinding equipment has been found at several of these sites, the material is soft, and lacks typical wear from grinding food. Rather, they are often stained with red pigment, indicating they were used for grinding ochre (Ambrose 1984c citing Sassoon 1968).

After the onset of bimodal rainfall, cattle-based pastoralism became widespread on East African savannas. Marshall (1990b; Robertshaw and Marshall 1990) distinguished age-specific culling patterns at the large, Elmenteitan pastoralist site of Ngamuriak (2300-1700 BP), and found that cattle were slaughtered when they reached their maximum weight. Marshall (1990a, b) argued this strategy is usually employed by pastoralists living in relatively unstressed conditions. Similar age-specific mortality patterns are evident at SPN sites in the Central Rift, including Crescent Island Main and also at Narosura, where cattle clearly dominate the assemblage, and their teeth also exhibit much more wear, suggesting that they were kept alive for milk production (Gifford-Gonzalez and Kimengich 1984; Gramly 1972). Both Elmenteitan and SPN sites can have either specialized pastoralist economies or mixed economies of pastoralism and hunting/fishing, although there is a clear emphasis of cattle over caprines at SPN sites.

Once the assumption that pottery use equals food production is abandoned, determining the subsistence economies at some south-central Kenya and north

Tanzania Holocene sites is more difficult, given the array of both wild and domestic animal remains at sites such as Gogo Falls, Prolonged Drift, Naivasha Railway Shelter, and Maasai Gorge (Gifford, et al. 1980; Gifford-Gonzalez 1985; Gifford-Gonzalez and Kimengich 1984; Marshall and Stewart 1995). Mutundu (2010) and Prendergast (2010) have developed criteria for using faunal evidence to distinguish sites created by hunter-gatherers, those of hunter- gatherers transitioning to pastoralism, emerging pastoralists, and established pastoralists. These are based on Mutundu's (1999) ethnoarchaeological and ethnohistorical work with the Mukogodo, foragers who recently transitioned to pastoralism. Criteria include the proportional representation of wild and domestic fauna, livestock age structures, the range of wild fauna exploited, and site location with respect to the environment.

A key difference between hunter-gatherers and pastoralists who hunt is that pastoralists are usually much more selective, focusing on medium- to large-sized ungulates (see also Marshall and Stewart 1995). Foragers transitioning to pastoralism also differ in that they first adopt small stock, which are hardier and less expensive than cattle, and such patterns may be reflected at caprine-dominated sites like the Kansyore site of Wadh Lang'o (Cronk 1989; Mutundu 2010; Prendergast 2010; Prendergast and Mutundu 2010). Ambrose (1984c), citing Spencer (1973), uses the recent Okiek as a model for Eburran 5A adaptations to the Mau Escarpment. Okiek trap, forage, maintain beehives, and exchange honey, skins, and horns for grain, domestic stock, and iron from pastoral and agricultural groups. Some Okiek increased their dependence on livestock as they moved out of the forest and into the savanna highlands, and Ambrose argues for this adaptation in Eburran 5B sites in the savanna grasslands, like Hyrax Hill and Crescent Island Causeway, which have significant amounts of domestic stock by 2400 BP (Ambrose 1984c).

Other sites with a mix of wild and domestic fauna have been interpreted differently. The west Kenyan site of Gogo Falls, where Elmenteitan levels date 1990-1779 BP, has significant proportions of both wild and domestic animals (Marshall and Stewart 1995). Rather than argue that the occupants were hunter-gatherers with a few goats, the authors posit that the focus on wild fauna indicates that the site occupants were pastoralists living in unsuitable, tsetse-ridden bush, and that they had to supplement their diet with wild fauna. However, Mutundu (2010) urges caution when interpreting proportions of small stock to cattle at pastoral sites. Special meat-feasting locales, for example, may be located away from homesteads, and therefore may present a biased sample of livestock demography. Sites like Crescent Island Main and Prolonged Drift, with more cattle than small stock, may thus not simplistically reflect a cattle-dominated system. Animal health may also indicate economic circumstances at that site. Mutundu (2010) noted that caprines at Maasai Gorge Elmenteitan levels have much hypoplastic banding, a rare condition at other Elmenteitan sites (Gifford-Gonzalez 1985, Marshall 1990b). Gifford-Gonzalez (1985) posits that the Maasai Gorge occupants may have been poor pastoralists with few animals, killing only the very ill, or obtaining less fit culls from better-off neighbors. Recent work suggests that higher elevation sites have higher rates of hypoplasias, possibly due to different herding patterns (Upex 2009). The evidence above strongly suggests that the modern East African pattern of “mosaics” of interacting hunter-gatherers and pastoralists had emerged by 2000-3000 years ago.

The advent of iron-using economies in East Africa

Dates for an independent origin of iron smelting in sub-Saharan Africa cluster around 2800-2400 BP (Childs and Herbert 2005; Killick 2009). In Kenya, ironworking is associated primarily with Urewe pottery and is generally attributed to the immigration of Bantu-speaking farmers. In contrast to Pastoral Neolithic sites, “Pastoral Iron Age” (PIA) sites are distributed evenly across ecozones (Bower, et al. 1977; Robertshaw 1993). Dates for the beginning of the PIA cluster around 1400 BP in Kenya’s Central Rift Valley. PIA sites in the Central Rift highlands, including Enkapune Ya Muto and Maasai Gorge, are characterized by "Pastoral Iron Age" Lanet Ware Tradition, elongated, twisted cord-roulette ceramics with handles (Bower, et al. 1977; Posnansky 1967), whereas Urewe tradition (sometimes called “dimple based” pottery), characterized by complex decorations including grooves and comb stamping, is distributed from the Lake Victoria Basin to Kenya’s coast. Lelesu pottery is found in northern Tanzania. The latter Early Iron Age traditions have been grouped into the Chifumbaze complex by Phillipson (2005).

PIA components often overlie PN assemblages, including at Salasun, Maasai Gorge, GvJm47 (Lukenya Hill), and an “Iron Age” burial at Lukenya Hill (GvJm41). Bower and Nelson (1978) describe a trend away from formal lithic technologies in sites spanning the PN to PIA transition, as well as an increase in the presence of

Urewe wares. According to Bower (1977) PN sites display regional differentiation of ceramic types, as people were constrained in terms of settlement and mobility, whereas PIA has fewer variants. However, Bower (1991) lumps all the PN sites together, so whether this is really a single characteristic of “the PN” is questionable.

Iron technology was not uniformly adopted by people living in East Africa. Rather, hunter-gatherer and pastoralist use of stone tools persisted for a millennium until c. 500-400 BP, possibly in part due to the lack of iron ore, as well as readily available obsidian and ignimbrite, in the Central Rift Valley (Bower and Nelson 1978). Evidence for the transition to iron use is found at Deloraine Farm, a so-called Pastoral Iron Age site situated in the western side of the Central Rift Valley, and dating to 1100 BP. Collett and Robertshaw (1983) initially placed it within the Elmenteitan tradition, due to similarities to ceramics at Ngamuriak, Remnant, and Gamble’s Cave II. However, its young age and wider range of decorative motifs, as well as similarities to modern Okiek pottery, suggest it may be a late phase in the Elmenteitan tradition (Ambrose 1984a). Lithics at Deloraine, while generally ad hoc in nature, display some continuity across the Neolithic/Iron Age boundary, reflecting a shift from cattle pastoralism with LSA tools to ironworking with mixed agriculture and pastoralism Ambrose (1984).

Recent research has shown that Pastoral Neolithic ceramics in western Kenya sometimes overlap temporally with Iron Age ceramics as they do at Gogo Falls and Wadh Lang’o (Lane, et al. 2007; Robertshaw 1991). Overlap of dates for Elmenteitan and Urewe levels at Wadh Lang’o suggest that these two traditions used this riverine locale during the same time span, though subsistence strategies differ significantly, with a greater emphasis on mammalian fauna in Urewe levels (Lane, et al. 2007).

The lithic industry of Usenge 3, near Lake Saru and Lake Victoria, displays continuity from Kansyore through later Urewe levels, suggesting similarities in everyday practices (Lane, et al. 2007). Most Usenge 3 ceramic vessels, while similar in form to Urewe pottery, are coarser and poorly fired, suggesting that, rather than being subsumed within Urewe-making populations, indigenous communities near Lake Saru developed a version of Urewe ceramics, termed Contact Urewe (Dale and Ashley 2010; Lane, et al. 2007). Wadh Lang'o and Usenge 3 also show more variation in Urewe ceramic vessels form in contrast to the fairly narrow range of ceramic variation in Kansyore and Elmenteitan levels, likely due to less reliance on roasting and more pot-based food preparation and consumption.

Such transitions are documented in the ethnographic and ethnohistorical literature, and show how changes in the subsistence economy and technology can be quite fluid (Mutundu 2010). Similarly, evidence from Wadh Lang'o and Usenge 3 show that the transitions from herding to agriculture and iron use were not "profound and over-arching", but rather, Lane and colleagues argue that a more nuanced reading of evidence reveals how deeply rooted cultural practices, including culinary and ceramic production, adapted and transformed in the context of new economic strategies (Lane, et al. 2007).

Lingering Questions, New Methods, Further Research

Many questions still surround the origins and spread of pastoralism in East Africa, including whether pastoralists moving into East Africa absorbed the native foraging populations, or if local people adopted pastoralism through contact with herding populations elsewhere. While metric analyses of human dental remains suggest a population discontinuity in the Lake Turkana basin, possibly associated with the migration of herders in the mid-Holocene (Sawchuk and Pfeiffer 2014), some lines of evidence from the Central Rift Valley point to local adoptions. The occurrence of sites with much wild fauna and occasional domesticates indicates perhaps that hunter-gatherers were incorporating domestic stock (Gifford-Gonzalez 1984), and lithic analysis shows continuity of assemblages associated with the Nderit with earlier Late Stone Age traditions (Barthelme 1985; Gifford-Gonzalez 1998). Marshall and Hildebrand (2002) argue that social interactions between hunter-gatherer and pastoralist groups were fairly fluid in East Africa, and herders could fall back on ties with hunter-gatherer groups, or adopt foraging as a means of subsistence if their herds were decimated by disease. At the same time some hunter-gatherers adopted herd animals as insurance and for scheduled feasting.

As Holocene East African archaeology emerges from its normative, culture-historic background, new approaches to archaeological material are warranted to explore new questions brought about by shifts theoretical perspectives. Rather than viewing artifact traditions and industries as static reflections of bounded cultural entities, recent work uses ceramic traditions to discern relationships and exchange between peoples. Artifacts do not produce or travel by themselves; they are made by people for varying purposes and can move distances through exchange. Karega-Munene (1996) notes that many ethnographically documented groups in East Africa did not produce their own pottery, instead obtaining pots though trade with other groups (see also Grillo 2014). Thinking of ceramics as something other than "cultural badges" allows archaeologists to examine interactions between groups of people (Dale and Ashley 2010). It facilitates distinguishing pastoralist sites with "pastoralist ceramics" from hunter-gatherer sites where foragers obtained and used "pastoralist ceramics" from those sites where "pastoralist potters" may have lived and made pottery with foragers, possibly through intermarriage (Mutundu 2010; Prendergast and Mutundu 2010). Such theoretical advances, as well as methodological ones, will lend a more nuanced view onto the cultural and economic mosaics of the past, illuminating interactions between economic groups.

CHAPTER 4: GEOLOGY, HYDROLOGY, VEGETATION AND CLIMATE OF KENYA

The modern landscape of Kenya is very diverse, characterized by significant variation in elevation, vegetation, and rainfall across the landscape. This chapter begins with an overview of the geological, hydrological, and vegetational environment of Kenya, which is central to the interpretation of isotopic data recovered from archaeological livestock remains. It also reviews climate change and vegetation shifts over the course of the Holocene, with a note on how these changes would have facilitated or hindered the expansion of pastoralism throughout East Africa. I conclude with an overview of the current rainfall and vegetation patterns of Kenya, as it is generally accepted that the modern climatic regime had set in by 2,500 BP, the time frame of this study.

Geology

The geology of Kenya is quite varied, with much of the topography situated along the Kenyan Rift Valley, part of the East African Rift system. The East African Rift system is several thousand kilometers long, comprised of a series of adjacent, discrete tectonic rift valleys, usually bordered by uplifted graben shoulders. The eastern branch of the rift stretches from the Afar Triangle in the north, through Ethiopia, the Omo-Turkana low lands, and the Kenya Rift, to the North-Tanzanian divergence. The western branch extends from Lake Albert in the north to Lake Malawi in the south. Two high-altitude regions of uplift, above 1200 meters above sea level (masl), are found in the East African Rift system: the Ethiopian Dome to the north and the Kenyan and Tanzanian Domes to the south (also called the Ethiopia-Yemen plateau and East-African plateau, respectively), which are separated by the Omo-Turkana low lands (Chorowicz 2005; Schlüter 2008). The Kenya Rift region, also called the Gregory Rift, is associated with the Kenyan Dome. The evolution of the Rift Valley spans tens of millions of years, and its development has been dictated by the underlying tectonics and mantle dynamics (Ebinger 2005; Smith and Mosley 1993).

The exposed basement in the African continent is quite old and largely Precambrian in age; this is true for Kenya as well. The Tanzanian Archean craton underlies the western portion of the country, and at its eastern margin lies the Proterozoic Mozambique Belt. It is here, along the craton margins, where rifting preferentially occurs, due to the differences in the structural fabrics of the stronger lithosphere of the craton and the weaker lithosphere of the younger belt (Ebinger 2005; Smith and Mosley 1993). The East African Rift system is a product of the main African plate and the Somalian plate drifting apart in the NW–SE direction, although this is an immature plate boundary (Chorowicz 2005).

In Kenya, rifting likely started in the Late Cretaceous. Mantle plume hypotheses have been suggested as the source of volcanism and uplift in the Tertiary, though there is still debate on the number of mantle upwellings (Chorowicz 2005; Corti 2009; Ebinger, et al. 1993; Moucha and Forte 2011; Pik, et al. 2006, 2008). While southern Ethiopia and northern Kenya saw early volcanism, and the origin of basin topography began by as early as 45 million years ago, the volcanic activity generally associated with the beginning of the East African Rift system began with extensive basalt eruptions in Ethiopia during the Oligocene, resulting from mantle plume processes and lithosphere thinning (Ebinger, et al. 1993). During the Late Oligocene to Early Miocene, the central area of Kenya underwent uplifting to form the Kenya Dome, also associated with mantle plum activity (Chorowicz 2005; Pik, et al. 2006; Schlüter 2008; Smith and Mosley 1993).

Over the course of the middle Miocene, the northern and central parts of the rift saw significant faulting, which continued to propagate the rift southwards during the Pliocene (Baker and Wohlenberg 1971; Morley, et al. 1992). In particular, flood style volcanism occurred on the edge of the Kenya Dome towards Lake Bogoria in the south (King, et al. 1972; Smith and Mosley 1993). Much of the Rift Valley is covered in volcanics. Most early volcanic eruptions in the Oligocene took place west of the rift near Mt. Elgon (King, et al. 1972). Later volcanic activity in the Miocene was more widespread, within and on the flanks of the proto-rift. This includes activity in the Aberdares area during the Late Miocene, which may have continued through the early Pliocene. Pliocene volcanism tends to be confined within the rift, including the development of Mt. Kenya toward the end of the Pliocene. Quaternary activity occurred within the rift and in areas well to the east. During the Quaternary, volcanic activity included a series of volcanoes along the central graben. These include Mounts Suswa, Longonot, Eburru, and Menengai in the Central Rift region. North of Lake Baringo sit Mounts Karossi, Pakka, Silali, Emuruangogolak and the 'Barrier' volcano separating Lake Turkana and the Suguta Valley to the south (Figure 4.1). This volcanism produced large calderas and basalts erupted in later phases (King, et al. 1972; Nash, et al. 1969). By the middle Pleistocene the Rift Valley had formed into a distinct graben, and faulting occurred on the valley floor with uplift on the flanking rift shoulders continued throughout the Quaternary (Schlüter 2008; Smith and Mosley 1993).

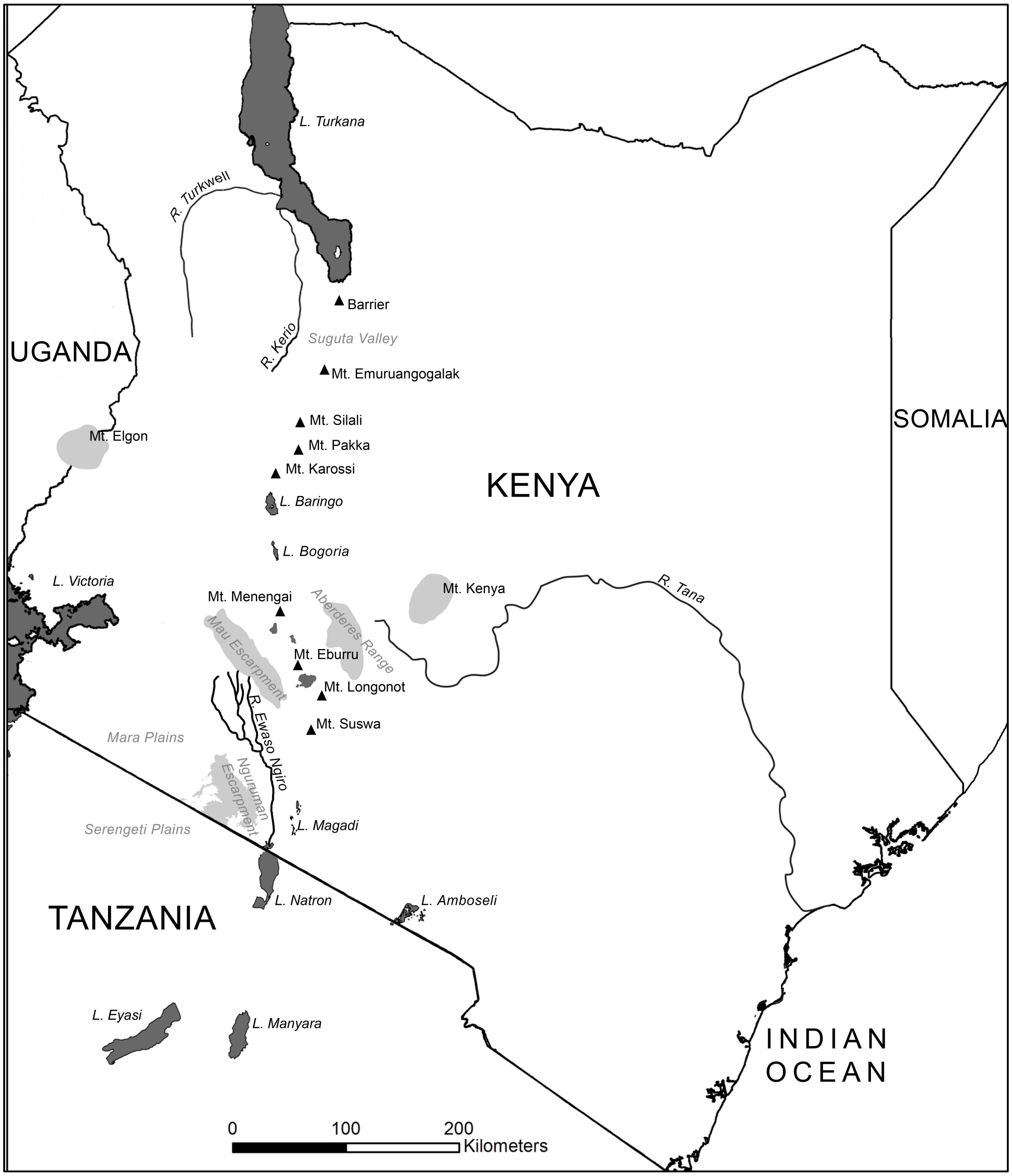


Figure 4.1: Map of Kenya with locations mentioned in text.

This history of geological activity produced the bedrock distribution observed in Kenya today, with the Kenyan section of the Eastern Rift system characterized by relatively recent volcanics and much older Precambrian basement rocks exposed on its peripheries. The oldest basement rocks belong to the Neoarchean Nyanzian System (also referred to as the Nyanza Greenstone Belt, 2.8– 2.5 billion years old) found primarily in the west near Lake Victoria. Metamorphic rocks of the Proterozoic (650–475 million years old) Mozambique Belt mainly in the central part of the country, sediments ranging from Late Paleozoic to Recent times along the coast. The present-day structure of the Kenyan Rift is thus a graben flanked by fault zones roughly 50-80 km apart, with a high elevation at the Rift Valley floor around 1900 masl near Lake Naivasha, and lower elevations to the north and south, including around 300 masl in the Lake Turkana Basin to the north and 600 m at Lake Magadi, just north of Lake Natron in southern Kenya. The Kenya Rift has major fault scarps; the Nguruman escarpment in southwest Kenya reaches 1500 m above the Rift Valley floor and in the central rift the eastern rift escarpment (Aberdare Range) reaches about 2000 m above the floor of the valley at 4000 masl. Beyond the escarpments, elevations outside the Rift decrease in the adjacent plains, though they can still be quite high, as in the Loita Plains of southwestern Kenya, situated at 1700-1900 masl, due to uplifting associated with the Kenya Dome. South and west of the Kenyan highlands lie the Athi-Kapiti, Mara, and Serengeti plains.

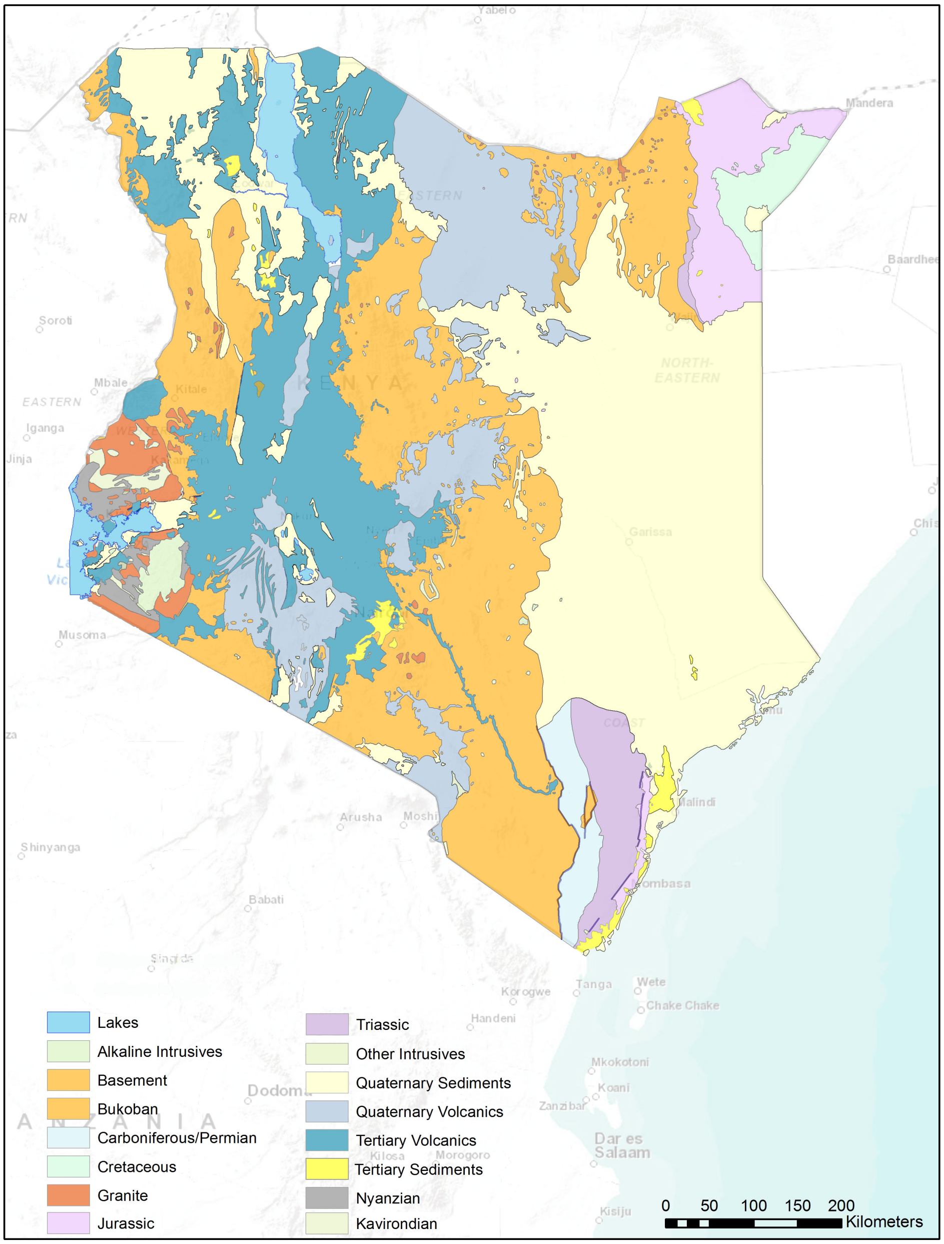


Figure 4.2: Geologic map of Kenya.

This diverse geology allows for tracking the movements of animals and people using strontium stable isotope analysis. Given that each geological formation has a different chemical composition and age, variation in $^{87}Sr/^{86}Sr$ ratios are distinct among formations. The relatively young basalts of the Central Rift Valley have comparatively low $^{87}Sr/^{86}Sr$ ratios, ranging between 0.7030 –0.7055 (Davies and Macdonald 1987; Rogers, et al. 2000). Older rocks have higher $^{87}Sr/^{86}Sr$ ratios, such as the Archaean Kavirondian, a component of the Tanzanian craton in Kenya, with values ranging from 0.7102–0.7236 (Bell and Dodson 1981).

Hydrology

Kenya is home to several lakes situated within the Central Rift Valley. Today, most of these are closed-basin lakes and either saline or hypersaline, including Lake Elmenteita, Lake Nakuru, and Lake Turkana. Lake Turkana is the largest non-outlet lake in East Africa, and is supplied primarily by the Omo River, flowing from the volcanic Ethiopian Highlands to the north (Yuretich and Cerling 1983). The Turkwel River, which flows from the Precambrian rift margins in Uganda eastwards to Lake Turkana, drains, along with the Kerio River, a mixed metamorphic and volcanic terrain.

To the south lie Lakes Baringo and Bogoria. These are relatively small, non-outlet lakes. Lake Bogoria is fed by about 200 hot springs as well as ephemeral streams draining the surrounding catchment (Renaut and Tiercelin 1994). Lake Baringo is a relatively freshwater lake but has no surface outflow, so its low salinity is likely a product of subsurface seepage (Darling, et al. 1996).

Farther south, between the Mau Escarpment and Aberdare Range on the Rift Valley floor lie Lakes Elmenteita, Nakuru, and Naivasha (Figure 1.1 and 4.1). Lakes

Elmenteita and Nakuru are today quite shallow and, due to their location farther west in the Rift Valley, they receive relatively more rainfall than does Lake Naivasha, and precipitation is their primary input (Richardson and Dussinger 1987). No present-day outlet is known for these lakes. Lake Naivasha and is one of two freshwater lakes in the Rift Valley and is fed by two major rivers: the Malewa River, providing most of the surface waters, and the Gilgil River. Its freshwater status is a consequence of the dilute source waters, likely due to rapid loss of lake water through an underground outlet system, indicated by a short residence time for chloride (Åse 1987; Ojiambo and Lyons 1996). Ground waters south of Lake Naivasha also correspond to the evaporative concentration line defined by the lake (as indicated by O and H stable isotopes), indicating that a significant component of groundwater south of the lake originates from Lake Naivasha (Ojiambo, et al. 2001).

Lake Magadi is the southernmost lake in Kenya, situated directly northeast of Lake Natron (Jones, et al. 1977). It is quite saline, with an upper body of very concentrated brine and is fed by a number of sources, including ground waters, to which the Ewaso Ngiro, rim streams, and runoff from the Rift Valley contribute, as well as hydrothermal springs and seeps. Lake Victoria is the largest lake in East Africa. It was likely formed by downwarping between the Eastern and Western Rifts (Schlüter 2008). It is the source of the Nile River, and receives its input from precipitation and streams (Yin and Nicholson 1998).

The morphology, outlets, and water levels of these lakes can vary considerably due to changes in precipitation. Over the course of the Holocene, rainfall patterns have shifted in response to changes in insolation, resulting in marked changes to hydrological and vegetation patterns in North and East Africa.

Climate in Holocene Northern and Eastern Africa

In tropical Africa, precipitation patterns are primarily governed by the strength of the African-Asian monsoonal circulation and the seasonal migration of the Intertropical Convergence Zone (ITCZ). The ITCZ forms as the northeast and southeast trade winds meet, and warming sea surface temperatures and the differential heating between land and sea causes moisture to follow the ITCZ as it migrates, resulting in seasonal rainfall (Kingston 2007). This track of maximum precipitation follows the latitudinal position of the sun. Insolation also dictates the strength of the ITCZ. Orbitally induced changes in monsoon strength are largely responsible for large-scale changes in climate, as increased summer insolation reinforces monsoon circulation by augmenting the pressure contrast between land and sea, bringing monsoon winds inland (Gasse 2000; Kutzbach 1981). Climate is thus largely forced by Milankovitch cycles: changes in orbital geometry that dictate the level of solar insolation received on different parts of the earth.

During the Last Glacial Maximum Africa saw arid environmental conditions (Kuper and Kröpelin 2006), evidenced by desiccation of lakes, including Lake Victoria (Johnson, et al. 1996), increased biogenic silica mass accumulation rates at Lake Malawi (Johnson, et al. 2002), increased varve thickness at Lake Challa, indicating a longer windy season, and overall reduced interannual climatic variability

(Wolff, et al. 2011). Beginning about 12,500 years ago, the climate in Africa shifted from this arid phase. Changes in insolation shifted the ITCZ north, and as a consequence Africa underwent a wet phase that extended to about 8,000 BP (Butzer et al. 1972; Hassan 1997; Thompson et al. 2002). During the early Holocene Humid Phase, winter rains in Saharan areas resulted in vast grasslands covering the Sahara (Kuper and Kröpelin 2006). Between 9500–8500 BP, African lakes reached high stands up to 100 m higher than to present levels (Grove 1993), and rainfall in the Ethiopian Highlands created a "wild Nile" phase (Said 1993; Vermeersch 2002; Wetterstrom 1993), making the lower Nile Valley uninhabitable for a span.

From 8,000 BP onward, a general trend of progressive aridification began as weakening insolation led to a decrease in intensity of the African monsoon (Gasse 2000; Kröpelin, et al. 2008a), and the climate oscillated between wet and dry periods (Grove 1993; Hassan 2000; Mercuri, et al. 2011; Nicholson and Flohn 1980; Thompson, et al. 2002). The overall reduction in rainfall from 8,000 BP onward had a drastic effect on the Saharan landscape, and large areas shifted from grassland to desert (Kröpelin, et al. 2008b; Neumann 1989). Hassan (2000) argues that this drying prompted the independent domestication of cattle, emergence of pastoralism in northeastern Africa, and its spread from there. In contrast, Smith (2005) argues that a wet phase around 7700 years ago facilitated the migration of domesticated animals from Southwest Asia into northern Africa as a "package" of sheep, goats, and cattle. This debate over the origin of domesticated cattle is ongoing.

Like North Africa, East Africa had a much wetter climate in the early

Holocene. During the early Holocene, hunter-fisher-foragers with bone harpoons and ceramics occupied sites in this region (Barthelme 1985; Robbins 1972). Many of the non-outlet Rift Valley lakes have clear records of high stands at this time, as well as evidence for outlets in the early Holocene (Butzer, et al. 1972; Hillaire-Marcel and Casanova 1987; Richardson and Richardson 1972). During the early Holocene wet phase Lakes Elmenteita and Nakuru were joined to form one deep lake (Butzer, et al. 1972; Richardson and Dussinger 1987). Eastern Africa was linked to the White Nile drainage via Lakes Albert and Victoria to the west, and from Lake Turkana through the Sobat channel system to the north. Old strand lines show that Lake Turkana rose to 85 m above its present-day height, and it was linked to the Nile (Forman, et al. 2014; Grove 1993). These linkages would have facilitated human movements into East Africa. As in north Africa, lake levels reflect oscillations between wet and dry periods in East Africa. After the humid phase of the early Holocene, a brief arid period at 7,000 BP was followed by a second humid period c. 6,500-4,500 BP (Forman, et al. 2014; Nicholson and Flohn 1980). In the Sudan, the Nile valley, and parts of eastern Africa, there is evidence for similar trends of gradually increasing aridity throughout the Holocene, such as isotopic evidence for the expansion of the savanna ecotone up the Mau Escarpment by 5365 BP (Ambrose and DeNiro 1989). At roughly that time period the savanna ecotone was, eventually pushed south as the Sahara became increasingly arid reaching its current distribution by 3300 BP (Neumann 1989).

Sediment cores indicate that East Africa saw an especially dry period in the mid-Holocene, from 4600-4000 BP (Butzer, et al. 1972; Hassan 1997). This period of severe aridity is marked by a reduction in water levels in Rift Valley lakes, with some disappearing completely, (Grove 1993; Richardson and Richardson 1972). Evidence from Lake Malawi suggests this arid period in northeast Africa is linked to longer stays of the ITCZ at its southern limit in the austral summer (Johnson, et al. 2002).

Around 4,000-3,000 BP there was an overall reduction of forest vegetation and an expansion of savanna in the Central Rift (Maley 1991; Thompson et al. 2002). The drier conditions led to the spread of grassy vegetation, and are also associated with the appearance of domesticates in Central Rift Valley sites. By around 2,500 BP the current climatic conditions had developed in East Africa, including a bimodal precipitation pattern, inferred by the contrast between one clear rainy season visible from the Naivasha core from 9,200 until 2500 BP, followed by a sequence of indistinct laminations, likely reflecting the "gently bimodal modern rainfall pattern" (Richardson and Richardson 1972). Upex (2009) identified a bimodal pattern in hypoplastic defects in caprines from Neolithic Kenyan sites dating to about 2500 BP. These likely correspond to two dry seasons per year. Marshall (1990c) suggests that the bimodal rainfall pattern allowed specialized pastoralism to take place.

While the modern climatic regime set in around 2500 BP, there is still evidence for oscillations between wet and dry periods over the past few millennia, with restricted/muted variability between 2250 and 1650 BP, likely due to ENSO activity, followed by increased variability from 1550 to 1250 BP (Wolff, et al. 2011). The Medieval Warm Period/Climatic Anomaly (950 – 680 BP) was marked by a significantly drier and less variable climate than today, and a relatively wet climate during the `Little Ice Age' (680 – 200 BP) which was punctuated by three episodes of severe aridity in East Africa (Verschuren, et al. 2000; Wolff, et al. 2011).

Modern Precipitation and Vegetation Patterns

Like Kenya's geology, the vegetation patterns of the country today are quite diverse, ranging from semi-arid plains to forests. Vegetation distributions are largely tied to temperature and precipitation patterns. Today, much of Kenya has a bimodal rainfall pattern, with long rains occurring in April through May and short rains in October through November (Figure 4.3), though some regions in the Central Rift area, including the Nakuru-Naivasha region, have a trimodal pattern, with another peak occurring in July or August (Kenya Meteorological Department Nicholson 1996). This pattern is a consequence of the migration of the ITCZ over equatorial regions, as maximum rainfall follows the latitudinal position of the sun. In general, seasonal precipitation varies, from east to west owing to different circulation patterns, topography, and large inland lakes.

Kenya also experiences significant interannual variation in rainfall (Figure 4.3). The year-to-year variations in the seasonal migration and intensity of the ITCZ are often linked to the El Niño Southern Oscillation (ENSO) (Gasse 2000; Nicholson 1996; Ropelewski and Halpert 1987), which generally increases rainfall in East Africa. The ultimate cause of increased precipitation is due to altered atmospheric circulation that results in warmer sea surface temperatures in the western Indian

Ocean, which intensifies the ITCZ (Black, et al. 2003; Nicholson 1996). However, Nicholson (2000) cautions that sea surface temperature patterns do not consistently produce the expected precipitation anomalies.

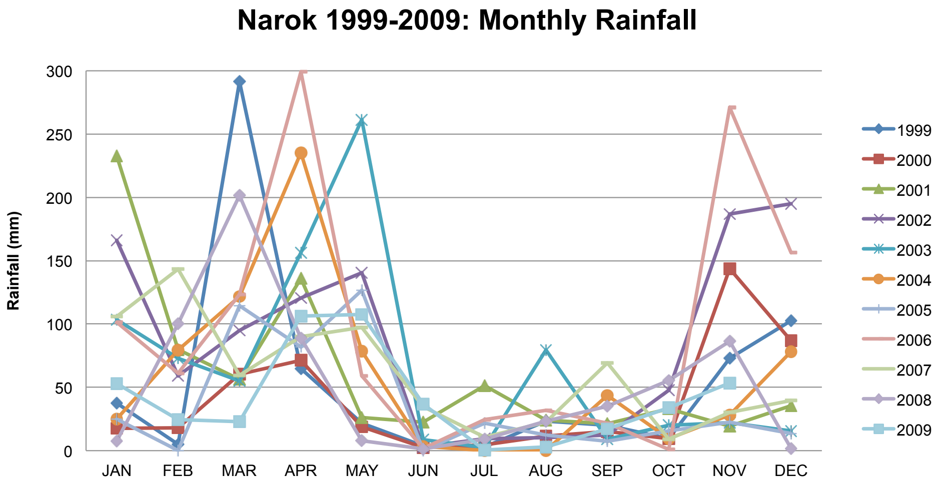


Figure 4.3: Monthly variation in precipitation (mm) for 11 years. Kenya Meteorological Department, Narok weather station in southwestern Kenya.

Beyond interannual and seasonal variation in precipitation, considerable variation exists with topography. Rainfall in the Central Rift Valley varies markedly with altitude. The western slopes of the Aberdares, which flank the Rift Valley on the east, receive as much as 1,500 mm annually, whereas Naivasha, on the floor of the Rift Valley, receives roughly 600 mm annually, due to the progressive condensation from air masses as they move up mountain slopes (Gonfiantini 2001, Kenya Meteorological Department, 2014). In general, the more semiarid regions of equatorial Africa exhibit extreme variability in inter-annual rainfall, with frequent droughts. For example, northern Kenya is quite arid, seeing well under 300 mm of precipitation annually, and exhibits a very high coefficient of variation (Rodhe and Virji 1976). This variability is likely related to many factors including topography, marine effects, and local wind systems (Kingston 2007). This diversity in rainfall therefore produces considerable variability in the vegetation.

Both mesic and xeric grasslands exist in Kenya, each exhibiting different carbon isotope compositions. These vegetation patterns are based largely on moisture regimes, though in some cases soil chemistry also influences the distribution of grasses, as at Nakuru National Park, where despite its mesic conditions, xeric grasses predominate due to alkaline soils (Cerling, et al. 2003). The Athi-Kapiti plains region, located near Nairobi, at 1500-1900 masl is one example of a mesic grassland (Cerling and Harris 1999). While it includes some riparian forests, the vegetation of this extensive grassland is dominated by taxa including *Themeda triandra*, *Hyparrhenia* sp. and other C4 grasses. Most of these grasses use the NADP subpathway, which usually is found in more mesic environments (Hattersley 1992). NADP grasses also have $\delta^{13}C$ values averaging -11.7 ± 0.7 (Cerling and Harris 1999).

In contrast, the drier xeric savanna grasslands and bushlands include *Aristida* (an NADP grass that occurs in xeric environments), and primarily NAD and PCK grasses that favor drier climates, exhibiting $\delta^{13}C$ values averaging about -12 and -12.7‰, respectively (Cerling and Harris 1999; Ellis, et al. 1980; Hattersley 1992; Ohsugi, et al. 1988). Today, xeric savannas and bushland are represented in Kenya in the Turkana region in northwestern Kenya, Tsavo East and West National Parks, the Loita Plains, and the Samburu area (Cerling, et al. 2003; Glover, et al. 1964).

A strong correlation exists between grass species distribution and altitude. For example, the Laikipia Plateau exhibits a transition from xeric grasslands at lower elevations to mesic at higher elevations (Cerling, et al. 2003). More generally, a transition occurs from C_4 grass dominance at low elevations to C_3 grasses at higher elevations. This reflects changes in moisture and temperature with altitude; almost all grasses growing below 2,500 m in Kenya are C_4 (Tieszen, Senyimba, et al. 1979; Young and Young 1983). Beyond shifts in grasses using different photosynthetic pathways, vegetation communities differ greatly with altitude. For example, the transition from the valley floor at Lake Naivasha up the Mau Escarpment exhibits several different vegetation zones, with open to wooded savanna grasslands on the valley floor, bush from 2000-2300 m, montane forest from 2300-2700 m, and bamboo forests and open montane grasslands above 2700 m.

Forested regions are limited, situated primarily on the slopes of the main mountain masses of Kenya: Mount Elgon, the Aberdare Range, the Laikipia Escarpment and the Mau-Elgeyo-Cherangani mountain system (Edwards 1940). The margins of rivers and lakes also support forest, for example, the *Acacia xanthophloea* woodland and forest around the margin of Lake Naivasha (Ambrose and Sikes 1991). Evergreen forest patches can also be found on alluvial soils along rivers, such as the Mara (White 1983).

This diverse landscape makes it possible to track mobility of humans and animals throughout Kenya. Its varied hydrology and rainfall patterns produce differences oxygen isotope ratios, from large lakes to smaller bodies of water, and differential isotopic composition of rainfall with topography. This may allow for identification of water sources, and possibly seasonality, although interannual variability in precipitation may complicate such analyses. Marked differences in vegetation communities and their corollary carbon isotope composition also can be used to track mobility across the landscape, especially vertical mobility, which reflects strong changes in vegetation. Finally, its varied geology, particularly differences between the relatively young volcanics of the Central Rift and the older basement rocks of the Tanzanian craton and Mozambique belt, can be distinguished using strontium stable isotope analyses. While there have clearly been some changes in climate, precipitation, and vegetation over the Holocene, scholars generally accept that the modern climatic regime set in roughly by 2500 BP, including the interannual variability characteristic of today's climate. Thus, the present day ecology can be a useful analog for the conditions in which pastoralism developed in the Central Rift Valley and its adjacent plains in this time period.

Owing to the diverse geology, hydrology, and vegetation patterns of Kenya, stable isotope analysis can be used to assess ancient pastoral mobility. The following chapter reviews the systematics of carbon, oxygen, and strontium stable isotopes which are used in this study.

CHAPTER 5: STABLE ISOTOPES IN THE BIOSPHERE

Analyses of stable isotopes in archaeofaunas have been useful in illuminating diet, mobility, and birth patterns among prehistoric herds. A basic review of the systematics of carbon, oxygen, and strontium stable isotopes is useful. I begin with a description of carbon, oxygen, and strontium (hereafter C, O, and Sr, respectively) systematics, including carbon isotopes in plant tissues, oxygen isotopes in the hydrosphere and plant tissues, and strontium in geology. The chapter concludes with a review of species-specific fractionation patterns in various tissues and stable isotopes used in analysis of archaeological materials. I limit my discussion to terrestrial systems, as this is the focus of the study.

Definitions

Different isotopes of an element have the same number of protons in the nucleus (i.e. the same atomic number, which determines the identity of the element), but differ in the numbers of neutrons in the nucleus, and therefore in atomic mass. Isotopes can be grouped into three categories: radioactive, radiogenic, and stable. Radioactive isotopes are those that undergo radioactive decay at a constant rate. For example, ^{14}C is a radioactive isotope that decays into the stable ^{14}N. Radiogenic isotopes are stable isotopes produced from the decay of radioactive isotopes, as in the case of ^{87}Sr, which is the product of the decay of ^{87}Rb. Stable isotopes do not undergo decay.

Behavior of Isotopes

Reactions such as photosynthesis or synthesis of animal tissues often lead to sorting of isotopes. Different isotopes of an element undergo the same chemical and physical reactions, but the differences in mass among isotopes can influence the rate and extent of reactions through two routes (Schoeninger 1995; Sulzman 2007). First, heavier isotopes of a particular element have a lower kinetic energy than lighter isotopes, and therefore travel at a slower velocity, resulting in differences in reaction kinetics. Second, the atomic mass of an isotope determines the vibrational energy of the molecule. Heavier isotopes vibrate more slowly, and hence form more stable and stronger bonds. Consequently, molecules containing heavier isotopes react more slowly (Faure and Mensing 2005; Sulzman 2007). Due to these differences, isotopes undergo sorting, or fractionation, during chemical, physical, and biological processes. This difference in reaction rate can result in significant difference between the isotopic ratio of the substrate/reactant (e.g. diet) and product (e.g. tissue) of a reaction. Typically the heavier isotope is discriminated against: due to the greater mass and bond strength, chemical bonds with heavier isotopes break and form less rapidly than do those involving light isotopes (Faure and Mensing 2005; Schoeninger 1995).

Isotopic fractionation can occur through several different processes: these are nuclear spin, equilibrium and kinetic fractionation reactions. Nuclear spin effects are only briefly mentioned here, as its importance in fractionation in most biological systems is not entirely clear (Sulzman 2007). Equilibrium fractionation reactions, also called isotopic exchange or thermodynamic fractionations, are reactions in which the reactants and products exist in a closed, well-mixed system, and the isotope distribution changes between different chemical substances, phases, or individual molecules (Hoefs 2009; Sulzman 2007). In these situations isotopically heavier molecules tend to accumulate in phases with the stiffest bonds. Equilibrium fractionation is largely dependent upon temperature. At low temperatures the magnitude of fractionation is higher; fractionation decreases as temperature increases, as the vibrational energy increases with temperature (Faure and Mensing 2005; Sulzman 2007).

Kinetic fractionations occur in systems with branching reactions or in unidirectional reactions in open systems, where back reactions are prevented from occurring. An example of this is rainwater precipitating out of a cloud, where the product (rain water) moves away from the substrate (the cloud). In these cases the heavy isotopes tend to accumulate in the product, and the substrate becomes progressively isotopically lighter as the isotopically heavy product is distilled from it (Faure and Mensing 2005; Sulzman 2007).

The fractionation factor, α, is the ratio, R, of heavy to light isotopes in the product to the ratio of heavy to light isotopes in the substrate:

$$\alpha = \frac{R_p}{R_s}$$

Isotopic enrichment, ε, also called the separation factor, is the result of fractionation:

$\varepsilon \equiv (\alpha - 1) \times 1000$

Stable isotope ratios are measured as the ratio R, where R is the heavy/light isotope ratio for a particular element. Because the isotopic differences between materials are usually very small, the ratio is expressed as parts per thousand:

$\delta(‰) = ((R_{sample}/R_{standard}) - 1) \times 1000$

This notation system is used for the lighter elements (e.g. C, H, O, N). For some heavier isotope systems, (e.g. Sr) isotopic variation is sometimes reported using ratios (e.g. $^{87}Sr/^{86}Sr$). A more negative δ value indicates that the sample is depleted in heavier isotope relative to the standard, while a more positive value indicates the sample is enriched in the heavier isotope relative to the standard. However, the difference in mass is quite substantial for isotopes of elements with lower mass (e.g. a 12% mass difference between ^{18}O and ^{16}O), and thus they have very different rates of reaction. Consequently, the degree of fractionation is quite large. Conversely, the difference in mass between isotopes of heavy elements is quite small (e.g. a 1% mass difference between ^{87}Sr and ^{86}Sr); yielding identical reaction rates and thus very little fractionation during reactions.

Carbon

Three common isotopes of carbon exist: ^{12}C and ^{13}C are stable, and ^{14}C is radioactive. The stable isotopes ^{12}C and ^{13}C occur at 98.9% and 1.1%, respectively

(Schoeller 1999). Stable carbon isotope ratios are expressed in a normalized form as $\delta^{13}C$. Values are relative to an international standard: originally Pee Dee Belemnite (PDB), which is now exhausted, and now a new standard, Vienna-PDB. These standards have relatively more ^{13}C than do most biological materials, so samples generally have a negative $\delta^{13}C$ value.

In terrestrial systems carbon enters the foodweb through plants, which derive their carbon from the atmosphere. Today, atmospheric CO_2 has a $\delta^{13}C$ value of -8‰, compared to -7‰ in the mid-1950s. This value has been decreasing from the burning of ^{13}C-depleted fossil fuels since the latter half of the 19th Century (Francey, et al. 1999; Keeling, et al. 1979). As atmospheric CO_2 is taken up by the plant, the heavier isotope is discriminated against, resulting in more negative plant $\delta^{13}C$ values relative to that of atmospheric CO_2.

Differences in $\delta^{13}C$ values exist in plants due to different carbon-fixing pathways (O'Leary 1988; Smith 1972; Smith and Epstein 1971). There are three main photosynthetic pathways for atmospheric CO_2 fixation: C_3 photosynthesis, C_4 photosynthesis, and CAM (Crassulacean Acid Metabolism). These differences in carbon fixation pathways result in $\delta^{13}C$ values of approximately -12.5 ‰ for C_4 plants, and approximately -27 ‰ for C_3 plants, although there is a wide range of $\delta^{13}C$ values for C3 plants, as discussed below (Smith 1972). CAM plants have a $\delta^{13}C$ values that fall between those of C_3 and C_4 plants.

The C_3 pathway evolved first, and occurs in all trees, most shrubs, and forbs, as well as in grasses in environments where the growing season is cool. These plants fix carbon through the Calvin cycle. The $\delta^{13}C$ value arises from a balance between the fractionation of carbon isotopes by diffusion of CO_2 across the stomata (4.4‰) and carboxylation by RuBisCo in the mesophyll cell (~30‰) (Farquhar, et al. 1989).

C_3 plants in drier, open sites tend to be enriched in ^{13}C and can have values as high as -22‰, whereas C_3 plants growing under closed canopies are depleted in ^{13}C, with values as low as -37‰ (Cerling, et al. 2003; van der Merwe and Medina 1989; Vogel, et al. 1978). The C_3 pathway, however, is not very efficient, due to the problem of photorespiration, which involves RuBisCo binding with O_2 and releasing CO_2. Early in Earth history when the Calvin Cycle first appeared, this was not an issue due to high atmospheric CO_2 levels, but today's low CO_2 levels result in conditions within the chloroplasts that allow for significant photorespiration to occur (Ehleringer and Monson 1993). Photorespiration is especially of concern in hot, dry areas, where stomata close to prevent water loss, thus preventing CO_2 from entering leaves, resulting in uptake of O_2 molecules.

C_4 plants, which include grasses in areas with warm growing seasons and some arid adapted dicots, have relatively higher $\delta^{13}C$ values, with an average of about -12 to 13‰ (Hattersley 1982; Teeri and Stowe 1976; Vogel, et al. 1978). This difference in average $\delta^{13}C$ value is due to adaptations for more efficient CO_2 fixation that limits photorespiration. Isotopic data from paleosol carbonate and fossil tooth enamel indicate that C_4 ecosystems significantly expanded around 6-7 million years ago (Cerling, et al. 1993), though the molecular evidence suggests the pathway appeared around 20 million years ago (Edwards, et al. 2010). Plants using the C_4

pathway (also called the Hatch-Slack cycle) use PEP carboxylase to initially fix CO_2. PEP carboxylase is very efficient at capturing CO_2, and does not take up O_2 (Farquhar, et al. 1989). The 4-carbon sugar (usually malate) generated from this initial step in the mesophyll cells is then transported to bundle sheath cells. At this location the 4-carbon sugar is decarboxylated, releasing CO_2, which is fixed by RuBisCo. This difference in C_4 plant anatomy (called *Kranz* anatomy) spatially separates the carboxylation enzymes, allowing for more efficient photosynthesis as the location of fixation by RuBisCo (in the bundle sheath cells) has a much higher concentration of CO_2 and lower concentration of O_2 in C_4 plants than that of C_3 plants (mesophyll cells). Overall, C_4 plants have an advantage relative to C_3 plants when atmospheric CO_2 concentrations are low, and also have a higher water use efficiency than C_3 plants (Ehleringer and Monson 1993).

The smaller fractionation in C_4 plants, averaging -5.9‰ relative to atmospheric CO_2, largely reflects fractionation during diffusion through the stomata, but is sensitive to the leakage rate of CO_2 out of the bundle sheath. While $\delta^{13}C$ values of C_4 plants exhibit a much narrower range than do C_3 plants, there is some variation among plants using different subpathways of C_4 photosynthesis. These C_4 variants differ in their respective C_4 acid decarboxylases (after which they are named), their leaf structures, and their geographic distributions. NADP-ME grasses, which favor wetter climates, have $\delta^{13}C$ values that average about -11.4‰, 1-2‰ higher than NAD-ME and PCK grasses, which favor drier climates and average about -12 and -12.7‰, respectively (Cerling and Harris 1999; Ellis, et al. 1980; Hattersley 1992;

Ohsugi, et al. 1988). The leaves of NADP-ME and PCK grasses are characterized by suberized lamellae in the bundle sheath cell walls, while some NAD-ME taxa are not (Hattersley 1992; Ohsugi, et al. 1988). This configuration better inhibits CO_2 leakage from the bundle sheath cell, thus enriching the tissues in ^{13}C (Hattersley and Browning 1981; Ohsugi, et al. 1988). This greater CO_2 retention also contributes to higher light-use efficiency (Ehleringer, et al. 1997).

The geographic distribution of plants is related to their photosynthetic pathways. The distribution of C_4 plants is highly linked to growing season temperature (for monocotyledonous plants) and aridity (for dicotyledonous plants) (Ehleringer, et al. 1997; Epstein, et al. 1997; Stowe and Teeri 1978; Teeri and Stowe 1976; Tieszen, et al. 1997). Tieszen and colleagues also recorded a strong correlation of grass species distribution and altitude: all grasses at high altitudes are C_3, with a transition zone between 2,000 and 3,000 m (Tieszen, Senyimba, et al. 1979). Similar patterns are found elsewhere, though at higher latitudes the C_3 to C_4 crossover seems to occur at lower elevations (Cabido, et al. 1997).

Plants that use the CAM pathway prevent water loss by opening their stomata at night to take up CO_2. Similar to C_4 plants, they synthesize malate, but rather than spatially separating PEP carboxylase and RuBisCo, there is a temporal separation. Malate accumulates overnight, and is decarboxylated during the day when the stomata are closed (Ehleringer and Monson 1993). The CAM pathway, which occurs in desert plants and succulents, can yield $\delta^{13}C$ values anywhere in the range exhibited by C_3 and C_4 plants (O'Leary 1988).

A wide range of $\delta^{13}C$ values have been recorded for aquatic plants (Osmond, et al. 1981). Aquatic primary producers assimilate carbon from dissolved CO_2, and, unlike terrestrial plants, can also use HCO_3-. Most aquatic primary producers use the C_3 pathway. Water flow-rate also has an effect, with plants in sluggish waters exhibiting much higher $\delta^{13}C$ values due to differences in CO_2 concentrations (Osmond, et al. 1981). Plants in freshwater systems generally have a wider range in $\delta^{13}C$ than those in marine systems (France 1995; Raven, et al. 2002).

As with aquatic plants, photosynthetic pathway is not the only source of variation for $\delta^{13}C$ values in terrestrial land plants. As mentioned above, significant variations exist in the $\delta^{13}C$ values in C_3 plants (Tieszen 1991). The $\delta^{13}C$ values for a single species can also vary throughout the year (Lowdon and Dyck 1974). Plant $\delta^{13}C$ values vary with aridity: C_3 plants can become enriched in ^{13}C during periods of drought. In dry conditions, plants close their stomata to prevent water loss through evapotranspiration, but this also inhibits CO_2 diffusion into the plant. This lowers the intercellular partial pressure of CO_2, which is eventually used up completely by carbon fixation, with no discrimination against $^{13}CO_2$, resulting in higher $\delta^{13}C$ values (O'Leary 1988). As C_4 plants always use CO_2 more efficiently, their $\delta^{13}C$ values are less affected, resulting in an isotopic difference of only 11-12‰ in drought conditions (Cerling et al. 2003).

Very low $\delta^{13}C$ values of C_3 plants occur in closed forest conditions (called the “canopy effect”). Such low values are found close to the forest floor, a consequence of recycling ^{13}C depleted CO_2 produced by soil respiration (Ehleringer, et al. 1987;

van der Merwe and Medina 1989, 1991; Vogel 1978). Low-light conditions also lower the rate of photosynthesis, thus producing lower $\delta^{13}C$ values from the full fractionation by Rubisco (Ehleringer, et al. 1986; Sternberg, et al. 1989). Carbon isotope values of leaves can also vary with branch length, with higher $\delta^{13}C$ values as branch length increases (Panek and Waring 1995).

Altitude has been shown to affect the carbon isotope composition of leaves in plants, as the decrease in the partial pressure of CO_2 with increasing elevation results in higher $\delta^{13}C$ values (Körner, et al. 1988). This trend was observed between plant groups and even within species. Ehleringer and Cooper (1988) have shown $\delta^{13}C$ values vary with soil moisture, with plants in drier areas exhibiting less negative $\delta^{13}C$ values than those in wetter areas.

Oxygen

There are three common stable oxygen isotopes, ^{16}O, ^{17}O, and ^{18}O. ^{16}O is the most abundant, occurring at 99.755%, while ^{17}O and ^{18}O are found at much lower abundances; 0.039% and 0.206%, respectively (Schoeller 1999). Oxygen isotope ratios are measured as ^{18}O:^{16}O, and are expressed as $\delta^{18}O$. Values are relative to a standard, often to the now exhausted Standard Mean Ocean Water (SMOW), and later the recalibrated Vienna-Standard Mean Ocean Water (V-SMOW). However, Vienna-PDB is also used in many studies, including this one. The equations used to transform between these two standards are as follows (Copen 1996):

$(\delta^{18}O)$ (VSMOW) = 1.03092[$\delta^{18}O$ (VPDB)] + 30.92

$(\delta^{18}O)$ (VPDB) = 0.97001 [$\delta^{18}O$ (VSMOW)] - 29.29

Differences in oxygen isotope ratios in water arise through equilibrium fractionations associated with evaporation and condensation, where isotopes are sorted due to differences in vibrational energies of isotopes of different masses. I discuss oxygen isotopes here, but hydrogen isotopes (D/H, or δD) are also very commonly used to examine patterns in hydrology, and follow similar fractionation patterns, though at a much greater scale due to greater mass difference, relative to oxygen isotopes.

The oceans contain the vast majority of water at the Earth's surface and show relatively little oxygen or hydrogen isotope variability. Precipitation is typically depleted in ^{18}O relative to its marine source, but shows considerable $\delta^{18}O$ variation in space and time (Craig and Gordon 1965; Sternberg, et al. 1991). However, there is considerable variation in $\delta^{18}O$ values of precipitation, which can change with temperature and rainfall over time. During evaporation to form atmospheric moisture and clouds, ^{16}O concentrates in the vapor phase; conversely, during condensation to form precipitation, ^{18}O is concentrated in the rain or snow, and is subsequently lost from the cloud. This process follows a Rayleigh distillation model, in which the isotopically heavier condensate is immediately removed from the vapor after formation. Unlike ice and snow, raindrops experience some evaporation and exchange with environmental vapor before they hit the ground, and hence aridity can affect $\delta^{18}O$ values of precipitation (Dansgaard 1964; Gat 1996; Gonfiantini 2001; Rozanski, et al. 1993). These processes form the foundation of oxygen isotope patterns in meteoric water.

There are several clear spatial patterns in $\delta^{18}O$ values of precipitation across the globe. Oxygen isotope values are negatively correlated with latitude. The majority of water vapor originates from tropical ocean waters, and as it moves to higher latitudes, the heavier oxygen isotope is rained out, resulting in more negative $\delta^{18}O$ values toward the poles (Bowen and Wilkinson 2002; Craig and Gordon 1965; Rozanski, et al. 1993). Similarly, there is a progressive rain-out of ^{18}O moving from oceanic sources to continental interiors, resulting in lower $\delta^{18}O$ values as distance from oceans increases. This phenomenon is called the "continental effect" (Dansgaard 1964; Rozanski, et al. 1993). As air masses move across continents, there is also a progressive rain-out of ^{18}O over mountain ranges resulting in lower $\delta^{18}O$ values at higher altitudes (Dansgaard 1964). $\delta^{18}O$ values decrease with increasing altitude because of the progressive condensation and loss of the heavier isotope from air masses in rainwater as they move up mountain slopes and cool (Gonfiantini 2001).

Seasonal variations in the oxygen isotope ratios of precipitation also exist. In the low latitudes, the "amount effect" is responsible for most of the seasonal variation in $\delta^{18}O$ values. Wet season rains tend to be depleted in ^{18}O relative to dry season rains due to the amount of precipitation as a result of the decreased evaporation of raindrops due to the higher relative humidity during the rainy season, while dry season aridity contributes to increased evaporation of precipitation, resulting in ^{18}O-enriched rainfall (Dansgaard 1964; Gonfiantini 2001).

At middle and high latitudes, where there is a greater seasonal temperature difference, winter precipitation is characterized by lower $\delta^{18}O$ values, whereas summer precipitation has higher $\delta^{18}O$ values. At higher latitudes the amount effect is diminished, as evaporation from falling precipitation is reduced (Dansgaard 1964; Marshall, et al. 2007; Yurtsever 1975).

On the ground, $\delta^{18}O$ values of meteoric water can be extremely variable. Isotopic ratios of rainfall can be affected by interactions with the canopy, leading to variations in the isotopic composition of water on the ground (Dewalle and Swistock 1994). The $\delta^{18}O$ values of water bodies are a function of water input, residence time, and evaporation. Some large bodies of water may not show great seasonal differences in $\delta^{18}O$ values, while small bodies of water in particularly arid regions may exhibit large isotopic variations (Craig 1961; Craig and Gordon 1965; Gonfiantini 1986). Soil waters can also undergo changes in $\delta^{18}O$ values, particularly in arid regions via evaporation through dry soils (Fontes, et al. 1986; Gat 1996).

Plants take up oxygen through water and atmospheric CO_2, though the $\delta^{18}O$ value of plant tissues depend primarily on oxygen supplied from water. Sources may include ground water, recent precipitation, or fog. There is no fractionation of water isotopes from groundwater to stems, allowing for the identification of source waters for plants (Dawson and Ehleringer 1991; Ehleringer and Dawson 1992; Thorburn and

Ehleringer 1995; White, et al. 1985). However, water taken up by roots is not always clear, with plants sometimes switching sources with changes in water availability; pinpointing the exact source of water can be difficult (Thorburn and Ehleringer 1995; White, et al. 1985).

Unlike stems, leaves are highly enriched in $\delta^{18}O$ relative to the soil water (Dawson and Ehleringer 1991; Dongmann, et al. 1974). This enrichment is due to evapotranspiration, where light isotopes are preferentially lost in water vapor (DeNiro and Epstein 1981; Sternberg 1989). For both C_3 and C_4 plants there is some diurnal variation, as they become increasingly ^{18}O-enriched throughout the course of the day as the stomata are open (Dongmann, et al. 1974). Historically, the Craig-Gordon model has been used to predict the $\delta^{18}O$ value of leaf water (Craig and Gordon 1965). However, within monocot leaves an isotopic gradient exists, called the Péclet effect (Helliker and Ehleringer 2000). This effect is characterized by a progressive ^{18}O-enrichment of leaf water along the length of the leaf. This enrichment leads to relatively high $\delta^{18}O$ values in C_4 grasses compared to C_3 grasses, a consequence of the parallel vein structure and short distance between veins in monocotyledonous species. C_4 plants also exhibit greater variation in $\delta^{18}O$ values due to their ability to survive in low-water conditions, such as droughts (Hattersley 1983; Tieszen, Senyimba, et al. 1979). The $\delta^{18}O$ values of leaf water in C_4 plants are generally higher than those of C_3 plants when grown in similar conditions (Helliker and Ehleringer 2002).

δ^{18}O values of leaf cellulose are largely explained by leaf water values, indicating that oxygen isotope ratios in cellulose production are not influenced by photosynthetic pathway (Helliker and Ehleringer 2002).

Differences in δ^{18}O values in plant tissues can exist within individual plants. As with carbon isotope ratios, there is an oxygen isotope gradient from the forest floor to the top of the canopy. The tops of canopies are less humid than forest understories, and experience increased evapotranspiration. Thus, leaves in the canopy close stomata to minimize water loss, leading to leaf water plant tissues enriched in ^{18}O relative to those in the understory (Sternberg 1989). These differences in oxygen isotope values have significant consequences for paleoclimate and paleodietary reconstructions, as discussed below.

Strontium

Strontium is an alkaline metal, with four naturally occurring stable isotopes: ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr, present at 0.56%, 9.87%, 7.04%, and 82.53% abundance, respectively. Only ^{87}Sr is radiogenic and is formed by the radioactive decay of rubidium (Rb)-87, which has a half-life of approximately 4.88×10^{10} years.

Strontium has two valence electrons, and an ionic radius of 1.18 Å. These properties are very similar to those of calcium, which is also divalent and has an ionic radius of 1.00 Å; thus strontium substitutes for calcium in a variety of minerals, including plagioclase feldspar, apatite, sulfates such as gypsum and anhydrite, and carbonates (Capo, et al. 1998). Therefore the concentration of Ca in a particular mineral is a good indicator of the concentration of Sr.

In many studies, $^{87}Sr/^{86}Sr$ ratios are generally recorded as such, without any normalization to a standard. In cases where a standard is used, strontium isotope values are reported using the δ notation. Most commonly the National Institute of Standards and Technology strontium carbonate standard (NBS 987) is used. This standard has a $^{87}Sr/^{86}Sr$ value of 0.71025 (Faure and Mensing 2005). Other standards can also be used, such as seawater. The formula is as follows:

$$\delta^{87}Sr = 10^{3}[[^{87}Sr/^{86}Sr_{sample}/^{87}Sr/^{86}Sr_{standard}] -1]$$

$^{87}Sr/^{86}Sr$ ratios vary with rock type and age. Variations in radiogenic ^{87}Sr come from the decay of ^{87}Rb in minerals, so soils with older minerals have relatively high amounts of ^{87}Sr (with $^{87}Sr/^{86}Sr$ ratios up to 0.716), and rocks formed recently (within the last 10 million years) have fairly low $^{87}Sr/^{86}Sr$ ratios, generally lower than 0.704. There is also variation in $^{87}Sr/^{86}Sr$ due to differences in the amounts of minerals with different ratios of Rb to Sr at the time of formation (Bentley 2006; Capo, et al. 1998). For example, limestones and basalts have low Rb/Sr ratios, and rocks like continental granites have high initial Rb/Sr ratios. Because of this, similarly aged rocks can have different $^{87}Sr/^{86}Sr$ ratios.

The $^{87}Sr/^{86}Sr$ ratios of the underlying bedrock of a particular region may not necessarily correspond to the strontium isotope composition of the labile, or “bioavailable” strontium that makes its way into local soils, water bodies, plants, and eventually up into higher trophic levels. Because the mass difference between ^{87}Sr and ^{86}Sr is so small (less than 1%) there is minimal fractionation as strontium weathers from rocks or is processed in ecosystems. Several other factors influence the isotopic composition of bioavailable strontium in a given area, including variations in strontium concentration, differential weathering of minerals with different ^{87}Sr/^{86}Sr ratios, as well as aeolian and hydrological processes.

The average concentration of strontium in rock or mineral can vary greatly. Strontium concentration in crustal rocks averages roughly 370 ppm, but can range from 1 ppm in some ultramafic rocks up to 2% in some corals. Soils usually averages around 240 ppm, but in some cases can range between 10 ppm to 1000 ppm **(**Bohn et al. 1979 cited in Capo, et al. 1998). Of weathering rocks or minerals contributing to the bioavailable strontium pool, those with higher strontium concentrations will override the ^{87}Sr/^{86}Sr ratio of geological entities with lower strontium concentrations. Another factor influencing the ^{87}Sr/^{86}Sr ratio of bioavailable strontium is the fact that minerals weather at different rates, and this can lead to differences in the strontium isotope composition of local waters and soils versus geology, depending upon which rocks and minerals weather more readily to release strontium (Blum, et al. 1994). Finally, dust from weathered rocks can be transported through aeolian processes, and contribute to the soil chemistry in quite distant regions (Muhs, et al. 2010).

Strontium is relatively abundant in marine waters, with a concentration of 8 ppm, and the modern ^{87}Sr/^{86}Sr ratio is uniform in seawater (0.709) and is often higher than what is found in fresh water (Aberg, et al. 1989; Capo, et al. 1998). Precipitation, however, has a similar $^{87}Sr/^{86}Sr$ ratio to ocean water, yet the strontium concentration is much lower (Aberg, et al. 1989). Through precipitation, a minor amount of marine strontium winds up in the continents (Blum, et al. 1994; Capo, et al. 1998). Further contributions to the $^{87}Sr/^{86}Sr$ ratios of terrestrial water bodies are derived from the weathering (mostly chemical) of bedrock. For rivers, this is in the catchment area through which the river flows, and lakes reflect the concentration of strontium and $^{87}Sr/^{86}Sr$ ratios of inflowing rivers and groundwater (Ojiamboa, et al. 2003).

Although it is not an essential nutrient for plants, calcium is (White and Broadley 2003). Both calcium and strontium have two valence electrons, and thus have similar chemical properties. Because this similarity to calcium, plants do not discriminate against strontium, although animals do. Plants can take up strontium from atmospheric sources and, to a lesser extent, weathering bedrock (Graustein and Armstrong 1983). However, different species of plants show varying concentrations of calcium and strontium, which depends to a large extent upon rooting depth and soil history (Poszwa, et al. 2004). Strontium to calcium ratios are greatly reduced in each trophic level, and thus can serve as an indicator of trophic position in paleodietary studies, to be discussed below (Schoeninger 1985; Sillen and Kavanagh 1982). However, as noted above, because of the small mass difference between ^{87}Sr and ^{86}Sr, there is very little fractionation as strontium is incorporated with trophic level. Therefore, the isotopic ratio of the source should be directly reflected in the tissues of the organism. The preservation of the isotopic ratio through trophic levels has allowed for numerous studies focusing on tracing human and animal movements and migrations, in both ancient and modern times.

The environmental and biological factors discussed above have significant impacts on the baseline $\delta^{13}C$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ values of the resources that contribute to animal diets. Understanding the underlying processes that affect these baseline values is crucial to the accurate interpretation of isotopic values of different tissues in organisms at higher trophic levels. In the next section I move onto a review of these stable isotopes in animal tissues.

Stable Isotopes in Animal Tissues

Stable isotope ratios in animal tissues are a product of ingested and inhaled inputs and metabolic processes. Numerous controlled-feeding experiments provide data on diet-to-tissue fractionation for various isotopes in different biochemical components (such as protein, bioapatite, lipids, etc.). Field studies on animals with reasonably well-known diets have also yielded important information on the shift in isotopic composition between diet and biochemical components. Tissue growth and turnover time is also an important factor, and many of these controlled feeding studies have shed light on tissue turnover rates. If the isotopic ratios of food and isotopic fractionation rates for different tissues in various species are known, it is possible to reconstruct their diets and ecologies (Balasse, et al. 2005; Cerling and Harris 1999; Cerling, et al. 2003). This section reviews these studies, which provide essential data for examining the diets and ecologies of both human and non-human archaeological and paleontological mammalian populations.

Carbon isotopes in animal bodies

Carbon is taken up by animals in food, and diet-to-tissue fractionation occurs through metabolic processes. This is balanced by fractionations in breath CO_2 and excretions. Breath CO_2 is the main flux for carbon loss from the body, and is depleted in ^{13}C relative to diet. Animal tissues and feces are enriched in ^{13}C (DeNiro and Epstein 1978). The level of fractionation from diet to tissue differs with tissue type, as listed in Table 5.1 (Ambrose and Norr 1993; DeNiro and Epstein 1978; Warinner and Tuross 2009).

Proteins are comprised of amino acids, which can be divided into two categories: essential and non-essential. Essential amino acids must be obtained from dietary protein, while non-essential amino acids can be synthesized by the animal or obtained through food. For carnivores and herbivores with monoisotopic diets, where protein and non-protein components of diet have the same isotopic ratio, the carbon isotopic composition of bone collagen is enriched in ^{13}C by about 5‰, relative to diet (Ambrose and Norr 1993; Jim, et al. 2004). However in cases where the protein source in the diet differs greatly in $\delta^{13}C$ value from the overall energy source, the carbon isotope composition of bone collagen depends largely on the amount of protein in the diet.

Table 5.1: Diet-to-tissue enrichment for carbon isotopes

Tissue	**Taxon**	**Mean ^{13}C-enrichment relative to diet**	**Reference**
Enamel	Ruminants	+14.1± 0.5 ‰	(Cerling and Harris 1999)
Enamel	Equid	+13.1‰	(Cerling and Harris 1999)
Enamel	Suid	+12.2	(Warinner and Tuross 2009)
Bone Bioapatite	Suid	+14.3	(Warinner and Tuross 2009)
Bone Bioapatite	Suid	10.2 ‰ ±1.3‰	(Howland, et al. 2003)
Bone Bioapatite	Rats	+9.5±0.6‰	(Ambrose and Norr 1993)
Bone Bioapatite	Rats	+9.5‰	Jim et al. 2004
Muscle	Carnivore	+1.1‰	(Roth and Hobson 2000)
Bone Collagen	Rats	-2.2 to +9.6‰ range monoisotopic diet= 3.8‰	(Ambrose and Norr 1993)
Bone Collagen	Rats	+5.4‰ monisotopic diet	(Jim, et al. 2004)
Bone Cholesterol	Rats	–3.3‰	(Jim, et al. 2004)
Horn keratin	Ruminants	+3.1 ± 0.7‰	(Cerling and Harris 1999)
Hair	Ruminants	+3.0 ± 0.1‰	(Zazzo, et al. 2007)
Hair	Carnivore	+2.6‰	(Roth and Hobson 2000)
Hoof	Ruminants	+2.8 ± 0.1‰	(Zazzo, et al. 2007)

Non-essential amino acids in animal proteins may be assembled with carbon from various sources including protein, carbohydrates, and lipids. For bone collagen and other proteins, the $\delta^{13}C$ values are largely controlled by dietary protein (Ambrose and Norr 1993; Krueger and Sullivan 1984; Tieszen and Fagre 1993). About 20% of carbon in collagen comes from essential amino acids, and thus in animals with low-protein diets, minimally 20% of carbon in collagen may come from dietary protein, with the remainder of carbon originating from other sources including carbohydrates and lipids (Ambrose and Norr 1993; Howland, et al. 2003). Animals with higher protein diets show greater routing of essential amino acids to protein, with inhibition of non-essential amino acid synthesis (Howland, et al. 2003; Schwarcz 2000).

Because bone is continuously remodeled throughout life, bone collagen presents an average of an individuals diet over a period of time. In contrast, keratinized tissues such as hair, hooves, and horns, are inert once formed and can grow continuously, recording changes in diet over time. Keritanized tissues are commonly analyzed for their carbon stable isotope composition. For ruminants, the enrichment between horn and diet is approximately 3‰ (Cerling and Harris 1999; Zazzo, et al. 2007).

Compound-specific stable isotope analysis can provide more information on protein sources, with $\delta^{13}C$ values of essential amino acids (such as phenylalanine) reflecting protein sources, while carbon isotope ratios of non-essential amino acids (e.g. glycine and glutamate) are representative of bulk diet. For example, phenylalanine and other essential amino acids show very little isotopic variation relative to diet, which is expected given that these are routed directly to collagen synthesis (Howland, et al. 2003), and are usually depleted in $\delta^{13}C$ relative to diet (Fogel and Tuross 2003). The non-essential amino acid glycine, the most abundant amino acid in collagen, is roughly 8‰ higher in its carbon isotope ratio than that of diet, and contributes to collagen's overall enrichment in carbon relative to diet (Hare, et al. 1991; Howland, et al. 2003).

Carbon isotope ratios also vary with trophic level, as there is also evidence for small successive fractionations of carbon isotope ratios in bone collagen up the food chain, about 1‰ with each trophic level, (Bocherens and Fogel 1995; DeNiro and Epstein 1978; Schoeninger 1985). Collagen from nursing mice shows an enrichment of $\delta^{13}C$ values of about 1‰ (Ambrose and Norr 1993), and Bocherens and Drucker (2003) report a 1‰ enrichment in ^{13}C for wolf bone collagen relative to ungulate prey species from an Upper Paleolithic site in France. However, this amount is so small it does not work well as a trophic indicator.

In contrast to collagen, Ambrose and Norr (1993) have shown that bioapatite reflects bulk diet, with no routing of macronutrients to biomineral synthesis. The carbonate fraction of bioapatite is formed from blood bicarbonate (HCO_3^-), which is in equilibrium with respired CO_2 (Schwarcz 2000). For omnivorous taxa, including humans, analysis of bioapatite alone can underrepresent protein sources, and analysis of collagen can underrepresent the plant component of the diet (Ambrose, et al. 2003; Ambrose, et al. 1997).

Taxonomic differences in diet-to-bioapatite fractionation have been recorded. For example, many large herbivores show a roughly 14‰ ^{13}C-enrichment for bioapatite in comparison to their dietary intake (Cerling and Harris 1999; Passey, et al. 2005). These values are a consequence of the production of ^{13}C-depleted methane gas, resulting in ^{13}C-enriched CO_2, which may enter the bloodstream and thus contribute to enriched bioapatite $\delta^{13}C$ values (Metges, et al. 1990). In contrast, smaller herbivores (e.g. rodents) and some large herbivores that do not rely as heavily on methanogenesis, usually display a 9-11‰ enrichment of bioapatite relative to diet (Ambrose and Norr 1993; Howland, et al. 2003; Jim, et al. 2004). Recent work by Warinner and Tuross (2009) has shown a 2.3‰ enrichment of enamel bioapatite over bone bioapatite relative to diet in suids.

While bioapatite and bone collagen are the primary tissues available for analysis in archaeological specimens, some discussion of other biochemical components and tissues are warranted. Lipids in general are depleted in ^{13}C relative to diet, (DeNiro and Epstein 1978), and are comprised of fatty acids, some of which are essential. Compound-specific analyses of essential fatty acids, such as linoleic acid, show minimal fractionation relative to diet, indicating direct incorporation from diet. Non-essential fatty acids, however, did have slightly lower (roughly 3‰) $\delta^{13}C$ values relative to bulk diet (Howland, et al. 2003; Stott, et al. 1997). Cholesterol $\delta^{13}C$ values are strongly correlated with whole diet, and are generally 3‰ lower than bulk diet. Cholesterol $\delta^{13}C$ values are also strongly correlated with non-essential fatty acids, indicating it is not routed from diet, but rather *de novo* synthesis (Howland, et al. 2003; Jim, et al. 2004).

Oxygen isotopes in animal tissues

The oxygen in bioapatite that is typically used for isotopic analysis is found in the carbonate and phosphate groups. Oxygen in bioapatite is ultimately supplied by body water. Oxygen in PO_4 and CO_3 rapidly equilibrates with body water, and the half-life of body water turnover is just a few days (Luz, et al. 1984; Podlesak, et al. 2008). Isotopic measurements on rodent tooth enamel in controlled feeding experiments showed that isotopic equilibrium was reached after about 25 days (Podlesak, et al. 2008).

The oxygen isotope fractionation between body water and bioapatite is dependent upon the temperature at which the mineral is formed. For exothermic animals, this fractionation increases with a decrease in temperature (Epstein, et al. 1953; Killingley 1981). In homeothermic animals, bone mineral is formed at a constant body temperature, about 37˚C, so this fractionation is relatively constant. In mammals, the offset between body water and the phosphate fraction of bioapaptite is roughly 18‰ (Kohn and Cerling 2002). Phosphate and carbonate ^{18}O values are strongly correlated: there is a roughly 9‰ offset between phosphate and carbonate fractions (Bryant, et al. 1996; Iacumin, et al. 1996; Longinelli and Nuti 1973; Martin, et al. 2008), although studies have defined slightly different equations for each species analyzed (Pellegrini, et al. 2011).

The $\delta^{18}O$ value of body water is controlled by a balance between oxygen inputs and outputs: both their $\delta^{18}O$ values and fractionations associated intake and outflow). In many large terrestrial mammals, drinking water is the dominant oxygen input, and there is a linear relationship between drinking water and body water $\delta^{18}O$ values (Ayliffe, et al. 1992; Bryant and Froelich 1995; Kohn, et al. 1996; Longinelli 1984; Luz, et al. 1984). There is, however, a great deal of species specific and environment dependent variation in these relationships that depend upon other inputs and outputs and animal physiology.

With respect to inputs, in addition to drinking water, water in food, and oxygen in food dry matter, roughly 25% of oxygen is taken up through inhalation of O_2, which is converted to CO_2 and H_2O through respiration. While ingested sources of oxygen are not fractionated at uptake, inhaled O_2 is: through kinetic processes as oxygen diffuses across the pulmonary membrane and through formation of oxyhemoglobin (Bryant and Froelich 1995; Kohn and Cerling 2002; Luz, et al. 1984; Podlesak, et al. 2008). Oxygen influxes are balanced by oxygen fluxes out of the body, including respired CO_2, which accounts for about 25% of output, exhaled water vapor, oxygen in urine and feces, and water lost in sweat (40%) and transcutaneous evaporation (10%) (Kohn and Cerling 2002; Luz, et al. 1984). Oxygen lost as respired CO_2, exhaled water vapor, and transcutaneous evaporation is fractionated relative to body water, but water lost through sweat, feces and urine is not (Kohn and Cerling 2002).

Variations in oxygen isotope values among species in similar environments are caused by differences in food and water sources (including amount of water ingested), humidity, and metabolic differences (Kohn and Cerling 2002; Kohn, et al. 1996). Several studies have shown that rates of drinking and respiration can affect $\delta^{18}O$ values of body water in mammals raised in identical environments. Physiologically, animals vary in how much water is lost through feces and urine, as well as in respiration. Although body size was initially proposed as a driving factor of $\delta^{18}O$ values among species, drinking and feeding behaviors seem to be more important (Bryant and Froelich 1995). Animals that obtain a greater percentage of their oxygen through drinking tend to have lower $\delta^{18}O$ values (Kohn and Cerling

2002; Kohn, et al. 1996; Levin, et al. 2006; Luz and Kolodny 1985). Humidity also influences $\delta^{18}O$ values in animal bioapatite (Ayliffe and Chivas 1990; Luz, et al. 1990). This is particularly true among animals that obtain much of their water from leaves (Levin, et al. 2006). Finally, tissues of nursing animals are enriched in ^{18}O (Luz and Kolodny 1985; Wright and Schwarcz 1999).

Strontium in animal tissues

Because the mass difference between ^{87}Sr and ^{86}Sr is so small (less than 1%), mass dependent fractionation is insignificant as strontium is incorporated up the food chain. Therefore, the isotopic signal of a source is transmitted without significant change to the organism, making it a useful indicator for animal and human migration among areas with differing geology. Strontium concentrations, however, do vary with trophic level. Because of its similarity in chemical properties to calcium, plants do not discriminate against strontium, although animals do. Strontium concentrations are thusreduced in each trophic level, and thus can serve as an indicator for the amount of meat in a diet (Schoeninger 1985; Sillen and Kavanagh 1982). The concentration of strontium in enamel generally ranges between 25 and 600 ppm; these values are dependent on the local environmental concentrations, trophic level and extent of mineralization in the tissue (Hillson 2005).

Tissue growth and turnover

Many animal tissues are commonly analyzed for their stable isotope composition, including enamel apatite, dentine and bone collagen, hair keratin, and many other soft tissues. Except for keratin, enamel, and dentine, these tissues are constantly remodeled during life, and thus present a time-averaged isotopic signal of an animal's diet and environment at a particular time. The rate of turnover is variable, even within tissues, and thus has implications for the recovery of isotopic signals.

The turnover rates of different tissues depend upon their metabolic activity; more metabolically active tissues have faster turnover rates (Hobson and Clark 1992; Tieszen, et al. 1983). For example, tissues such as liver and adipose have relatively high turnover rates, in contrast to bone collagen, which averages dietary records diet for up to 30 years (Hedges, et al. 2007; O'Connell, et al. 2001), although bone collagen turnover rate is variable, with some bones, such as ribs, exhibiting faster rates than others (Richards, et al. 2002).

Different components of various tissues (e.g. proteins, lipids) also differ in their turnover rates. In particular, amino acids show a very high rate of reutilization in the body, contributing to a relatively lower rate of turnover in blood relative to blood bicarbonate (see Waterman 1978 in (Ayliffe, et al. 2004)). Blood bicarbonate changes rather quickly, with a near total switch (~87%) from a C3 to C4 diet recorded in breath CO_2 in the first week (Ayliffe, et al. 2004). Thus there should be a shorter turnover time recorded in the initial production of bioapatite, compared to a longer turnover time in the tissues with higher organic components.

Initially an animal's overall metabolic rate, which correlates with body size, was thought to dictate rates of tissue turnover (Hobson and Clark 1992; MacAvoy, et al. 2006). However, recent studies indicate that, in the case of protein, rates of synthesis plus catabolism govern turnover rates (Carleton and Rio 2005; Martínez del Rio, et al. 2009). Recently, workers have used multi-pool or multi-compartment models to explain rates of tissue turnover and to model isotopic incorporation (Ayliffe, et al. 2004; Cerling, et al. 2007; Zazzo, et al. 2010). These pools equilibrate with diet at different rates, and explain the differences in the timing of isotopic changes in various tissues.

Diagenesis

Tissues available for stable isotope analysis of archaeological specimens include bone, dentine, and enamel. Postmortem processes can change isotopic values in both the mineral and protein fractions of these tissues. Many have noted that the impacts of diagenesis on bone and dentine bioapatite make these poor choices for stable isotope analysis (Koch, et al. 1997; Lee-Thorp and van der Merwe 1987). Enamel is most resistant to diagenetic alteration (Hoppe, et al. 2003; Zazzo, et al. 2004). Porosity is much greater in bone than enamel or dentine, and varies considerably in different types of bone (Robinson, et al. 2003; Wang and Cerling 1994). In particular, skeletal elements of juveniles have much higher porosity, providing space for exogenous fluids, rendering the bone more susceptible to diagenesis (Munson 2000; Robinson, et al. 2003). Furthermore, bone and dentine apatite crystals are small, and can allow for recrystallization or for the contamination by exogenous carbonates more readily than enamel (Zazzo, et al. 2004). Enamel is therefore most likely to preserve biogenic isotopic values, and has been used consistently in isotopic studies of archaeological and paleontological material (Hoppe, et al. 2003; Koch, et al. 1997; Wang and Cerling 1994).

Following burial, exogenous strontium, carbon, and oxygen can permeate the bone. This may take place through exogenous materials filling pore-space, absorption onto the surfaces of bioapatite crystals. These two forms of contamination may be easily remedied by pretreatment of samples, as discussed in the following section (Krueger 1991). Diagenetic materials may also become incorporated into the bioapatite crystalline structure through recrystallization and remineralization, as well as through direct exchange with diagenetic materials (Hoppe, et al. 2003; Koch, et al. 1992; Nelson, et al. 1986; Sealy, et al. 1991; Tuross, et al. 1989). Tissue that is not fully mineralized is particularly susceptible to such changes (Bentley 2006).

Oxygen isotope ratios derived from carbonate and phosphate have been shown to be differentially affected by diagenetic processes, and work by Kolodny, et al. (1983) suggested that PO_4 is quite resistant to diagenesis, due to the stronger P-O bond (Fricke, et al. 1998; Wang and Cerling 1994). Work by Zazzo, et al. (2004) clarified this difference, showing that bone PO_4 oxygen was less subject to change than carbonate oxygen via inorganic processes, while carbonate oxygen was more resistant to change than phosphate oxygen via biological processes.

Pretreatment to remove diagenetic carbonates is common in many studies of archaeological and paleontological specimens. Treatment of sampled material is not a standardized practice, however, so it is important to note the methodology so that results can be compared across studies. Treatment of tooth enamel with a weak acid to remove exogenous carbonates is a common practice (Balasse, et al. 2002; Hoppe, et al. 2003; Koch, et al. 1997). A consistent shift in oxygen isotope profiles from before to after treatment is known to occur (Koch, et al. 1997) and (Frémondeau, et al. 2012) report a slight shift in both $\delta^{18}O$ and ^{13}C values with pretreatments involving acetic acid to remove carbonates, as well as sodium hypochlorite used to remove organic matter.

Summary

Isotopic analysis has proved to be a powerful tool in assessing past environments, climatic reconstructions, as well as assessing human and animal diets, migrations, and life histories. Controlled feeding experiments continue to provide more information on species-specific fractionation patterns and are essential for interpreting archaeological data. Similarly, studies on tissue turnover have provided essential information for interpretation of isotopic data. The next chapter narrows its focus to the materials of this study and addresses tooth growth and development.

CHAPTER 6: STRUCTURE, GROWTH, AND DEVELOPMENT OF TEETH

A review of the process of tooth growth and development and research is necessary for the different components of this project. An understanding of the timing and geometry of tooth growth is required for identifying chronologies of enamel defects in teeth. Knowledge of tooth formation is crucial as the stable isotopic composition of an animal's food and water are recorded in dental tissues as they form and mineralize, and thus recovery of an isotopic signal can only be accurately interpreted if the link to tooth development is known. In particular, isotopic studies of individual animals' life histories, seasonality and mobility are based upon an understanding of tooth formation. The latter half of the chapter presents a discussion of how dental eruption and wear is used to estimate age-at-death, and includes a summary of dental development in cattle and caprines. The chapter closes with a review of how such estimates are used to infer livestock management strategies.

Tooth Structure

Mammalian teeth have two basic parts, a crown and root (Figure 6.1). These structures are composed of various dental tissues: enamel, dentine, and cementum.

The inorganic component of both tissues is hydroxylapatite, or bioapatite. The general chemical formula is $Ca_{10}\,[PO_4]_6\,[OH]_2$, though other ions may substitute for the phosphate and hydroxyl groups. Collagen is the primary organic component of bone and dentine; enamel contains other organic constituents. The organic composition of dentine is closer to that of bone, roughly 20% (Hillson 2005), but unlike bone dentine does not remodel. Mature enamel is highly inorganic, comprising 97% biomineral, approximately 1% organics, and water making up the remaining percentage. Cementum is a mineralized connective tissue. The chemical composition of cement is similar to that of bone, composed of approximately 70% of bioapatite and 21% collagen.

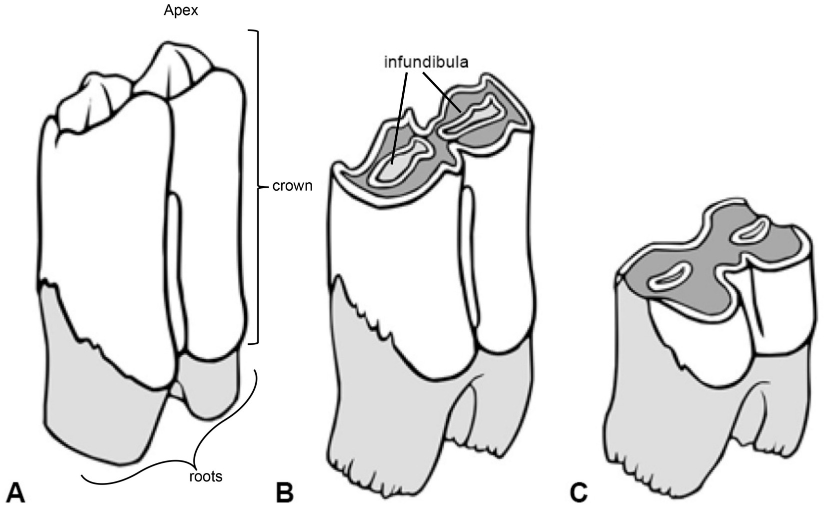


Figure 6.1: Illustration of *Bos taurus* lower first molars in various stages of wear (A: unworn; B: medium wear; C: worn). Note that in A the roots are still developing. Adapted from Hillson, 2005, p. 137, Figure 1.93.

Dentine comprises most of the interior of the tooth crown, as well as the root (Figure 6.2). Enamel covers the dentine on the exterior surface of the crown. Cattle, sheep, and goats are the focus of this study, and, like all members of the family Bovidae, have very high-crowned, or hypsodont, molars. This characteristic enables grazers to cope with very abrasive diets, as the tooth can wear for a longer period of time (Damuth and Janis 2011). While the tooth initially erupts with its occlusal surface capped by enamel, over time the enamel is worn away to expose dentine and cementum (Figure 6.1). As wear advances, infundibula, depressions along the side of the crown, become isolated. These changing patterns of exposed enamel and dentine form the basis of estimations of age at death based on dental wear, as discussed below. Cementum functions as an attachment for the periodontal ligament, which fixes the tooth into the socket. In hypsodont animals it covers not only the root of the tooth, but the crown and the infundibulum as well (Figure 6.2) (Kierdorf, et al. 2006).

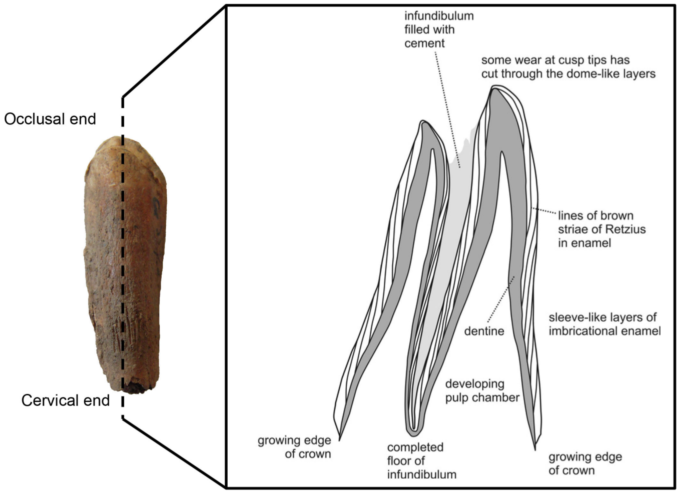


Figure 6.2: Illustration of longitundinal section of dental tissues in mineralizing cattle tooth (Right), from Hillson, 2005, Figure 1.93, p. 162. Location of longitudinal section on tooth (Left).

Tooth Growth and Development

The essential sequence of tooth growth begins with the crown developing first, from the crown apex (which becomes the occlusal surface), towards the roots. Hypsodont teeth erupt quite gradually, and often come into wear before the crown is fully mineralized. Root development is also delayed in the high-crowned herbivores, as the high crown functions to anchor the tooth in the jaw while the tooth is erupting. (Hillson 2005; Weinreb and Sharav 1964).

In the developing embryo, dental structures begin to form with the growth of tooth germs. Tooth germs arise on the edge of the dental lamina, a band of epithelium (one of the four basic animal tissue types) overlying the mesenchyme, the latter developing into the jaw. This first phase of development is called the bud stage. During this stage mesenchyme cells multiply to surround the bud of epithelial cells, forming the dental papilla, which eventually form the dentine and pulp of the tooth. The bud of epithelial cells forms the enamel organ. Second is the cap stage, characterized by the indentation of the enamel organ so that it sits over the dental papilla and other mesenchyme cells like a cap. During the latter portion of this stage the cells of the dental organ differentiate and form the internal enamel epithelium. Dental tissue deposition does not begin until the third stage of tooth development, called the bell stage, when the enamel organ and the internal enamel epithelium become increasingly indented and bell-shaped, enclosing the dental papilla. Surrounding this whole structure is the dental follicle, derived from mesenchyme cells, which will later give way to cementum. During the bell stage dental tissues become increasingly differentiated. Cells on the dental papilla differentiate into odontoblasts, which deposit the first layer of dentine matrix. Soon after cells of the internal enamel epithelium differentiate into ameloblasts. These tightly packed cells then begin to secrete the first layer of enamel matrix (Hillson 2005).

Dental Tissue Growth

Dentine

Dentine is the first dental tissue to be deposited during the bell stage of tooth development (Hillson 2005). It is formed in two phases: the first involves the apposition of an organic matrix (called predentine) into which bioapatite crystals are seeded. It is deposited in conical layers, stacking one inside another as dentine is formed from the apex of the tooth to the root, and these layers expand in length as more odontoblasts begin matrix secretion. To form the top end of the pulp cavity eventually dentine is deposited in cylindrical, sleeve-like layers, which narrow to form the root canal (Hillson 2005). The long odontoblasts stretch from the walls of the pulp chamber and extend processes from the predentine through the dentine. Dentine formation, in contrast to enamel, involves a shorter mineralization period. In many mammals, root formation begins only once the crown is erupted. However, in hypsodont species, roots do not develop until long after the crown erupts, and dentine is still forming the interior of the pulp chamber (see Brown, et al. 1960; Weinreb and Sharav 1964).

Enamel

Various histological studies on animal tooth development have shown that amelogenesis (enamel formation) is a multi-stage process (Robinson, et al. 1978), which can be broken down into two main stages. First an organic matrix with a relatively lower mineral content is deposited by the ameloblasts. Each ameloblast is involved in every stage of amelogenesis for the whole thickness of enamel on a region of the tooth, and with these stages come changes in ameloblast morphology (Hillson 2005; Sasaki, et al. 1997). The deposition of the enamel matrix follows from apex to the root-enamel junction. Ameloblasts begin secretion of a highly organic matrix seeded with bioapatite crystals shortly after dentine mineralization begins (Arsenault and Robinson 1989). In the very early stages of secretion, the end of the cell that is in contact with the enamel is flat but soon develops a protuberance called the Tomes' process, where matrix secretion takes place. At this stage of secretion, only the anterior portion of the process is present; the posterior portion of Tomes' process, which projects into the matrix, is involved only in later stages of secretion. The matrix is slightly mineralized immediately, except for the narrow innermost layer, which is, in contrast, quite heavily mineralized soon after formation, and this layer does not increase in thickness throughout amelogenesis (Suga 1982).

Although mature enamel is highly inorganic, various studies have measured this initial mineral content of the outer layer to be between 20 and 30% by volume, and then this mineralizes over time (Balasse 2002; Passey and Cerling 2002;

Robinson, et al. 1978; Sakae and Hirai 1982). The second stage, maturation, involves changes in the shape of the ameloblast; it reduces in size and the distal end of the cell loses the Tomes' process and develops becomes "ruffled" in appearance. This change in morphology reflects the removal of protein and water from the matrix by the ameloblast, and also facilitates growth of the bioapatite crystals in the enamel matrix (Hillson 2005). Histological studies of enamel formation have shown this stage can be broken down into three substages:

1. Soon after the deposition of the matrix, a secondary mineralization front moves from the surface of the enamel to the deeper layer near the enamel-dentine junction.
2. Soon after the first substage of increased mineralization reaches the innermost layer of enamel, the front of mineralization moves from the enamel-dentine junction to the outer layer of enamel. With the completion of this step all layers except for the subsurface layer of enamel are fully mineralized.
3. The final stage of maturation involves the rapid mineralization of the subsurface layer, which then becomes the most heavily mineralized layer of the enamel (Suga 1982).

The duration of the entire second stage varies between species, with the maturation stage taking 4 times as long as the initial matrix formation stage in rodents (Suga 1979), and about twice as long in caprines (Suga 1982). Sakae and Hirai (1982) demonstrated that in cattle crystalinity of enamel still increases after the tooth has erupted. Hoppe, et al. (2004) have noted variation even in the rate of mineralization in different portions of different cusps.

Crystallites of mature mammalian enamel are organized into bundles called prisms or rods, and are interspersed with inter-rod or aprismatic enamel. Crystallites vary in orientation, and the boundaries of these 4-12μm wide bundles are formed by changes in orientation between rods (Hillson 2005). The initial secretion of enamel is aprismatic, as the Tomes' process only has a proximal portion, but, as secretory activity increases, the distal portion of the Tomes' process forms rod enamel, while inter-rod enamel continues to be formed by its proximal end. Near the end of enamel formation, when secretion slows, the distal portion of the Tomes' process is lost, and ameloblasts lay down a final thin surface layer of aprismatic enamel.

The patterns of enamel formation are visible in incremental laminae. Microscopic bands spaced 4-5μm apart, are called prism cross striations, and represent a circadian rhythm growth pattern (Hillson 2005; Hoppe et al. 2004). On a larger scale, striae of Retzius record the shape of initial matrix secretion, in which enamel is formed in cone-shaped increments at the tip of the cusp, and sleeve-like increments are deposited near the cervical end of the crown (Figure 6.2). The larger the spacing between the striae, the greater is the rate of organic matrix formation. The angle of the striae in hypsodont ungulates is quite low, nearly parallel, relative to the enamel-dentine junction. However, the front of mineralization during the maturation stage cuts across these the increments, and thus, they are not helpful identifying areas for isotopic sampling (Balasse, 2003b; Hillson 2005; Hoppe et al. 2004). On the outer surface of the tooth, the striae of Retzius outcrop to form perikymata, or imbricational lines.

Cementum

Cementum is deposited on the roots of teeth, initially on the dentine, and then in layers over the earlier cementum deposits, and is deposited continuously throughout the life of the tooth. In hypsodont animals, cementum is also deposited on the crown, after the enamel matrix has formed, but not necessarily fully mineralized (Listgarten 1968). Cementoblasts, originating from mesenchymal cells in the periodontal ligament, initially begin depositing cementum on the root dentine among the collagen fibers (Sharpey's fibers) of the periodontal ligament. Initially an organic matrix (cementoid or precement) is deposited by the cementoblasts. The matrix later mineralizes.

Several types of cementum exist: acellular afibrillar cementum, acellular extrinsic fiber cementum, cellular intrinsic fiber cementum, and mixed fiber cementum (Bosshardt and Selvig 1997; Hillson 2005). These types are found on different parts of the tooth and root. Cellular cementum is generally laid down near the coronal end of the tooth root. Near the cervical end, acellular cementum is often deposited at a rate that changes seasonally, with alternating bands that appear as translucent and opaque when stained (Lieberman and Meadow 1992). Bands that appear wider and more transparent are deposited during times of rapid tissue growth and include fewer cementocytes, while the more opaque and usually narrower bands are deposited in fall and winter (Lieberman 1994). Changes in cementum deposition as a result of nutritional stresses is thought to produce these bands, and changes in occlusal strain caused by seasonal variations in food availability also contributes to the orientation of collagen fibers, producing banding. Life history events such as dietary history, starvation, chronic illness, or pregnancy can influence banding patterns, as well as their visibility.

Disruptions to growth and development: Enamel defects

A number of stresses can cause disruptions to amelogenesis, including nutritional deficiencies, diseases, and physical trauma (Goodman and Rose 1990). These either slow or halt enamel production during the secretory phase, resulting in enamel hypoplasias. Hypoplasias follow the perikymata, and are clearly linked to the structure and development of the tooth.

Enamel hypoplasias can result from a variety of health complications, although it is not possible to link particular kinds of defects to specific causes (Witzel, et al. 2006). Parasitic infections, which contribute to severe anorexia and diarrhea, leading to malnutrition, have been shown to cause hypoplasias (Balasse, et al. 2010b; Suckling, et al. 1986). Physical trauma to teeth have also been linked to hypoplasias (Suckling and Purdell-Lewis 1982b). Other common causes of hypoplastic defects involve dietary stress (Goodman and Rose 1990; Larsen 2000; Rudney 1983), including weaning (Franz-Odendaal, et al. 2003).

Fluorosis, caused by high concentrations of fluoride ions in drinking water, can manifest in enamel in different ways, including producing hypoplastic defects, particularly in areas where fluoride concentrations exceed 0.5 ppm (Hillson 2005). Hypoplastic lesions have been found in free-ranging deer populations in areas of high fluoride emissions (Kierdorf, et al. 1993), as well as in experimental settings (Suckling and Purdell-Lewis 1982a).

Recent research on hypoplasias includes examination of enamel microstructure, with deviations representing a range in the intensity and duration of disruption to amelogenesis. Relatively low stresses may manifest in a shortening of intervals between striae of Retzius, whereas anomalous regions of aprismatic enamel can indicate partial impairment of the distal Tomes' process, and macroscopic hypoplastic bands representing a severe reduction or cessation of enamel production (Witzel, et al. 2006). The type of macroscopic hypoplastic defect may also lend insight into the duration and intensity of the physiological stress (Witzel, et al. 2006).

Because they are often caused by dietary deficiencies, it is tempting to link hypoplasias to changes in diet that can be recorded isotopically. However, as Franz-Odendaal, et al. (2003) caution, a hypoplasia represents a stress event at the time of initial enamel matrix deposition, while the oxygen and carbon stable isotope composition of the enamel reflects the accumulation of carbonates during the whole course of enamel formation.

Tooth mineralization and recovery of isotopic signatures

Acquisition of mineral component

The documentation of changes in the stable isotope composition of dental tissues is inextricably linked to the chemical composition and development of those tissues. A small percentage of CO_3^{2-} substitutes for the phosphate and hydroxyl groups, and various cations (Sr^+ or Na^+) will substitute in for the calcium (Hillson 2005). Dental tissues are essentially formed from body fluids, and there are some lags in the turnover of its key constituents. Body water, and thus oxygen isotopes, have been found to have a rather rapid turnover time, within a few days (Podlesak, et al. 2008). Carbon isotope turnover for blood bicarbonate is also quite rapid, though a slow turnover pool, likely skeletal material, contributes a small percentage to the bicarbonate (Ayliffe, et al. 2004).

Despite the fast turnover in the building blocks of dental tissues, any sample of tooth enamel provides a time-averaged isotopic record. Because amelogenesis is a slow and discontinuous process, the duration of enamel mineralization dampens the amplitude of variation in seasonal changes of carbon and oxygen isotope ratios (Balasse 2002; Passey and Cerling 2002; Zazzo, et al. 2005).

The duration of mineralization differs among taxa. Among bovids, cattle second molars and sheep third molars both have a 6-month delay in mineralization (Balasse, et al. 2013; Balasse, Obein, et al. 2012). Therefore, even when abrupt changes in diet occur, they appear in dental enamel as gradual shifts in carbon and oxygen isotopic profiles, due to a long duration in integration time as the enamel mineralizes (Balasse 2002; Balasse 2003a). Passey, et al. (2005) present a model for recovering primary isotopic inputs from enamel microsamples, but only for teeth of taxa with well-understood growth and enamel mineralization times and patterns.

Because of its similar atomic radius and valence, strontium can substitute for calcium in tooth enamel. The concentration of strontium in mature enamel can be variable (Hillson 2005). Strontium isotope ratios are subject to the reservoir effect, as with calcium, strontium has a very long residence time in the body, and can be mobilized long after its incorporation into skeletal tissue (Gulson, et al. 1998; Gulson, et al. 2003). Therefore strontium isotope ratios in teeth may reflect an average of several months or years of ingested strontium before incorporation into the enamel (Balasse, et al. 2002; Montgomery, et al. 2010). Detection of changes in strontium isotope ratios depends heavily on the relative concentration in the food source (Meiggs 2007; Montgomery, et al. 2010). Few studies have looked closely at strontium and tooth mineralization, but recent work suggests that strontium is incorporated into tooth enamel in cattle enamel roughly over one year, a considerably longer span than that estimated for carbon and oxygen (Montgomery, et al. 2010).

Sampling techniques for recovery of isotopic signatures

Sampling technique can also affect the precision of stable isotope measurement. Enamel is most commonly sampled by drilling enamel parallel to perikymata on the exterior surface of the tooth, with time series created by collecting a series of such samples perpendicular to the growth axis of the tooth (Balasse 2003b;

Fricke and O'Neil 1996). Despite recent advances in sampling methods, handmilling remains the most common technique, as micromilling is time consuming and does not substantially increase the resolution of the time series. However, samples collected this way include enamel layers that have mineralized over a considerable amount of time, as the geometry of enamel mineralization is characterized not only by a gradient moving downwards from crown to neck, but also in stages across the thickness of enamel, as the thin innermost layer of enamel is most heavily mineralized immediately after matrix secretion, but the middle and outer layers mineralize at different, and slower rates (Arsenault and Robinson 1989; Balasse 2002, 2003b; Suga 1979; Zazzo, et al. 2005). Controlled feeding experiments sampling inner versus outer layers of enamel have been shown to recover more of the isotopic signal of an animal’s diet (conventional hand milling underestimates dietary shift by about 15%) (Zazzo, et al. 2005). Transverse sequences obtained through micromilling techniques record this horizontal component of mineralization, thus providing more high-resolution isotope profiles (Zazzo et al. 2005). Although it is not as resistant to diagenesis, dentine, unlike enamel, has a large organic component, and does not undergo a long period of mineralization. When sampled from transverse sections, can demonstrate a higher temporal resolution than enamel (Zazzo et al. 2006).

Laser ablation is another method for obtaining isotopic profiles from tooth enamel. Laser ablation techniques have been used to obtain oxygen, carbon, and strontium isotope values (Cerling and Sharp 1996; Copeland, et al. 2008; Lee-Thorp, et al. 2010). These methods sample portions of enamel about 100-200 μm, and have destruction halos that extend to 400 μm (Montgomery, et al. 2010), and, while samples are indeed smaller, laser ablation sampling techniques do not provide a solution to time-averaged samples caused by the slow process of enamel mineralization. Laser ablation methods also require analysis on the entire specimen, the export of which to labs with appropriate equipment is often impossible. Therefore, hand-milling, which uses a simple drill with a diamond bit, continues to be the most widely used methodology for collecting enamel samples, because it uses portable equipment, is relatively quick, inexpensive, and simple (Balasse 2002; Balasse, et al. 2013).

Developing Chronologies

The development of chronologies using dental remains has traditionally taken the form of using age-at-death estimates. The mortality profiles derived from those estimates, are frequently used to examine hunting and herd management strategies. These methods require a detailed understanding of the timing of tooth development and eruption of the species. This section reviews methods for assessing age-at-death, livestock tooth development, and mortality or slaughter profiles. Because cattle and caprines are the focus of this study, I then turn to a discussion of tooth development in these species, as well as studies of birth seasonality and herd management.

Age-at-death can be determined in several ways, including through identification of woven bone, cranial suture and epiphyseal fusions, and dental eruption and wear, the latter most commonly used due to the abundance of tooth specimens, their ability to survive taphonomic processes, and its use in studying skeletally mature animals. There is also relatively little variation in the sequence and timing of tooth eruption in mammal species, making teeth the best indicators of age.

Several methods for determining age based on dental attrition have been developed; one set assesses occlusal surface wear patterns; and the other measures dental crown height, typically in mandibular dentitions. Measuring dental attrition does not yield exact chronological ages. Rather, the teeth at different degrees of occlusal wear are grouped into broad but useful ”wear stages.” Payne (1973) first described successive occlusal wear stages for sheep and goat mandibles. Grant (1975, 1982) developed occlusal wear pattern stages for individual teeth, as well as mandible wear stages. These were applicable to a wider range of taxa, which also included more stages, producing more refined age structures. This method is more accurate when performed on complete tooth rows, which are not always available in very fragmented assemblages (Jones 2006). Recent work tackled the issue of the lack of resolution (in age-at-death estimates) for older cattle, using the position of the cementum/enamel junction and the root arch in relation to the alveolar border in molars (Jones and Sadler 2012a).

When assigning age values to occlusal wear stages, zooarchaeologists had traditionally assumed: (1) tooth wear rates are consistent within a population, and (2) the rate of tooth wear remains the same throughout the life of the individual. By iteratively sampling wear stages in known-age goat flocks, Deniz and Payne (1983) showed that this is not the case, and others have found differences in the rates of wear during an individual's lifetime (see also Gifford-Gonzalez 1991). Similarly, Greenfield and Arnold (2008) recorded greater variation in age-at-death estimates for animals under six months of age, which could also result from a number of factors, such as forage type and quality (Zeder 2006).

Age estimation methods based on remnant crown height have been widely used by some zooarchaeologists, the major advantage being that individual teeth can be analyzed easily, and that metrical analysis removes the issue of analyst subjectivity (although not all analysts measure crown height the same way) (Klein 1982; Klein, et al. 1981; see Steele 2005). Methods that use crown height to determine age either assume that wear rates follow a linear pattern throughout the life of the individual (Ducos 2000), or use a quadratic formula, assuming a curvilinear relationship between age and crown height (Klein and Cruz-Uribe 1983). Spinage (1971), observing initially rapid dental attrition rates in impala, hypothesized that as the occlusal surfaces of the teeth became smoother and friction decreased, wear rates slowed, and that this attrition curve may be universal and applicable to all ungulate species. Finding similar patterns in red deer, Klein, et al. (1981) developed the quadratic crown height measurement method (QCHM), which describes a faster rate of wear during the early stages of tooth growth.

Age estimates from enamel crown heights are problematic. The linear crown height method incorrectly assumes a consistent rate of wear through out the life of the tooth (Ducos 2000). Among know-age bison, the QCHM has a tendency to underestimate ages for older individuals and overestimate the ages of young individuals (Gifford-Gonzalez 1991), and its accuracy appears influenced by the age structure of the assemblage under study (Pike-Tay, et al. 2000). Gifford-Gonzalez (1991) found that no mortality profiles based on this method approximated the actual age distribution. A study of various methods for age estimation, including crown height measurements (both the linear and the quadratic methods) and those that relied upon occlusal wear, showed that each method produced different mortality profiles, highlighting the differences between age-at-death estimation methods (Twiss 2008).

An alternative to dental attrition methods in age estimation involves counting cementum annuli in thin sections of teeth, a method used in wildlife management for decades (Keiss 1969). Since it is deposited continuously throughout the life of the tooth, and the rate of deposition changes seasonally, with alternating bands that appear as translucent and opaque when stained, annulations can be used to assess chronological age (Lieberman 1994; Wittwer-Backofen, et al. 2004). Season of death of mammals may also be identified using dental cementum increment analysis. While tooth eruption and wear may be used to estimate season of death in young individuals of species with restricted birth seasonality, this technique is particularly useful in identifying season of death in older individuals. This technique has been successfully applied on dental remains of ungulate species (Burke and Castanet 1995; Lieberman, et al. 1990; Pike-Tay and Bricker 1993; Pike-Tay, et al. 2014) as well as human teeth (Klevezal and Shishlina 2001; Wedel 2007). While this method has been shown to accurately estimate age in modern and archaeological cattle specimens (Beasley, et al. 1992), there are some drawbacks to this method: (1) the method is destructive and time consuming; and (2) the annular structure in fossil teeth may not be preserved (Lieberman and Meadow 1992; Stutz 2002). However, proper microscopy techniques can be used to identify these problems.

Mortality profiles derived from age at death estimates are often used to interpret hunting and herding strategies. Such profiles have been used to examine the predator-prey relationships strategies of particular animals (e.g. Klein 1982; Steele 2003; Stiner 1990). Mortality profiles from herding economies are considered to reflect culling patterns in relation to the types of products desired (Marshall 1990b; Payne 1973; Vigne and Helmer 2007). Ethnographic accounts indicate that herders often selectively slaughter animals at ages when they begin to consume more resources than they provide or to compete with more productive animals (Dahl and Hjort 1976; Roderick, et al. 1998). Mortality profiles constructed to study these practices rely upon finer-grained age subdivisions and show a focus on much younger age classes than are usually found in profiles constructed to study hunting. Payne (1973) first outlined expectations for caprine mortality patterns produced by three different economies: meat-production, dairy-production, and wool-production. In a meat-producing economy, most males are slaughtered when they reached their optimum weight, and most females are kept for breeding and slaughtered only when old or infertile. If dairying was the objective, males would be slaughtered early in life to reduce competition with humans and heifers for milk, and to remove competition with females for pasturage. In a wool-producing economy, both sexes would be kept alive for their wool, males would be castrated, with lambs or kids kept to maintain the stock. Several other factors can influence kill-off patterns, however. For example, if a herder were trying to maximize herd growth, very few animals would be killed. The physiology of the animal is also an important factor. Because unimproved cattle breeds cannot release milk without the presence of the calf, infant cattle will not be slaughtered until weaning is completed (Balasse 2003a). This would result in different mortality profiles for different species (Vigne and Helmer 2007). Ritual, too, may play a role in determining such patterns, especially if taboos exist against killing certain animals for consumption, or if animals are kept for scheduled rituals and feasts (Mutundu 1992; Nicolaisen and Nicolaisen 1997). Finally, few flocks or herds are kept for a single product, so such patterns may not exist in their purest forms in the archaeological record (Halstead 1998b; Vigne and Helmer 2007). Finally, mortality profiles constructed from archaeological materials have far lower percentages of very young individuals compared to ethnographic and historic profiles, likely due to taphonomic impacts, such as destruction by dogs or pigs lower the numbers of recoverable and identifiable juvenile skeletal remains (Halstead 1998b; Munson 2000).

Dental chronologies and stable isotopes: Tooth development in domestic livestock

The tooth development of various livestock species has thus been extensively studied so that links between chronological age and the degree of tooth eruption and/or wear can be made. While many resources for timing of tooth eruption exist (see Jones and Sadler 2012b for a review), few detail tooth development, which is essential for interpreting isotopic data, as well as estimating age of death in younger individuals. The duration of enamel mineralization continues for some time after the tooth erupts, and, due to the slow and discontinuous process of mineralization, the isotopic record displayed in the enamel is delayed by several months beyond what is expected based on the chronology of tooth formation. Isotopic studies of domestic species have significantly contributed to understanding the period of time actually recorded in the enamel, which is crucial for accurate appraisal of herding strategies, including birth seasonality.

For cattle, references are limited (to my knowledge) to a review of prenatal tooth development by Soana, et al. (1997) and postnatal tooth development by (Brown, et al. 1960) (Table 6.1). However, it should be noted that such observations are made on modern livestock, and unimproved breeds most certainly developed at different rates. For example, Silver (1969) notes later ages of molar eruption for 19th Century cattle relative to modern breeds. This can be problematic when inferring age at which tissues developed, particularly because most bovid teeth come into wear before the crown has completed growth and mineralization. However, though isotopic studies of archaeological specimens have shown that the rate of development for each tooth is similar to what is described by Brown, et al. (1960).

Table 6.1: Summary of dental development of molars in cattle. Ages are presented in months (abbreviated mo).

Source	M1	M2	M3
Silver 1969	5-6 mo: eruption	15-18 mo: eruption	24-30 mo: eruption
Brown et al. 1960	*In utero*: formation begins 2-3 mo: crown complete	1 mo: crown formation begins 12-13 mo: crown complete	9-10 mo: crown formation begins 23-24 mo: crown complete
Soana et al. 1997	*In utero* (3 mo before birth): formation begins	Not studied	Not studied

Literature on caprine tooth development includes a study on primitive fat-tailed Awassi breeds (Weinreb and Sharav 1964), and one of Shetland sheep from the Orkney island of Hoy (Upex 2009). Three studies on improved breeds have also documented crown development: a study on "southern Pre-Alps" (Préalpes du Sud) ewes (Milhaud and Nezit 1991), a study on Suffolk cross sheep (Zazzo, et al. 2010), and a study on fetal domestic sheep (breed unspecified) (Witter and Míšek 1999). The differences in timing of tooth development in these breeds is likely due to different conditions: the improved breeds likely develop faster than unimproved breeds, the study by (Milhaud and Nezit 1991) examined animals living under optimum nutritional conditions, and the two studies on unimproved sheep are from different regions (Table 6.2).

Table 6.2: Summary of dental development of molars in caprines. Ages are presented in months (abbreviated mo).

Source	M1	M2	M3
Milhaud and Nezit, 1991	In utero: formation begins 3 mo: eruption 6-7 mo: root formation begins	1 mo: formation begins 9 mo: in occlusion 11-12 mo: roots begin to form	9-10 mo: formation begins 18-24 mo: eruption 20-22 mo: root formation begins
Weinreb and Sharav, 1964	birth: ½ of crown formed 3-6 mo: crown 2/3 formed, eruption 9mo: crown complete, roots start to form	3-6 mo: 1/3 crown formed 9 mo: crown unerupted 12 mo: occlusion 24mo: 1/3 root formed	12 mo: buds visible 18-24 mo: crown formation nearly complete, eruption 30-36 mo: root formation begins
Upex, 2009	*In utero*; formation begins 9 mo: crown complete	3 mo: formation begins 17 mo: crown complete	15 mo: formation begins 31 mo: crown complete
Zazzo et al. 2010	*In utero*; ~ 1 mo before birth, formation begins 6 mo: crown complete	1 mo: formation begins 12 mo: crown complete	10 mo: formation begins 22 mo: crown complete

The delay in mineralization/maturation of the enamel causes the stable isotope composition of enamel to correspond to a later time period than expected according to the timing of tooth formation. Several isotopic studies have shown this in domestic mammals (Balasse 2002; Balasse, Obein, et al. 2012; Hoppe, et al. 2004; Zazzo, et al. 2010). Figure 6.3 shows an example of the delay in maturation of tooth enamel in sheep molars. In cattle only second molars have been studied, and they exhibit delays in mineralization of roughly 6 months (Balasse 2002). As highlighted by Balasse, Obein, et al. (2012) understanding this delay is particularly important for studying birth seasonality, which cannot be estimated solely based upon the timing of tooth growth.

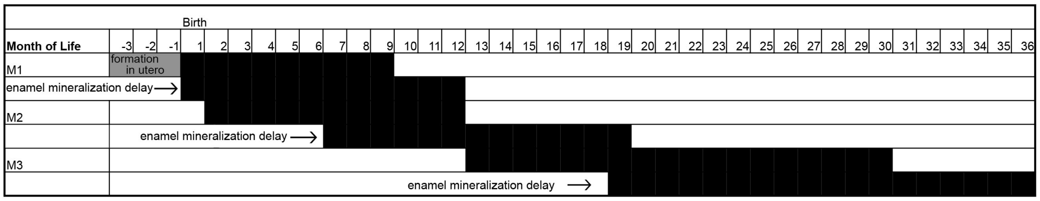


Figure 6.3: Timing of formation of molars in sheep and timing of enamel mineralization, after Balasse et al. 2013.

Summary

Understanding the formation of dental tissues is crucial to deciphering animal life histories and, consequently, herd management strategies. Studies of known-age populations have illuminated the timing of dental eruption and wear, which are crucial for the reconstruction of slaughter patterns to assess past herd management strategies. Such studies are also useful for developing chronologies in terms of hypoplasias and stress events. On a smaller scale, studies of dental tissue formation and mineralization affect the recovery of isotopic signatures, and species-specific studies over the last 15 years have allowed for more detailed investigations of animal husbandry and herding practices. These investigations form the basis of the next chapter, which delves into studies of diet, mobility, and herd management strategies using isotopic methods.

CHAPTER 7: DIET, MOBILITY AND HERDING STRATEGIES ASSESSED THROUGH STABLE ISOTOPES

Many applications exist for isotopic analyses, including assessing past climates, human and animal diets, and migrations (Ambrose and DeNiro 1986a; Ayliffe, et al. 1992; Badgley, et al. 2005; Balasse, et al. 2002; Balasse and Tresset 2002; Balasse, et al. 2005; Copeland, et al. 2011; Lee-Thorp, et al. 2010; Levin, et al. 2006). In this chapter I cover historical applications, and move into a more specific overview of how seasonality, migrations, and herding practices are assessed through analyses of the isotopic composition of animal tissues.

Assessing Past Climates and Environments

Analysis of the stable isotopic composition of animal tissues has proven to be a powerful tool for examining past climates and environments. Oxygen isotope ratios are an indicator of temperature and have been used to identify climatic changes over time (Ayliffe, et al. 1992; Emiliani 1966; Fricke and O'Neil 1999; Shackleton 1967).

Beyond temperature studies, measurements of the stable oxygen isotope composition of fossil and subfossil tooth enamel can also be used to assess the level of aridity in past environments. In such studies the drinking behavior of the animals must be taken into account, as evaporation insensitive animals, which drink more water, eat non-leafy portions of plants, and are often large, are "buffered" from increasing $\delta^{18}O$ values as aridity increases. In contrast, evaporation sensitive species obtain most of their water from ^{18}O-enriched vegetation, and are thus better indicators of aridity. As water deficit/aridity increases, so does the difference of δ^{18}O values of enamel between evaporation sensitive and insensitive animals, allowing for the examination aridity in modern and fossil ecosystems (Levin, et al. 2006). Beyond large-scale changes in temperature and aridity, seasonal changes are also measured isotopically within individual teeth, with cold/warm seasons measured in the higher latitudes, and wet/dry seasons in the tropics (Bernard, et al. 2009; Dansgaard 1964; Fricke and O'Neil 1996; Gonfiantini 1986).

Analysis of carbon isotope ratios of animal tissues has provided information on habitats and vegetation. For example, lower apatite δ^{13}C values indicate denser woodlands, while higher δ^{13}C values signal more open, drier habitats (Ambrose and DeNiro 1986a; Morgan, et al. 2009). Differential habitat use can also be identified, including feeding at different elevations (Ambrose and DeNiro 1986a; Drucker and Bocherens 2009). Carbon isotope studies have also documented widespread vegetation changes over time, such as the expansion of C_4 grasslands in the late Miocene/early Pliocene (Badgley, et al. 2005; Cerling, et al. 1997).

Assessing Paleodiet

Studies of human and animal past diets have long been a focus of isotopic analyses (Schoeninger and DeNiro 1984). Numerous archaeological investigations of human have used stable isotope analysis, ranging from trophic studies, early hominid diets, the introduction of agriculture in the Americas, marine resource use, and social, economic, and gender-based differences in diet.

Stable isotope analysis has shed light on diets of many early hominin species. Combined with dental microwear studies, isotopic analysis of tooth enamel inform on diets and ecological niches of species, revealing the contribution of C_4 plants to the diets of early hominids. A combination of high $\delta^{13}C$ values and low $\delta^{18}O$ ratios indicate hominins were consuming either non-leafy plant foods or ubiquitous underground storage organs (Lee-Thorp, et al. 2003). Enriched in ^{13}C, underground storage organs may have been a major food source, only accessible to hominins digging with tools and wielding fire (Dominy, et al. 2008; Yeakel, et al. 2007).

Studying the consumption of C_3 and C_4 plant materials has been particularly useful in identifying the introduction of maize agriculture in the Americas (van der Merwe and Vogel 1978; Vogel and van der Merwe 1977). One of the earliest studies of human diet change in North America compared bulk bone collagen samples from hunter-gatherer populations with local C_3 diets to Mississippian and Upper Mississippian populations who had transitioned to primarily maize agriculture, with diets comprising up to 70% C_4 plants (van der Merwe and Vogel 1978), with similarly high estimates for Pueblo populations (Decker and Tieszen 1989). Isotopic evidence also testifies to the variability in adoption of maize agriculture in Central America (White, et al. 1993) as well as regional and temporal variation in the dependence upon maize in the central Mississippi Valley (Buikstra and Milner 1991).

More recent work focused on gender- and status-based dietary differences, using carbon (and nitrogen) isotope studies to identify differential maize and meat consumption between groups in where there is significant social stratification, at sites like Cahokia (Ambrose, et al. 2003), and at Maya sites in Belize (White, et al. 1993). Larsen, et al. (2001) documented an increase in maize consumption, along with an overall homogenization of diet, in Spanish Florida as Roman Catholic missions were established throughout the region.

Beyond assessing past environments and human dietary changes, in the last few decades stable isotope analysis has proved to be especially useful in tracking migrations of animals and seasonal resource use. Combined, these methods allow us to explore herding practices of archaeological pastoralist groups in ways beyond traditional zooarchaeological analyses of seasonal site and resource use. The next section focuses on studies of seasonality, migration, and herd management using stable isotope analysis.

Intra-tooth Analyses: Life histories, seasonality, migrations

Since the late 1980's tissues of modern, archaeological and paleontological organisms have been sampled sequentially to examine seasonal changes in diet and habitat use. In particular, animals with continuously growing hard parts, such as shells or teeth have been selected for such sampling, including mollusk shells, fish otoliths and vertebrae, proboscidean tusks, and high-crowned herbivore teeth (Bacon, et al. 2004; Balasse 2002; Eerkens, et al. 2014; Koch, et al. 1989; Koch, et al. 1992). Because these tissues form by accretion, stable isotopic ratios can be used to reconstruct time series in the lives of individual animals. Water $\delta^{18}O$ values vary seasonally, and these changes are recorded in animal tissues as they form. Analysis of

δ^{18}O values in teeth and corollated changes in other isotope values can identify seasonally-based movements or dietary changes (Balasse et al. 2002; Kirsanow et al. 2008; Koch et al. 1989). This section begins with a review of intra-tooth analyses in investigations of ancient herding patterns, as well as a refinement of methodologies used to explore birth seasonality, foddering, and mobility.

Isotopic studies of herding strategies

Seasonality: Birth, Weaning

Numerous species have restricted birth seasons, and zooarchaeologists have long used birth seasonality to identify season of occupation at archaeological sites (Gifford, et al. 1980; Wheat 1967). Restricted reproduction/birth seasonality in wild animal populations ensures that the young of the year are born at a time when resources are sufficient to support lactation and growth. Birth seasonality in animals with high crowned teeth can be determined using oxygen isotope ratios through sequential sampling methods, and this method has been applied to many archaeological populations, particularly domesticates, with the aim of identifying herder intervention in livestock breeding (Balasse, et al. 2003; Blaise and Balasse 2011; Frémondeau, et al. 2012; Henton, et al. 2010; Towers, et al. 2011). Birth seasonality may be identified between individuals by comparing the location of the high or low point of δ^{18}O values on a particular tooth. Such investigations require a good understanding of the species' tooth development, and several factors can cause variation in the positioning of isotopic values along the tooth (Balasse, Obein, et al. 2012). For example, interindividual variation in the size of the tooth and the timing of tooth development will influence where on the crown maximum and minimum $\delta^{18}O$ values occur. Another issue is that the delay in enamel mineralization may have an effect on the location of isotopic values along the crown. Therefore it is particularly useful to have a good knowledge of not only the timing of tooth growth, but also of the delay in mineralization for a particular species (Balasse 2002; Hoppe, et al. 2004; Zazzo, et al. 2010). Recent work by Balasse, Obein, et al. (2012) has shown that the sequence $\delta^{18}O$ values along the tooth can be modeled using a cosine function, and that the location (relative to the enamel-root junction) of the highest and lowest oxygen isotope values can be normalized to the period (the length of the tooth crown formed over one year) so that individuals may be directly compared when tooth size differs among individuals. For extinct species the period can be inferred by comparing the enamel growth rate within one yearly oxygen isotope cycle to similar, well-studied species (Zazzo, et al. 2002).

Intervention by the herder can influence birth seasonality of domesticates. This is a tradeoff between subjecting animals to stress and accessing milk year-round. At the site of Kasteelberg in South Africa’s Southwestern Cape, while one birthing season and significant seasonal mobility of flocks were historically documented, oxygen isotope analysis indicated two lambings per year, while mobility, as inferred through carbon and strontium, were low, likely to avoid stressing ewes further (Balasse, et al. 2003). At the Neolithic site of Bercy calving took place over a longer period than that of unmanaged populations in similar environments, and $\delta^{13}C$ values suggest winter foddering, possibly due to herder intervention (Balasse, Boury, et al. 2012), and similar patterns have been suggested for Early Bronze Age sites in Britain (Towers, et al. 2011).

Age at weaning can be inferred by carbon and nitrogen isotopes. Nitrogen isotopes are more commonly used, as a ~3‰ shift in $\delta^{15}N$ values can be seen as young animals feed at a higher trophic level than their mothers as they consume milk (Newsome, et al. 2006). Carbon isotope ratios can also be used to identify weaning as milk is rich in lipids, which are depleted in ^{13}C relative to proteins and carbohydrates (DeNiro and Epstein 1978). Weaning-related shifts in carbon isotope profiles can be distinguishable in taxa with milk that has a high lipid content, including marine mammals, though nitrogen isotopes still are the best indicator for identifying weaning (Hobson and Sease 1998; Newsome, et al. 2006).

Foddering

Foddering is often identified in the archaeological record by the occurrence of carbon isotope ratios characteristic of plants that animals would not have access to in the wild. Cases of foddering have been extensively documented ethnographically throughout the globe (Franzel, et al. 2014; Halstead 1998a; Halstead, et al. 1996; Makarewicz and Tuross 2006). Some cases where foddering has been explored using stable isotope analysis include European Neolithic sites, where winter leaf foddering may have taken place, as evidenced by low $\delta^{13}C$ values in association with the low $\delta^{18}O$ values of the coldest months (Balasse, et al. 2013). Other methods include comparing nitrogen, oxygen and carbon isotope ratios in bone collagen of domesticates to that in wild species with similar diets (Makarewicz and Tuross 2012). Foddering may also be indicated by isotopic values consistent with domestic plants (Balasse, et al. 2013; Chase, et al. 2014; Dantas, et al. 2014). Foddering can also be disproven using multiple isotopes, as evidence for seaweed ingestion in the Holm of Papa Westray may suggest foddering practices, though in this case another line of evidence for ingestion of seawater negates the use of dry seaweed fodder by herders (Balasse, et al. 2006).

Tracking mobility

Both strontium and oxygen isotope profiles, based on local differences in geology and precipitation, respectively, can be used to track animal and human migration. As discussed in Chapter 2, the oxygen isotope ratios of precipitation vary with latitude, distance from coasts, and elevation. $\delta^{18}O$ values of tissues correlate well with geography (Ehleringer, et al. 2008). Using oxygen isotope ratios of bone phosphate, workers were able to are able to identify the geographic histories and relocation patterns among individuals at sites including Huacas de Moche on the northern coast of Peru (Toyne, et al. 2014), as well as Bronze Age burials around Stonehenge in England (Evans, et al. 2006). Care must be taken to assess what water sources would be available to the species under study, and to account for seasonal and year-to-year variations in the oxygen isotope composition of drinking water, especially in regions with high climatic variability (M. Balasse pers. comm.).

Strontium isotope analysis has had a longer history as a tool for tracking human and animal movements. Because of the negligible fractionation of strontium as it is incorporated into animal tissues, $^{87}Sr/^{86}Sr$ values in bone mineral closely reflect the local bioavailable strontium of the environment at the time the tissue was formed. While geologic maps of the region of interest are useful in identifying areas where strontium isotope analysis may be a useful indicator of mobility, local bioavailable values should be measured, because in a given geological setting, bedrock, soils, ground water, etc. all may have different $^{87}Sr/^{86}Sr$ ratios, and may differentially contribute to the bioavailable strontium pool. Local bioavailable strontium signatures are best determined by analyzing the remains of local plants or of animals with small home ranges (Bentley, et al. 2004).

Among hominids and animals with low-crowned teeth, relocations are evidenced by comparing strontium isotope ratios between teeth formed early in life to local strontium ratios, or, in cases where more complex migration patterns are suspected, to teeth formed later. These techniques have successfully identified hominid and modern human relocation patterns (Copeland, et al. 2011; Evans, et al. 2006; Ezzo, et al. 1997; Slater, et al. 2014; Tafuri, et al. 2006). Identification of non-local animals in archaeological sites can point to trade and resource acquisition patterns (Minniti, et al. 2014; Thornton 2011), even fish otoliths can also be analyzed to track movements of individuals (Ingram and Weber 1999). In taxa with hypsodont teeth or large canines or tusks, changes in strontium isotope ratios in a single tooth can show evidence for migrations. This technique has shown migration patterns in extant and extinct proboscideans in the North America and Africa, and has documented changes in migration patterns over time (Hoppe and Koch 2007; Koch, et al. 1995), and analysis of wild ungulate tooth enamel has also identified migration patterns (Britton, et al. 2009; Britton, et al. 2011).

Over the past decade, management and mobility of herd animals has also been extensively investigated using stable isotope analysis. Carbon, oxygen, and strontium stable isotope analyses are most commonly used to examine mobility, though in some cases nitrogen and sulfur from collagen are also used as they reflect environmental differences and geology and distance to coastline, respectively (Makarewicz and Tuross 2012; Richards, et al. 2001; Towers, et al. 2011). Mobility studies can be grouped into studies using either single samples or sequential sampling techniques. Most studies involving single samples from animal dental or skeletal material examine broad herding practices, while sequential sampling can be used to identify an individual's history over the course of a year. Mobility across landscapes is often documented using strontium isotope analysis as well as carbon and oxygen, as indicators of geology, vegetation, and hydrological patterns, respectively. Studies of pastoral mobility make use of intra-tooth sampling and can document seasonal differences in diet, foraging location, etc., while other isotopic studies based on one sample per individual generally are more suited towards identifying trade patterns or large scale differences in herding practices between groups (Minniti, et al. 2014; Pearson, et al. 2007). Studies using sequentially sampled enamel have the advantage of providing a picture of seasonal mobility patterns.

Most studies using single samples use bone collagen. These reflect diet averaged over many years, and are limited to examining broad trends in herding or foddering strategies of different species (Balasse, et al. 2013; Makarewicz and Tuross 2009; Pearson, et al. 2007; Thompson, et al. 2008). For example, differences in carbon and nitrogen isotope values can signal herding in different environs, such as forested areas or open grasslands. Several studies have successfully used isotopic data from bone collagen to identify herding strategies. Madgwick, et al. (2012) identified household-level herding practices for pigs during the late Bronze Age in Britain based on interindividual variability of specimens. Differences in herding were also found between cattle and caprines at Aşıklı Höyük in Neolithic Anatolia, with cattle showing a much higher diversity in carbon isotope ratios indicating herding in different areas (Pearson, et al. 2007). The authors also identified diachronic changes in herding practices of caprines at Çatalhöyük, signaled by an increasing diversity in $\delta^{15}N$ and $\delta^{13}C$ values. Several studies have also contrasted isotope data from early domesticates with that of wild animals to identify early herding strategies (Balasse, et al. 2013; Makarewicz and Tuross 2012). However, these studies are limited by averaging several years of potentially seasonal variation in isotope data, and therefore many studies of pastoral mobility rely on sequential sampling of tooth enamel to identify seasonal movements, and are discussed below.

Strontium isotope ratios have documented mobility across a range of localities. Smith, et al. (nd) used strontium isotope ratios to document changes in herding patterns in the Shashe-Limpopo River Basin in southern Africa, ranging from

AD 880-1290, a time that spanned three different political centers. Strontium has also been used to look at horse mobility in Iron Age Britain (Bendrey, et al. 2009).

Multiple isotopic analyses are often used to gain a finer understanding of mobility patterns. When combined with oxygen isotope data, carbon and strontium isotope ratios can indicate movement of herds to different regions, characterized either by differing vegetation or geology. For example, carbon and strontium isotope analyses on cattle and sheep from Kasteelberg in South Africa yielded evidence against the argument for a seasonal occupation at the site (Balasse, et al. 2002; Klein and Cruz-Uribe 1989). And Chase, et al. (2014) identified differences in herding patterns for cattle and caprines in Gujarat, India. Isotopic studies can also inform on social and ritual patterns. For example, Henton, et al. (2014) combined isotopic studies with dental microwear and showed that at a monumental site in Yemen, cattle were raised in different regions, but all died in the same place in the same season.

Altitudinal mobility of herd animals has been tracked using carbon isotope ratios, as C_3 and C_4 plants favor different growing conditions and, as a result, are distributed differently at varying altitudes (Livingstone and Clayton 1980; Tieszen, Senyimba, et al. 1979; Young and Young 1983). They therefore can be used to track seasonal migrations of animals to different elevations (Balasse and Ambrose 2005b; Dufour, et al. 2014).

Herd composition

Isotopic analyses have also been used to differentiate sheep from goats, based on diet (Ambrose and DeNiro 1986a; Balasse and Ambrose 2005a). Sheep are primarily grazers, and thus have on average higher $\delta^{13}C$ values than goats (browsers). And although the range of $\delta^{13}C$ values overlaps, the averages do not, even in mixed herds. This method works only when both C_4 and C_3 sources are available, and if the animals are allowed to choose the plants they eat. Differences in species' diets are also evidenced in livestock enclosure sediments (Shahack-Gross, et al. 2008), as the result of dung deposits. Nitrogen isotope values indicate the presence of an enclosure versus a non-anthropogenic area, while $\delta^{13}C$ values indicate the animals' diets.

Summary

The successful interpretation of isotopic data recovered from dental tissues is linked to the timing and morphology of the development of those tissues. This is useful for understanding how the geometry of dentine and enamel deposition can influence the recovery of isotopic signals recorded in those tissues. Furthermore, detailed studies the development of the tooth, in conjunction with isotopic studies, have shed new light on the time span reflected in the isotopic composition of tooth enamel, allowing for more accurate assessments of birth seasonality and other herd management practices.

CHAPTER 8: LIVESTOCK, HERD MANAGEMENT STRATEGIES, AND PASTORAL MOBILITY IN AFRICA

This chapter introduces the livestock species analyzed in this study. Knowledge of their dietary requirements and growth and reproduction necessary to interpret isotopic, mortality pattern, and hypoplasia data, which inform on pastoral mobility, herd management, and herd health. In this chapter I also review detailed data on slaughter patterns of livestock in modern pastoral contexts, illustrating how the growth and reproduction of livestock influence herd management strategies. The chapter concludes with a brief discussion on pastoral mobility and exchange in Africa.

Livestock in Kenya

The previous chapter addressed the introduction of domestic cattle, sheep, and goats into East Africa. Some basic information on the dietary requirements of these animals is presented below.

Cattle (*Bos taurus* and *Bos indicus*) are primarily grazers (Pratt and Gwynne 1977). They are obligate drinkers, requiring roughly 60 liters of water daily. In East Africa today, most cattle breeds are some cross between *Bos taurus* and *Bos indicus*. The most common cattle breed in the study area today is the Small East African Zebu or the indigenous Masai cattle (Butt, et al. 2009; Nyariki, et al. 2009)

Sheep (*Ovis aries*) are also grazers. However, in East Africa they are usually herded together with goats. They graze primarily on short/low growing grasses and forbs, but will browse if grass is unavailable (Blackburn and Field 1990; Pratt and

Gwynne 1977). Sheep tend to be quite fatty, and some breeds carry fat tails. Most common to the study area are the Red (Brown) Masai Sheep and Black-headed Somali Sheep (Nyariki, et al. 2009).

Goats (*Capra hircus*) are primarily browsers, and will climb into trees to access leaves. Particularly adaptable in their feeding, goats can even consume bark and roots. However, they will also graze, especially at the beginning of the wet season when palatable browse is rare and new grass is high in nutrients (Pratt and Gwynne 1977). They are also partial to acacia pods. Despite their browsing preference, goats have quite high-crowned teeth due to their common hypsondont ancestry with sheep. The Small East African Goat is the most common breed in the study area. As with cattle and sheep, new breeds are being introduced, though the local breeds are best adapted to the environment (Nyariki, et al. 2009).

Livestock life histories and herd structures

In this section, I outline the ages at which major life events occur for cattle and caprines managed in pastoral systems in Africa. This section is necessarily data-rich because it directly informs the age groupings for cattle and caprines used in creating mortality profiles, to be described in the next chapter. Here I cover age at weaning, weight gain trends, age of first parturition, and age at which fertility in females declines.

Cattle growth and reproduction

Calves in traditionally managed African pastoral societies are not weaned until at least 6 months of age. Calves are generally weaned late because their presence is necessary to stimulate milk let-down (Balasse 2003a). Significant variation exists in the timing of weaning, as indicated for West African shorthorn cattle (Rege, et al. 1994 and references therein). Age at weaning may extend until 8 months, as recorded for cattle in Mali (ILCA 1977; Wilson 1986) and East African zebu (Reinhardt and Reinhardt 1981). In some cases calves may not be weaned until one year of age (Bekure, et al. 1991; Roderick, et al. 1998). Weaning for both cattle and caprines in general is quite gradual in Maasailand (Bekure, et al. 1991).

Traditionally managed cattle grow quite slowly, in central Mali averaging only 185 g/day weight gain from birth to 7 months of age, and slowing further after weaning (Wilson 1986). Data from female cattle show that on average they reach 53% of their mature weight at 2 years old, and do not reach final mature weights of around 225 kg until after 5 years of age (Wilson 1986). Five years is also listed as the mature weight for N’dama cattle at the Dairy/Beef Cattle Research Station of the University of Science and Technology, Kumasi, Ghana (Karikari, et al. 1994). Improved cattle breeds generally show a more rapid and constant weight gain, reaching two-thirds of their mature body weight by two years (ILCA 1977).

Cows in traditionally managed systems usually do not give birth until they reach around 4 years of age (Roderick, et al. 1998), though the age at first calving in traditional cattle breeds can vary greatly: for *Bos indicus* cattle it is about 44 months

(Mukasa-Mugerwa 1989 and references therein). Cattle from Niono, Mali are on average 43 months old at first calving (ILCA 1977) , and Wilson (1986) reports an average age at first calving for cows in central Mali of about 50 months. However, averages listed by Pratt and Gwynne (1977) for different breeds are wide ranging, with Boran calving at 36-52 months, and some of the lower ranges for Bukedi and Nganda calving as early as two years; though the higher end of the range for those breeds extends to 61 and 55 months, respectively. A similar early age for first calving calving for N'dama cows in Ghana is around 36 months (Karikari, et al. 1994). A younger age for East African zebu, around 40 months, is given by Semenye (1980).

Cattle reproduce slowly relative to caprines (described below). The average length of gestation is around 9 months (Soana, et al. 1997). The length of the intervals vary greatly, with longer intervals of ~468 days reported for cattle in Niono, Mali (ILCA 1977) and about 443 days for Karimojong cattle (Dyson-Hudson 1982), and a range of 18 to 24 months for Maasai in eastern Kajiado District, Kenya (Bekure, et al. 1991). Pratt and Gwynne (1977) once again provide relatively shorter intervals, with ranges as short as 11 months for Boran, Bukedi, Nandi, Tanzania zebu breeds. Ankole, Tuni, and Nganda breeds have birth intervals at 16, 12, and 14 months, respectively. Overall 18 months seems to be the norm, with an average of 8-10 calves over the life of the cow (Dahl and Hjort 1976).

The average cattle lifespan is approximately 12-14 years (Dahl and Hjort 1976; Roderick, et al. 1998). Cows are normally culled after their fertility drops around age 8 to 12 years old (Bekure, et al. 1991; Dahl and Hjort 1976; Pratt and

Gwynne 1977), although milk yields peaked at the 4-5th lactation, about 9 years of age for cattle in Mali (ILCA 1977). Despite the usual decline in fertility after 8 years, many cattle older than this age are often kept in herds. For example, the Dassanetch will keep cows alive for a few years after fertility has dropped, especially if these were known to be good mothers or have other positive traits (Gifford-Gonzalez pers. comm., 2015).

Cattle herd structures

Age structures of modern East African herds can be quite variable, due to local environmental conditions, household wealth, etc. (King, et al. 1984). King, et al. (1984) report that at a Maasai group ranch in Kenya, male calves (grouped with weaners) make up almost 20% of the herd, but are slaughtered once they reach maximum weight (up to 400 kg). The remaining males are a small percentage of mature steers (~ 2%) and bulls (slightly over 5%). Few steers are kept beyond finishing weight. They may be kept for sale or for local consumption, either at scheduled feasts or in cases when sufficient milk is not produced, and provide blood during the dry season, though blood only contributes a small percentage of nutrition/food gained from a herd (Dahl and Hjort 1976; Dyson-Hudson 1982; King, et al. 1984). However, in contemporary systems oriented for meat production, roughly 20% of herds are composed of mature steers and 7% are bulls, and approximately 50% of cattle herd animals are cows (Nyariki, et al. 2009). Mutundu (2005) reports similar data for males in herds on the Kuku Plains in southern Kenya, and notes that while cattle herds can be maintained with just a few bulls, many East

African pastoralists keep more bulls than necessary as an “insurance policy” in cases of losses due to disease, drought or raiding. Nyariki, et al. (2009) report that 5 to 11% of herds in the Mara area of Kenya are composed of bulls. Female cattle make up a the majority of the herd in systems geared towards milk production. Female calves comprise almost 10% of the herd, and heifers, 20% (King, et al. 1984). Cows make up an additional 35 to 45% of herds (King, et al. 1984; Meadows and White 1979).

Natural mortality for cattle in traditional systems at various age stages can relatively high (Dahl and Hjort 1976). Mortality rates for calves in East Africa range from 20 – 40% (Oba 2001; Roderick, et al. 1998), though a lower rate of 9.5% is reported for calves at Niono, Mali, with a rate of 9.7% for weaners of 6-12 months (ILCA 1977). High mortality rates generally occur when calves were sent out to graze: only 88% of calves survived to 7 months of age in one study (Bekure, et al. 1991). By contrast, mortality rates for heifers of 2 to 4 years and breeding cows is usually low, averaging 2.8%, and is due to disease, accidents, and nutritional deficiencies (ILCA 1977), though higher percentages (up to 9%) have been reported for cows (Roderick, et al. 1998). The culling rate of cows among Maasai in the Kajiado district, Kenya is about 10%. Most of the sales in those herds (41.5%) were of weaned males (Roderick, et al. 1998). Maasai do not regularly eat cattle, usually slaughtering only for emergencies or ceremonial purposes. Animals are also slaughtered if death is imminent due to injuries, drought, or starvation (Bekure, et al. 1991; Nyariki, et al. 2009; Roderick, et al. 1998). In the case of ceremonies usually healthy, prime age cattle are slaughtered (Mutundu 1992). In contrast, steers kept for meat, are slaughtered around 4-5 years of age, when they reach their maximum weight (Dahl 1979; Pratt and Gwynne 1977).

Among East African pastoralists today, cows are often culled after their fertility drops around age 8 to 12 years old (Bekure, et al. 1991; Dahl and Hjort 1976; Pratt and Gwynne 1977). In Mali, cows completed their productive lives at 10 years of age (with an average of 5 calvings) (ILCA 1977), and the average lifespan for Maasai cattle is 12 years (Roderick, et al. 1998). Unfortunately, estimates of the percentage of aged cows in a herd are few. Demirüren (1974 cited in Dahl and Hjort 1976) notes the percentage of old (over 9 years of age) cattle in "general nomadic herds" as 15%. Mutundu (2005) reports that only an average of 5% of cattle in herds on the Kuku Plain are beyond breeding age.

Caprine growth and reproduction

The average age at weaning among African caprines is 5 to 6 months (Blackburn and Field 1990; Ndlovu and Simela 1996; Sacker and Trail 1966a, b; Wilson 1989; Wilson 1986, 1991). Caprines gain weight quite steadily (Blackburn and Field 1990; Wilson 1991 and references therein.), and there is no marked decline in rate of weight gain before reproductive age.

The age at first parturition is around 15-18 months for many traditionally managed flocks and herds, usually due to use of an apron on the stud ram or buck to control breeding (de Leeuw and Peacock 1982; Kosgey, et al. 2008; Sacker and Trail 1966a, b; Wilson 1991). Sheep and goats continue to grow after they reach reproductive age, and usually reach their mature/maximum weights at around 3 years of age (Bekure, et al. 1991; Peacock 1984; Wilson 1986, 1991).

Caprine gestation lasts around 140-160 days, and caprines may give birth twice in one year, or three times in two years (Dahl and Hjort 1976; Pratt and Gwynne 1977). Birthing intervals have been recorded as averaging 306 days, with a range of 155-600 days for goats and an average of 311 days with a range of 180-600 days for sheep among Maasai pastoralists in Western Kajiado, Kenya (de Leeuw and Peacock 1982). The average lambing interval is 255±2.3 days for East African Blackhead sheep in western Uganda (Sacker and Trail 1966a).

In many traditional African pastoral systems, ewes and does with more than seven parturitions are rare (Sacker and Trail 1966a, b; Wilson 1989). Wilson, et al. (1981) report that few female caprines over 5 years old were kept among Maasai pastoralists in Kajiado district, Kenya. Males that are very successful as herd studs are occasionally kept to 6-8 years of age (Kosgey, et al. 2008).

Caprine herd structures

East African pastoralists today usually slaughter small stock for meat, and rarely slaughter cattle (Bekure, et al. 1991; Nyariki, et al. 2009; Roderick, et al. 1998). For sheep castrates of all ages made up 21.4% of flocks, while females of all ages made up just over two-thirds of the flock. Mature breeding males, as defined by presence of 2-6 adult incisors indicating ages of 15 to 27 months for sheep and 14 to 24 months for goats, made up 3.2% of the sheep/goat flock, indicating early slaughter of caprines, before they reach maximum weight. Mature castrates comprise nearly 7% of the total goat flock (King, et al. 1984; Wilson and Durkin 1984).

The overall mortality rates to weaning can range from 15 to 40% among caprines in East African Blackhead sheep in western Uganda (de Leeuw and Peacock 1982; Peeler and Wanyangu 1998; Sacker and Trail 1966a, b). Data on mortality rates for older individuals are not common, but Mutundu (2005) notes that, out of 128 caprine mortalities during his 1988-1990 study period, 55.2% of all juvenile deaths were due to disease, drought, or accident, while 64% of adult deaths were due to the same causes. Eighty-three percent of deaths in aged caprines resulted from natural causes, while 100% of neonate deaths succumbed to disease, droughts, or accidents. While these data do not give the actual mortality rates for each age class, they do illustrate the greater percentage of voluntary slaughter of juvenile and adult caprines. Because Maasai will rarely slaughter animals intentionally, the higher rates of slaughter in the prime age groups is indicative of the lower natural mortality.

Differing reports on the modal age of slaughter for male caprines exist. Most male sheep and goats are slaughtered at maximum weight at about 36 months. Males in Maasai herds in Kajiado are killed, though castrates will continue to gain weight in the form of fat, after 3 years (Wilson, et al. 1981). However, in other cases, such as in western Sudan, the majority of male caprines are slaughtered around 15 months of age (Dahl and Hjort 1976; Hunting Technical Services 1974). Similarly King, et al. (1984) show that most male caprines are culled by 15 months, leaving goat herds composed of only 1% mature breeding males, and 2.2% mature breeding males in sheep flocks. Castrates are kept alive for somewhat longer and are often slaughtered from 15 to 36 months, and castrates of all ages comprise around 11% of sheep flocks, and 15% of goat herds. Sheep and goats typically live until 6 years of age, and females are not kept beyond their reproductive prime, though data on the percentage of older individuals in a herd or flock are rare (Dahl and Hjort 1976; King, et al. 1984).

Movement of animals in pastoralist systems

Seasonal movements

Numerous ethnohistorical sources document the importance of mobility in pastoralist societies. Stenning (1957) described three types of movement among mobile Fulani herders, arguing that seasonal patterns had to be distinguished from changes that occurred over several years, and that movements responding to environmental changes should be distinguished from large scale movements responding to political events. Similar distinct classes of movements have been described by Evans-Pritchard (1940), McCabe (1994; 2004), Gulliver (1955).

Seasonal movements for pastoralists are crucial, as changes in water availability and vegetation quality require livestock to be pastured at different areas during the year. In particular, East African pastoralists use mobility to cope with unpredictability in rainfall (Coughenour, et al. 1985; Nicholson 1996). Many factors influence specific mobility patterns among herders. Herds may be divided up by species and age according to forage and water requirements (Coppolillo 2000; Fratkin and Smith 1994). Because caprines are not as valuable, even in very dry years, small stock are not moved very far, as migrations can be too strenuous for the animals, and populations can be replenished quickly from losses due to malnutrition. Sheep can also utilize the short stubble of grass that cattle cannot (Nicolaisen and Nicolaisen 1997; Nyariki, et al. 2009).

Such herding patterns require significant division of labor, with a segment of the population leaving the main household settlements to care for herds for part of the year. Pastoral production requires a maintenance of a balance between the household labor force and the household's herd size (Dahl and Hjort 1976; Stenning 1959). Fratkin and Smith (1994) note that among pastoralists such as the Turkana, extra labor is obtained by fostering children, and young children often are responsible for herding small stock.

Turton (1991) also notes that young Nyangatom men herded animals to more mountainous areas during the dry season, residing there in special purpose camps. Traditional Turkana settlements also changed in demographic composition according to seasonal herding requirements. During the wet season, groups gathered into large neighborhood associations comprising all family members and livestock. During the dry season, herd owners would often separate their cattle from the other animals and usually young adult sons would move the cattle to higher elevations, where herbaceous vegetation is available, while Turkana households remain at lower altitudes. Livestock were also divided according to productive status, with milking animals herded in areas with better forage (McCabe 1994b; 2004). In less altitudinally zoned regions, a similar strategy of moving non-milking stock to far-off pastures has been documented, as among the Dassanetch (e.g. Carr 1977; Gifford-Gonzalez 1989) or traditional Samburu (Spencer 1965). The Maasai move animals over long distances, and movements across districts are not uncommon during dry seasons (Nyariki, et al. 2009).

Pastoralists not only move livestock to forage and water logistically, but mobility also may be used as a means of coping with disease. For example, Maasai know to avoid wildebeest birthing grounds due to the risk of wildebeest-derived malignant catarrhal fever (Gifford-Gonzalez 2000). Waller and Sobania (1980) note that in precolonial times, East African pastoralists would avoid areas known to have diseases or parasites, and that they would seek to "outrun" emerging epidemics, with the understanding that a certain amount of mortality would occur (see also Sobania 1980).

Livestock exchange among pastoralists: another axis of mobility

Herd animals may also travel between settlements or even between ethnic groups through exchange. Such transfers have been extensively documented in the ethnographic literature on African pastoralists. Livestock may be obtained through several types of transaction, including bridewealth payments, barter for food and other resources, gifts (often with clear, culturally defined expectations of delayed reciprocity), and raiding (Evans-Pritchard 1940; Gulliver 1955; Kelly 1985; Spencer 1965). McCabe (2004) and Gulliver (1955) also underline the importance of stock associations and partnerships among Turkana herders, and even with members of other tribes, as does Almagor (1978) for the Dassanetch. Such non-kin-based relationships are important for maintaining herds if animals are lost to disease, drought, or raiding, or mobilizing a surplus for ceremonies. McCabe (2004) underlines the importance of stock associations among Turkana herders. These relationships may be formed between agnatic or affinal kinsmen, and may even be formed with members of other tribes. These relationships are crucial for maintaining herds. If animals are lost to disease, drought, or raiding, a herder can go to his livestock associates and obtain animals to rebuild his herd. Likewise, if an animal has to be slaughtered for a ceremony, he can beg a sacrificial animal from associates.

One other important aspect of pastoral life that pervades ethnographic accounts is pastoralists' reliance upon other groups for exchange. Most pastoralists who focus solely on herding would have to rely on trade with agriculturalists to supply them with food to achieve a more balanced diet (Nicolaisen and Nicolaisen 1997). However, similar relationships between hunter-gatherer groups and pastoralists have also been documented, such as with the Elmolo and Samburu of southeastern Lake Turkana (Sobania 1988). Such networks can make up for shortfalls in livestock production, and are crucial in times of crisis, such as drought, extreme flooding, or disease epidemics (Sobania 1991; Waller and Sobania 1994).

In times of environmental crisis the importance of exchange relationships are obvious. Nineteenth Century East Africa was populated by many small-scale societies with fluid boundaries, social structures and subsistence systems (Sobania 1991). A series of three disasters in the last twenty years of the century that richly described in multiple oral traditions illustrates this. These included an outbreak of bovine pleuropneumonia (early 1880s), rinderpest (late 1880s), and smallpox coupled with a drought in the 1890s. These epidemics prompted people to use all of their social networks to trade goods and transfer livestock and labor. Cattle and camel pastoralism, agro-pastoralism, and hunting and gathering, were options for all individuals living in the eastern Lake Turkana area, though most were committed to herding. For agro-pastoralists like the Dassanetch, grain production provided a good supplement to animal products, and grain could be sold to acquire more animals, as the pastoral Turkana, Samburu, and Rendille would look to the Dassanetch for millet. In contrast, the Rendille were committed camel pastoralists, and families relied on the sharing of labor and property with other families. Johnson (1991) described accounts of exchange of food resources between Nuer and Dinka groups, these contacts were especially necessary in periods of extreme flooding and disease epidemics in the upper Nile. Evans-Pritchard (1940) also described accounts of sharing food resources in his 1929-1936 period of fieldwork. Sobania (1991) also notes the importance of alliances between the Samburu and the Ndorobo hunter-gatherers in times of crisis. Inter-societal partnerships clearly are valuable in that they provide each partner with increased knowledge of the region and his options in the economic sphere.

Exchange and social relationships provide routes for the transition to, and formation of, new ethnic identities, and shifts along the spectrum of pastoral production are not uncommon, and are usually facilitated by exchange relationships

(Waller and Sobania 1994). For hunter-gatherers, specialized artifacts as well as live animals may be acquired in such transfers. Adoption of herding by hunter-gatherers is often facilitated by such pre-existing exchange relationships (Cronk 1989; Cronk 2004; Jacobs 1965). For example, Elmolo hunter-fisher-gatherers offered refuge to many Samburu pastoralists during a time of economic crisis, resulting in some Elmolo women marrying into Samburu society, as well as some Elmolo adopting livestock (Sobania 1988). Similarly, origin traditions indicate that such friendships across exchange networks facilitated elements of Samburu and Rendille to become part of the Dassenetch, forming the Kuro and Randal sections, respectively (Sobania 2011). Populations can also be assimilated as a result of raiding, with the conquering population absorbing part of the raided population (Deng 1972; Kelly 1985).

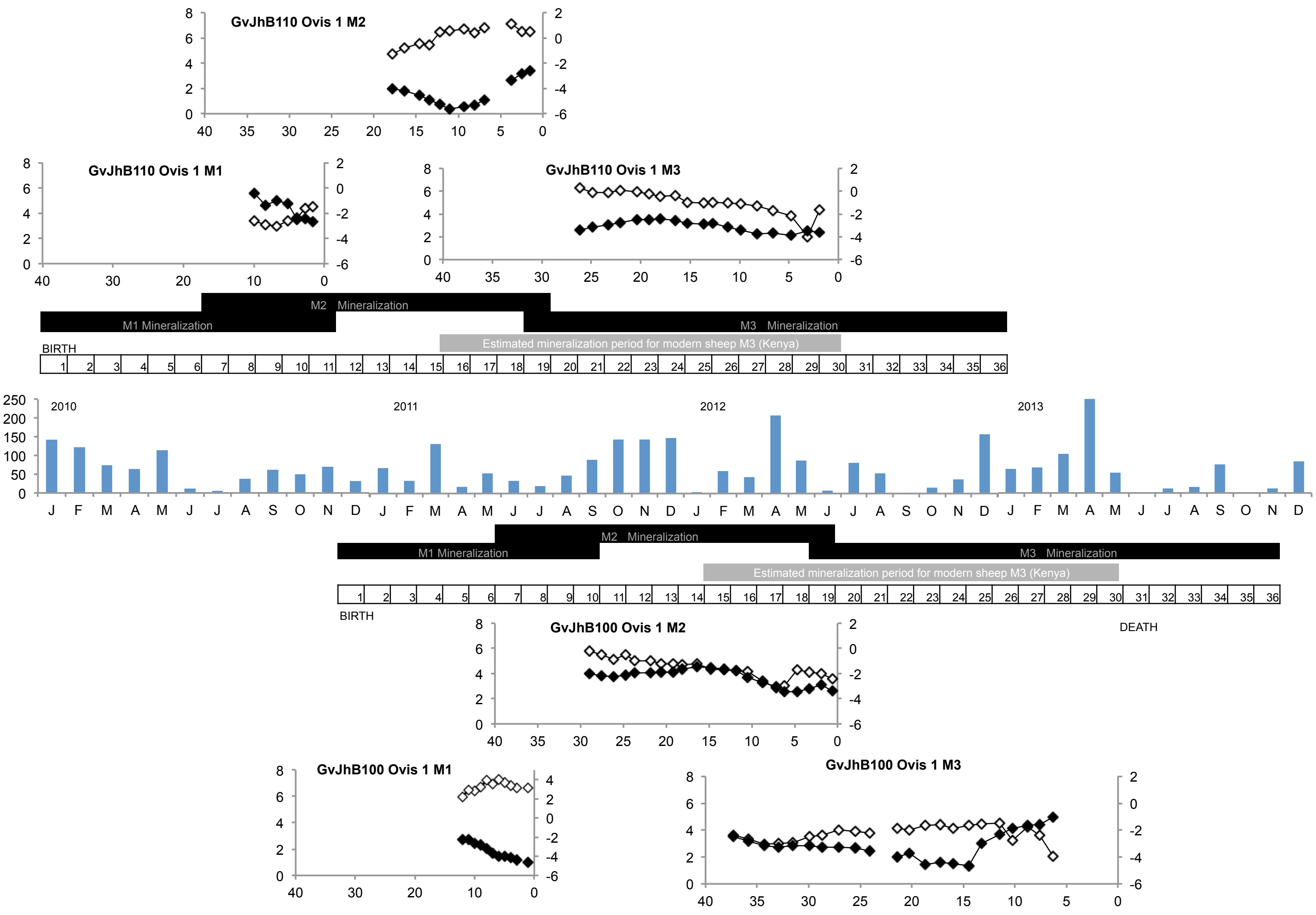
The diets and physiologies of different domesticated species have implications for how they are managed and herded across the landscape. However, the pervasive movement and exchange of livestock among pastoralist groups has not been documented archaeologically. The next chapter outlines the methodologies utilized to explore ancient mobility and herd management strategies in south-central Kenya.

CHAPTER 9: METHODS FOR ESTIMATING AGE AT DEATH, RECORDING DENTAL HYPOPLASIAS, AND STABLE ISOTOPE ANALYSIS

This chapter reviews the methodologies for the analyses used in project. Archaeological livestock teeth were subject to several analyses. I begin by outlining the rational for age at death estimates based upon the livestock growth and reproduction data presented in the previous chapter. I then outline methods for recording hypoplasias on livestock teeth. The latter part of this chapter is dedicated to the methods of sampling and analyzing livestock tooth enamel to determine the carbon, oxygen, and strontium stable isotope composition. I also include the methods for collecting, sampling and analyzing microfauna for strontium stable isotope analysis for the creation of a strontium isoscape of south-central Kenya. First, however, I briefly outline the goals of the project and how each set of analyses of archaeological livestock remains contributes to exploring the research questions outlined in Chapter 1.

Table 9.1: Archaeological sites included in study.

Site	Location	Dates (Years BP) * indicates calibrated dates	Lithic Industry	Ceramic Tradition	Fauna
Prolonged Drift: GrJi 1	Open Site, Floodplain of Nderit River, SW of L. Nakuru, Central Rift	2530 ± 160 uncal BP (collagen) *2590±183 cal BP	Elmenteitan, Eburran 5	Undecorated few Narosura sherds	Wild and Domestic
Crescent Island Main: GtJj 2	Open site, L. Naivasha, Central Rift	2405±150 (apatite), 2660±120 (collagen) *2535±140, (A) 2795±155 cal BP (C)	SPN	Narosura	Mostly domestic
Crescent Island Causeway: GtJj 3	Open site, on island on SE side of L. Naivasha, Central Rift	2045 ± 125 BP (apatite) *2038±155 cal BP)	Eburran 5	Narosura	Domestic
Ndabibi: GtJi 3	Open site, between Lake Naivasha and Mau Escarpment, Central Rift	1255 BP ± 125 BP to 2225 ±155 BP (collagen) *1159±120 cal BP to 2294±215cal BP	SPN	Narosura	Mostly domestic
GvJm-44 (Lukenya Hill)	Athi-Kapiti Plains	Narosura levels: 2030 ± 125 BP and 2085 ± 135 BP *2015±152 cal BP to 2086±170cal BP	SPN	Narosura	Domestic
GvJm-52	Athi-Kapiti Plains	1855±186 (apatite), 2050±115 (collagen) *1803±217 cal BP (A), 2043±143 cal BP (C)	SPN	Narosura	Domestic
Narosura: GwJh 2	On Narosura River, West of Mau Escarpment, on edge of the Loita Plains	2640 ± 115, 2660 ± 115, 2360 ± 110, 2760 ± 115 BP (charcoal) *2707±162, 2738±165, 2918±131 cal BP	SPN	Narosura	Mostly domestic


GvJhB110 Ovis 1 M2
GvJhB110 Ovis 1 M1
GvJhB110 Ovis 1 M3
M2 Mineralization
M1 Mineralization
M3 Mineralization
Estimated mineralization period for modern sheep M3 (Kenya)
BIRTH
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
250 200 150 100 50 0
2010
2011
2012
2013
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
DEATH
GvJhB100 Ovis 1 M2
GvJhB100 Ovis 1 M1
GvJhB100 Ovis 1 M3
8 6 4 2 0
2 0 -2 -4 -6
4 2 0 -2 -4 -6
40 35 30 25 20 15 10 5 0
40 30 20 10 0

Archaeological Sites Included in Study

The archaeological sites selected for study include sites from the steep-sided Central Rift Valley, as well as the neighboring Loita and Athi-Kapiti Plains. These sites are situated in diverse environments, which may have some effect on the herding strategies of the site occupants. The sites indicated in Figure 1.1 and Table 9.1 are described below.

Prolonged Drift (GeJi1) is an open-air, single component site situated on the floodplain of the Nderit River southwest of Lake Nakuru. Radiocarbon dates from an elephant ivory pestle, of which the collagen fraction yielded a date of 2530 ± 160 uncal BP 2590±. A few sherds resembling Narosura wear are present, but the majority of the ceramics at the site are primarily undecorated. A reanalysis of the ceramic assemblage is necessary to determine whether the undecorated sherds are in fact Elmenteitan pottery (S. Ambrose personal communication 2014). The large lithic assemblage comprises both Elmenteitan and Eburran 5 materials (S. Goldstein personal communication, 2015). The faunal assemblage is remarkably varied: 83% of the MNI are wild animals, primarily medium to large bovids, including *Connochaetes taurinus* (wildebeest), *Alcelaphus buselaphus* (hartebeest), and *Equus burchelli* (zebra). The majority of domesticates represented at the site, however, are cattle (Gifford, et al. 1980; Gifford-Gonzalez and Kimengich 1984).

Crescent Island Main, an open-air site, is located on Lake Naivasha's Crescent Island. It is likely single component midden site, with a very large faunal assemblage (Gifford-Gonzalez and Kimengich 1984; Onyango-Abuye 1977). Radiocarbon dates on collagen place the site in the middle of the third millennium BP, ranging from roughly 2800 to 2500 cal BP (Onyango-Abuye 1977). Its lithic assemblage comprises SPN lithics and ceramics are Narosura. Domesticates dominate the assemblage, with cattle outnumbering caprines by three to one in terms of NISP (Gifford-Gonzalez and Kimengich 1984).

Crescent Island Causeway is situated just a short distance from Crescent Island Main. The ceramic assemblage is composed of Narosura ware, but the lithic industry is Eburran 5B site (Ambrose 1984c). Most of the bone comes from what is likely a midden. Cattle outnumber caprines (Gifford-Gonzalez and Kimengich 1984).

Ndabibi, located on the Ndabibi Plain west of Lake Naivasha is likely a single-component site, though bioturbation is a concern (J. Bower pers. comm cited in Gifford-Gonzalez and Kimengich 1984). Dates of occupation range from roughly 2300 to 1200 BP. Its small faunal assemblage, approximately 300 pieces, is composed primarily of domestic livestock (Gifford-Gonzalez and Kimengich 1984).

Narosura is another open-air Savanna Pastoral Neolithic site. It is situated on the Narosura River, on the edge of the Loita Plains and several radiocarbon dates on charcoal range from about 2760 to 2360 uncal bp (Odner 1972). Narosura is one of the few SPN sites with evidence for architecture, in the form of numerous post holes, and likely represents a long term occupation. Narosura's lithic assemblage is primarily obsidian from Njorowa Gorge obsidian sources south of Lake Naivasha, and to a far lesser extent Sonanchi sources just west of the lake (Merrick and Brown 1984). It is the type site for Narosura ceramics. Domestic livestock comprise the majority of the assemblage, and caprine remains outnumber those of cattle (Gramly 1972).

The two sites on the Athi-Kapiti Plains, GvJm44 and GvJm52, are located at Lukenya Hill. The hill is a ∼16 km^2 inselberg of Precambrian gneiss. It rises ∼100–200 m above the grasslands. GvJm44, also called Vaave Makongo, is situated on the southern end of Lukenya Hill. This is a stratified site with levels containing Savanna Pastoral Neolithic lithics and Narosura ceramics dating to 2015±152 cal BP to 2086±170cal BP These levels overly a level containing Nderit ceramics, which dates to 3290±145 BP (3547±164 cal BP) on charcoal (C. M. Nelson, personal communication to Gifford-Gonzalez, 1992). Domesticates dominate the assemblage (Nelson and Kimengich 1984).

GvJm52 is also situated on Lukenya Hill. It is a large open site with large open site with ash heaps. The ceramic assemblage is also composed of Narosura ware, and SPN lithics are present. Conventional radiocarbon dates on bone apatite yielded a date of 1803±217 cal BP, and bone collagen yielded a date of 2043±143 cal BP. Unpublished data from Diane Gifford-Gonzalez reports a predominance of cattle and caprines at the site.

Estimating age at death

In this study age-at-death estimates are used to explore broad patterns in ancient herd management strategies, and to further interpret the subsistence strategies of occupants of Prolonged Drift, a site with a mixed faunal assemblage. Differences in mortality profiles may be used to distinguish sites created by pastoralists and sites created by hunter-gatherers who obtained domesticates from herders (Prendergast and Mutundu 2010). In the case of the latter, ages at death of domesticates should not cluster modally, reflecting prompt slaughter of animals obtained instead of pastoral management of herds or flocks.

To assess herding practices, age at death was estimated using Grant's (1982) system based on dental eruption and wear. This method is more accurate when performed on complete tooth rows, which are not always available in very fragmented assemblages (Jones 2006). However, the teeth of larger ungulates in Kenyan pastoralist sites are almost always recovered as isolated specimens, likely due to a combination of culinary processing, trampling, and abiotic factors (Gifford-Gonzalez 1991). Because each site contained mostly isolated teeth, specimens were grouped into broad age categories: Infant, Young Juvenile, Older Juvenile, Young Adult, Mature Adult, and Aged. Many more teeth were included in the age-at-death study than were included for the hypoplasia study, as only the occlusal surface of the tooth was needed to estimate age at death. Livestock age groups are broadly defined, based upon the lower deciduous fourth premolars, first, second, and third molars. In different species, each tooth's Grant Wear Stage (Grant 1982) correlates with a different age, based upon when in the animal's life that tooth erupts and comes into wear (see Table 6.1 for cattle, Table 6.2 for caprines). Age-at-death profiles are constructed in terms of percent Minimum Number of Individuals.

Defining age classes in terms of life history

In this project, I attempted to provide a life-history perspective to each broad age grouping for cattle and caprines, so that the archaeofaunal evidence for pastoralist management can take on a more dynamic dimension. These age groups are drawn from data on age at weaning, weight gain trends, age of first parturition, and age at which fertility in females declines, presented in the previous chapter.

For cattle, the Infant age class is marked from birth to weaning, here set from 0-6 months. Growth rates were used to classify ages marking Young versus Older Juveniles. Traditionally managed cattle grow quite slowly, and data from female cattle show that on average they reach 53% of their mature weight at 2 years old (Wilson 1986). Therefore, for this study, Young Juveniles are grouped from 6 months to 2 years, and Older Juveniles from 2 to 4 years.

The chronological age range for the Young Adult classification is based roughly upon the age at first calving in females and age at when full weight is reached listed in the literature. The age at first calving in traditionally managed herds of unimproved cattle in Africa is around 4 years of age (Mukasa-Mugerwa 1989; Wilson 1986). Several studies note that cows reach their mature weights until around 5 years of age (Karikari, et al. 1994; Wilson 1986), though mature weights may be reached as early as 40 months (Semenye 1980). Therefore the Young Adult age class spans 4 to 6 years. The Mature Adult age class spans 6 to 8 years.

The Aged age class is the broadest, including cattle ranging from about 8 to 14 years. The average cattle lifespan is approximately 12-14 years (Dahl and Hjort

1976; Roderick, et al. 1998). This Aged age class is also the largest due to the high degree of variation in age associated with each tooth wear stage, particularly in older individuals (Jones and Sadler 2012a, b)

Grant's tooth wear stages (TWSes) were linked to chronological ages using several resources. Data on erupting cattle teeth are listed in Table 6.1 and references therein, while data from teeth in wear come from the Jones and Sadler (2012a) study of known-age cattle from Halle, Germany. Chronological age and TWS correlations were also based upon correlations between analyzed archaeological and African cattle specimens housed at the National Museums of Kenya (NMK) Osteology Museum in Nairobi by D. Gifford-Gonzalez (unpublished data). In the literature, the range of ages associated with each stage increases with age, due to variability in grazing conditions and inter-individual variability in tooth development, as well as the "arbitrary" assignments of the age stages. Tooth wear stage end-members were chosen based upon their frequency in each age category. The age classes and corresponding TWS for each tooth are outlined in Table 9.2.

Table 9.2: Wear stages and age classes for the lower deciduous fourth premolar (dp_4) and lower first, second, and third molars (M_1, M_2, M_3) of cattle. *See Table 6.1.

	Grant (1982) Wear Stage			
Broad Age Class	**dp_4**	**M_1**	**M_2**	**M_3**
Infant (0-6 mo.)	a-g	C, V, E, ½, U, a[1], b	C, V	n/a*
Young Juvenile (6 to 24 mo.)	h-m	c-h	E, ½, U, a-f	C, V, E ½, U
Older Juvenile (2-4 years)		j	g-h	a-f [2,3]
Young Adult (4 to 6 years)		k	j	g
Mature Adult (6 to 8 years)		l	k	h-j
Aged (> 8 years)		m-p	l-p	k-m

Grant's (1982) tooth wear stages were also used for estimating caprine age at death. Caprines were grouped into the same six age categories as listed above for cattle. Grant's (1982) TWS for caprines were linked to chronological ages using known-age data (Deniz and Payne 1982; Greenfield and Arnold 2008; Jones 2006). Similarly to cattle, data on age at weaning, weight gain, age at first parturition, and declines in fertility were used to define the chronological age associated with each age group.

The average age at weaning among African caprines is 5 to 6 months (Blackburn and Field 1990; Ndlovu and Simela 1996; Sacker and Trail 1966a, b; Wilson 1989), and therefore, the Infant age class is categorized from 0 to 6 months. Caprines gain weight quite steadily (Blackburn and Field 1990; Wilson 1991 and references therein), and there is no marked decline in rate of weight gain before

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[1] The following footnotes are based upon Gifford-Gonzalez's notes on specimens

[2] Teeth at stage F match cattle at 36 months.

[3] M3 at stage B match individuals under 36 months.

reproductive age. Therefore the age classes Young Juvenile and Older Juvenile are set at 6-12 months and 12-18 months, respectively. The adult age class corresponds to the age at first kidding and lambing for goats and sheep. Age at first parturition is around 15-18 months for many traditionally managed flocks and herds (de Leeuw and Peacock 1982; Kosgey, et al. 2008; Sacker and Trail 1966a, b; Wilson 1991). Sheep and goats continue to grow after they reach reproductive age, and usually reach their mature/maximum weights at around 3 years of age (Bekure, et al. 1991; Peacock 1984; Wilson 1986, 1991). Therefore the Young Adult class is set from 1.5 to 3 years of age.

The Older Adult age class ranges from 3 to 6 years of age. The cutoff is 6 years because ewes and does are typically disposed of once their reproductive capacity declines, as parturition intervals lengthen with age, so older ewes are culled to “make room for” younger ewes in their reproductive prime (Wilson, et al. 1981). As with cattle, the tooth wear stage end-members were chosen based upon their frequency in each age category. Data on tooth eruption in caprines is presented in Table 6.2. The age classes and corresponding tooth wear stage for each tooth is outlined in Table 9.3. While caprines in the age-tooth wear studies referenced here, particularly for Deniz and Payne’s study (1982), live far longer than Kenyan caprines, the tooth wear stages of individuals over 6 years of age do not do not show much variation.

Table 9.3: Wear stages and age classes for the lower dp_4 and molars of caprines. * See Table 6.2.

	Grant (1982) Wear Stage			
Age Class	**dp4**	**M1**	**M2**	**M3**
Infant (0-6 mo.)	a-f	C, V, E, ½, U, a-d	C, V, E, 1/2	n/a*
Young Juvenile (6-12 mo.)	g	e	U, a-b	C, V
Older Juvenile (12-18 mo.)	h-n	f-g	c-e	E, ½, U
Young Adult (1.5-3 years)		h	f-g	a-c
Mature Adult (3 to 6 years)		j-k	h-j	d-g
Aged (>6 years)		l-o	k-o	h-m

Recording Enamel Hypoplasias

All analyses were carried out at the Archaeology Section of the National Museums of Kenya (NMK). The methods used here were developed by Dobney and Ervynck (1998) and Bethan Upex and colleagues (Upex 2009; Upex, et al. 2012). My hypoplasia study was restricted to three sites: Crescent Island Main, Narosura and Prolonged Drift. This method allows the comparison between two clearly pastoralist sites (Crescent Island Main and Narosura) and an unusual one with a significant component of hunted wild fauna, Prolonged Drift.

To avoid scoring teeth from the same individual multiple times, only complete first, second, and third lower molars were scored. Combined, these three teeth provide a continuous record of tooth development through the first 24 – 30 months of an animal’s life. Because the permanent premolars develop during the second year of life (Silver 1969; Weinreb and Sharav 1964), including them would be redundant.

Deciduous teeth were excluded from analysis for two reasons. First, the teeth form *in utero*, while the developing fetus is buffered from stresses by the mother, and thus may be shielded from developing hypoplasias (Kierdorf, et al. 1993). Second, these teeth develop very quickly, and thus do not allow sufficient time for indicators of stress to form on the teeth. Finally, because most data on tooth eruption and wear are for mandibular teeth (Grant 1982; Payne 1973), this protocol narrows the number of specimens analyzed, and also provides the possibility for correlating stress events with age (Balasse, et al. 2010a; Upex 2009).

Only fully mineralized teeth are included in the hypoplasia study. Following Upex's methods (Upex 2009; Upex, et al. 2012), teeth in the earliest stages of wear, or that were clearly not fully mineralized were not used, as hypoplasias are difficult to identify in partially mineralized enamel. Extremely worn teeth were also not used because dental wear may remove hypoplasias in the occlusal half of the tooth. Both left and right dentitions were used in this study, as the dental assemblages analyzed are comprised of primarily isolated teeth.

Upex and colleagues (Upex 2009; Upex, et al. 2012) note that hypoplasias in caprines are more frequent on the buccal aspect of the tooth, and are also more visible. Niven, et al. (2004) report similar patterns in bison mandibular molars, and the author has observed similar patterns are found in African domesticates. Therefore buccal surfaces of lower molars were examined for hypoplasias.

Because cementum may obscure hypoplasias (Kierdorf, et al. 2006; Upex 2009), all cementum was removed from the central portion of each buccal lobe of the analyzed teeth using a dental pick. Hypoplasias were assessed by shining a focused light source at a low angle to the tooth. Each lobe was examined for hypoplasias, and the position of each defect was measured relative to the root enamel junction with digital calipers. Hypoplasias were also defined in terms of severity and type (Witzel, et al. 2006). Hypoplasias can grouped into several categories: line, pit or depression (Dobney and Ervynck 1998), which can be linked to the duration and intensity of the stressor (Witzel, et al. 2006). The severity of linear hypoplasias was also scored (Table 9.4, Figure 9.1).

Table 9.4: Classification of severity of linear defects (Upex 2009).

Severity score	**Classification of linear defects**
1	Defect is only visible using a strong directional light source.
2	Defect is just visible without the light source.
3	Defect is clearly visible without light source.
4	Defect is clearly visible, enamel is clearly missing, disrupted or very poorly mineralized (4a) and/or defect covers a large area (4b).

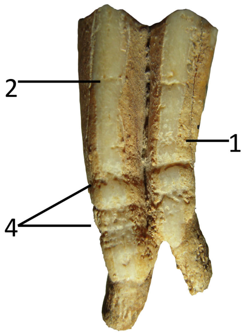


Figure 9.1: Caprine tooth with scores 1, 2, and 4 hypoplasias indicated.

Selection of archaeological livestock specimens for stable isotope analysis

Dental remains of domestic ungulates were selected from seven archaeological faunal assemblages housed in the Archaeology section at the National Museums of Kenya (Tables 9.1, 9.5).

Table 9.5: Archaeological dental specimens selected for sequential sampling for stable isotope analysis.

Site	**Cattle**	**Caprines**
GtJj2 - Crescent Island Main	4	4
GtJj3- Crescent Island Causeway	4	4
GtJi3- Ndabibi	3	4
GrJi 1- Prolonged Drift	6	2
GvJm44- Vaave Makongo	4	0
GvJm52 – Lukenya Hill	4	4
GwJh2- Narosura	4	4

The original faunal analysts had previously identified the faunal remains, and I verified these identifications, with specific identifications of caprines to *Ovis aries* or *Capra hircus* made when possible, using more recently developed criteria (Balasse and Ambrose 2005a; Halstead and Collins 2002). Following previous isotopic studies of herd mobility, a sample size of four cattle and four caprines was selected for each site (Balasse and Ambrose 2005a; Balasse et al. 2002). Because most of the teeth are isolated, care was taken to minimize the chance of sampling teeth from the same individual. When possible, the same tooth was sampled within each site, such as the left M_3, or right M^3. In cases where this was not possible because the assemblage was too small, teeth with significantly different wear stages were selected (e.g. right lower

M_3 from a juvenile, and a left lower M_3 from an adult). In some cases the numbers of taxa sampled differed due to a paucity of sufficient specimens. For example, very few caprine remains are present at GrJi1 (Prolonged Drift), and only two were appropriate for sampling. Similarly, the assemblage from GtJi3 (Ndabibi) is quite small and only three cattle teeth were deemed appropriate for sampling. Specimens amenable to sampling and analysis included those that were relatively complete, that did not have an adhesive or consolidant applied to the sampling area, and that were not too fragile to withstand the sampling procedure. After careful searching at the NMK, no caprine remains were located for GvJm44, so they were also not sampled.

Sampling Procedure for Archaeological Livestock Enamel

Sequential sampling was carried out in the Palynology Laboratory at the National Museums of Kenya from late September to early November in 2012. All specimens were photographed before sampling, and hypoplasias and eruption and wear stages were recorded. All specimens were dry brushed clean with a toothbrush to remove dirt or dust. Only one lobe from each tooth was selected for sampling. The lobe chosen was typically the longest and most complete. When possible, the same lobe was sampled for all teeth in a site to allow for any future examination of birth seasonality. Then cementum and any dirt that could not be removed by dry brushing was removed from the selected lobe using a hand-held Dremel® drill with a tungsten carbide drill-bit. Enamel was sampled on the buccal aspect for lower molars and on the lingual aspect for upper molars (Figure 9.2). Once the cementum was removed, any newly discovered hypoplasias were recorded. Teeth were then again brushed dry and photographed.

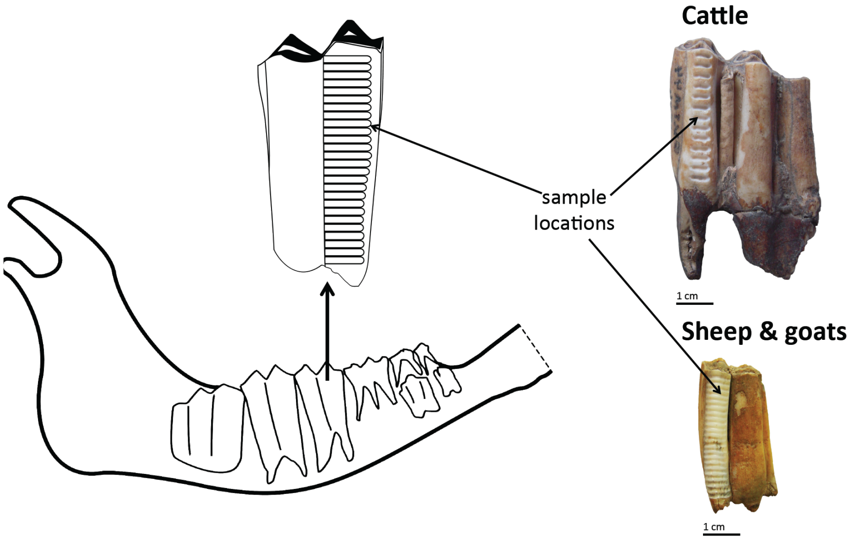


Figure 9.2: Illustration showing sample locations. Samples are approximately 1mm in width.

Enamel was removed using a 1.0 mm cylindrical diamond drill bit on a hand-held Dremel® drill, except for a few cattle teeth that were sampled early on. Dr. Thure Cerling graciously allowed me to use his drill before I acquired my own, and the smallest diamond drill bit was slightly conical, with a tip measuring 1.2mm. Only cattle specimens were sampled using this drill bit, as the spacing between samples is much wider in cattle than in caprines, and resolution would not be compromised. Teeth were wrapped in rubber bands to cushion them from the drilling surface and to prevent any cracking that might occur during drilling. Each tooth was sampled sequentially, beginning from the most occlusal part of the tooth and moving down toward the root. Sample weights averaged about 7-8 mg, though there was some variation due to the presence of hypoplasias and an electronic balance with faulty readings. Enamel powder was collected on a piece of aluminum foil and then transferred to a labeled 1.5 ml microcentrifuge tube. To minimize cross contamination, after each sample was removed and weighed, the tooth was brushed clean and the drill bit was removed and rinsed in distilled water, sonicated in distilled water, rinsed again, and then dried with a Kimwipe. The drill and drilling surface were also wiped clean with distilled water and a Kimwipe between each sample. An average of 18 samples were obtained from each cattle and caprine molar, with longer, unworn teeth yielding up to 25 samples, while short, heavily worn teeth yielded a minimum of 7 samples. In total 890 samples were collected. Samples were stored and shipped in 1.5 ml microcentrifuge tubes.

Enamel samples were processed and the CO_3 component of bioapatite was analyzed for carbon and oxygen stable isotope ratios in the at the Muséum National d'Histoire Naturelle in Paris. Immediately upon arrival in Paris, enamel samples were reweighed on a more accurate electronic balance. Diagenesis can affect isotopic values in tooth enamel, and often pretreatment to remove diagenetic $CaCO_3$ of tooth enamel is employed. Because carbonate minerals are more soluble than enamel bioapatite, they may be removed by leaching with dilute acid (Koch, et al. 1997). Each sample was processed with 0.1M acetic acid for four hours (0.1 ml per 1.0 mg) to remove exogenous carbonates and then rinsed four times with distilled water. The sample preparation procedure follows the methods outlined in Balasse, et al. (2002) but does not include processing in NaOCl. Because enamel contains so little organic material and the teeth are all at least 1,000 years old, this step, intended to remove organic material, is unnecessary (M. Balasse, pers. comm.).

Following processing, samples were freeze-dried to remove all moisture. Bioapatite samples weighing approximately 600 μg were reacted with 100% phosphoric acid at 70 ˚C for 240 seconds in individual vessels in an automated cryogenic distillation system (Kiel IV device), interfaced with a Delta-VAdvantage isotope ratio mass spectrometer. Reaction with phosphoric acid releases CO_2 gas, the carbon and oxygen components of which are then analyzed in the mass spectrometer. Over the span of analysis, 233 of runs of the laboratory internal carbonate standard, Marbre LM, yielded a mean $\delta^{13}C$ value of $2.06 \pm 0.01‰$ (1σ) (theoretical value normalized to NBS 19 = 2.13‰) and a mean $\delta^{18}O$ value of $-1.67 \pm 0.02‰$ (1σ) (theoretical value normalized to NBS 19 = −1.83‰). The analytical precision within each run, calculated from 4 to 8 measurements of the Marbre LM standard, varied from 0.01 to 0.03‰ for $\delta^{13}C$ and from 0.02 to 0.07‰ for $\delta^{18}O$.

Dental specimens of modern livestock with known life histories were sampled to provide a comparison to the archaeological materials. These specimens were collected in South Narok in 2013. The sampling procedure is the same as above, and was carried out in the Zooarchaeology Lab at the University of California, Santa Cruz. Samples were processed according to protocols outlined by the Stable Isotope

Laboratory at the University of California, Santa Cruz. This involved a treatment with 2–3% NaOCl (0.1 ml per 1.0 mg) to remove organic contaminants and then rinsing four times with water from a Milli-Q® system. Samples were then treated with 0.1M acetic acid for four hours (0.1 ml per 1.0 mg) to remove exogenous carbonates and rinsed four times with Milli-Q water. The sample preparation procedure follows the methods outlined in Balasse, et al. (2002). As with the archaeological specimens, samples were freeze-dried to remove moisture, and weighed to approximately 600 µg. Samples were reacted at 75°C in orthophosphoric acid in individual vessels in a Kiel IV carbonate device interfaced to ThermoScientific MAT-253 dual-inlet isotope ratio mass spectrometer.

Samples for $^{87}Sr:^{86}Sr$ analysis

Due to expense of running strontium isotope analyses, only a few sample locations along each tooth were selected for analysis. Sample locations were chosen based on visual inspection of individual sequential $\delta^{13}C$ and $\delta^{18}O$ values. If the isotopic values of either element clearly varied seasonally in a sinusoidal pattern, then high and low points were chosen for the strontium analysis. In cases where $\delta^{13}C$ and $\delta^{18}O$ values did not clearly vary seasonally, they were graphed on a bivariate plot, and samples with particularly high and low $\delta^{13}C$ and $\delta^{18}O$ values were selected for the strontium analysis, while ensuring these samples were evenly spaced along the axis of the tooth (Figure 9.3). My approach would record seasonal movements to different regions but also longer-term residential mobility during the growth period of the tooth

(Balasse, et al. 2002). However, there may be a significant residence time for heavy isotopes, including strontium, in the body (Montgomery, et al. 2010). Therefore, even in specimens where distinct seasons were identified based on changes in δ^{18}O, and occasionally in δ^{13}C values, along the tooth, it is not clear that changes in strontium isotope ratios will track changes in the other isotopic systems. In teeth that did not exhibit any variation in δ^{13}C or δ^{18}O values along the growth axis, samples were analyzed from three or four evenly spaced locations on the tooth.

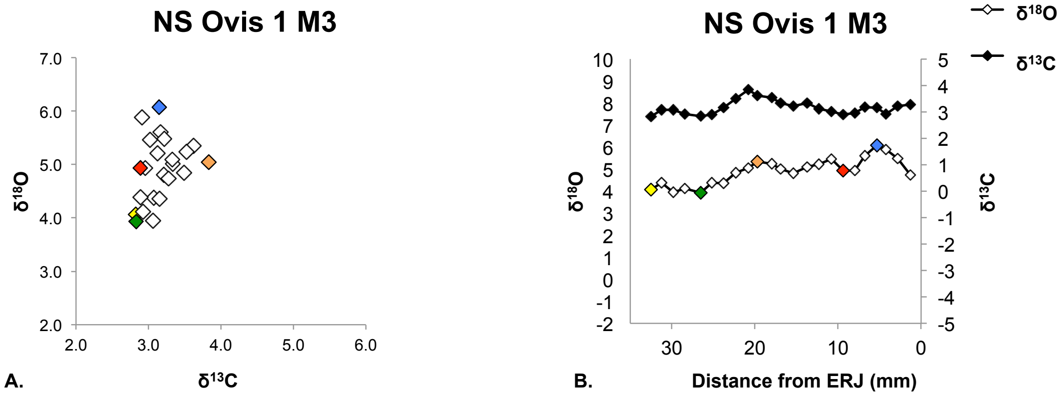


Figure 9.3: Method for selecting samples for strontium isotope analysis. Example shown is a sheep (*Ovis aries*) from the site of Narosura (indicated as NS here). A. Bivariate plot of δ^{13}C and δ^{18}O values with colored markers indicating particularly high and low values. B. Isotopic profile of same individual showing variation in δ^{13}C and δ^{18}O values (y-axes) plotted against distance from the enamel-root-junction (ERJ). Colored markers indicate strontium sample locations.

Samples for strontium analysis had previously undergone processing in acetic acid and freeze-drying as described above. The samples slated for analysis were shipped to the University of Illinois Urbana-Champaign for analysis. For the strontium analysis, the samples are dissolved in 0.5 ml of 3N nitric acid. To remove other cations from the samples, exchange columns were loaded with Eichnomn strontium spec resin, washed with 4 ml of 0.05N nitric acid (HNO_3) and pre-conditioned with 2 ml of 3N HNO_3. The uptake of strontium by the resin increases with increasing nitric acid concentration. Each 0.5 ml sample is then loaded onto a column.

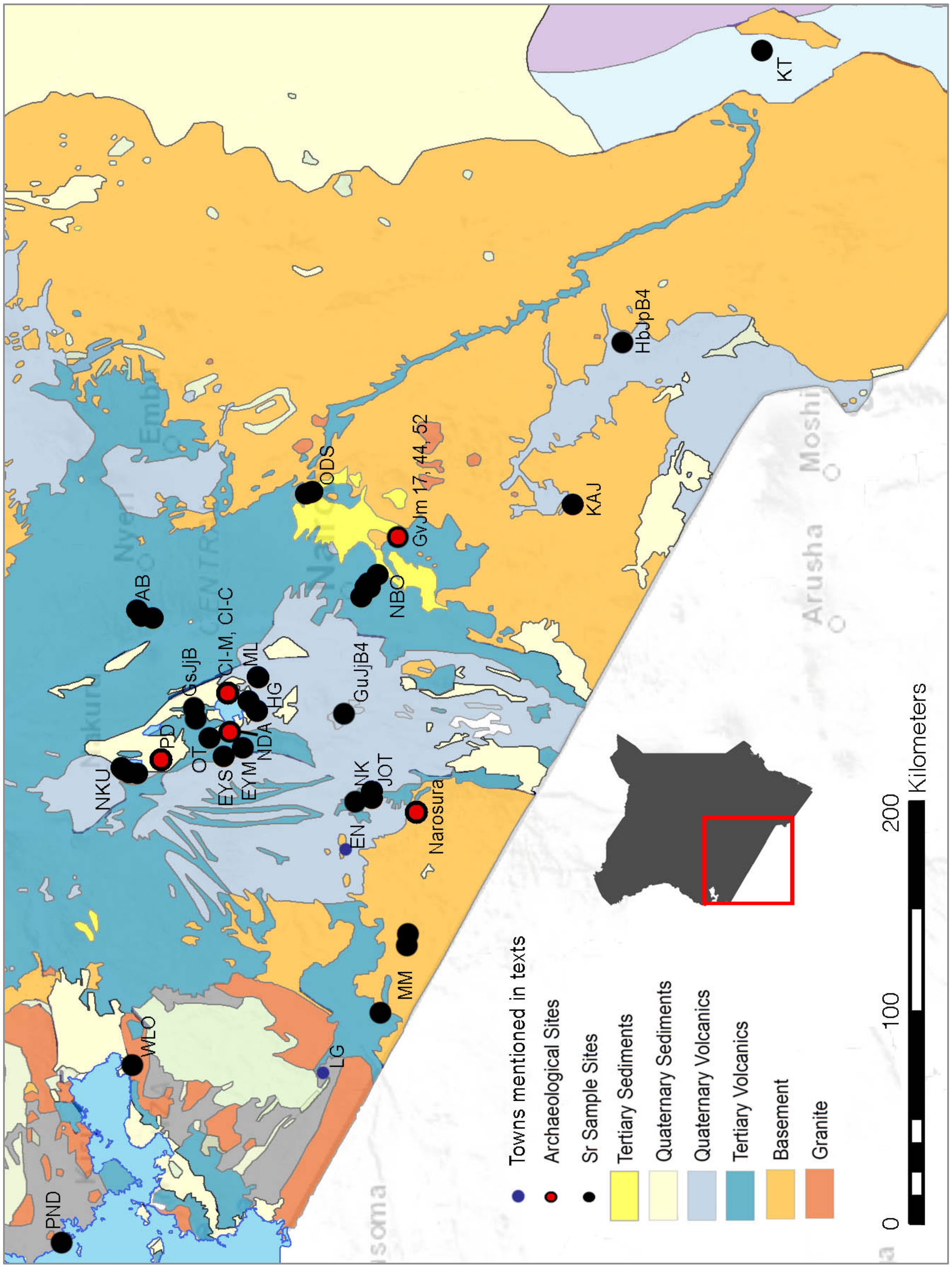
Columns with samples were then washed with 1.2 ml of 3N HNO_3 (4 washes of 0.3 ml each) to remove other cations. At this point the waste beaker under the column was removed and a 4 ml autosampler vial (used for analysis on the mass spectrometer) is put in its place. Strontium was eluted with 1 ml of 0.05N HNO_3 and 3 ml of distilled water. The resulting 4 ml samples were then diluted and run on the mass spectrometer. Exact dilutions were determined during machine set up based upon its sensitivity that day. Column 'blanks' and sample replicates were included for monitoring possible contamination and reproducibility in column procedure. Blank samples consisted of 0.5 ml of 3N HNO_3.

Strontium isotope measurements were performed at the University of Illinois on a Nu Plasma Multi-Collector-Inductively-Coupled-Plasma-Mass-Spectrometer (MC-ICP-MS, Nu Plasma HR; Nu Instruments, UK). In a multi-collector inductively coupled plasma mass spectrometer, an argon plasma is created, the sample solution converted to an aerosol by means of a nebulizer, and is introduced into the inductively coupled plasma torch. Over the span of analysis, 107 runs of the NBS 987 standard yielded a difference between $^{87}Sr/^{86}Sr$ ratios of >0.00002 (1σ).

Creating a Strontium Isoscape: Sample selection

In a given geological setting, rocks, ground water, etc. may all have different $^{87}Sr/^{86}Sr$ ratios, so it is best to measure local strontium signatures by analyzing the remains of archaeological specimens with small home ranges, as they would have, over a lifetime, averaged the values in the environment (Bentley, et al. 2004). While some published strontium isotope ratios were used to create an isoscape to track pastoral mobility (Koch, et al. 1995), in this study, archaeological and modern microfaunal remains were analyzed to obtain more values for the regions of interest. Various diagenetic processes can change isotopic values, and enamel mineralization is a slow and discontinuous process, leaving recently formed enamel particularly susceptible to diagenetic alteration (Balasse 2002; Passey and Cerling 2002; Zazzo et al. 2005). Sometimes washing in mildly acidic solutions can rid samples of diagenetic strontium, but strontium will increasingly permeate bone with time during burial, and may eventually be incorporated as the bioapatite crystalline structure changes, and even replace the biogenic strontium and calcium (Koch, et al. 1992; Nelson, et al. 1986; Sealy, et al. 1991; Tuross, et al. 1989). These impacts of diagenesis on bone and dentine bioapatite make these poor choices for stable isotope analysis (Koch, et al. 1997; Lee-Thorp and van der Merwe 1987). Therefore, only enamel can be sampled from archaeological microfauna. Rodent dental enamel could not be sampled without destroying the tooth, so only sites with abundant microfaunal dental remains could be sampled. These sites included Enkapune Ya Muto (GtJj12), Enkapune Ya Sauli (GsJi10), Ol Tepesi Rock Shelter (GsJi53), Pundo (GqJa4), Wadh Lang'o (GrJd9), Kathuva (HeJu5), and GvJm17 (Figure 9.4).

Figure 9.4: Geologic map of study area with archaeological sites and sample locations marked.


Towns mentioned in texts
Archaeological Sites
Sr Sample Sites
Tertiary Sediments
Quaternary Sediments
Quaternary Volcanics
Tertiary Volcanics
Basement
Granite
0
100
200
Kilometers
PND
WLO
LG
MM
NKU
PD
OT
EYS
EYM
NDA
HG
GsJjB
CI-M, CI-C
ML
AB
GuJjB4
EN
NK
JOT
Narosura
NBO
GvJm 17, 44, 52
ODS
KAJ
HbJpB4
KT
Nakuru
Nyeri
Embu
Nairobi
CENTRAL
Arusha
Moshi

To supplement this dataset, modern microfaunal skeletal samples were collected from a variety of sources to identify $^{87}Sr/^{86}Sr$ values for various geological substrates throughout the Central Rift Valley, Athi Plains. This was accomplished by collecting microfaunal remains from various national parks and reserves throughout South-Central Kenya in January and June of 2014, as well as sampling fauna collected by S. Ambrose (Figure 9.4, Table 9.6). Sampling modern fauna for strontium stable isotope analysis avoids the issue of diagenesis (Koch, et al. 1992; Nelson, et al. 1986; Sealy, et al. 1991; Tuross, et al. 1989); thus both dental and skeletal elements were selected.

Table 9.6: National Parks and Reserves from which microfauna were collected.

Location
Aberdares National Park
Hell's Gate National Park
Masai Mara National Reserve
Mount Longonot National Park
Ol Donyo Sabuk
Nakuru National Park
Nairobi National Park
Maasai Mara National Park

Sampling and analysis of microfauna

Microfaunal remains were brushed clean and then sonicated in distilled water to remove any debris. Rodent incisors were the most common archaeological element sampled. Enamel cannot be drilled off of a rodent incisor as it is too thin, tends to break, and much of the enamel powder is lost during drilling, even at very low speeds. Rather, the dentine was carefully drilled out from under the thin enamel layer. The enamel was then crushed in a mortar and pestle and processed. Larger specimens were sampled using a drill, using the same protocol as was used for sampling livestock tooth enamel. Both bone and teeth were sampled from modern specimens. Tooth enamel was sampled following protocols for archaeological specimens, and in the case of sampling skeletal remains, a chunk of bone was removed and then crushed in an agate mortar and pestle until fully powdered.

Samples were processed using the methods described above (Balasse, et al. 2002). All specimens were then shipped to the University of Illinois for analysis on a Nu Plasma Multi-Collector-Inductively-Coupled-Plasma-Mass-Spectrometer (MC-ICP-MS, Nu Plasma HR; Nu Instruments, UK). For most samples run, a difference between $^{87}Sr/^{86}Sr$ ratios of >0.00002 (the 95% confidence interval of the NBS 987 standard). Due to some equipment issues, some samples had rather high barium concentrations, contributing to increased uncertainty of the precision of the value.

CHAPTER 10: LIVESTOCK HEALTH AND DEMOGRAPHICS, RESULTS AND INTERPRETATION

Some archaeological sites, such as Prolonged Drift, have assemblages containing substantial portions of both wild and domestic fauna, hinting at interactions between pastoralists and hunter-gatherers. Analysis of dental hypoplasias as well as age-at-death patterns of cattle and caprines at early pastoralist sites can inform on how livestock may have been managed before the appearance of agricultural groups, and lend further insight into how strategies may differ among sites. And, in the case of the mixed assemblage site of Prolonged Drift, such data may shed light onto the mechanism of the spread of pastoralism, whether the site was created by foragers transitioning to pastoralism, or inform on the interactions between herders and foragers.

Theoretical Framework

Age-specific slaughter patterns of domesticates may inform on the subsistence strategies of the site occupants, as the age at death patterns may differ at sites created by hunter-gatherers versus those by pastoralists or foragers transitioning to pastoralism (Prendergast and Mutundu 2010). Modern East African pastoralists in Kenya slaughter animals at specific times, creating mortality profiles that emphasize juveniles and prime-age adults (Mbae 1986; Mutundu 2005) (further described below). In contrast, foragers who obtain animals from nearby pastoralists through trade, for example, will slaughter animals for immediate consumption, generating varied mortality patterns. Foragers acquiring livestock from nearby herders will also create sites that lack remains of neonatal animals. Mutundu (2010) notes that while sites of established pastoralists will include significantly higher proportions of neonates and sub-adults, foragers transitioning to pastoralism will hold off on slaughtering livestock until old age. However, Prendergast and Mutundu (2010) caution that such patterns may arise through many processes, including density-mediated attrition, drought and disease, and therefore mortality data should not be considered on its own.

Animal health may also indicate economic circumstances at a site. Mutundu (2010) noted that caprines at Maasai Gorge Elmenteitan levels have much hypoplastic banding, a rare condition at other Elmenteitan sites (Gifford-Gonzalez 1985; Marshall 1990a). Gifford-Gonzalez posits that the Maasai Gorge Rockshelter occupants may have been poor pastoralists with few animals, killing only the very ill, or obtaining less fit culls from better-off neighbors. Recent work on hypoplasias suggests that higher elevation sites in Kenya have higher rates of hypoplasias, possibly due to different herding patterns (Upex 2009).

Results of hypoplasia study

In all three sites, sheep and goats show relatively higher frequencies of hypoplasias relative to cattle (Tables 10.1 and 10.2), with at least 70% of all caprine teeth exhibiting hypoplasias. The percentage of cattle teeth with hypoplasias at each site varies slightly. Cattle at Crescent Island Main display the highest frequency of hypoplasias among cattle among the sites, with 54% of teeth exhibiting the defect. This difference suggests divergent management practices for cattle and caprines at pastoral sites (see Intepretation, below). Narosura and Prolonged Drift showed lower rates, 43% and 42%, respectively (Table 10.1). Many teeth from each site that were excluded from the study also exhibited hypoplasias, but these specimens were broken, and it was not possible to ascertain exactly how many hypoplasias each tooth had.

Table 10.1: Cattle teeth with hypoplasias.

Site	**Tooth**	**No. Teeth with Hypoplasias**	**Total No. Teeth**	**% Teeth with Hypoplasias**
Crescent Island Main				
	LM1	3	12	25%
	LM2	12	18	67%
	LM3	12	20	60%
	Total	**27**	**50**	**54%**
Prolonged Drift				
	LM1	2	8	25%
	LM2	2	9	22%
	LM3	9	14	64%
	Total	**13**	**31**	**42%**
Narosura				
	LM1	6	14	43%
	LM2	6	13	46%
	LM3	4	10	40%
	Total	**16**	**37**	**43%**

Due to the low number of caprines at Prolonged Drift and Crescent Island Main, statistical comparisons of caprines between sites are not possible. The high frequency (100%) of hypoplasias on caprine specimens at Prolonged Drift, relative to 70% at Crescent Island Main and Narosura could simply be due to chance (Table 10.2).

Table 10.2: Caprine teeth with hypoplasias.

Site	Tooth	No. teeth with hypoplasias	Total No. Teeth	% Teeth with hypoplasias
Crescent Island Main				
	LM1	2	2	100%
	LM2	2	4	50%
	LM3	3	4	75%
	Total	**7**	**10**	**70%**
Prolonged Drift				
	LM1	3	3	100%
	LM2	1	1	100%
	LM3	3	3	100%
	Total	**7**	**7**	**100%**
Narosura				
	LM1	36	53	68%
	LM2	15	22	68%
	LM3	22	30	73%
	Total	**73**	**105**	**70%**

Figure 10.1 shows the distribution of hypoplasias along the crown of each lower molar of cattle specimens in the three analyzed sites. In general, hypoplasias are concentrated in the cervical half of the tooth. Lower first molars clearly exhibit the lowest crown heights due to occlusal wear, which may remove hypoplasia in the occlusal half of the tooth. Teeth from aged individuals were included in the study,

though it is possible that the lower frequency of hypoplasias in first molars, 25% at Prolonged Drift and Crescent Island Main, is due to occlusal wear, indicated by the drop off in hypoplasias recorded as the number of teeth at higher crown measurements decreases (Figure 10.1). However, Narosura shows similar rates of hypoplasias in all teeth. In any case, dental wear does not appear to be a “threat” to recording hypoplasias in the lower second and third molars. Third molars from cattle from all three sites show a more even distribution of hypoplasias along the cervical half of the crown, compared to the lower second molar, where hypoplasias are clustered near the cervical end of the tooth, except, again in the Narosura sample, which displays a continuous distribution of hypoplasias along the second molar, as well. Cattle third molars at Prolonged Drift also exhibit substantially higher rates of hypoplasias relative to the first and second molars, a pattern not evident at the other two sites.

The number of available caprine teeth for study at Crescent Island Main and Prolonged Drift was quite low. Only one lower molar was suitable for analysis from Prolonged Drift, so upper molars are discussed here.

Upex (2009) summarizes analytic results from caprines from Narosura, as well as Ngamuriak, Lemek North East, and Enkapune Ya Muto, which were part of her study. Results from Narosura will be presented in this section, and implications of Upex’s findings at other Neolithic sites are discussed later in this chapter. Due to the low sample size for two of the sites, sheep and goat specimens are not considered separately. The distribution of hypoplasias in caprines at Crescent Island Main, Prolonged Drift, and Narosura (data from Upex 2009) are shown in Figure 10.2. Only first molars at about ½ the full crown height are present for Prolonged Drift an Crescent Island Main, potentially erasing hypoplasias located on the occlusal half, and hypoplasias on caprine first molars from Narosura do seem to be concentrated in the cervical 16 mm of the tooth and numbers of hypoplasias drop remarkably at crown heights greater than 20 mm. Hypoplasias on caprine second molars from Prolonged Drift are concentrated at the occlusal half of the (represented by just one specimen), while hypoplasias on the same tooth from Crescent Island Main are concentrated at the cervical third of the tooth. At Narosura hypoplasias are found along nearly the full height of the crown, though higher frequencies are located at the cervical third of the tooth (61% of hypoplasias are found within the first 16 mm of tooth crowns). Hypoplasias on third molars at Prolonged Drift and Crescent Island are clustered in the cervical third of the tooth. Narosura caprines show a similar pattern (67% of hypoplasias occur within the cervical 16 mm of the crown), but hypoplasias are also found along nearly the entire height of the tooth.

Figure 10.1: Plot of hypoplasias along tooth crown for cattle. X-axis indicates height of crown. For columns, the Y-axis indicates number of hypoplasias at a particular crown height. For diamond symbols, Y-axis indicates number of teeth with exhibiting a crown height of the value indicated on the x-axis.

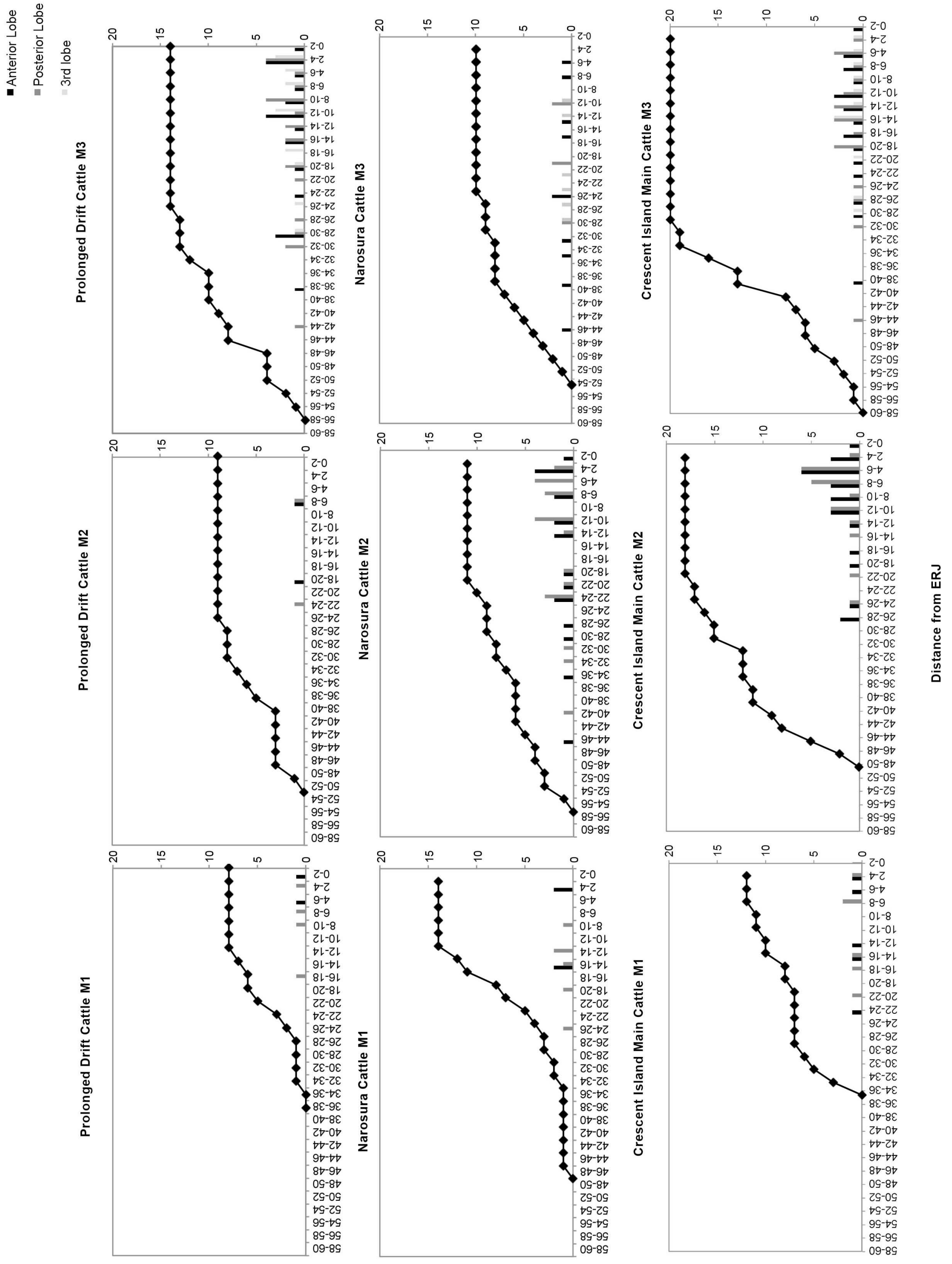
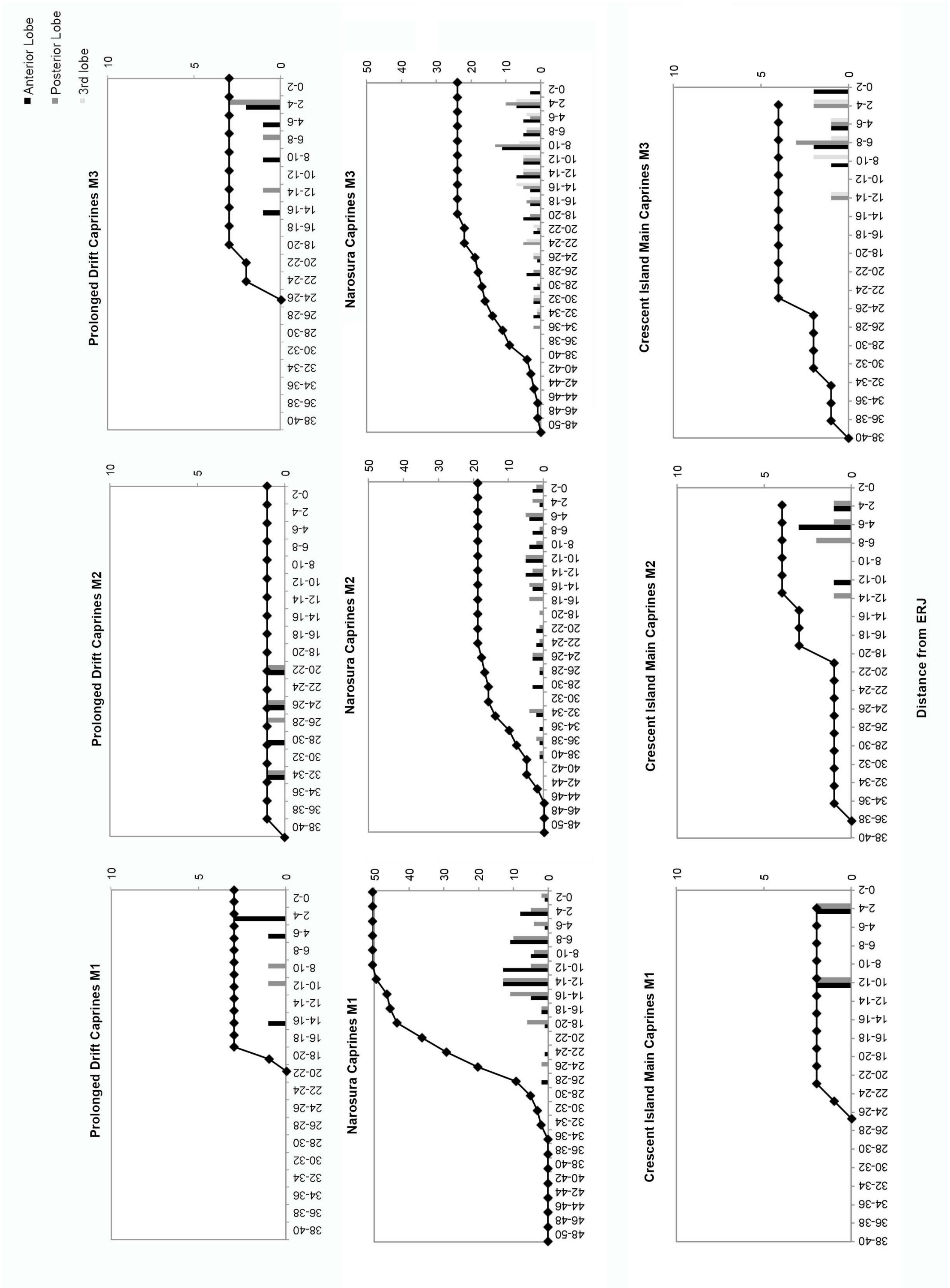

■ Anterior Lobe
■ Posterior Lobe
■ 3rd lobe
Prolonged Drift Cattle M1
Prolonged Drift Cattle M2
Prolonged Drift Cattle M3
Narosura Cattle M1
Narosura Cattle M2
Narosura Cattle M3
Crescent Island Main Cattle M1
Crescent Island Main Cattle M2
Crescent Island Main Cattle M3
0
5
10
15
20
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-22
22-24
24-26
26-28
28-30
30-32
32-34
34-36
36-38
38-40
40-42
42-44
44-46
46-48
48-50
50-52
52-54
54-56
56-58
58-60
Distance from ERJ

Figure 10.2: Plot of hypoplasias along tooth crown for caprines. X-axis indicates height of crown. For columns, Y-axis indicates number of hypoplasias at a particular crown height. For diamond symbols, Y-axis indicates number of teeth with exhibiting a crown height of the value indicated on the x-axis.


Prolonged Drift Caprines M1
Prolonged Drift Caprines M2
Prolonged Drift Caprines M3
Narosura Caprines M1
Narosura Caprines M2
Narosura Caprines M3
Crescent Island Main Caprines M1
Crescent Island Main Caprines M2
Crescent Island Main Caprines M3
Anterior Lobe
Posterior Lobe
3rd lobe
Distance from ERJ
0
5
10
20
30
40
50
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-22
22-24
24-26
26-28
28-30
30-32
32-34
34-36
36-38
38-40
40-42
42-44
44-46
46-48
48-50

The severity of linear hypoplasias differs among cattle from all three sites. Severe hypoplasia scores (3 and 4) are less common than moderate scores (1 and 2) in the pastoralist sites, with severity scores 3 and 4 making up less than 20% of the total linear hypoplasias present in each sample (Figure 10.3, Table 10.3). The cattle from Prolonged Drift show a more even distribution of hypoplasias, with scores 1, 2, and 3 comprising 28.6% of hypoplasias, each. There is a drop in the rates of the most severe hypoplasias (score 4), but still 14.3% of hypoplasias were extremely severe (Table 10.3).

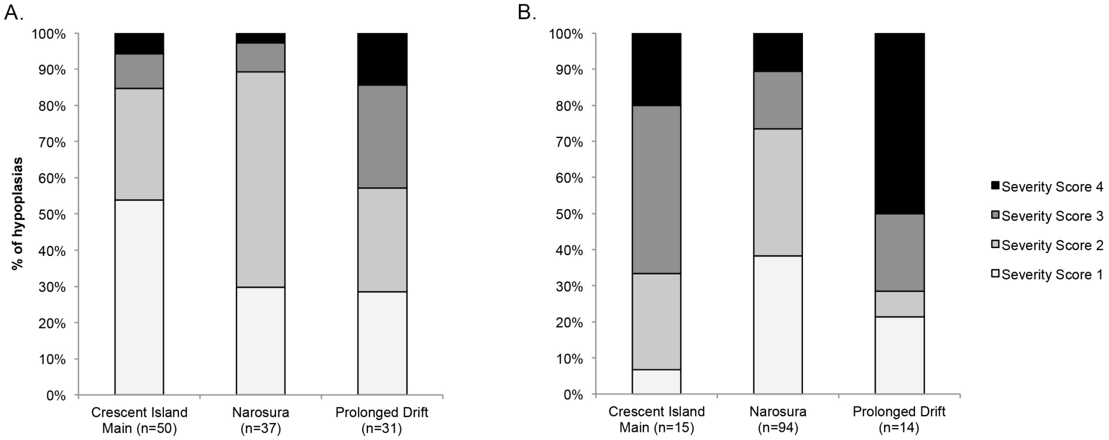


Figure 10.3: Frequency of linear hypoplasias by Severity Score in Cattle (A) and Caprines (B).

The higher frequency of more severe hypoplasias at Prolonged Drift relative to Crescent Island Main and Narosura is striking, particularly considering that overall the total frequency of teeth with hypoplasias is lower than at Crescent Island Main and equal to that of Narosura (Table 10.1). The severity of hypoplasias on cattle teeth from Crescent Island Main and Narosura are not significantly different (χ^2=7.544, p=0.056), but Prolonged Drift does have significantly more severe hypoplasias than Crescent Island Main (χ^2=8.145, p=0.043) and Narosura (χ^2=10.03, p=0.018). The higher number of severe hypoplasias at Prolonged Drift may be due to a skewed dataset; Prolonged Drift had the smallest sample size, with only 31 teeth suitable for analysis. It is also worth noting that all but one of the score 3 and 4 hypoplasias at Prolonged Drift are located on third molars, and distributed across individuals, rather than one or two teeth from particularly unhealthy individuals. This pattern suggests a decrease in health later in life in the Prolonged Drift cattle.

Table 10.3: Summary of hypoplasias by severity and tooth type for cattle at Crescent Island Main, Prolonged Drift, and Narosura.

	Severity	**M1**	**M2**	**M3**	**Total**	**Percent**
Crescent Island Main	1	2	14	12	28	54%
	2	3	7	6	16	31%
	3	1	1	3	5	9%
	4		2	1	3	6%
	Total	**6**	**24**	**22**	**52**	**100%**
Prolonged Drift	1	1	1	6	8	29%
	2	2	1	5	8	29%
	3	1		7	8	29%
	4			4	4	14%
	Total	**4**	**2**	**22**	**28**	**100%**
Narosura	1	2	7	2	11	29%
	2	2	12	8	22	60%
	3		2	1	3	8%
	4		1		1	3%
	Total	**4**	**22**	**11**	**37**	**100%**

Caprines had a grater number of severe hypoplasia scores than did cattle (Figure 10.3, Table 10.4). Similar to the cattle at Prolonged Drift, caprines at Prolonged Drift also had higher frequencies of severe linear hypoplasias compared to sheep and goats from the other two sites, with 50% of linear hypoplasias occurring as severity score 4. However, it should be noted that these occur as sets of multiple hypoplasias located on two teeth, from two different individuals, an M2 and one M3. Narosura has the lowest percentage of very severe linear hypoplasias, with 11% and 16% of hypoplasias classed at severity score 4 and 3, respectively (see Upex 2008).

Table 10.4: Summary of hypoplasias by severity and tooth type for caprines at Crescent Island Main and Prolonged Drift. Data for Narosura are presented in Upex (2009).

	Severity	M1	M2	M3	Total	Percent
Crescent Island Main	1		1		1	6.7%
	2	2		2	4	26.7%
	3	1	2	4	7	46.7%
	4	1	2		3	20.0%
	Total	**4**	**5**	**6**	**15**	**100.0%**
Prolonged Drift	1	2		1	3	21.4%
	2			1	1	7.1%
	3	3			3	21.4%
	4		4	3	7	50.0%
	Total	**5**	**4**	**5**	**14**	**100.0%**

The severity rates for hypoplasias were compared using a Chi-Square test (Table 10.5). Overall, hypoplasias in caprines at Crescent Island Main are significantly more severe than those at Narosura (χ^2=11.08, p=0.01). Hypoplasias in caprines from Prolonged Drift are also significantly more severe than those at Narosura (χ^2=16.199, p=0.001), but not significantly more severe than at Crescent-Island Main (χ^2=5.973, p=0.1129), though only two cells here have expected count over 5, and thus the two assemblages are too small to compare statistically. Hypoplasias in caprines at Crescent Island Main and at Prolonged Drift are not significantly more severe than caprines at Enkapune Ya Muto (Upex 2009).

Compared to assemblages analyzed by Upex (2009), hypoplasias at Narosura are more severe than those at the Elmenteitan site of Ngamuriak (χ^2=10.966, p=0.0119) but not Lemek North-East (χ^2=6.145, p=0.1048). While the sample sizes for Crescent Island Main and Prolonged Drift are small, the data here do not align with results from a study of modern caprines, which demonstrated more severe hypoplasias in samples from the semi-arid Narok South district than from the mesic Central Rift Valley (Balasse, et al. 2010a).

Table 10.5: Chi-Square test results comparing severity of hypoplasias in caprines from sites in this study and those from Upex (2009). Site abbreviations: Crescent Island Main (CI-M), Prolonged Drift (PD), Narosura (NS), Ngamuriak (NGA), Lemek North East (LENE), Enkapune Ya Muto (EYM). *Chi-Square test suspect due to low sample size. **Note that even when compared to large assemblages, the results for Crescent Island Main and Prolonged Drift are suspect because 20% of expected values are under 5.

	CI-M	**PD**	**NS**	**NGA**	**LENE**	**EYM**
CI-M	–	$\chi^2=5.973$, $p=0.1129$*	$\chi^2=11.08$, $p=0.01$**	$\chi^2=31.822$, $p<0.001$ **	$\chi^2=19.656$, $p=0.0002$**	$\chi^2=2.452$, $p=0.4840$**
PD		–	$\chi^2=16.199$, $p=0.001$**	$\chi^2=33.245$, $p<0.001$**	$\chi^2=26.825$, $p<0.0001$**	$\chi^2=10.577$, $p=0.0142$**
NS			–	$\chi^2=10.966$, $p=0.0119$	$\chi^2=6.145$, $p=0.1048$	$\chi^2=28.216$, $p<0.0001$
NGA				–	$\chi^2=1.833$, $p=0.6078$	$\chi^2=99.488$, $p<0.0001$
LENE					–	$\chi^2=54.141$, $p<0.0001$
EYM					–	–

Results: Age at Death Profiles

Age at death patterns of cattle are presented in Figure 10.4 and those of caprines in Figure 10.5. Recall that these profiles encompass a wider sample of sites than did the hypoplasia analysis. They also include Crescent Island Causeway, Ndabibi, GvJm44 and GvJm52. For the cattle, specimens of all age groups are present at all sites, except for the site of Ndabibi, as its low MNI does not allow for comparison to the other sites. In all sites, infants make up less than 10% of the MNI. Crescent Island Main cattle show a curve with a peak at the Young Adult age class. A similar pattern occurs at Crescent Island Causeway, with a peak in mortality in the Young Adult range, but this curve is shifted to the right, with peaks in mortality in the Young Adult to Mature Adult stages. However, the Prolonged Drift bovine age-at-death pattern displays a spike at Older Juvenile and Young Adult stages, each comprising 30% of the assemblage.

The two Lukenya Hill sites, GvJm44 and GvJm52 show divergent mortality profiles. GvJm44, like Prolonged Drift, has a peak at the Older Juvenile age class. GvJm52 has a pattern unlike the other sites, with a peak in mortality at the Young Juvenile Age class and one at the Mature Adult age class. Cattle at geographically distinct Narosura show a comparatively broad profile, with minor peaks in the Young Juvenile and Aged classes, and no age class comprising more than 25% of the total MNI.

Caprines at all sites with MNIs greater than four show slaughter patterns focused on Older Juveniles, Adult and Aged individuals, though there is some variation between sites. Samples with very low MNIs are not discussed in detail here, but are presented in Figure 10.5. Caprines from Crescent Island Main and Crescent Island Causeway show similar spikes in mortality for Mature Adults, with roughly 40% of the MNI composed of that age class. However, Crescent Island Main does have relatively higher mortality in the Older Juvenile and Young Adult classes, while Crescent Island Causeway (MNI 8) has nearly 30% of the MNI falling into the Aged category. Prolonged Drift has a small number of caprines, only 7 individuals. Individuals are present at every age class except for infant, with two peaks (two individuals instead of one) in the Older Juvenile and Aged classes. Narosura, the only site with a respectable caprine sample, shows a pattern with large peaks in mortality at the Older Juvenile (12-18 months) and Mature Adult (3-6 year) stages. All other age stages are represented by under 10% of the MNI.

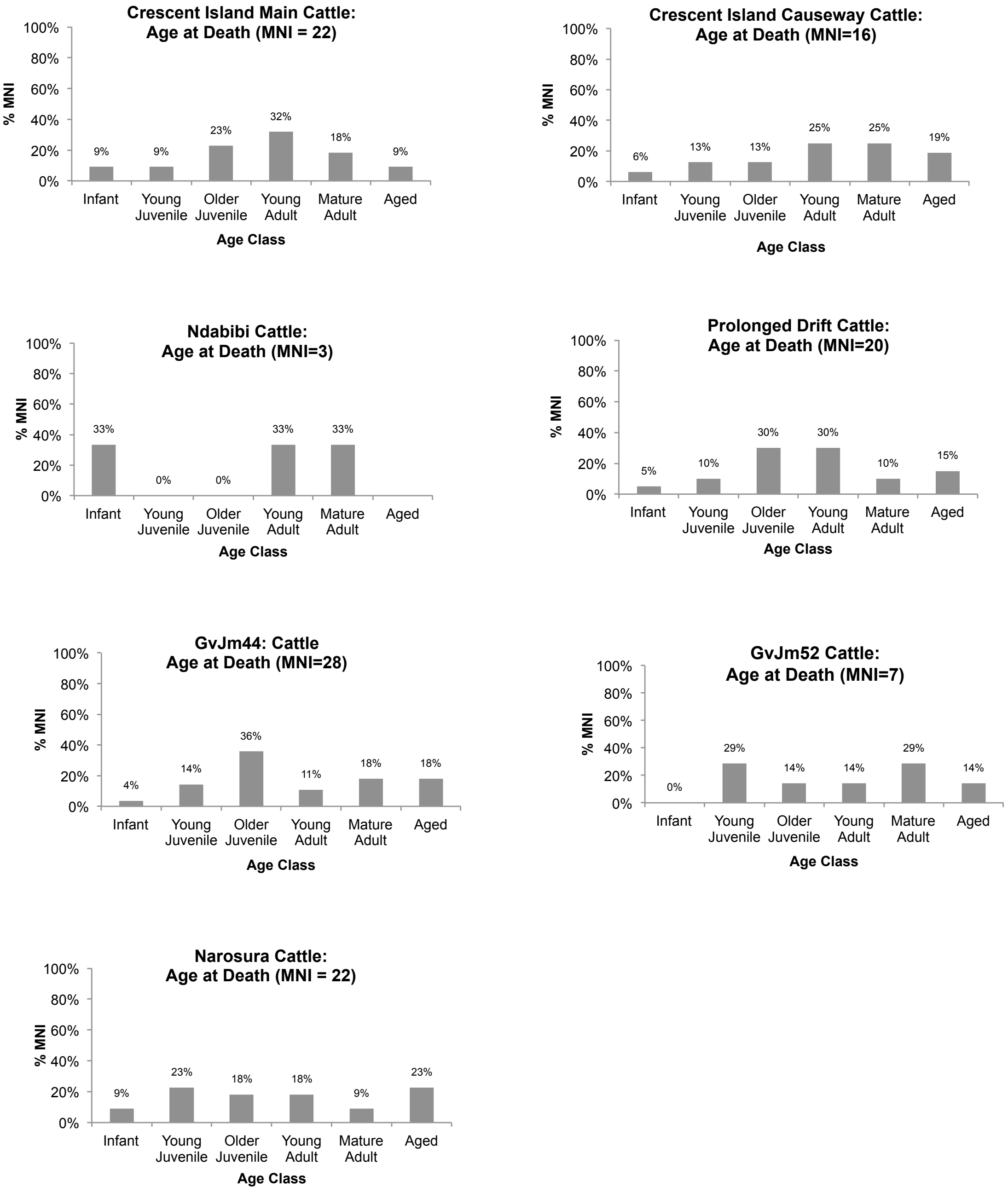


Figure 10.4: Cattle mortality profiles based on Minimum Number of Individuals (MNI).

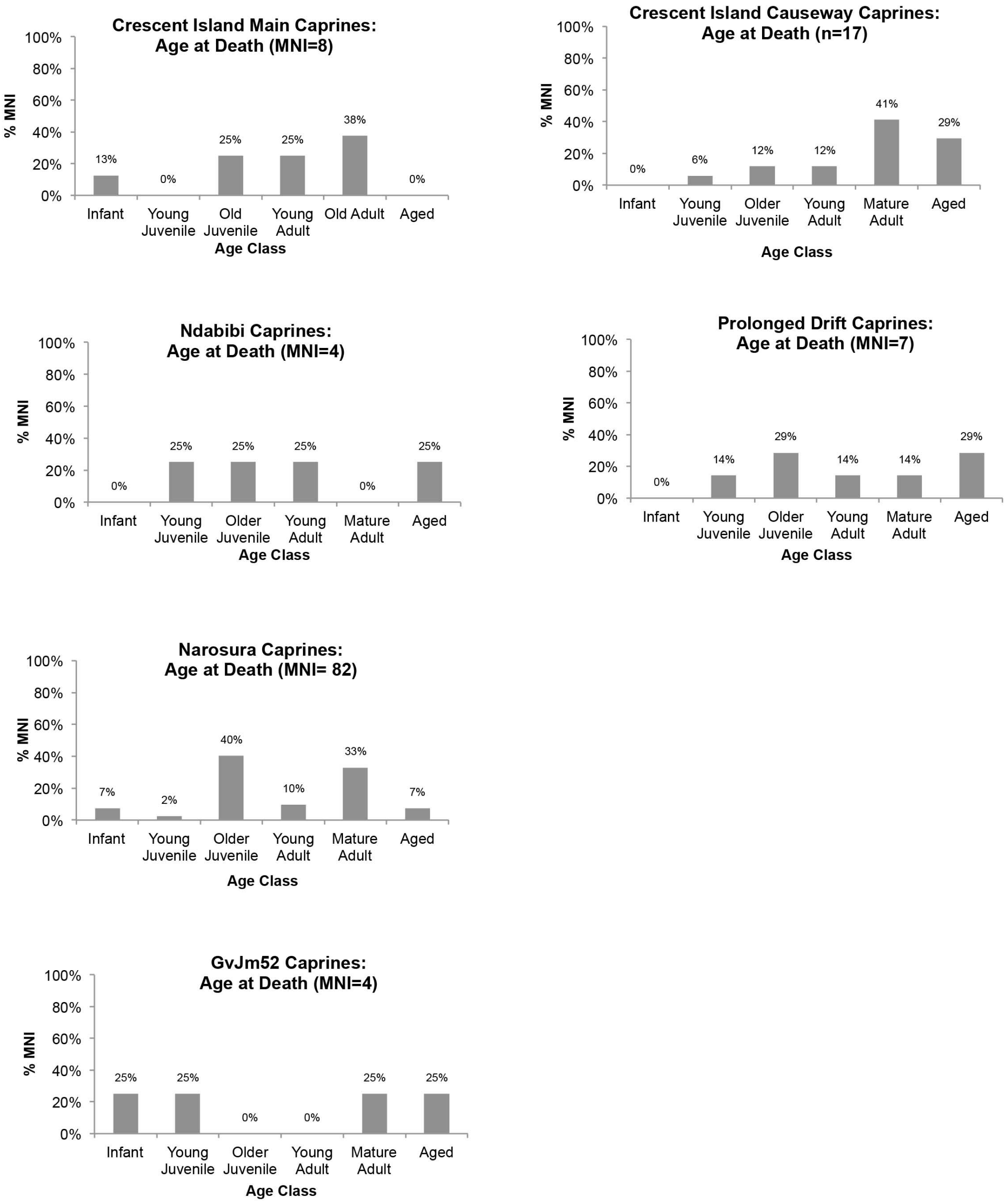


Figure 10.5: Caprine mortality profiles based on minimum number of individuals (MNI). Note that no caprines from GvJm44 were located at the National Museums of Kenya.

Kolmogorov-Smirnov tests are often used to assess differences in mortality profiles between sites, but these are not appropriate for data binned into broad age categories. Therefore Chi-Square tests were used to compare frequencies of age classes between archaeological sites, except for assemblages with MNIs under 10 (Table 10.6). However, due to the low number of individuals in some age groups at each site, the Chi-Square tests are suspect.

Table 10.6: Chi-Square test results comparing mortality profiles of cattle from sites with MNIs higher than 10. Site abbreviations: Crescent Island Main (CI-M), Crescent Island Causeway (CI-C), Ndabibi (NDA), Prolonged Drift (PD), Narosura (NS).

Cattle	CIM	CIC	PD	GvJm44	NS
CIM	–	χ^2= 3.175, p=0.6731 low counts	χ^2=1.701, p=0.8888, low counts	χ^2=6.274, p=0.280, low counts	χ^2=4.998, p=0.416, low count
CIC	–	–	χ^2=2.655, p=0.7530, low counts	χ^2=3.761, p=0.584, low counts	χ^2=2.569, p=0.766, low count
PD	–	–	–	χ^2=2.830, p=0.7261, low count	χ^2=3.208, p=0.668, low count
GvJm44	–	–	–	–	χ^2=3.779, p=0.582, low count
NS	–	–	–	–	–

Interpretation: Hypoplasias

Cattle

To my knowledge, there are no similar hypoplasia data for modern cattle in Kenya, nor any other archaeological populations, so it is not known if these frequencies are significantly different from other populations. Several other studies on faunal material from other pastoralist sites include data on enamel hypoplasias (Gifford-Gonzalez 1985; Marshall 1990a). However, they cannot be compared to the data presented because these were not gathered using the same methods as applied by Upex and myself, which reveals many more hypoplasias.

Cattle from Prolonged Drift did not exhibit significantly different frequencies of hypoplasias than cattle from definite pastoralist sites (Table 10.1). However, a more consistent distribution of hypoplasias across the first and second molars is evident at Narosura and Crescent Island Main. The relatively lower frequency of cattle first molars exhibiting hypoplasias at Crescent Island may be due to dental wear obliterating hypoplasias on the M1. In contrast, frequencies of hypoplasias for all molars of cattle at Narosura are same, suggesting similar stresses throughout life (Table 10.1). The marked increase in frequency of hypoplasias in the third molars of Prolonged Drift cattle suggests an increase in stress somewhat later in life compared to the cattle specimens at the other sites.

The distribution of hypoplasias along the tooth crown may be linked to stress events throughout the life of the animal. A clustering of hypoplasias near the cervical half of the M1 may be linked to birth, but this pattern is not particularly apparent in the archaeological cattle. Ungulate births are relatively quick, and therefore may not be stressful enough to affect enamel growth. Overall, the paucity of first molars with hypoplasias at Crescent Island Main and Prolonged Drift may be a consequence of a "buffering" effect by the mother. This tooth begins to form *in utero*, and continues to develop while the calf is nursing. First molars in cattle generally complete mineralization around 6 months of age, which is the lower end of what has been reported for age of weaning, which ranges from just under 6 months to a year or more, even in areas with a bimodal rainfall regime (Roderick, et al. 1998; Semenye 1987; Wilson 1986) (Figure 10.1). Therefore it is likely that hypoplasias resulting from weaning would not be present on the first molar, but rather in the occlusal half or middle of the length of the second molar. This is likely the case for the pattern of hypoplasias in cattle at Narosura. It is important to note that calves are generally weaned late because their presence is necessary to stimulate milk let-down (Balasse 2003a). The lack of clustering in the third molar therefore may be due to pregnancy, though cows generally conceive sometime after 36 months of age and give birth around 4 years old (ILCA 1977; Roderick, et al. 1998; Wilson 1986). First estrus for local cattle breeds in Central Africa occurs around 20 months of age, and therefore calving could take place as early as 29 months (Rakha, et al. 1970). So, hypoplasias localized in the cervical half of the M3 may result from pregnancy, though notwithstanding the mixed data presented by Pratt and Gwynne (1977), traditionally managed herds cows usually do not calve so early. A clustering of hypoplasias in the cervical half of the tooth may also be due in part to the slower rate of enamel growth of that part of the tooth. This results in more densely spaced perikymata, and more easily detectable hypoplasias (Newell, et al. 2006).

Caprines

Caprines from the sites show much higher frequencies of hypoplasias than cattle. Because the sample sizes for Crescent Island Main and Prolonged Drift are so small, sheep and goats are not considered separately here. Compared to other PN sites analyzed in a similar fashion, the rates of hypoplasias among caprines in the sites analyzed here are similarly high, with 67%, 79%, and 93% of caprine specimens exhibiting hypoplasias at Ngamuriak, Lemek North-East, and Enkapune Ya Muto, respectively (Upex 2009). The higher frequency of hypoplasias at the rockshelter site of Enkapune Ya Muto was attributed to different herding techniques than animals from open sites, as modern caprines from the Central Rift Valley usually exhibited lower frequencies of hypoplasias than those from Narok South District (Balasse, et al. 2010a). These frequencies are similar to those found in modern caprines in Kenya, with 79% of teeth in Narok South District and 72% of teeth in the Central Rift Valley showing the defect (Balasse, et al. 2010a).

Other reports of hypoplasias at pastoral sites with assemblages that have not been reanalyzed here or by Upex (2009) include Sambo Ngige and Masai Gorge. At Sambo Ngige, one caprine tooth row (out of 27 teeth) exhibited hypoplastic banding (Marshall 1990b). Four individuals (represented by 4 teeth) out of a minimum of 11 individual caprines from Elmenteitan levels from Masai Gorge (Gifford-Gonzalez 195). However, as with the cattle specimens, we cannot compare these reports to this study, due to differences in method of reporting and recording hypoplasias (likely recording only the most severe). For example, Gifford-Gonzalez (1985) found much lower frequencies of hypoplasias at Prolonged Drift and Narosura (0 and 2 teeth, respectively) than recorded in this study.

Even though the Prolonged Drift sample size is very small and consists of upper molars, the rate of hypoplasias is still high, despite observations that upper molars do not exhibit hypoplasias as frequently as do lower molars. However, it is not possible to identify whether this higher rate at Prolonged Drift is a meaningful difference relative to the other sites. The sample size is simply too small for a statistically defensible comparison.

Due to the very low sample sizes of Prolonged Drift and Crescent Island Main caprine dental remains, it is difficult to interpret the distribution of hypoplasias along tooth crowns. Only Narosura has a large enough sample for analysis. Some hypoplasia distributions may be related to life events, such as the clustering at the cervical half of the M1 crown in Narosura caprines, which may be related to weaning stress, which usually occurs at 6 months (when the M1 is completing mineralization) in modern herds. The higher frequency of hypoplasias at the cervical third of the M2 (61% of defects in the first 16 mm) in Narosura caprines may, in some cases, be due to gestation, but given the broad distribution of hypoplasias along the teeth it is likely that many of the enamel defects are due to environmental stresses (Figure 10.2) (see also Balasse, et al. 2010a). Interestingly, there is a clustering of hypoplasias on the occlusal third of the second molar, though this pattern is represented by just one individual at Prolonged Drift (Figure 10.2). The hypoplasias are very severe, and may correspond to stresses related to weaning. Third molars at Narosura show a similar pattern, with most hypoplasias (67%) occurring in the cervical third of the tooth. One hundred percent of hypoplasias occur within the cervical third of the third molar in Prolonged Drift and Crescent-Island Main caprines.

Overall, the data presented here indicate different management strategies for cattle and caprines, with caprines experiencing differentially more stress events leading to hypoplasias. The rate of hypoplasias in caprines at SPN sites is similar to that measured in the Elmenteitan sites that have been analyzed, but unfortunately it is not possible to accurately compare the frequency of hypoplasias in caprines from Prolonged Drift to clearly pastoralist sites due to small sample size. The cattle assemblages are much larger, and Prolonged Drift cattle, while exhibiting similar frequencies of teeth with hypoplasias, have more severe hypoplasias. Prolonged Drift cattle have relatively more hypoplasias on the third molar.

Bimodal Rainfall and Milk Production

Patterns in hypoplasias may also shed light on rainfall seasonality, with more hypoplasias forming during dry periods when food is scarce. Today, much of Kenya has a bimodal rainfall pattern, with long rains occurring in April through May and short rains in October through November (Kenya Meteorological Department; Nicholson 1996).

Today, Maasai do not actively control cattle breeding, but the timing of cows' conception rates, and therefore cattle births, are governed largely by the availability of fodder, and therefore these largely coincide with the two rainy seasons (de Leeuw, et al. 1984). Marshall (1990c) argues that only once the bimodal rainfall pattern emerged could specialized, milk-based pastoralism develop. Before the onset of bimodal rainfall, pastoralists would have had to supplement milk produced along with one rainy season with either wild animals or meat from their herds. In her analyses of caprines from Narosura as well as other PN sites in Kenya, Upex (2009) found that a slight bimodal pattern is observed in hypoplasias in caprines, particularly at Narosura, which may indirectly reflect a bimodal rainfall pattern. This also may be present in the pattern of hypoplasias along the crown of the second molar in cattle at Narosura and Crescent Island Main (Figure 10.1) but the other sites do not show similar patterns.

Interpretation: Age-at-death patterns

Cattle

As no statistically significant differences between profiles were found, we may visually assess them to identify herd management strategies. Among the sites in the study, cattle mortality profiles show a consistent representation of all age classes. The MNIs of cattle at Ndabibi and GvJm52 are too low to infer patterns that can be compared to other sites. Across all sites with MNIs greater than 7, infants comprise less than 10% of the total MNI. This is likely not attributable to preservational biases, given the sample's relatively high number of adult teeth that were still mineralizing, with delicate cervical halves intact. I hypothesize that Infants and Young Juveniles were likely kept to stimulate the milk-let down reflex of the mother (Balasse 2003a).

One notable feature of the Narosura age profile is the higher mortality of Young Juveniles (defined here as 6-24 months). This age class corresponds to the post-weaning slaughter, and may reflect a less productive environment in the Loita Plains relative to that of the Central Rift Valley and Athi-Kapiti Plains. In contrast, higher mortality in the Older Juvenile and Young Adult age classes, evident at Crescent Island Main, Crescent Island Causeway, Prolonged Drift, and GvJm44, are likely associated with slaughtering at maximum weight, which cattle usually achieve around 4 or 5 years of age (Wilson 1986). GvJm44 shows a slightly heightened mortality moving from the Young Adult to the Mature Adult age class, and Crescent Island Causeway maintains the same percentage as in the Young Adult class. Higher mortality at the Mature Adult stage (6-8 years) is perplexing, as cows are still in their reproductive prime at this point, but may represent culling animals who were sick or undergoing declines in fertility around 8 years of age. If so, this would suggest herding was occurring in more stressed conditions where older animals could not be kept alive past their reproductive prime. Aged animals are represented at every site, except for the small Ndabibi sample, and in some sites (Crescent Island Causeway, Narosura and GvJm44), aged cattle are represented by very advanced tooth wear stages, and likely represent female cattle kept well past their reproductive prime. In contrast, in some cases (Crescent Island Main, Crescent Island Causeway), Mature Adult mortality is higher than that in the Aged class. This pattern is indicative of a herding strategy in which males were slaughtered after being allowed to achieve maximum weight, and females were not kept very long beyond their reproductive prime, perhaps no older than 12 years (Jones and Sadler 2012a). This strategy would seem to favor a mixed production mode, emphasizing both meat and milk.

Table 10.7: Mortality profiles from other PN sites. Data from (Gifford, et al. 1980; Marshall 1990b). Abbreviations for age classes used by Gifford and Marshall: N: Neonate; J: Juvenile; OJ: Old Juvenile; YA: Young Adult; Ad: Adult; Ag: Aged; VO: Very Old.

Site		**MNI**	**N**	**J**	**OJ**	**YA**	**Ad**	**Ag**	**VO**
Prolonged Drift									
	Bos sp.	22	1	5	n/a	n/a	10	6	n/a
	Caprini	5	0	2	n/a	n/a	3	0	n/a
Sambo Ngige									
	Bos sp.	3	0	0	0	2	0	1	0
	Caprini	4	0	0	0	1	2	1	0
Lemek North-East	*Bos* sp.	4	0	0	0	1	3	0	0
	Caprini	17	4	2	1	1	9	0	0
Ngamuriak									
	Bos sp.	26	4	2	4	0	14	2	0
	Caprini	68	8	16	2	12	27	4	0

We may contrast the results and interpretations presented here with previously constructed mortality profiles from several sites. For Prolonged Drift, my age-at-death profiles are more detailed than the profiles presented previously, as I include more age classes (Gifford, et al. 1980). The original mortality profiles indicated an MNI of 1 neonate, 5 juvenile, 10 adult, and 6 aged cattle (Table 10.7). The profile presented here shows a low proportion of Infant cattle; though my definition of Infant includes a broader range of ages than as indicated in Gifford, et al. (1980) (see Table 10.8). The Juvenile stage outlined in Gifford et al. corresponds to some of the tooth wear stages in the Infant stage described here. Gifford et al.'s adult stage is broad, and encompasses my Young Juvenile to the Aged stage for some teeth, and their Aged stage corresponds to only the most extreme tooth wear stages within my Aged category. Because of these incongruities, it is clear that these two techniques would generate different age-at-death profiles. The profiles for cattle at Prolonged Drift presented here do, however, show a spike in the Older Juvenile and Young Adult stages corresponding to the spike in Adult in Gifford et al.'s study, and represent the mortality of large individuals, though the data presented here shows a smaller proportion of aged cattle at the site (Gifford, et al. 1980).

Table 10.8: Age class criteria for teeth from Prolonged Drift (Gifford, et al. 1980) and corresponding age categories used in this study.

Gifford et al. 1980 Age Categories			**Corresponding Age Classes (Janzen)**
Code	Age Class	Description	
I	Neonate	completely unworn deciduous teeth	dp4: Infant (C, V, E ,1.2, U only)
II	Juvenile	deciduous teeth in wear, M1 either unworn or with minimal wear	dp4: Infant M1: Infant
III	Adult	adult teeth in all but the most extreme stages of wear	M1: Young Juvenile M2-3: Older Juvenile to Aged
IV	Aged	adult teeth in the most extreme stages of wear with little or no enamel above the roots	M1-3: Aged

Gramly (1972), though not explicitly outlining the criteria for grouping domesticates at Narosura into age groups, counted a maximum of five young, four mature, and two old individual cattle at the site, and argued that cattle were slaughtered “either in their prime or later” (p. 89). The reassessed mortality patterns presented here show a much broader age distribution for cattle at Narosura, with no single age class comprising more than 25% of the total assemblage. In her critical analysis of the quadratic crown height method, Gifford-Gonzalez (1991) showed, using that method, that cattle at Narosura were culled at every age up to 10 years, with mortality spike at 2 years, based upon the deciduous p_4 and the M^1, and at 8 years, based upon measurements of the lower deciduous fourth premolar and upper third molar. However, the Grant tooth wear stage of many lower first molars are at least stage “M”, which does not appear in cattle under 13 years of age (Jones and Sadler 2012a). This finding agrees with Gifford-Gonzalez’s argument that the QCHM method underestimates age at death for older individuals.

Of the two sites at Lukenya Hill, mortality profiles only for cattle at GvJm44 were originally created using crown height measurements, and the quadratic crown height formula (Gifford-Gonzalez 1991). In that study 10 age classes were used, and each combination of the deciduous P_4 and an adult molar show quite different profiles, though the spike in mortality in animals age 2-3 in the deciduous p_4 and M_3 chart does match the spike in mortality in Older Juveniles (2-4 years) (Figure 10.4), and is likely associated with culling animals as they reach maximum weight. A major discrepancy between the two methods (QCHM and occlusal wear) is that for the lower third molar, crown height measurements again underestimate the age at death of the specimen, assigning a younger chronological age than methods using dental eruption and wear.

These patterns described here are quite similar to livestock culling patterns from several other sites, including the Elmenteitan sites of Ngamuriak and Sambo Ngige, and the SPN site of Lemek North-East (Table 10.7) described by Marshall (1990b). It should be noted that while Marshall (1990b) used dental eruption and wear to assign teeth into broad age classes, they differ somewhat with the Grant tooth wear stage method used here. Marshall's own system for cattle is outlined below with comparisons to the age classes presented here (Marshall 1990b). The Aged category described in this study encompasses both Marshall's Aged and Very Old categories (Table 10.9).

Table 10.9: Wear classes (Marshall 1990b) and corresponding age classes used in this study.

Wear Class	**Descriptor**	**Corresponding Age Classes (Janzen)**
Neonate	unworn deciduous dentition	Infant
Juvenile	worn deciduous dentition, deciduous p_4 (dp_4) stage 5[4], first molar in early wear, pre-stage 5	Young Juvenile
Old Juvenile	deciduous dentition worn, stage 6[5], second molar in early wear, pre-stage 5	dp_4: Older Juvenile M2: Young to Older Juvenile
Young Adult	M3 in early wear, 1st molar stage 5	M3: Older Juvenile M1: Older Juvenile
Adult	Adult dentition in full wear, third molar stage 5	M3: Young & Mature Adult
Aged	1st and 2nd molars well worn, second molar stage 6	Aged
Very Old	all teeth extremely worn, very low crown heights , third molar stage 6	Aged

At Ngamuriak, the modal cattle ages at death fall into the Adult class, which comprises the Young Adult and Mature Adult classes described here (Marshall 1990b). Marshall has interpreted this pattern as indicative of herding in a relatively unstressed environment, where young males can be left alive for longer to reach maximum weight before slaughter, rather than culled early in life to avoid competing

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[4] Stage 5: all cusps worn, more than 50% dentine exposed.

[5] Stage 6: Very worn tooth, anterior loph 100% dentine

with humans and female calves for milk, and with female cattle for forage (Marshall 1990b, c). While they have very small MNIs, the cattle from Lemek North-East and Sambo Ngige show similar profiles (Table 10.7). These patterns are roughly similar to those of the PN sites analyzed here, with visible increases in mortality among cattle as they reach maximum weight.

Caprines

The caprine assemblages at the sites analyzed here are much smaller, and therefore present some challenges to interpretation. Ndabibi and GvJm52 yielded only 4 individual caprines, so those sites will not be discussed here. Crescent Island Main, Prolonged Drift have higher MNIs (8 and 7, respectively), but still cannot be compared statistically. A Chi-Square test comparing the frequencies of age classes from Narosura and Crescent Island Causeway does show that the site mortality profiles are significantly different (χ^2=11.547, p=0.0416). Few infants are present at all sites, indicating that either conditions were unstressed enough for herders to rear males for meat, or that those remains did not survive due to taphonomic processes. Caprines at Crescent Island Main and Crescent Island Causeway show similar profiles with peaks in mortality in the Mature Adult class, which may correspond to slaughter at maximum weight (Figure 10.5). However, Crescent Island Main does have relatively higher mortality in the Older Juvenile and Young Adult classes, while at Crescent Island Causeway nearly 30% of the MNI falls into the Aged category. Like Crescent Island Main, Prolonged Drift also has a low MNI, so the peaks in mortality at the Older Juvenile and Aged stages, simply represented by one extra individual in each age class, cannot be interpreted with much certainty, beyond that caprines were slaughtered in nearly every age class. The two Juvenile and three Adult caprines initially reported by Gifford, et al. (1980) do not align with the age structure presented here, as at least one individual is present in every age class aside from Infant.

In contrast to the Central Rift sites, the site of Narosura has a large caprine assemblage (82 MNI). Large peaks in mortality are present at the Older Juvenile (12-18 months) and Mature Adult (3-6 year) stages, while all other age stages are represented by less than 10% of the MNI. This does broadly match Gramly's (1972) interpretation from four young, seven mature, and one aged MNI that caprines were slaughtered in their prime, as indeed few caprines were kept beyond their peak reproductive years. The peak in mortality in the Older Juvenile age class occurs long past weaning age, which is usually around 6 months of age. Herders at Narosura may have allowed males to gain some more weight before slaughter at 18 months, though maximum weight is usually reached around 3 years of age (Wilson 1991).

Overall, caprine mortality patterns are difficult to generalize due to the smaller sample sizes, but at most site samples reflect an emphasis on slaughtering animals in the Mature Adult and Aged classes, with some bimodality probably expressing male vs. female offtake, and likely reflecting retention of females up through the end of their reproductive prime. Caprine ages from other PN sites such as Ngamuriak, exhibit a lack of clustering and Marshall attributes this to their relatively steady weight gain. Marshall's caprine age-classes, based upon Payne's (1973) system are close to those presented here (Table 10.10). A peak in adult caprine mortality at Ngamuriak could result from slaughtering males at maximum weight, similar to patterns seen at Crescent Island Main, Crescent Island Causeway, and Narosura where peaks in mortality at the Mature Adult age class. A similar peak is evident at Lemek North East (Marshall 1990b).

Table 10.10: Payne's (1973) wear stages for caprines with corresponding age classes from Marshall's (1990b) and Janzen's systems.

MWS	Descriptor	Marshall	Janzen
A	dp4 unworn	Neonate	Infant
B	dp4 in wear; m1 unworn	Young Juvenile	Infant
C	M1 in wear, M2 unworn	Juvenile	Part Young juvenile
D	M2 in wear, M3 unworn	Old Juvenile	Older Juvenile
E	M3 in wear, posterior cusp unworn	Young Adult	Young adult
F	Posterior cusp of M3 in wear	Adult	Mature Adult
G	◫– M3; ◫ M2	Adult	Mature Adult
H	◫– M3; M2 ◫ post-	Aged	Mature Adult
I	M3 post- ◫–	Very Old	Aged

Taking both cattle and caprines into consideration, some interesting patterns emerge. Both cattle and caprine mortality curves are shifted to the right at Crescent Island Causeway. While not significantly different from other sites (Table 10.6), this slight difference may be a reflection of the Eburran 5B herding adaptation, a shift in subsistence made by indigenous Eburran 5-making foragers (Ambrose 1984c). Foragers transitioning to herding livestock may be keeping animals alive until old age- before they are slaughtered to maximize herd growth (Prendergast and Mutundu

2010). The reverse is true at Crescent Island Main, which possesses the lowest percent MNI of Aged cattle and caprines. Cattle at the site were primarily slaughtered in their prime, reflecting management practices most closely resembling those of modern pastoralists (see below). Finally, the peaks in mortality of relatively young cattle and caprines, before they reach maximum weight, at Narosura, may indicate herding in a less productive environment where male animals could not be allowed to grow to large sizes and compete with females for forage. The rather high frequencies of older cattle at the site suggest that the site occupants were emphasizing milk production.

Finally, it is important to note that there seems to be no great difference in livestock culling practices between the SPN sites analyzed here and Ngamuriak, an Elmenteitan site, although the mortality profiles cannot be compared statistically due to differences in methods of assigning age classes.

Comparisons to modern herd structures

We may compare slaughter patterns of livestock from archaeological sites to modern herd structures and culling patterns. As outlined in Chapter 7, age- and sex-specific slaughter patterns are clearly found in cattle and caprine herds in East Africa. Summarized briefly, modern East African pastoralists generally slaughter male cattle once they reach maximum weight, around 4-5 years of age, keeping a few steers and bulls in the herd (King, et al. 1984). These mature males may be kept for sale or for consumption, and to provide blood during the dry season, and more bulls than necessary are generally kept as back-up (Dahl and Hjort 1976; Dyson-Hudson 1982;

King, et al. 1984). Cows generally comprise the majority of the cattle herd, particularly in systems oriented towards milk production (King, et al. 1984; Meadows and White 1979; Nyariki, et al. 2009). Cows are only culled after their fertility drops, around 8 to 12 years old (Bekure, et al. 1991; Dahl and Hjort 1976; ILCA 1977; Pratt and Gwynne 1977; Roderick, et al. 1998). Unfortunately, estimates of the percentage of aged cows in a herd are few, but these generally report 15% or under of the total herd (Demirüren 1974; Mutundu 2005).

East African pastoralists today usually use small stock for meat (Bekure, et al. 1991; Nyariki, et al. 2009; Roderick, et al. 1998). Male caprines may be slaughtered at maximum weight, as in Maasai herds in Kajiado (Wilson, et al. 1981), or by 15 months in cases where pastures are not adequate, but young animals are considered to provide the best meat (Dahl and Hjort 1976; Hunting Technical Services 1974; King, et al. 1984). Female caprines make up the majority of goat herds, and are slaughtered around 6 years of age, once their reproductive capacity diminishes (Dahl and Hjort 1976; King, et al. 1984).

These mortality and culling patterns should result in specific mortality profiles around homesteads. A few ethnoarchaeological studies have examined the distribution of age classes in abandoned Maasai habitation and feasting sites, including Mbae's (1986) in the Lemek area of southwestern Kenya, as well as Mutundu's (2005) study on Kuku Plain in southern Kenya. These studies have all identified slaughter patterns that skew towards younger individuals, with juveniles and adults dominating the assemblages. Mbae's analysis of fauna from an abandoned meat feasting site shows a high representation of juvenile and prime age adult cattle, as Maasai generally slaughter healthy cattle for ritual purposes. Fauna from a boma/homestead show similar patterns, but infant remains are present as well. No aged individuals were recovered from the boma (Mbae 1986).

Mutundu (2005) also reports livestock age-at-death profiles dominated by juvenile and adult individuals for both cattle and caprines (using Marshall's age classes condensed into 4 major categories of Neonate, Juvenile, Adult, and Old). Neonatal remains are very rare, and aged individuals make up a small fraction of the total assemblage - just 11% for cattle and 15% for caprines. Overall, these patterns are similar to those found in this study, though a few differences are of note. First, a higher percentage of infant remains are found in the PN assemblages analyzed here, suggesting some differences in disposal practices for very young individuals, particularly caprines, who succumbed to illness. Second, aged individuals comprise a higher percentage of both cattle and caprine mortality profiles in the PN assemblages relative to the modern ones, indicating that a higher proportion of PN cows were kept alive until old age.

Finally, the modern practice of primarily consuming small stock for meat is reflected in modern archaeofaunal assemblages in Mbae's (1986) report, with caprines outnumbering cattle. However, Mutundu (2005) reports a lower number of caprines in the modern faunal assemblages on the Kuku Plain, likely due to the fact that Maasai never consume caprines killed by disease, and many small stock are consumed at special meat-feasting sites located away from homesteads. For such reasons, Prendergast and Mutundu (2010) caution that mortality profiles may differ substantially based upon site-purpose, and therefore should not be used alone to interpret subsistence and herd management strategies.

Summary

From the pioneering zooarchaeological studies of these early pastoralist assemblages, researchers have commented on the differences in management strategies of ancient herders. Immediately striking is the dependence upon cattle rather than caprines for meat, as cattle remains in all sites but Narosura far outnumber those of caprines, which are more common in cattle in modern family herds. Early analyses also highlighted slaughter patterns showing animals culled as they reached maximum weight, indicating herding in unstressed conditions (Gifford-Gonzalez and Kimengich 1984; Marshall 1990b). The hypoplasia and mortality data presented here demonstrate on a finer-grained scale that cattle were managed somewhat differently than they are among modern pastoralists.

The hypoplasia data show that overall cattle were less subject to health challenges as they grew than were caprines, exhibiting lower rates of hypoplasias, as well as less severe hypoplasias. In all contemporary or documented herding systems, cattle are more valuable than caprines, and are often herded in prime grazing areas, while small livestock are herded near the homestead or relatively marginal environments, likely resulting in relatively less nutritional stress among cattle. Caprines are also often herded by younger and less knowledgeable herders than are cattle (Dahl and Hjort 1976). Similar practices may have been in place 2500 years ago, even before farming populations appeared in the region.

Age-specific slaughter patterns, however, are somewhat different from those recorded among modern pastoralists. Overall, archaeological age-at-death profiles presented here show an emphasis on keeping cattle, presumably both males and females, alive for longer spans of their lifetimes. Most site assemblages do suggest that males were allowed to reach maximum weight before slaughter. These culling strategies indicate a different ecologic and economic situation, in which herders are maximizing herd growth, possible only if land and fodder are abundant in relation to the standing herd of cattle. These data strongly indicate that ethnographic studies, while a useful starting point, do not necessarily reflect practices of herders one to two millennia ago, before the introduction of agriculture into the region, or the demographic growth of those successful pastoralist groups themselves. In particular, the social and ecological context in which these pastoral groups were managing herds is different from anything documented historically, and therefore detailed zooarchaeological analyses are necessary to identify subtle differences in herd management strategies.

Variation in herd management strategies is displayed within the prehistoric specialized pastoralist sites, including Narosura, where peaks in mortality of cattle and caprines occurs earlier than at other sites with substantial sample sizes. This may be a strategy employed by the pastoralists responding to herding in a less productive environment. However, livestock from Narosura do not exhibit higher frequencies of hypoplasias, and the hypoplasias of cattle and caprines are less severe than seen in the livestock from the other sites analyzed here. However, (Balasse, et al. 2010a) noted no increase in the frequency of hypoplasias in caprines that had experienced a very severe drought in the year 2000, possibly due to herders' culling animals that were sick. It is possible that herders at Narosura coped with the their environment by culling male animals earlier, and thus did not subject animals to food stress as they developed.

Beyond environmental conditions, another source of variation in herding strategies may be linked to the economic history of the herding group. The site of Crescent Island Causeway was occupied by indigenous Eburran 5B herders, who shifted from foraging to keeping livestock (Ambrose 1984b, c). Mortality profiles for both cattle and caprines skew toward older individuals. This may reflect a management strategy focused on herd growth, and, although the site was clearly occupied by specialized pastoralists, keeping as many animals as possible alive until old age may be a marker of the relatively recent transition to herding by this group (Prendergast and Mutundu 2010).

These new data also shed more light on how livestock were managed at Prolonged Drift. The age-at-death profiles show that the cattle from Prolonged Drift were managed very similarly to herds from pastoralist sites throughout Kenya, with cattle (presumably males) culled at maximum weight and cows kept alive until old age, suggesting relatively unstressed conditions. Caprines show similar patterns (albeit with a small sample size), with some slaughtered at maximum weight and old age. These patterns align closely with those at definite pastoralist sites. The hypoplasia data, as well, indicate that cattle were not subjected to stressful conditions. In sum, it appears that the cattle were managed by knowledgeable herders. The presence of a significant proportion of wild fauna at the site suggests that the occupants of Prolonged Drift were taking advantage of available wild resources, even though the condition of the herd appears to be ideal.

The analyses presented here offer a window into herd management strategies of ancient pastoralists. However, stable isotope analyses provide another line of evidence of ancient pastoral production, and can clarify the economic situations of several sites listed above. The next chapter delves into the stable carbon and oxygen isotope analyses, which elucidate the mobility strategies of early herders.

CHAPTER 11: RESULTS AND INTERPRETATION OF STABLE CARBON AND OXYGEN ISOTOPE ANALYSIS OF MODERN AND ARCHAEOLOGICAL LIVESTOCK

This chapter has several components. First, I review how $\delta^{18}O$ and $\delta^{13}C$ values from sequentially sampled tooth enamel may be "read" to infer seasonal changes in diet and aridity. I then turn to a consideration of stable carbon and oxygen isotope data from modern livestock specimens with known life histories collected in one part of the study area. These results may be interpreted in conjunction with local rainfall data, and serve as a useful comparison for archaeological data.

The latter part of the chapter deals with results from the stable carbon and oxygen isotope analysis of archaeological livestock specimens. Data are presented with respect to each major geographic region: the Central Rift Valley, the Loita Plains, and the Athi-Kapiti Plains. Within each of these categories cattle will be discussed first, followed by caprines. Plots of carbon and oxygen isotope values for each specimen are included here, and all relevant data tables are located in Appendices 1 and 2. Means and standard deviations (1σ), as well as ranges of variation (as indicated by the minimum and maximum values) are reported for each taxonomic group. Following the results I include interpretations of herding strategies within each of these geographic regions.

Assessing seasonality and diet through stable oxygen and carbon isotope ratios

To estimate the proportion of C_4 plants in the diet of the archaeological specimens, carbon isotope values for modern vegetation are corrected by +1.4 ‰ to compensate for the fossil fuel effect (Cerling and Harris 1999). In the study area the corrected average $\delta^{13}C$ values are -10.2‰ and -25.4‰ for C_4 and C_3 plants, respectively (Ambrose and Sikes 1991). An ^{13}C-enrichment of 14.1‰ exists between diet and enamel for bovids (Cerling and Harris 1999), so $\delta^{13}C$ values of +3.8‰ and -11.3‰ indicate 100% C_4 and 100% C_3 diets, respectively. These estimates of diet are approximate, due to the uncertainty in the $\delta^{13}C$ values of ingested plants and the *exact* value of the enrichment factor.

Several factors may explain why $\delta^{13}C$ values as recorded in tooth enamel may change over the course of a year: 1) changes in the proportion of C_4 and C_3 plants or in the proportion of NADP, NAD, and PCK C_4 grasses consumed, or, 2) seasonal variations in the stable carbon isotope composition of those plants (Smedley, et al. 1991).

The types of plants consumed throughout the year by an animal can vary due to the change in location of the animal. Given the differences between the different C_4 subpathways, feeding in different areas may be detected in the isotopic record of tooth enamel. Animals grazing on mostly NADP grasses in mesic areas would exhibit higher enamel $\delta^{13}C$ values relative to grazers feeding in xeric habitats dominated by NAD and PCK grasses (Cerling and Harris 1999). The types of plants consumed may also vary greatly due to their availability and nutritional content within one region.

Significant changes occur in the quantity of grasses and forbs available throughout the year as a consequence of seasonal rainfall (Boutton, et al. 1988b). Even strict grazers may consume different types of grasses, and these are not consumed equally among species. For example, leaf blades of NAD C_4 grasses (which, with PCK grasses have lower $\delta^{13}C$ values than NADP grasses) may not be very digestible compared to other C_4 types (Wilson and Hattersley 1989) and therefore these types grasses are often only eaten by livestock during droughts (Bosch and Theunissen 1992). Grasses also tend to be depleted in protein during dry seasons, and mature vegetation also has lower nutrient concentrations than do young plants (Boutton, et al. 1988b). Herbivores selectively feed upon the most nutritious plants available, which in the rainy season include young forbs and NADP grasses. These vegetation types differ in their stable carbon isotope composition, and therefore, changes in the $\delta^{13}C$ of the diet are expected due to seasonal changes in plant availability and nutritional content (Stanley Price 1985). Small seasonal differences in $\delta^{13}C$ values have been noted for some C_4 plant species, but only on the order of 1-2‰ (Tieszen and Boutton 1988).

Vertical or altitudinal mobility may be documented by changes in carbon isotope values due to the differences in growing conditions for C_3 and C_4 grasses. A strong correlation of grass species distribution and altitude exists: the transition from C_4 grass dominance at low elevations to C_3 grasses at higher elevations is well documented in Kenya, reflecting changes in moisture and temperature (Tieszen, Senyimba, et al. 1979). Similar patterns are found elsewhere, though at higher latitudes, the C_3 to C_4 crossover occurs at lower elevations (Cabido, et al. 1997).

Some of the archaeological sites in the study area are situated on the floor of the Central Rift Valley. Because these sites are located in a region bordered by escarpments that reach up to 4000 masl (Figure 1.1), it is possible, particularly in those sites, that livestock may have been moved to higher elevations seasonally to access pastures. Therefore, carbon isotope values would reveal any mobility up to higher altitudes.

Seasonal changes in diet (as indicated by $\delta^{13}C$ values) of a specimen can be shown by correlated changes in $\delta^{18}O$ values. The oxygen isotopic composition of tooth enamel is linked to that of ingested water, which can vary seasonally due to seasonal changes in aridity and temperature (Dansgaard 1964; Gat 1996; Gonfiantini 2001; Iacumin, et al. 1996; Longinelli 1984; Rozanski, et al. 1993). At low latitudes, the $\delta^{18}O$ of precipitation varies depending on the amount of precipitation and lower in the rainy seasons (Dansgaard 1964; Rozanski, et al. 1996). In dry seasons the $\delta^{18}O$ values are relatively higher than in wet seasons, as the light isotope (^{16}O) is preferentially evaporated. Plant water also exhibits seasonal variation in $\delta^{18}O$ values, and animals who obtain most of their body water from vegetation show greater variation in $\delta^{18}O$ values over wet and dry seasons, as well as higher $\delta^{18}O$ values overall (Helliker and Ehleringer 2000). These seasonal changes can manifest as cyclical changes in oxygen isotope ratios along the growth axis of a high-crowned tooth.

Because of the potentially seasonal nature of mobility patterns, all carbon and oxygen results are plotted together along the long axis of the tooth. Lower molars of cattle and caprines have been shown to display an isotopic record of diet for at least one year (Balasse 2002).

The format of Figure 11.1 will be repeated for all livestock specimens, showing carbon isotope values plotted with oxygen isotope values, with carbon on the right axis, and oxygen on the left, and distance from the enamel-root junction (ERJ) in millimeters. All values are relative to V-PDB. As discussed in Chapter 7, cyclical or sinusoidal patterns are indicative of seasonal changes in the stable isotope composition of the tooth enamel.

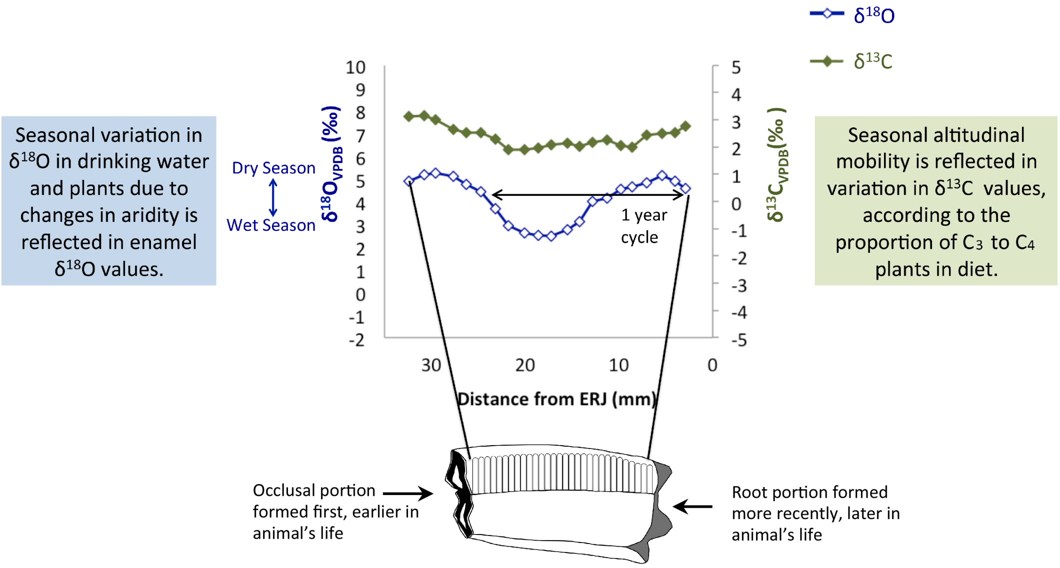


Figure 11.1: Example of an individual plot of δ^{1}C and δ^{18}O values against distance from enamel-root junction (ERJ) as indicated with a cartoon of a sampled specimen. Differences in δ^{18}O and δ^{13}C values are explained in the insets

In the next section I present data on modern livestock with known life histories as an introduction to the study area and to the isotopic differences in diet and drinking behaviors in cattle and caprines.

Modern Livestock

The purpose of including modern livestock specimens here is to examine the carbon and oxygen isotope composition of the tooth enamel in the context of seasonal and yearly changes in rainfall. In the next section, the strontium isotope composition of tooth enamel will then be considered in the context of known feeding areas and migration histories of the animals. Therefore, these specimens serve to introduce the interpretation of isotopic values with respect to seasonal changes in diet and rainfall, as well as providing a useful example for interpreting archaeological specimens. The three analyzed modern livestock specimens include the M_1, M_2, and M_3 of each animal. The specimens were collected in August of 2013 in South Narok District, from refuse piles around *bomas* or meat-feasting sites. Due to expense, only the specimens with the most known details of their life histories (birth dates, migration histories) were analyzed and are reported here. The results from the carbon and oxygen isotope analysis are shown in Figure 11.2, 11.4, and 11.5.

Modern Cattle

One cattle specimen was recovered from a meat-feasting site roughly 20 km south of Narok town. The specimen, GvJhB113, shows very little variation in its $\delta^{18}O$

values across the three lower molars (M1-M3), varying less than 1‰ in the M1 and M2 (Figure 11.2).

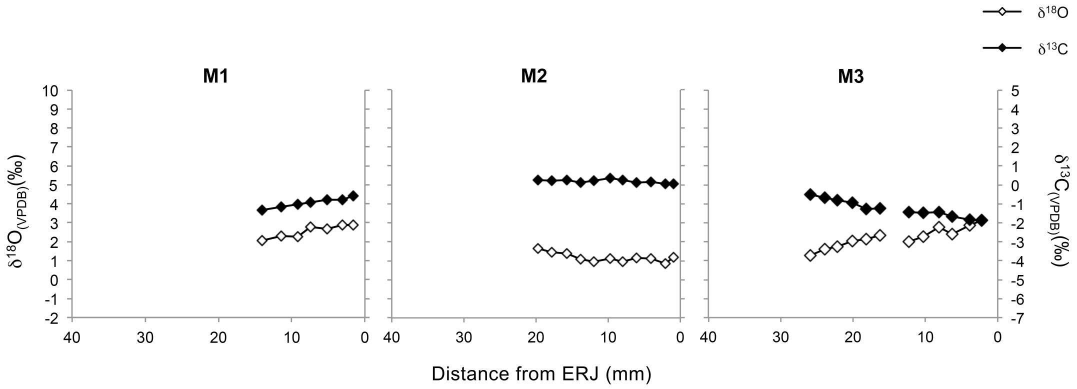


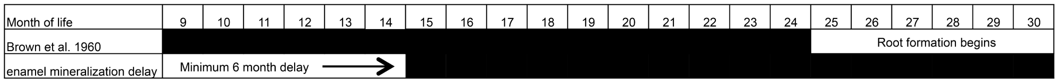
Figure 11.2: Modern cattle specimen from near Narok, M1-M3 (GvJhB113). Note that the incongruence between the isotopic values near the root of the M1 and the crown of the M2 is due to the relatively advanced wear on the M2.

This specimen displays little evidence for seasonal variation in $\delta^{18}O$ values, averaging 2.6‰ in M1, 1.2‰ in M2, and 2.2‰ in M3. The M1 and M2 exhibited less than 1‰ of variation, while the M3 has a range of variation just under 2‰ (Appendix 2). The lack of seasonal variation of $\delta^{18}O$ values in this specimen is likely not due to the turnover rate of body water, as this process in cattle is quite rapid (Ahmed and El Hadi 1996; Sharp and Cerling 1998). The lack of observed seasonality may be a consequence of several factors, including tooth mineralization rates, which in the M2 in cattle is six to seven months, and may contribute to a dampening of seasonal changes reflected in tooth enamel (Balasse 2002; Passey and Cerling 2002). Cattle are also obligate drinkers, obtaining most of their body water through drinking, and thus are generally buffered from seasonal changes in water relative to animals that obtain most of their water from plant matter, especially leaves.

The stable carbon isotope composition of the cattle tooth enamel is quite consistent over the growth of the three teeth, with the M1 averaging -0.9‰ (range, -0.6 to -1.3‰), the M2 averaging 0.2‰ (range, 0.3 to 0.1‰), and the M3 showing the greatest variation, averaging -1.3‰ (with a range of -0.5‰ to -1.9‰). After adjusting for trophic enrichment, even the lowest value at -1.9‰ corresponds to a diet $\delta^{13}C$ value of -15.8‰.

In Kenya, C_4 plants dominate low elevations (Tieszen, Senyimba, et al. 1979; Young and Young 1983). The average $\delta^{13}C$ value for C_3 plants in the study region is -26.8 ‰ ± 1.9‰, while the average for C_4 plants is -11.6‰ ± 0.9‰ (Ambrose and Sikes 1991). Cerling and Harris (1999) also report $\delta^{13}C$ values for various plants collected in Kenya, ranging from an average of -12.8 ± 0.8‰ for NAD and PCK grasses, which are found in more xeric environments, to a mean of -11.7 ± 0.7 ‰ for NADP grasses, which favor mesic environments. To my knowledge no published isotopic values of C_4 or C_3 plants in the Loita-Mara region exist. Here I use the average values of C_3 and C_4 plants from a 1890 m to 2600 m altitude transect in the Naivasha basin reported by Ambrose and Sikes (1991). Thus, the proportion of C_4 (%) in the diet is estimated to be ~73% at the minimum, which is lower than the expected percentage (80-100%) of grass in the diet of cattle (Coppock, et al. 1986). However, if we use the mean of NAD and PCK grasses as the C_4 endmember, the estimated percentage of C_4 grasses in the diet is raised to 80%. These low percentages may be a consequence of drier conditions of the Narok South district, with this cattle specimen feeding upon more NAD and PCK grasses and C_3 plants.

The stable oxygen isotope composition of the cattle tooth enamel varies only slightly within each tooth. Seasonal responses in herding strategies, as reflected in the isotopic record of this *Bos* individual, are therefore difficult to evaluate, and unfortunately the month of birth for this individual is not known, though it was born in 2001 south of the town of Ewaso Ngiro, and its mother was from Lolgorien. The individual died in 2013. The change in $\delta^{18}O$ values in the M3 may be linked to broad-scale changes in precipitation over the course of tooth mineralization. The M3 begins to form around the 9th month of life and develops until around 24 months (Brown, et al. 1960). The M2 has a delay of 6 months (Balasse 2002). While the delay of mineralization for the M3 is not known, it is reasonable expect a minimum of a 6 month delay, and that the duration recorded by the M3 spans at least the 15th through the 30th months of life (Figure 11.3).



Month of life	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Brown et al. 1960	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	Root formation begins					
enamel mineralization delay	Minimum 6 month delay ⟶						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Figure 11.3: Timing of formation and estimated minimum mineralization delay of M3 in cattle.

With a birth sometime in 2001, the M3 would record climatic conditions experienced by the animal in 2002 – 2003. The year 2002 was rather wet, with the Narok and Narosura stations recording 1045.2 mm and 811 mm, respectively. In contrast, those areas saw 806 mm and 451 mm, respectively, in 2003 (Kenya Meteorological Department). This marked decline in precipitation may be responsible for the rise in $\delta^{18}O$ values in the M3 over time. A correlated decrease in $\delta^{13}C$ values in the M3 suggest a decrease in the proportion of C_4 plants in the animals diet, as a consequence of the drier conditions during formation and mineralization of that tooth.

We may ascertain the water sources at which livestock were watered by estimating the $\delta^{18}O$ of body water (and thus drinking water) from the $\delta^{18}O$ values of the tooth enamel. This requires several steps, including converting $\delta^{18}O_{CO3}$ values to $\delta^{18}O_{PO4}$ values using the equation provided by Iacumin, et al. (1996):

$$\delta^{18}O_{PO4} = 0.98*\delta^{18}O_{CO3}-8.5$$

The fractionation factor (α) is 1.0090. Several fractionation factors have been produced for a variety of species, and results suggest that there are some slight taxonomic differences (Bryant, et al. 1996; Iacumin, et al. 1996; Martin, et al. 2008; Pellegrini, et al. 2011). However, because there has been no study on members of the family Bovidae, I use the equation provided by Iacumin et al. (1996) in their study of several modern mammalian taxa.

The relationship between the $\delta^{18}O_{PO4}$ of cattle bioapatite and that of precipitation is indicated by the following equation (d'Angela and Longinelli 1990):

$$\text{Mean } \delta^{18}O_{PO4} = 24.90+[1.01*\text{Mean } \delta^{18}O_{precipitation}]$$

To my knowledge, there is no equation for cattle from equatorial regions. Therefore the equation for cattle from New Zealand is used here, as the animals were raised on pastures and consumed only grass after weaning, as this best approximates the conditions in which traditionally managed African cattle would have been raised (d'Angela and Longinelli 1990). Both New Zealand and the study area have similar measures of relative humidity, so the equation may be appropriate.

Isotopic analyses of river waters in the Mara and Narok area yielded $\delta^{18}O$ values ranging from -3.3 to -3.7 (Levin, et al. 2009). To the southeast, values for streams feeding into the Ewaso Ngiro River, near Lake Magadi, have values of -3.9‰ and -3.1‰, and values for the Ewaso Ngiro river increase as it flows south towards Lake Natron, yielding $\delta^{18}O$ values of -1.6‰ near Lake Magadi, and increasing to +0.6‰ close to Lake Natron (Hillaire-Marcel and Casanova 1987). The estimated mean $\delta^{18}O$ values for each tooth of GvJhB113 range from -1.9 to -0.9‰. These estimates are higher than $\delta^{18}O$ values recorded for any stream or river in the area. There are no large lakes in the areas in which the cow was known to have lived, but it is possible that it was herded to rivers with higher $\delta^{18}O$ values. It is also possible that formula used to convert the $\delta^{18}O_{PO4}$ of cattle bioapatite to that of precipitation is not appropriate for this region.

Modern Sheep

The two modern sheep analyzed exhibited greater variations in their $\delta^{18}O$ values, both within and between teeth. Carbon and oxygen isotope values are displayed below for the lower first, second and third molars for specimens GvJhB100 *Ovis* (Figure 11.4) and GvJhB110 *Ovis* (Figure 11.5).

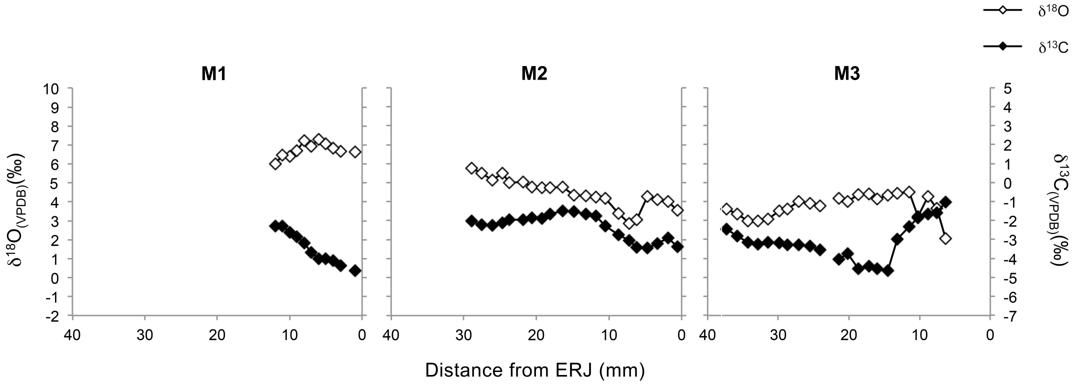


Figure 11.4: Modern sheep specimen from Narok (GvJhB100 Ovis) M1-M3. Individual was born December of 2011 and died June of 2013.

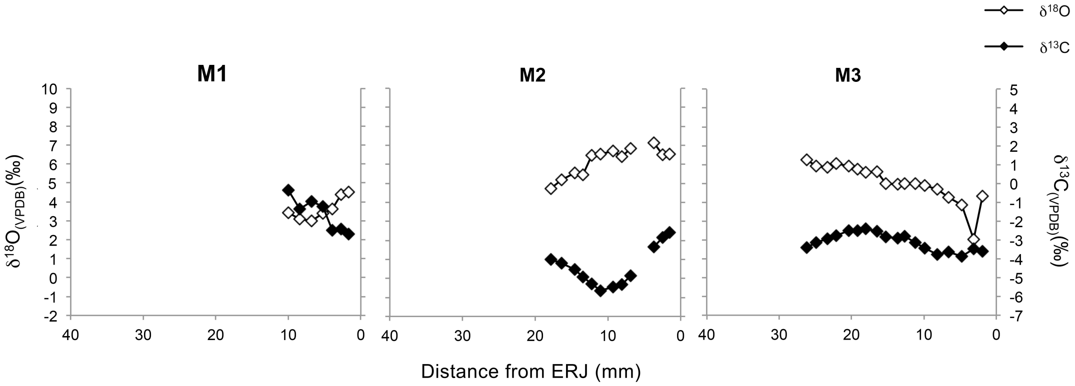


Figure 11.5: Modern sheep specimen from Narok (GvJhB110 Ovis) M1-M3. Individual was born in January of 2010 and died in August of 2013.

Overall, the sheep show higher and more variable δ^{18}O values than the cattle specimen, likely the result of two factors. First, sheep have a shorter delay in enamel mineralization than do cattle (Balasse 2002; Balasse, Obein, et al. 2012). Second, sheep obtain more of their water from leaves, which are quite sensitive to changes in aridity (Kohn, et al. 1996; Levin, et al. 2006). Leaves are highly enriched in ^{18}O relative to the soil water due to evapotranspiration (Dawson and Ehleringer 1991;

Dongmann, et al. 1974; Sternberg 1989). The Péclet effect leads to relatively high $\delta^{18}O$ values in C_4 grasses compared to C_3 grasses (Helliker and Ehleringer 2000). C_4 plants also exhibit greater variation in $\delta^{18}O$ values due to their ability to survive in low-water conditions, such as droughts, and C_4 plants have higher evapotranspiration rates, particularly in arid settings (see Sternberg 1989, Yakir 1992 (Hattersley 1983; Sternberg 1989; Tieszen, Senyimba, et al. 1979; Yakir 1992). The modern sheep analyzed exhibited ranges in $\delta^{13}C$ values of 3.6‰ and 5.3‰ for GvJhB100 Ovis 1 and GvJhB110 Ovis 1, respectively.

We may estimate the $\delta^{18}O$ value of drinking water for caprines as well. Using the same equation to convert from $\delta^{18}O_{CO3}$ values to $\delta^{18}O_{PO4}$ values using the equation provided by Iacumin, et al. (1996). The relationship between $\delta^{18}O$ values of sheep tooth enamel and the $\delta^{18}O$ of precipitation is indicated by the equation (d'Angela and Longinelli 1990):

$$\text{Mean } \delta^{18}O_{PO4} = 27.21+[1.48*\text{Mean } \delta^{18}O_{precipitation}]$$

An equation for goats is:

$$\text{Mean } \delta^{18}O_{PO4} = 24.39+[0.91*\text{Mean } \delta^{18}O_{precipitation}]$$

As with the equation to estimate the $\delta^{18}O$ of meteoric water from cattle specimens, these equations were not generated from African populations, but from sheep from New Zealand goats from various locations in Europe.

Estimated $\delta^{18}O$ values of drinking water for the modern sheep ranged from -2.3‰ to +1.3‰. The lower values are much closer to those reported for streams and rivers in the area, which have values ranging from -3.7‰ to -3.3‰ (Levin, et al. 2009), while the higher values match those for the Ewaso Ngiro as it reaches Lake Natron (Hillaire-Marcel and Casanova 1987). The sheep likely herded locally, so it is not likely that they ingested water from near Lake Natron. However, the degree of seasonal or inter-annual variation of Ewaso Ngiro river water is not known.

Even though the sample area has a bimodal rainfall pattern, this is not detectable in the δ^{18}O values in all caprine teeth. The short rains that occur from late October to December may be too brief and inconsequential to be recorded in the isotopic composition of the tooth enamel. However, the dramatic effect of the long rains on δ^{18}O enamel values can be seen, as in the samples between 10 and 5 mm from the ERJ in GvJhB100 *Ovis* 1 M2, when April 2012 rains reached over 200 mm (Figure 11.6). While the δ^{18}O patterns in that specimen do not clearly reflect the earlier rainy season during the time of tooth growth (October-December of 2011), the δ^{13}C values do show some variation as expected with the change in vegetation consumed during dry and rainy seasons. Consequently, oxygen isotope patterns in domestic caprine teeth may not be a consistently useful proxy for identifying the presence of a bimodal rainfall pattern in archaeological contexts, but may be used together with δ^{13}C patterns to gain a clearer picture of precipitation patterns.

The modern caprine results, when compared to rainfall data, are of particular interest, as the flock owner's strategies for keeping animals healthy during times of decreased precipitation may result in enamel isotope values *not* recording the drier conditions. A study of caprines in Kenya's Narok South district showed that the severe drought of

2000 did not result in higher frequencies of enamel hypoplasias. While it is possible that many individuals most affected by the drought were slaughtered during this event, it is also possible that herders changed tactics to keep the herds healthy (Balasse, et al. 2010a; Upex 2009). In normal times, Maasai herders in Narok South water their caprines every other day, but in times of drought, when forage is very dry, they may water the animals every day. Although high δ^{18}O values would be expected, given the increased aridity, this practice would decrease δ^{18}O values, as proportionately less water is obtained from leaves. Correlated increases in δ^{13}C values due to feeding on hardy shrub vegetation could mimic the expected isotopic signature for altitudinal mobility. Comparisons of enamel isotope values to precipitation data may shed more light on how herder management of flocks affects the isotopic intake of their flocks.

GvJhB110 was born in January 2010 and died in August 2013. As indicated in (Figure 11.5), its teeth are quite worn, unfortunately erasing the isotopic signal from the occlusal portion of much of the M1 and M2. GvJhB100 was said to have been born in December 2011 and died in June 2013. However, the isotopic record shown in the M3 suggests that the animal was actually born one year earlier (it is possible that the herder misspoke). Its M3 has come into wear, but the third of the crown closest to the ERJ is not fully mineralized.

The patterns of δ^{18}O and δ^{13}C values vary over time, though in ways that are rather difficult to interpret (Figure 11.6). In some cases δ^{18}O values decrease during times of high rainfall (see GvJhB100 *Ovis* 1 M1 at ~15m from ERJ corresponding to

April of 2012, or M2 of same individual between 10 and 5 mm from ERJ, corresponding to 208 mm of precipitation during April of 2012). Or, times of low rainfall show high δ^{18}O values in teeth, as indicated in GvJhB110 *Ovis* 1 M2 around 5 mm from the ERJ corresponding to low rainfall in April through July of 2011.

In these cases, where there are clear rises in δ^{18}O values brought on by low precipitation, there is a clear, associated decrease in δ^{13}C values, suggesting that as the climate became more arid, the amount of C_3 plants consumed by the animal increased. However, this sinusoidal pattern is not always evident. The marked dip in δ^{18}O values between 10 and 5 mm from the ERJ in GvJhB100 *Ovis* 1 M2 is met with a similar decrease in δ^{13}C values, suggesting that the animal fed upon more C_3 plants during this period of heavy rainfall. This is likely a consequence of increased forb consumption. While sheep are grazers, they do consume a larger quantity of forbs, especially during wet seasons (Coppock, et al. 1986; Stanley Price 1985). Most forbs are C_3, though C_4 forbs are also present, and do have relatively lower δ^{13}C values (average -13.8‰) (Tieszen 1991). Live forbs have higher nutrient levels than do grasses, and sheep may be selectively feeding upon those plants when available (Boutton, et al. 1988b). The subsequent increase in both carbon and oxygen stable isotope ratios in this specimen is likely the results of an increase in aridity and an increase in C_4 grasses in the diet. Other instances where δ^{18}O and δ^{13}C values covary include between 16.5 and 5 mm in GvJhB110 *Ovis* 1 M3. This period of tooth growth ranges from March to November of 2012, the dry season (Figure 11.6). While one would expect δ^{18}O values to increase steadily due to increasing aridity, they gradually drop instead from 5.7‰ to 3.9‰ and $\delta^{13}C$ values move from -2.5‰ to -3.9‰. The change in $\delta^{13}C$ values makes sense: the sheep is increasing its consumption of browse. However, the drop in $\delta^{18}O$ values does not follow rainfall patterns, and may be due to increased water consumption if vegetation is quite dry. However, $\delta^{18}O$ values never reach as low as those in the modern cattle specimen, suggesting that vegetation still contributes a significant amount of water. Nevertheless, 2012 was not a particularly dry year as indicated by precipitation data from the Narok station. It is nonetheless possible that *local* conditions were relatively dry.

Figure 11.6: Rainfall data (blue bars indicate mm of rainfall) from Narok weather station from 2010 – 2013 and individual profiles of GvJhB110 *Ovis* 1 and GvJhB100 *Ovis* 2. Black bars indicate estimated timing of tooth growth based on studies. Grey bar indicates estimated mineralization time of M3 in Kenya sheep. GvJhB100 *Ovis* 1 was noted to have been born December 2011 and died June 2013 (1.5 years old), but the isotopic record of the M3 does not support this. I believe the herder misspoke, and it was actually born in December of 2010, and thus died at 2.5 years.

Summary of Modern Livestock

These data from modern livestock specimens, in addition to data from other studies (Balasse and Ambrose 2005b) act as a useful comparison in interpreting data from archaeological specimens.

Seasonal variation in $\delta^{18}O$ values

The single cattle specimen showed very little seasonal variation in $\delta^{18}O$ values. This lack of a seasonal signal stands in stark contrast to sampled cattle from high latitudes, which show significant variation (Balasse, et al. 2002; Balasse, et al. 2013; Towers, et al. 2014), so it is not likely that cattle tooth mineralization time is entirely responsible for this pattern in Kenyan cattle. Rather, the consistent $\delta^{18}O$ values may be due to the fact that cattle obtain most of their water by drinking, and, if drinking water from large water sources potentially buffered from seasonal changes in aridity, their enamel will not show a strong seasonal signature.

The modern sheep analyzed here show more seasonal variation, but in general do not clearly record a bimodal pattern in $\delta^{18}O$ values as expected given the rainfall pattern in this region. In particular, GvJhB110 *Ovis* 1 M3 shows consistent $\delta^{18}O$ values despite tooth mineralization spanning a period with some months exhibiting no rainfall and others over 200 mm. Also of interest is the variation in $\delta^{18}O$ values between teeth. In GvJhB110 *Ovis* 1, $\delta^{18}O$ values range from 7.1 to 3.0‰, with means of 3.6‰, 6.2‰, and 5.2‰ for the M1, M2, and M3 respectively. GvJhB100 *Ovis* 1, $\delta^{18}O$ values range from 7.3 to 2.1‰, with means of 6.7‰, 4.4‰, and 3.7‰ for the

M1, M2, and M3, respectively. Though they are from different herds, these animals were herded locally their whole lives, and so, the range in values testifies to the significant inter- and intra-annual variation in precipitation and thus caprine $\delta^{18}O$ values within one area. Indeed, variations in seasonal monthly average rainfall $\delta^{18}O$ values of about 3.5‰ have been recorded in Tanzania and Uganda (Rozanski, et al. 1996).

Seasonal variation in $\delta^{13}C$ values

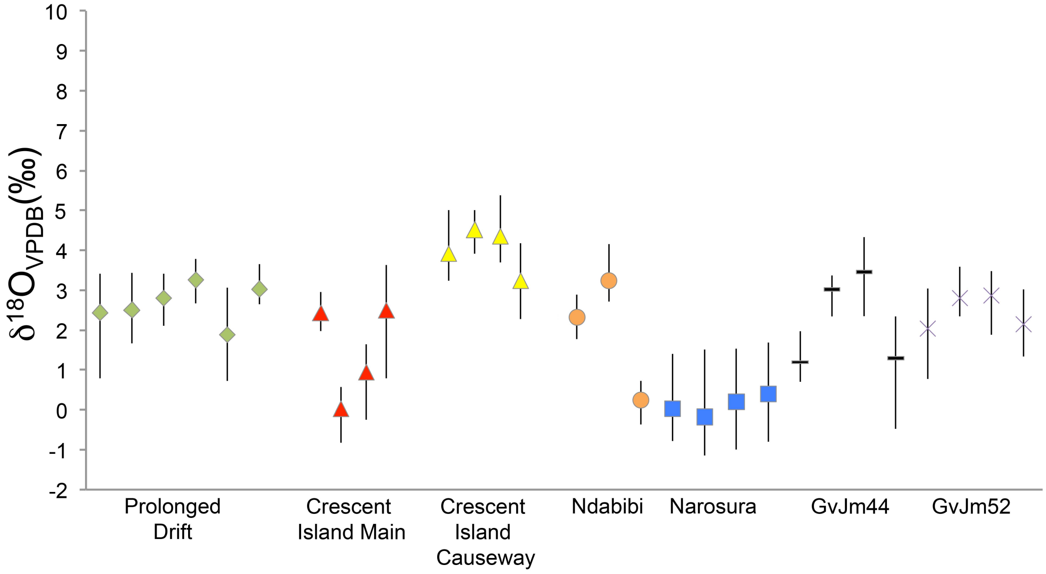
As a whole, the *Bos* specimen, GvJhB113, showed very little seasonal variation in carbon isotope values. Grasses make up at least 80% of the diet of cattle over a seasonal cycle (Coppock, et al. 1986). The lack of seasonal variation is similar to that reported for a modern cattle specimen feeding on the floor of the Central Rift Valley (Balasse and Ambrose 2005b). The $\delta^{13}C$ values are also quite similar, although GvJhB113 has slightly lower values, possibly owing to a greater consumption of NAD + PCK plants (Balasse and Ambrose 2005b).

In subtropical environments, caprines have divergent dietary strategies: sheep mainly graze and goats include a higher proportion of browse in their diet (Ngwa, et al. 2000). Indeed, this difference in diet has been recorded isotopically (Ambrose and DeNiro 1986a; Balasse and Ambrose 2005a). The two sheep specimens do exhibit lower $\delta^{13}C$ values than the range of mean $\delta^{13}C$ values recorded elsewhere for modern caprines in Kenya (Balasse and Ambrose 2005a). Enamel $\delta^{13}C$ values in these two specimens reach as low as -5.6‰, or a 49% C_4 diet. This value corresponds to low

$\delta^{13}C$ values for some sheep from the same area reported by Balasse and Ambrose (2005a). As described above, lower $\delta^{13}C$ values in sheep may be due to increased consumption of browse during the dry season or forbs during the wet season. Unfortunately, the simultaneous drop in $\delta^{18}O$ and $\delta^{13}C$ values due to increased focus on forbs in the wet season mimics the pattern expected for mobility to higher elevations. Therefore $\delta^{13}C$ values higher than -6‰ in archaeological specimens cannot be considered evidence of feeding at higher altitudes. Similar results from an earlier study show that sheep feeding at higher elevations (2994 m on the Mau Escarpment) have $\delta^{13}C$ values around -8‰ and lower (Balasse and Ambrose 2005b).

Archaeological Livestock

In this section I present the results of the stable carbon and oxygen isotope analyses on archaeological specimens. The means and ranges of variation of $\delta^{18}O$ and $\delta^{13}C$ values for each sampled specimen are presented in Figure 11.7 and Figure 11.8, as well as Tables 11.1 to 11.4. This information is also included in the results for each archaeological site for cattle and caprines.



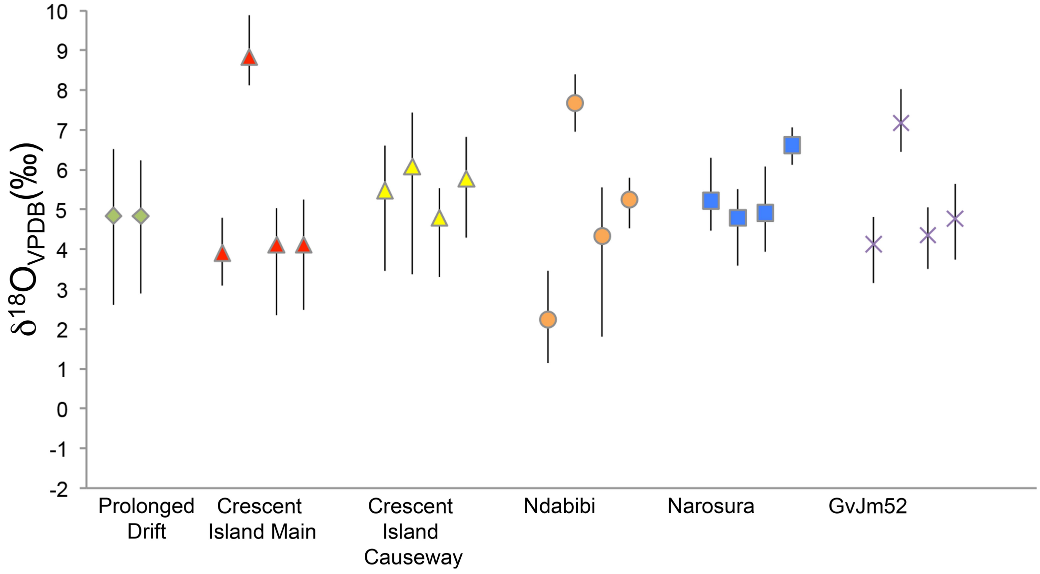


Figure 11.7: Upper chart shows mean and variation (maximum to minimum value) of $\delta^{18}O$ values of cattle from all sites. Lower chart shows mean and variation of $\delta^{18}O$ values from caprines at all sites.

Table 11.1: Mean, maximum, minimum, and range of variation of δ^{18}O values for all archaeological cattle specimens.

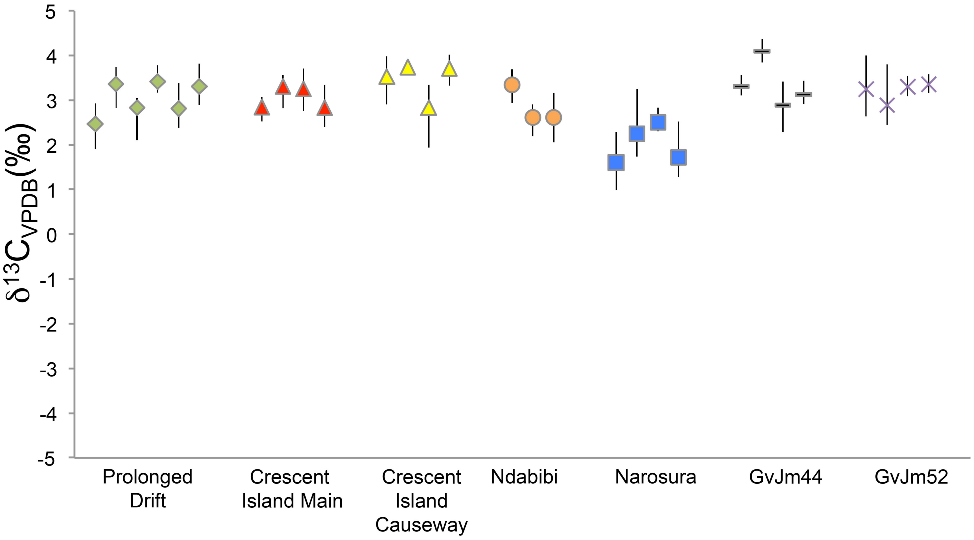
Specimen	**Mean δ^{18}O**	**Max δ^{18}O**	**Min δ^{18}O**	**Range of Variation**
CI-M *Bos* 1 M3	2.4	2.9	2.0	1.0
Cl-M *Bos* 2 M3	0.0	0.6	-0.8	1.4
CI-M *Bos* 3 M3	0.9	1.7	-0.3	1.9
CI-M *Bos* 4 M3	2.5	3.6	0.8	2.8
CI-C *Bos* 1 M2	3.9	5.0	3.2	1.8
CI-C *Bos* 2 M3	4.5	5.0	3.9	1.1
CI-C *Bos* 3 M3	4.4	5.4	3.7	1.7
CI-C *Bos* 4 M3	3.2	4.2	2.3	1.9
NDA *Bos* 1 M1	2.3	2.9	1.8	1.1
NDA *Bos* 2 M1	3.2	4.2	2.7	1.4
NDA *Bos* 3 M3	0.3	0.7	-0.4	1.1
PD *Bos* 1 M3	2.4	3.4	0.8	2.6
PD *Bos* 2 M3	2.5	3.4	1.7	1.8
PD *Bos* 3 M3	2.8	3.4	2.1	1.3
PD *Bos* 4 M3	3.3	3.8	2.7	1.1
PD *Bos* 5 M3	1.9	3.1	0.7	2.4
PD *Bos* 6 M3	3.0	3.7	2.7	1.0
GvJm44 *Bos* 1 M3	1.2	2.0	0.7	1.3
GvJm44 *Bos* 2 M3	3.0	3.4	2.3	1.1
GvJm44 *Bos* 3 M3	3.5	4.3	2.4	2.0
GvJm44 *Bos* 4 M3	1.3	2.3	-0.5	2.8
GvJm52 *Bos* 1 M3	2.0	3.0	0.8	2.3
GvJm52 *Bos* 2 M3	2.8	3.6	2.3	1.2
GvJm52 *Bos* 3 M3	2.9	3.5	1.9	1.6
GvJm52 *Bos* 4 M3	2.2	3.0	1.3	1.7
NS *Bos* 1 M3	0.0	1.4	-0.8	2.2
NS *Bos* 2 M3	-0.2	1.5	-1.1	2.7
NS *Bos* 3 M3	0.2	1.5	-1.0	2.5
NS *Bos* 4 M3	0.4	1.7	-0.8	2.5

Table 11.2: Mean, maximum, minimum, and range of variation of δ^{18}O values for all archaeological cattle specimens.

Specimen	Mean δ^{18}O	Max δ^{18}O	Min δ^{18}O	Range of Variation
CI-M *Ovis* 1 M3	3.9	4.8	3.1	1.7
CI-M *Ovis* 2 M3	8.8	9.9	8.1	1.8
CI-M *Ovis* 3 M3	4.1	5.0	2.3	2.7
CI-M *Ovis* 4 M3	4.1	5.3	2.5	2.8
CI-C *Ovis* 1 M3	5.5	6.6	3.5	3.2
CI-C *Ovis* M3	6.1	7.4	3.4	4.1
CI-C *Ovis* 3 M3	4.8	5.5	3.3	2.2
CI-C *Ovis* 4 M2	5.8	6.8	4.3	2.5
NDA *O/C*1 M3	2.2	3.5	1.1	2.3
NDA *O/C* 2 M1	7.7	8.4	7.0	1.4
NDA *Ovis* 1 M2	4.3	5.6	1.8	3.7
NDA *Capra* 1 M2	5.3	5.8	4.5	1.3
PD *O/C* 1 M3	4.8	6.5	2.6	3.9
PD *O/C* 2 M3	4.8	6.2	2.9	3.4
GvJm52 *Ovis* 1 M2	4.8	5.6	3.7	1.9
GvJm52 *Ovis* 2 M3	4.1	4.8	3.1	1.7
GvJm52 *Capra* 1	7.2	8.0	6.5	1.6
GvJm52 *O/C* 2 M3	4.4	5.1	3.5	1.5
NS *Ovis* 1 M3	4.9	6.1	3.9	2.1
NS *Ovis* 3 M2	6.6	7.0	6.1	0.9
NS *Ovis* 4 M3	4.8	5.5	3.6	1.9
NS *Capra* 1 M3	5.2	6.3	4.5	1.8

The δ^{18}O values of the cattle specimens are lower than those of caprines (Figure 11.7). This difference between taxa is due to drinking behavior and physiology, as cattle obtain most of their body water by drinking, while caprines, who are not obligate drinkers, obtain much more of their water from vegetation. Leaf water is highly evaporated, and consequently has very high δ^{18}O values. It is also more sensitive to seasonal changes in aridity (Helliker and Ehleringer 2000). Beyond these broad differences, we can interpret differences in δ^{18}O values of livestock with respect to environment and seasonal and interannual variation in precipitation. Interannual variation in precipitation is considerable in East Africa, and may thus preclude the identification of non-locally raised animals based solely upon oxygen isotope values. However, it is possible to identify the probable source of drinking water (i.e. lakes or rivers).

Overall, the differences in $\delta^{13}C$ values between cattle and caprines is clear; cattle generally have higher $\delta^{13}C$ values and exhibit little intra-annual variation (Figure 11.8). In contrast, caprines are more variable. While some caprines do exhibit $\delta^{13}C$ values similar to cattle, there are some with much lower values. Caprines generally display greater variation as well. Beyond these broad taxonomic differences, disparate $\delta^{13}C$ values shed light on the feeding environment of animals over the course of tooth growth. Each site's assemblage is discussed in more detail below with respect to the vegetation environment in which the site is situated today. The discussion focuses on the implications of these results for identifying early herder mobility and landscape use. In particular, carbon isotope values are examined for evidence of mobility to higher elevations. If such movements have a seasonal basis, correlated changes in oxygen isotope values are expected. Different herding practices or exchange of animals may also be identified by inter-individual variability in carbon and oxygen isotope values, though, as discussed below, teasing apart these two causes of variation is difficult.



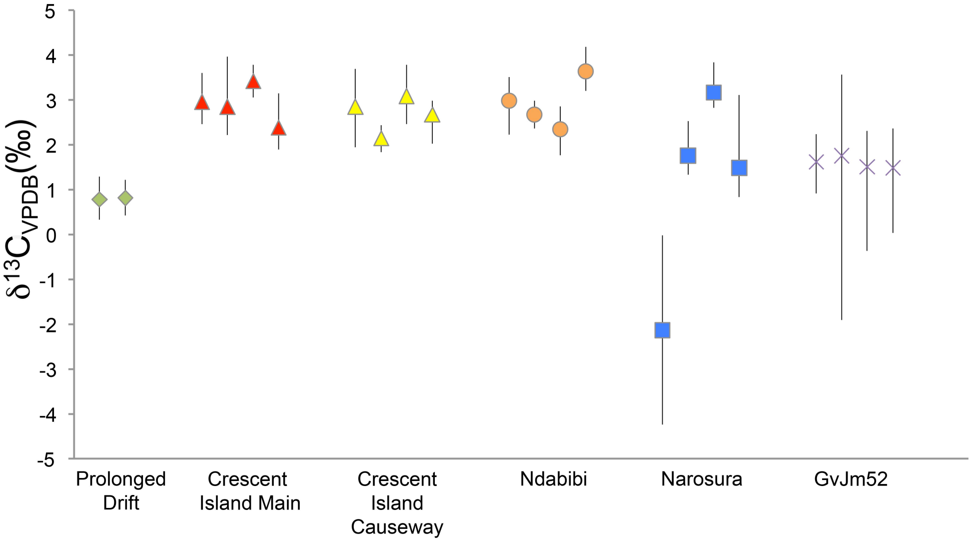


Figure 11.8: Upper chart shows mean and variation (maximum and minimum value) of δ^{13}C values of cattle from all sites. Lower chart shows mean and variation of δ^{13}C values from caprines at all sites.

Table 11.3: Mean, maximum, minimum, and range of variation of $\delta^{13}C$ values for all archaeological cattle specimens.

Specimen	**Mean $\delta^{13}C$**	**Max $\delta^{13}C$**	**Min $\delta^{13}C$**	**Range of Variation**
CI-M *Bos* 1 M3	2.9	3.1	2.5	0.5
Cl-M *Bos* 2 M3	3.3	3.6	2.8	0.8
CI-M *Bos* 3 M3	3.3	3.7	2.8	1.0
CI-M *Bos* 4 M3	2.8	3.3	2.4	0.9
CI-C *Bos* 1 M2	3.5	4.0	2.9	1.1
CI-C *Bos* 2 M3	3.7	3.9	3.6	0.2
CI-C *Bos* 3 M3	2.8	3.4	1.9	1.4
CI-C *Bos* 4 M3	3.7	4.0	3.3	0.7
NDA *Bos* 1 M1	3.3	3.7	2.9	0.8
NDA *Bos* 2 M1	2.6	2.9	2.2	0.7
NDA *Bos* 3 M3	2.6	3.2	2.1	1.1
PD *Bos* 1 M3	2.5	2.9	1.9	1.0
PD *Bos* 2 M3	3.4	3.7	2.8	0.9
PD *Bos* 3 M3	2.8	3.1	2.1	1.0
PD *Bos* 4 M3	3.4	3.8	3.2	0.6
PD *Bos* 5 M3	2.8	3.4	2.4	1.0
PD *Bos* 6 M3	3.3	3.8	2.9	0.9
GvJm44 *Bos* 1 M3	3.3	3.6	3.1	0.5
GvJm44 *Bos* 2 M3	4.1	4.4	3.8	0.5
GvJm44 *Bos* 3 M3	2.9	3.4	2.3	1.1
GvJm44 *Bos* 4 M3	3.1	3.4	2.9	0.5
GvJm52 *Bos* 1 M3	3.3	4.0	2.6	1.4
GvJm52 *Bos* 2 M3	2.9	3.8	2.5	1.4
GvJm52 *Bos* 3 M3	3.3	3.6	3.1	0.5
GvJm52 *Bos* 4 M3	3.4	3.6	3.2	0.4
NS *Bos* 1 M3	1.6	2.3	1.0	1.3
NS *Bos* 2 M3	2.2	3.3	1.7	1.5
NS *Bos* 3 M3	2.5	2.8	2.3	0.5
NS Bos 4 M3	1.7	2.5	1.3	1.2

Table 11.4: Mean, maximum, minimum, and range of variation of $\delta^{13}C$ values for all archaeological caprine specimens.

Specimen	**Mean $\delta^{13}C$**	**Max $\delta^{13}C$**	**Min $\delta^{13}C$**	**Range of Variation**
CI-M *Ovis* 1 M3	3.0	3.6	2.5	1.1
CI-M *Ovis* 2 M3	2.8	4.0	2.2	1.8
CI-M *Ovis* 3 M3	3.4	3.8	3.1	0.7
CI-M *Ovis* 4 M3	2.4	3.2	1.9	1.3
CI-C *Ovis* 1 M3	2.8	3.7	1.9	1.8
CI-C *Ovis* M3	2.1	2.4	1.8	0.6
CI-C *Ovis* M3	3.1	3.8	2.5	1.3
CI-C *Ovis* M2	2.7	3.0	2.0	1.0
NDA *O/C* 1 M3	3.0	3.5	2.2	1.3
NDA *O/C* 2 M1	2.7	3.0	2.4	0.6
NDA *Ovis* 1 M2	2.4	2.9	1.8	1.1
NDA *Capra* 1 M2	3.6	4.2	3.2	1.0
PD *O/C* 1 M3	0.8	1.3	0.3	1.0
PD *O/C* 2 M3	0.8	1.2	0.4	0.8
GvJm52 *Ovis* 1 M2	1.5	2.4	0.0	2.3
GvJm52 *Ovis* 2 M3	1.6	2.2	0.9	1.3
GvJm52 *Capra* 1 M2	1.8	3.6	-1.9	5.5
GvJm52 *O/C* 2 M3	1.5	2.3	-0.4	2.7
NS *Ovis* 1 M3	3.2	3.8	2.8	1.0
NS *Ovis* 3 M2	1.5	3.1	0.8	2.3
NS *Ovis* 4 M3	1.8	2.5	1.3	1.2
NS *Capra* 1 M3	-2.1	-0.0	-4.2	4.2

Central Rift Valley Sites

Crescent Island Main Cattle

Cattle at Crescent Island Main show differing trends in $\delta^{18}O$ values through the time of tooth growth (Figure 11.9). Together, the cattle specimens exhibit a mean of 1.4 ± 1.2‰, with a range of 3.6‰ to -0.8‰ (the maximum and minimum $\delta^{18}O$ values among all cattle at the site). All specimens overlap significantly in $\delta^{18}O$ values, in particular CI-M *Bos* 1 and 2. The oxygen isotope composition of CI-M *Bos* 1 does not vary significantly over time, varying slightly less than 1‰. In contrast, the other three specimens show some indication of a seasonal cycle, each varying at least 1.4‰ over time.

Carbon isotope values were remarkably consistent, with a mean and standard deviation of 3.1 ± 0.3‰, with a range of values from 3.7 to 2.4‰. This indicates that the cattle were consuming a near 100 – 91% C_4 diet over the entire duration of tooth growth. There is no indication of seasonal changes in diet. In fact, the $\delta^{13}C$ values in each cattle specimen vary less than 1‰ over the course of tooth growth. Changes in $\delta^{13}C$ values appear to be slightly correlated with $\delta^{18}O$ values only in CI-M *Bos* 1 and *Bos* 3, where values covary.

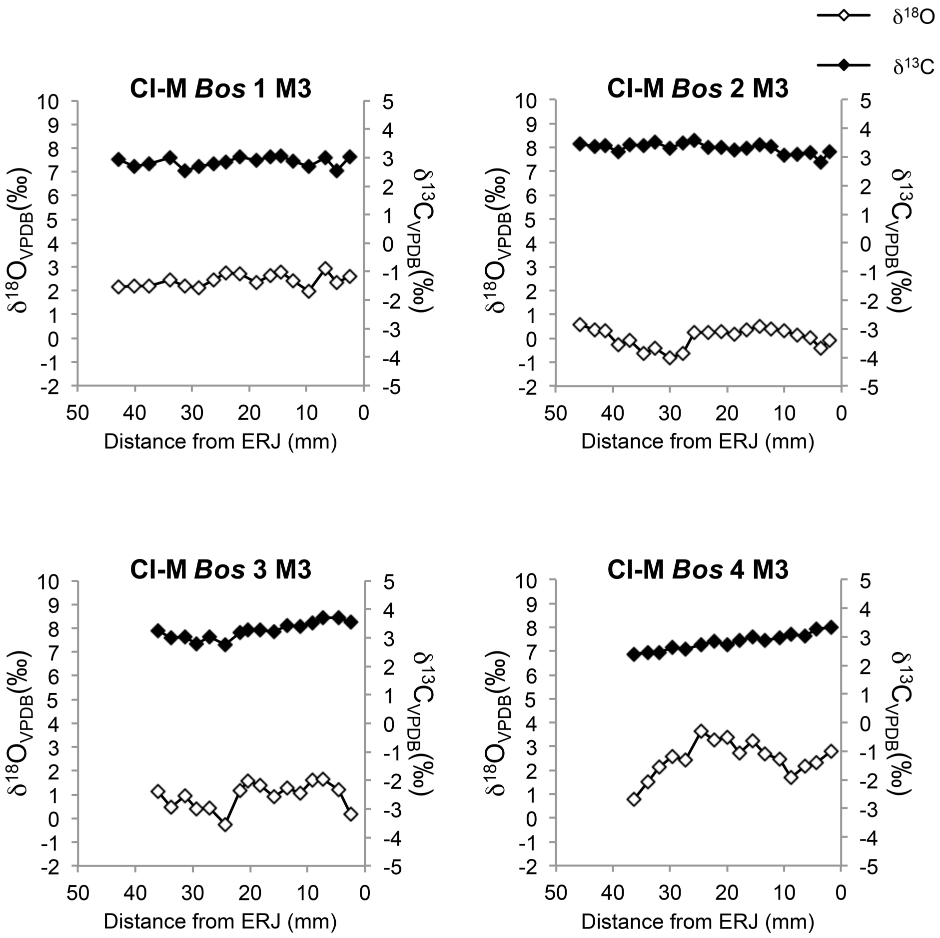


Figure 11.9: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from Crescent Island Main. ERJ= Enamel-root junction.

Crescent Island Main Caprines

Caprines analyzed from Crescent Island Main are all sheep. Overall the average δ^{18}O value of all specimens is 5.2‰, with a rather high standard deviation of 2.2‰. The δ^{18}O values of the specimens are quite variable (Figure 11.10). CI-M *Ovis* 2 has very high δ^{18}O values (9.9 to 8.1‰), which do not overlap with values from the other specimens. The other three specimens vary in δ^{18}O values from a high of 5.3‰

to a low of 2.3‰. The pattern of values over time varies among individuals, from CI-M *Ovis* 1 and *Ovis* 3 which lack evidence for seasonal variation, to a strong seasonal signature present in CI-M *Ovis* 4 and perhaps in CI-M *Ovis* 2.

In contrast, sheep $\delta^{13}C$ values show less variation, averaging 2.9 ± 0.6‰. Values ranged from 3.9 to 1.9‰, indicating a 100 – 88% C_4 contribution to diet. Changes in $\delta^{13}C$ values appear to be slightly correlated with $\delta^{18}O$ values, but not consistently among specimens. Isotopic values covary in CI-M *Ovis* 2 M3 (though the peaks in values are slightly offset from one another) and *Ovis* 4 M3, but in CI-M *Ovis* 1 M3 $\delta^{13}C$ values decrease as $\delta^{18}O$ values increase. CI-M *Ovis* 3 M3 shows a similar pattern in its last 10mm, but the majority of the length of the tooth shows very little variation in $\delta^{13}C$ values as $\delta^{18}O$ values varied over time.

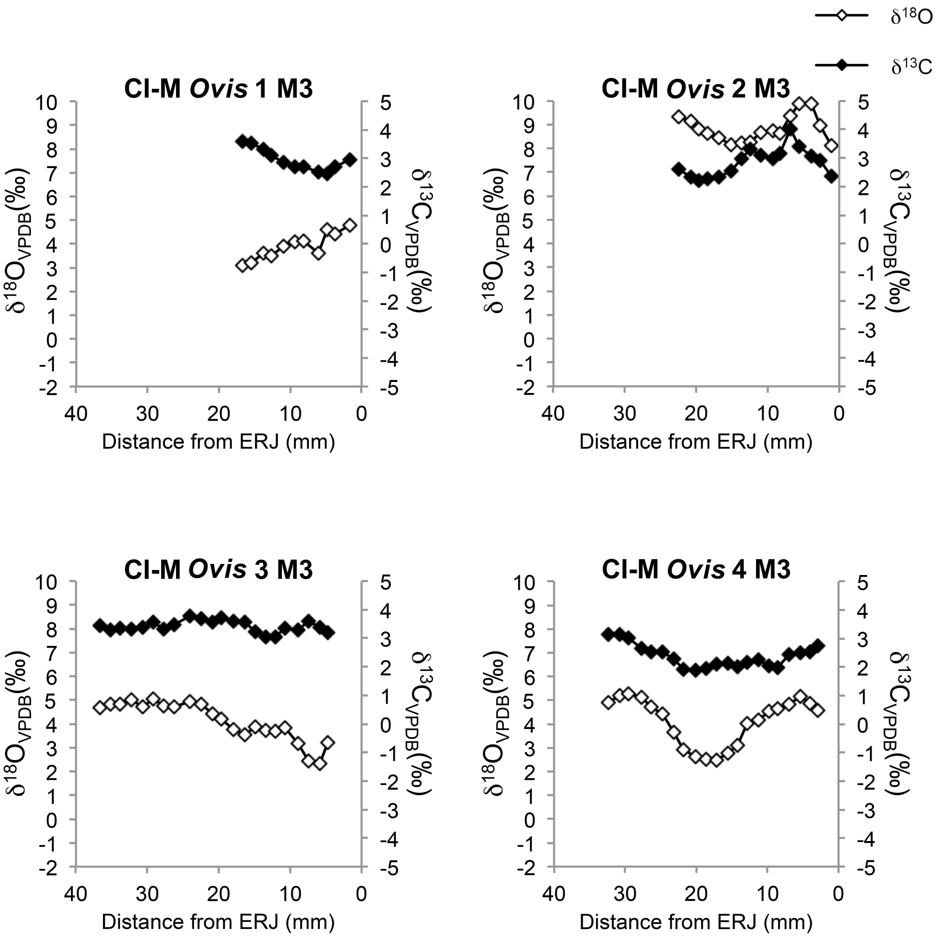


Figure 11.10: Results from carbon and oxygen isotope analysis of enamel of sheep specimens from Crescent Island Main ERJ= Enamel-root junction.

Crescent Island Causeway Cattle

Oxygen isotope values in cattle teeth from Crescent Island Causeway average 3.9 ± 0.8‰ (a range of 5.4‰ to 2.3‰). Intra-individual variation is under 2‰. Evidence for seasonal changes is weak (Figure 11.11).

Carbon isotope values are quite uniform in specimens, with an average of 3.3 ± 0.7‰, ranging from 4.0 to 1.9‰. CI-C *Bos* 3 M3 shows the most variation, displaying a range of 1.4‰, as well as the lowest value. This low value indicates an 88% contribution of C_4 plants to the diet. The low values for the other cattle specimens show a minimum 100% contribution of C_4 plants.

Correlated changes in $\delta^{18}O$ and $\delta^{13}C$ values are evident in two of the specimens, CI-C *Bos* 1 M3 and CI-C *Bos* 3 M3. A slight decrease in $\delta^{13}C$ values correlates with a decrease in $\delta^{18}O$ values. The other two specimens show very stable $\delta^{13}C$ values despite changes in $\delta^{18}O$ values.

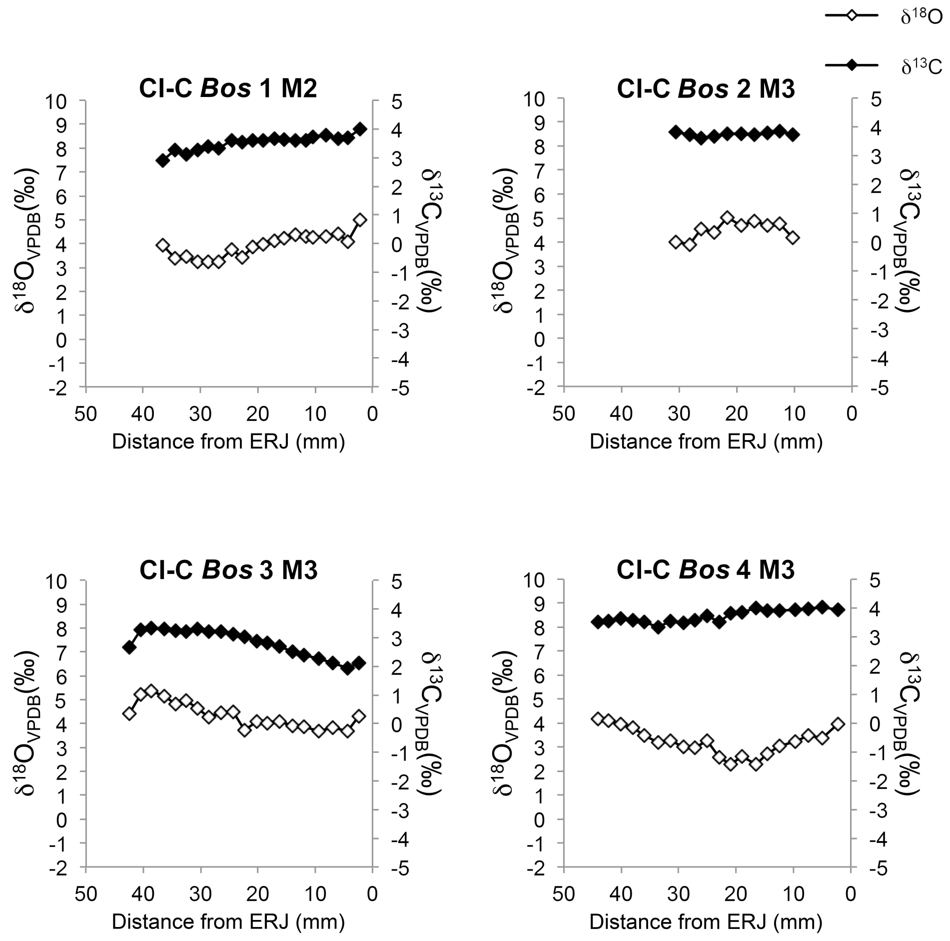


Figure 11.11: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from Crescent Island Causeway. ERJ= Enamel-root junction.

Crescent Island Causeway Caprines

The caprines analyzed from Crescent Island Causeway are all sheep, with CI-C *Ovis* 1, 2, and 3 represented by lower third molars, and CI-C *Ovis* 4 represented by an upper second molar. Relative to cattle, they show more variation in both oxygen and carbon isotope composition. Specimens have an average δ^{18}O value of 5.5 ±

1.0‰, with a high value of 7.4‰ and a low value of 3.3‰. Each specimen has an intra-individual range of variation of at least 2.2‰ (Figure 11.12).

Carbon isotope values are relatively stable, with an average of 2.7 ± 0.5‰, and values ranging from 3.8‰ to 1.8‰, giving a range of 100 – 87% C_4 contribution to diet. All specimens have an intra-individual range of variation under 1.8‰.

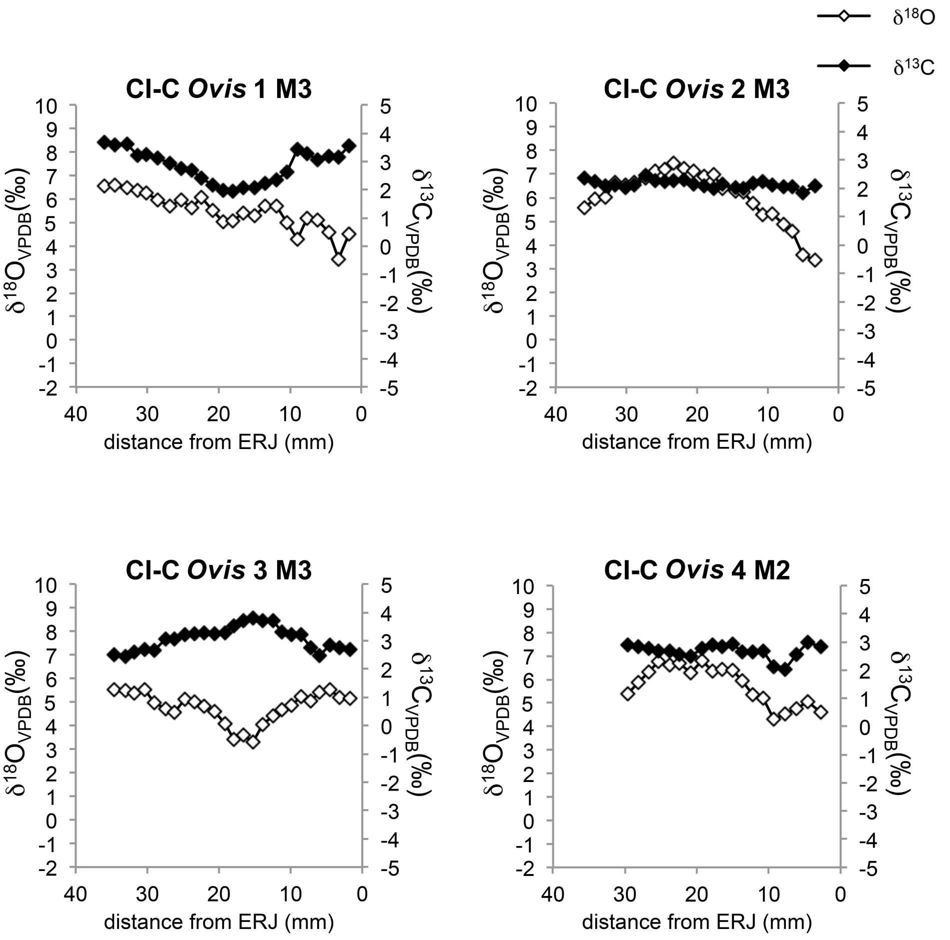


Figure 11.12: Results from carbon and oxygen isotope analysis of enamel of sheep specimens from Crescent Island Causeway. ERJ= Enamel-root junction.

No consistent correlation of $\delta^{13}C$ to $\delta^{18}O$ values exists. For example, CI-C *Ovis* 2 M3 does not show any variability of $\delta^{13}C$ values (a range of 0.61‰), though relative to the other sheep at the site, this specimen has the greatest variability in oxygen isotope values (a range of 4.1‰). CI-C *Ovis* 1 (the occlusal half) and *Ovis* 4 show some covariation in values, with decreases in $\delta^{18}O$ matched by decreases in $\delta^{13}C$ values. In contrast, in CI-C *Ovis* 3 and the root half of the crown of CI-C *Ovis* 1, decreases in carbon isotope values occur with increases in oxygen isotope values.

Ndabibi Cattle

The faunal assemblage from Ndabibi is small, and only 3 cattle teeth were amenable to sampling, all of them quite worn relative to those of other cattle sampled from SPN sites. Specimens have an average $\delta^{18}O$ value of 1.7 ± 1.4‰ and display considerable variability: NDA *Bos* 2 has a maximum value of 4.2‰ and NDA *Bos* 3 has a minimum value of -0.4‰, with little overlap in values among the three teeth (e.g., only the lowest values of NDA *Bos* 2 overlap with the higher values of NDA *Bos* 1). There is less than 1‰ variation over time in $\delta^{18}O$ values in all specimens (Figure 11.13).

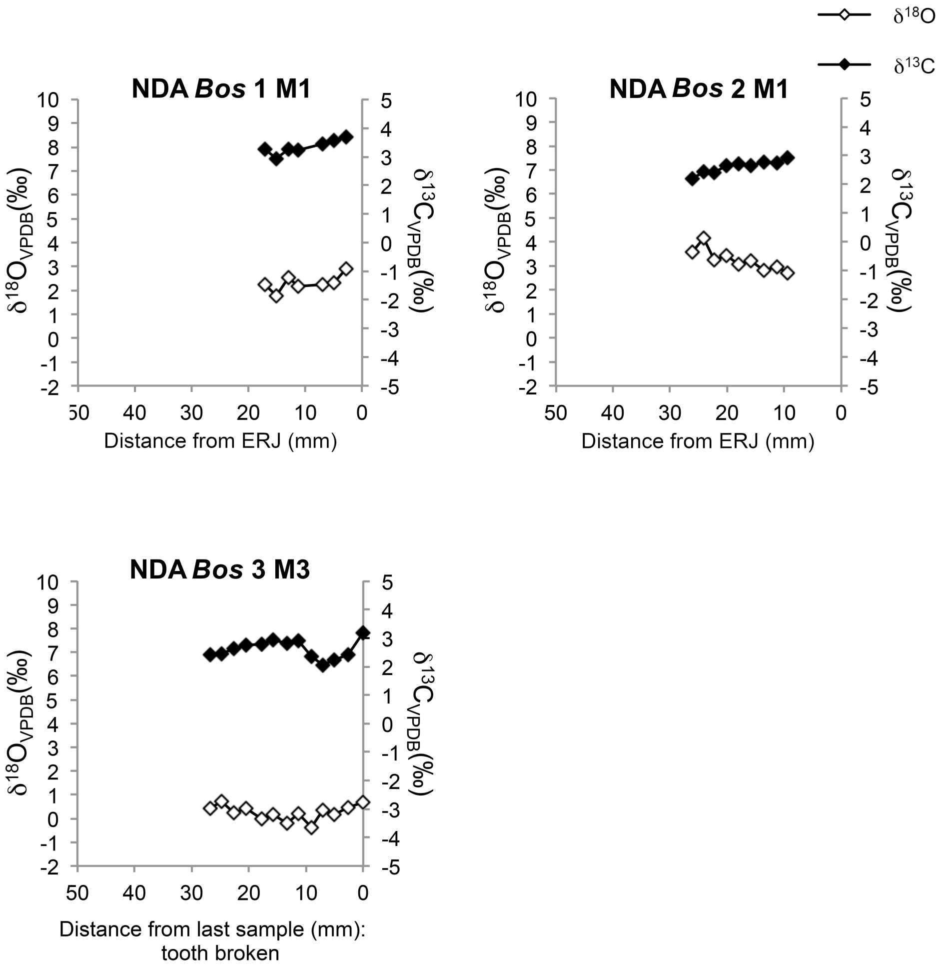


Figure 11.13: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from Ndabibi. ERJ= Enamel-root junction. NDA *Bos* 3 M3 was broken towards the root, and the samples shown likely represent the occlusal half of the crown.

The average δ^{13}C value of all specimens is 2.8 ± 0.4‰, with a range from 3.7 to 2.1‰, indicating a 100 – 89% C_4 contribution to diet. Carbon isotope values do covary with δ^{18}O values, though not consistently among specimens. In specimen NDA *Bos* 1 M1 values positively covary, but a negative covariation is observed in NDA *Bos* 2 M1 and the occlusal 20mm in NDA *Bos* 3 M3.

Ndabibi Caprines

Due to the small size of the assemblage, the caprine teeth I analyzed included an M1, M2, and M3, but varying age-at-death estimates based on occlusal wear suggest the teeth did not come from the same individual. Upon initial examination of specimens, it was not possible to definitively identify the taxa of upper molars (NDA o/c 1 M3 and NDA o/c 2 M1) to either *Capra hircus* or *Ovis aries*. However, given their high $\delta^{13}C$ values, these are tentatively classified as sheep (Balasse and Ambrose 2005a). Similarly, while one specimen was identified as *Capra hircus* by Gifford-Gonzalez, its $\delta^{13}C$ values also suggest it is actually a sheep, and therefore it has been labeled to reflect the new identification.

Oxygen isotope values are extremely variable among specimens. All together, the specimens average 5.1 ± 1.8‰, but only NDA o/c 1 and NDA *Ovis* 1 overlap in values. Those two specimens also show significant changes over time, with a range in values of 2.3‰ and 3.7‰, respectively (Figure 11.14).

In contrast, $\delta^{13}C$ values are stable among specimens, with an average of 3.0 ± 0.6‰. The samples range from a maximum value of 4.2‰ and a minimum value of 1.8‰, corresponding to a 100 – 87% C4 contribution to diet. Most of the specimens show positive covariation of $\delta^{18}O$ and $\delta^{13}C$ values, including NDA o/c 2, the last ~15 mm of NDA *Ovis* 1 and 25 to 5 mm. Otherwise increases in $\delta^{18}O$ are matched by decreases in $\delta^{13}C$ values.

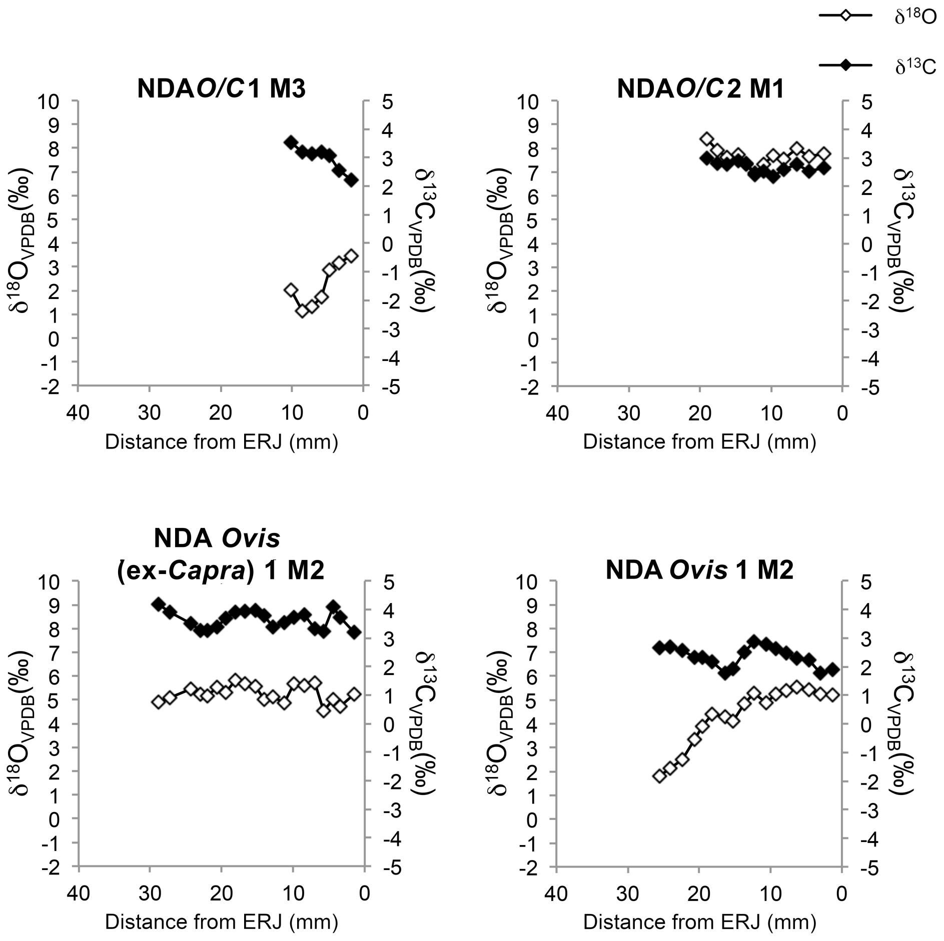


Figure 11.14: Results from carbon and oxygen isotope analysis of enamel of caprine specimens from Ndabibi. ERJ= Enamel-root junction.

Prolonged Drift Cattle

Because the site of Prolonged Drift is dominated by wild fauna, six cattle were analyzed from the site in an effort to learn whether the domesticates were part of a single herd or if they were obtained from various nearby pastoralist groups. The $\delta^{18}O$ values of all cattle specimens are remarkably consistent, with a mean of 2.6 ± 0.7‰. Values range from 3.8‰ to 0.7‰. Most specimens show a variation under 2‰, with the exception of PD *Bos* 1 M3 and PD *Bos* 5 M3. Only PD *Bos* 2 and *Bos* 5 display seasonal variation (Figure 11.15).

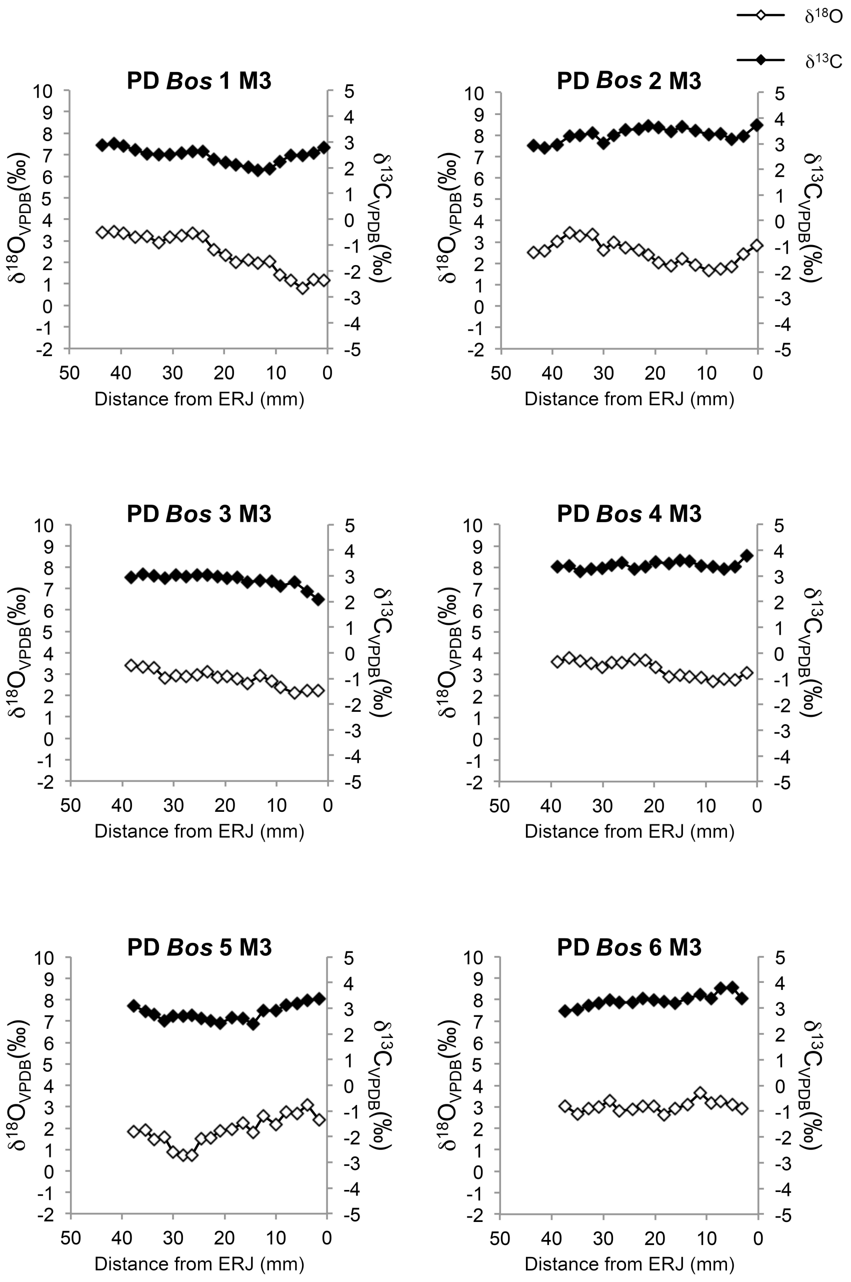


Figure 11.15: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from Prolonged Drift. ERJ= Enamel-root junction.

Carbon isotope values are also very consistent, with an average of 3.0 ± 0.4‰, and a range of values from 3.8‰ to 1.9‰, indicating a 100 – 88% C_4 contribution to diet. All specimens exhibit a range of variation around 1‰. Overall, there is no correlation of $\delta^{13}C$ values with $\delta^{18}O$ values, as $\delta^{13}C$ values remain constant over time.

Prolonged Drift Caprines

Due to the small number of caprines at the site, only two teeth, a right and a left upper M3 could be sampled. There is significant variation in $\delta^{18}O$ values, averaging 4.8 ± 1.2‰. Both specimens show a remarkably similar pattern in $\delta^{18}O$ values, with maximum and minimum values at 6.5 – 2.6‰ and 6.2 – 2.9‰ for PD o/c 1 and PD o/c 2, respectively. Given the variability among specimens at other archaeological sites, this strong similarity may indicate that these two specimens were from the same individual. Both show an increase in $\delta^{18}O$ values followed by a decrease toward the ERJ, suggesting a seasonal pattern (Figure 11.16).

Despite the variation in oxygen isotope values, $\delta^{13}C$ values vary less than 1%, and averaging 0.8 ± 0.3‰. High and low values of 1.3‰ and 0.3‰, respectively, indicate 84 – 78% C_4 contribution to the diet. The $\delta^{13}C$ values slightly decrease with increasing $\delta^{18}O$ values, indicating a minor increase in C_3 contribution to diet with increasing aridity.

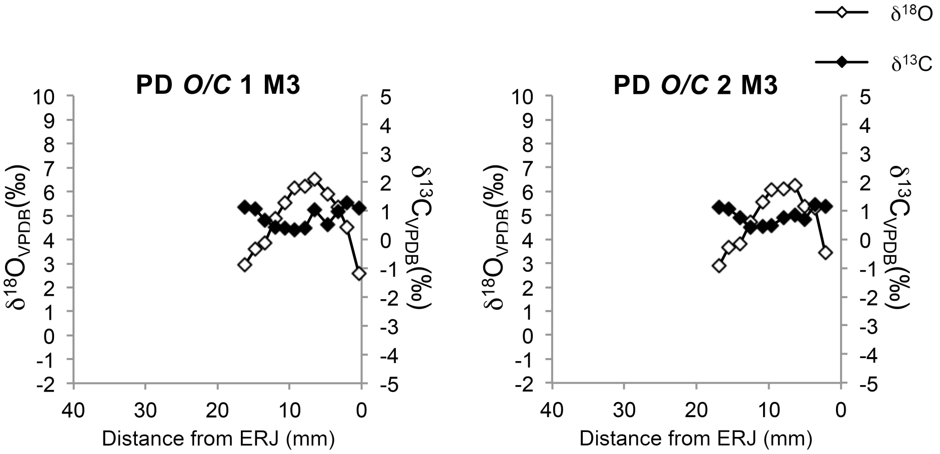


Figure 11.16: Results from carbon and oxygen isotope analysis of enamel of caprine specimens from Prolonged Drift. ERJ= Enamel-root junction.

Interpretation of Stable Oxygen Isotope Values

The cattle sampled from two neighboring sites on Lake Naivasha, Crescent Island Main and Crescent Island Causeway, have significantly different $\delta^{18}O$ values, averaging 1.4 ± 1.2‰ and 3.9 ± 0.8‰, respectively; Student's t-test $p < 0.001$).

This difference may be explained by variability in precipitation over time. To my knowledge, no seasonal precipitation oxygen isotope data exist for the study area. However, some lake and river waters have been sample. Lake Naivasha has $\delta^{18}O$ values averaging 4.0 ± 3.1‰ (SMOW), from seven samples taken from 1977 to 2003 (Cerling, et al. 2008). The variation in $\delta^{18}O$ values of the lake water highlight the degree of seasonal and interannual changes in precipitation over time. Radiocarbon dates place the occupation of Crescent Island Main earlier than Crescent Island Causeway. It is possible that the individuals from Crescent Island Main lived during a period of high rainfall, and thus had lower $\delta^{18}O$ values. The average 2.5‰ difference between the sites is within the range of variation for Lake Naivasha waters.

An alternative explanation for the difference between the two sites could be that cattle from each site reflect different watering strategies: accessing either lake water or meteoric water. Overall, waters from freshwater closed basin lakes are much more enriched in ^{18}O than are waters from springs, rivers, and groundwater (Cerling, et al. 2008; Ojiambo, et al. 2001). While waters of Lake Naivasha are quite ^{18}O-enriched (averaging 4.0 ± 3.1‰), meteoric sources in the Naivasha region have $\delta^{18}O_{SMOW}$ values of -3.0 ± 1.7‰ (Cerling, et al. 2008). Source water of Lake Naivasha includes two perennial rivers: the Malewa River, which provides most of the surface waters; and the Gilgil River; the Karati River contributes only during the rainy season, and the Kwamuya and Nyamithi streams are even more ephemeral (Åse 1987; Everard, et al. 2002) The Malewa, Gilgil, and Karati Rivers have $\delta^{18}O_{VSMOW}$ values of -2.7, -2.3, and -1.4‰, respectively (Ojiambo, et al. 2001). Thus, it is possible that the cattle from Crescent Island Main were accessing water from nearby rivers. We may compare the oxygen isotope data of water sources to $\delta^{18}O$ values of cattle to shed light on the source of drinking water.

Mean estimated $\delta^{18}O$ values of drinking water for individual cattle specimens from Crescent Island Main range from -0.6‰ to -3.0. The lower values correlate with those reported for river waters. Two specimens, CI-M *Bos* 1 and CI-M *Bos* 4, have estimated $\delta^{18}O$ values of -0.6‰, which do not match any recorded values for water sources in the area. The closest sources, though they differ from these estimates by at least 1‰, are Lake Naivasha and the Karati River.

The mean estimated $\delta^{18}O$ values of drinking water for cattle at Crescent Island Causeway range from 0.2‰ to 1.5‰. The higher values (displayed by CI-C *Bos* 2 and CI-C *Bos* 3) are in line with the lower range reported for Lake Naivasha (Cerling, et al. 2008). The lower values estimated for the other specimens are closer to the lower range reported for Lake Naivasha, rather than any values reported for rivers in the region. Therefore, the difference in values exhibited by cattle at the two Crescent Island sites could be due to differences in watering strategies at each site.

Estimated $\delta^{18}O$ values for drinking water among the caprines from the two Crescent Island sites range from +0.5‰ to -1.0‰, with the exception of CI-M *Ovis* 2, which has an estimated $\delta^{18}O$ value of +2.4‰. These estimates indicate that most caprines were watered at sources with $\delta^{18}O$ values between those recorded for nearby rivers and Lake Naivasha, while CI-M *Ovis* 2, was likely watered at Lake Naivasha.

The lower values of Crescent Island Main do not indicate vertical mobility. While the progressive rain-out of ^{18}O up mountain slopes should result in lower $\delta^{18}O$ values at higher altitudes (Dansgaard 1964; Gonfiantini 2001), such patterns on Mt. Kenya were not found to be significant (Rietti-Shati, et al. 2000). In addition, Balasse, et al. (2008) reported consistent $\delta^{18}O$ values for rivers along an altitudinal transect on the Mau Escarpment. These results suggest that $\delta^{18}O$ values may not be useful in assessing altitudinal mobility in this part of the world. In addition, the lowest estimated $\delta^{18}O$ values of drinking water from the cattle specimens match $\delta^{18}O$ values reported for rivers near the site.

Ndabibi, situated on the Ndabibi Plain between the Mau Escarpment and Lake Naivasha's western edge, has cattle with average $\delta^{18}O$ values of 1.7 ± 1.4‰. Considerable variation in $\delta^{18}O$ values is displayed between individuals, but the range of variation *within* each individual is lower than 1.5‰. This variation is likely due to inter-annual climatic variability, resulting in quite different $\delta^{18}O$ values for teeth formed in different years (see Figure 11.7). The floor of the Rift Valley receives little rainfall, averaging about 600 mm annually, though the steep escarpments that border the valley floor receive considerably more precipitation. The alluvium of the Ndabibi Plain is recharged by the Marmonet River, which drains the Mau Escarpment. It does not reach Lake Naivasha. A sample from the river yielded a δ^{18} O_{VSMOW} value of -4.1‰ (Balasse, et al. 2008). Other rivers draining the escarpment that have been sampled for oxygen isotope analysis include Balbal Loana Toli at 2492 m, Narienda and Oltiani at 2579 m and 2550 m, respectively, and Ilkarampuni near the summit of the Mau at 2994 m. These samples yielded δ^{18} O_{VSMOW} values ranging from -4.3 to -4.5‰ (Balasse, et al. 2008). Estimates of drinking water $\delta^{18}O$ values for the cattle range from 0.2‰ to -2.8‰, indicating the cattle were ingesting water from rivers, but not those draining the Mau Escarpment. The low estimated value of -2.8‰ does match the $\delta^{18}O$ values reported for the Malewa river, however.

Like Ndabibi's cattle, the caprines from the site show significant variation between individuals. This may be due to variability in rainfall. It is possible that some sampled individuals were developing teeth during a period of marked seasonal variation in precipitation, for example, NDA *o/c* 1 M3 and *Ovis* 1 M2, both presumed to be sheep. In contrast, the other two specimens, also presumed to be sheep based on $\delta^{13}C$ values, show far less variation over the course of tooth mineralization. Given the variability in $\delta^{18}O$ values from modern specimens herded in one area, it is possible that the caprines from Ndabibi are indeed part of one herd. However, it would be most useful to compare the livestock from Central Rift Valley sites to modern livestock herded together in the Central Rift Valley. There may be significant differences in the variation of $\delta^{18}O$ values of individuals in mesic and arid environments, due to interindividual differences in water sources ingested as well as leaf water. Estimated drinking water $\delta^{18}O$ values for the Ndabibi caprines range from -2.1‰ to +1.6‰, suggesting that one individual may have been drinking from a nearby lake (likely Naivasha), while others were drinking river water, but like the cattle, not those draining the Mau Escarpment.

Farther north, all cattle specimens from Prolonged Drift have remarkably consistent $\delta^{18}O$ values, with a mean of 2.6 ± 0.7‰. The site is located on the floodplain of the Nderit River, southwest of Lake Nakuru. The Nderit River is a seasonal stream that drains into Lake Nakuru, but most of the lake's water is supplied by the Njoro River. All rivers supplying Lake Nakuru drain from the Mau Escarpment (Gichuhi 2014). The consistency of $\delta^{18}O$ values among the cattle suggests less inter-annual variation than seen, for example, at Ndabibi. While the subtle inter-individual variation in $\delta^{18}O$ values may suggest that there was either some variability in precipitation year-to-year, or differences in feeding among individuals, as some specimens have evidence for seasonal changes in $\delta^{18}O$ values, while others do not. Again, analysis of modern livestock herded together in this region is necessary to better interpret the variation among specimens. Estimates of $\delta^{18}O$ values of drinking water for the cattle at the site range from -1.2‰ to +0.2‰. These values fall between those recorded for nearby lakes and rivers. Caprines from the site exhibit similar estimated $\delta^{18}O$ values for drinking water, indicating herding in a similar environment.

Because of the substantial number of wild mammals at the site, as well as the mixed lithic and ceramic assemblages (S. Goldstein, pers. Comm. 2015), the subsistence strategies of the occupants have been difficult to interpret. Currently it is not possible to rule out that the animals were of the same cohort. While all are roughly the same age category, they could still have been born in different years, and thus reflect variation in year-to-year rainfall patterns as well as herding practices. Nor is it possible to rule out that the animals were obtained from different herders who were nearby.

Interpretation of Stable Carbon Isotope Values

In the Central Rift Valley, vegetation communities vary with altitude, and low elevation areas (below 1900 m) are characterized by dry savanna grassland with scattered *Acacia* bushland and *Euphorbia* woodland. Grasses primarily use the NADP pathway (e.g., *Themeda triandra*, *Digitaria scalarum* and *Hyparrhenia* sp.), though the NAD grass *Cynodon dactylon* is also common (Kiringe 1990). Forming an ecotone between the savanna and upland forest, *Tarchoanthus* (leleshwa) bushland exists at higher elevations, ~1900-2000 m, on the Rift margins, with *Acacia drepanolobium, Psidia arabica*, *Themeda* sp., and *Rhyncalytrum* (which uses the PCK pathway) (Maitima 1991). Between 2000-2300 m vegetation is dominated by *Tarchoanthus, Acacia, and Olea africana* bush. The forest zone spans 2300-2700 m and is dominated by *Juniperus procera* and *Podocarpus* spp. Higher elevations are characterized by open C_3 prairies with *Hagenia abyssinica* trees and bamboo (Ambrose and Sikes 1991). Elevations above below 2000m comprise exclusively C_4 grasses, while elevations above 3000m on Mt. Kenya are dominated entirely by C_3 grasses, and intermediate elevations are characterized by the presence of both C_3 and C_4 grasses (Tieszen, Senyimba, et al. 1979) . Soil humic acid $\delta^{13}C$ values also show the presence of both C_3 and C_4 species between 2000 and 3000 m (Ambrose and Sikes 1991).

Because of the proximity to the high escarpments bordering the Rift Valley, it is possible that herders from the Central Rift Valley sites moved their animals seasonally to higher elevations to access available vegetation. Because of the differences in vegetation communities with altitude, changes in $\delta^{13}C$ values can track the movement of livestock between high and low elevation areas.

The cattle from the Crescent Island sites, while they do show different $\delta^{18}O$ values, have very similar $\delta^{13}C$ values, indicating 100 – 91% C_4 diet at Crescent Island Main, and 100 – 88% C_4 diet at Crescent Island Causeway. Occupants from both sites clearly herded cattle exclusively in low-elevation areas. Caprines from Crescent Island Causeway indicate a 100 – 87% C_4 contribution to diet. while Crescent Island Main caprines indicate a similarly high contribution (100 – 88%). The caprines do show evidence for some slight seasonal variation in diet, this does not strongly indicate seasonal movement to higher elevations. Rather, this range of variation suggests that animals were feeding at low elevations year-round, and that the $\delta^{13}C$ values of the types of vegetation available varied seasonally.

The similarity between the two Crescent Island sites is striking. Crescent Island Causeway, an Eburran 5b site, has evidence that some Eburran groups had transitioned from foraging to stock-keeping (Ambrose 1984c). In fact, isotopic values indicate that Eburran 5b herding practices did not differ markedly from that of the Crescent Island Main SPN herders.

Similarly to the Crescent Island sites, cattle from Ndabibi also had consistently high $\delta^{13}C$ values, indicating a 100 – 89% C_4 contribution to diet, demonsrating that they fed at low elevations year-round. Ndabibi caprines showed considerably more intra-individual variation, though the $\delta^{13}C$ values remain high, above 1.7‰. This indicates a similar herding strategy to those from Crescent Island Main and Crescent Island Causeway, with pastoralists emphasizing herding animals at low elevations year-round.

Carbon isotope values of cattle from Prolonged Drift are quite high, indicating a range of 100 – 88% C_4 contribution to diet. The *Bos* $\delta^{13}C$ values are also remarkably consistent over time. Caprines, on the other hand, show some seasonal variation in $\delta^{13}C$ values, with values much lower than found in cattle. This contrasts with findings from other Central Rift Valley sites, where $\delta^{13}C$ values from caprines overlap with those of cattle. However, the caprines from Prolonged Drift may come from just one individual, so it is possible that interannual climatic variation, as well as variation in herding strategies, may be the cause of this difference.

Given the significant proportion of wild fauna at Prolonged Drift, the subsistence strategy of the site's creators has been difficult to interpret (Gifford, et al. 1980; Prendergast and Mutundu 2010). The results from the cattle at the site could suggest that the occupants were herding animals in ways very similar to those of pastoralists at nearby sites, clearly the result of pastoralist pursuits. However, the strong similarity among individual cattle specimens does not necessarily refute the hypothesis that the cattle at the site were obtained from nearby pastoralists. Because the $\delta^{13}C$ values for cattle from nearby sites are very similar, it is still possible that the Prolonged Drift occupants obtained cattle from pastoralists herding their livestock at low elevations, with their isotopic uniformity suggesting a high likelihood that all derived from very similar management practices.

Loita Plains Site

Narosura Cattle

Cattle at Narosura, on the edge of the Loita Plains, have an average $\delta^{18}O$ value of 0.1 ± 0.8‰, with values ranging from 1.7‰ to -1.1‰. Each specimen exhibits a range in values between 2.2‰ and 2.7‰. Some specimens show a seasonal pattern (Figure 11.17). The variation in $\delta^{18}O$ values in NS *Bos* 3 is perhaps most clearly a result of seasonal variations in aridity, and NS *Bos* 2 and NS *Bos* 4 show some seasonal variation to a lesser extent. NS *Bos* 1 shows variability, but a seasonal pattern is not distinguishable.

The cattle from Narosura overall show little variation in $\delta^{13}C$ values, exhibiting and average of 2.0 ± 0.5‰. Values range from 3.3‰ to 1.0‰, indicating a 97 – 82% C_4 contribution to diet. Carbon isotope values vary by as little as 0.5‰ and by as much as 1.5‰ within a single tooth. All individuals except NS *Bos* 1 and NS *Bos* 3 have overlapping $\delta^{13}C$ values.

The $\delta^{13}C$ values of NS *Bos* 1 and NS *Bos* 2 appear to covary with $\delta^{18}O$ values, while $\delta^{13}C$ values of NS *Bos* 3 and NS *Bos* 4 exhibit only very slight variation, not correlated with any changes in $\delta^{18}O$ values.

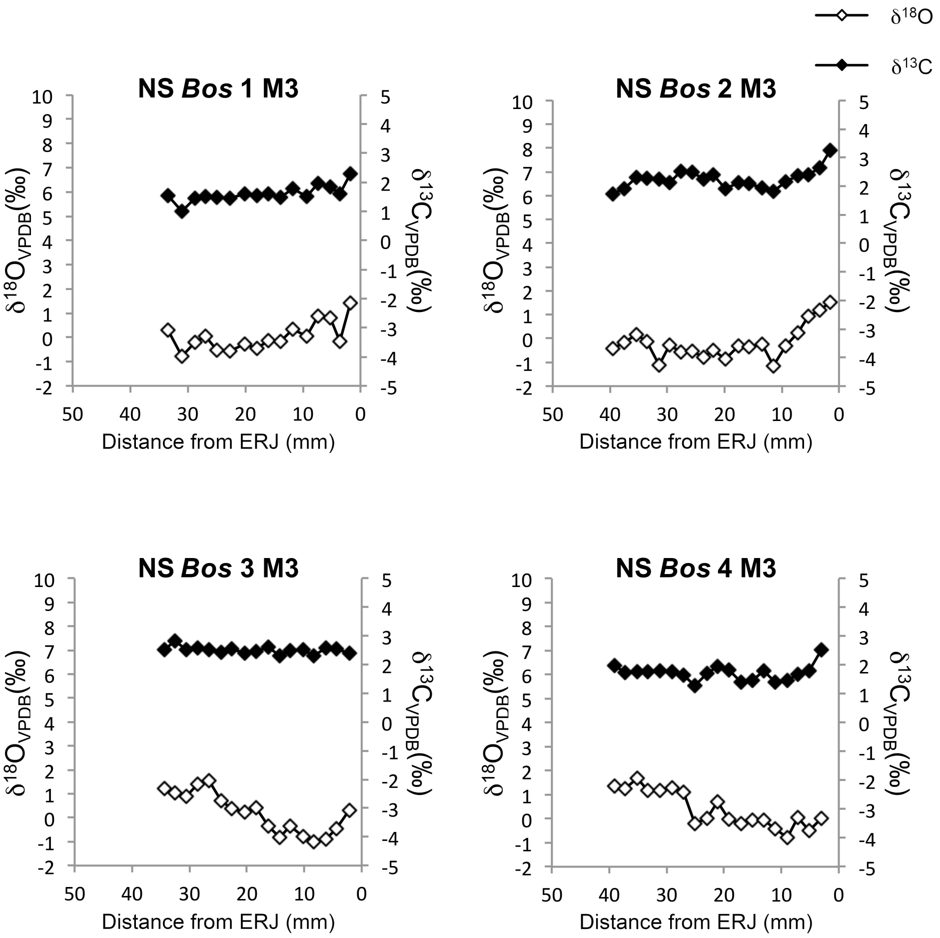


Figure 11.17: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from Narosura. ERJ= Enamel-root junction.

Narosura Caprines

In contrast to cattle, caprines at Narosura show considerable variation in δ^{13}C and δ^{18}O values (Figure 11.18). Three of the specimens were identified as sheep, and will be discussed separately from the goat specimen. The δ^{18}O of the caprines averages 5.4 ± 0.9‰, with values ranging from 7.0 – 3.6‰. NS *Ovis* 3 M2 exhibits the highest values, which do not overlap with the other specimens. The other specimens show significant overlap in oxygen isotope ratios. Intra-individual variation in δ^{18}O values suggests a weak seasonal pattern.

The three sheep have δ^{13}C values averaging 2.2 ± 1.0 ‰, with values ranging from 3.8‰ to 0.8‰. However, this low value is only reflected in one individual, NS *Ovis* 3 M2. This lowest values corresponds to an estimated 81% C_4 contribution to diet. The other two sheep do not exhibit values below 1.3‰. The goat specimen (NS *Capra* 1 M3) shows a markedly different pattern. Its δ^{13}C values range over 4‰, from, 0.0 to -4.2‰, with an average of -2.1 ± 1.4‰. These δ^{13}C values are quite low but within the range for sheep, as Balasse and Ambrose (2005a) list mean δ^{13}C values ranging from -3.1‰ to -1.3‰ for low-altitude grazing sheep. However, morphologically, the specimen appears to be a goat, as its mesial face narrows and curves slightly in the buccal direction (Balasse and Ambrose 2005a). It displays a seasonal pattern of variation in δ^{13}C values , as the values exhibit a sinusoidal pattern. However, this is not explicitly linked to changes in the oxygen isotope composition; only the superior half of the tooth shows some evidence for correlated variation, with δ^{18}O values decreasing with increasing δ^{13}C values, but this pattern does not continue past the last 20 mm to the ERJ.

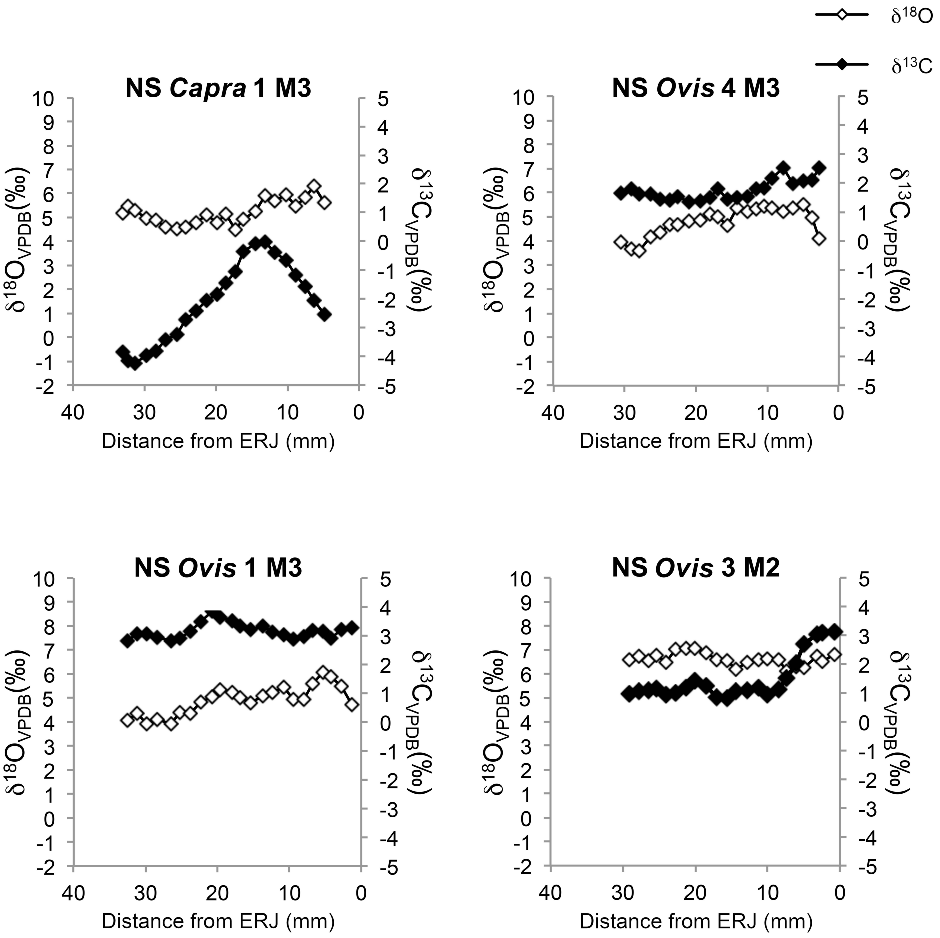


Figure 11.18: Results from carbon and oxygen isotope analysis of enamel of caprine specimens from Narosura. ERJ= Enamel-root junction.

Interpretation of Stable Oxygen Isotope Ratios

The site of Narosura is situated near the Narosura River, which drains the area east of the Loita Hills and disappears into the alluvium of the plains (Jones, et al. 1977). The perennial Ewaso Ngiro, the catchment of which is the Mau forest, is also nearby; it drains into Lake Natron. Cattle at Narosura exhibited average $\delta^{18}O$ values that are quite low compared to the cattle from the other archaeological sites, as well as those recorded in the modern cattle specimen discussed earlier. However, as discussed below, the carbon isotope values for those cattle are quite high, so it is possible that the low $\delta^{18}O$ values are a consequence of relatively rainy years during which the teeth were formed. The low $\delta^{18}O$ values are also likely to be a consequence of cattle drinking from rivers, as large lakes are not present in the area, and river water is depleted in ^{18}O relative to lake water. Around Narok, river and stream water $\delta^{18}O$ values range from -3.7 to -3.3 (Levin, et al. 2009). The $\delta^{18}O$ values of approximately 40 springs around Lake Magadi and Lake Natron ranged from -4.4‰ to -1.3‰, though most samples ranged from -4 to -3‰ (Hillaire-Marcel and Casanova 1987). Values for streams feeding into the Ewaso Ngiro River, near Lake Magadi, have values of -3.9‰ and -3.1‰, and values for the river increase as it flows south towards Lake Natron, yielding $\delta^{18}O$ values of -1.6‰ near Lake Magadi, and increasing to +0.6‰ close to Lake Natron (Hillaire-Marcel and Casanova 1987). Estimates of $\delta^{18}O$ values of drinking water for cattle from Narosura range from -2.7 to -3.2‰, suggesting that cattle were watered at springs or smaller streams rather than the Ewaso Ngiro River.

Caprines from Narosura show varied isotopic profiles. All specimens display slight evidence for seasonal variation in $\delta^{18}O$ values, though changes in these values do not always correlate with changes in $\delta^{13}C$ values, as discussed below. Estimates of mean $\delta^{18}O$ values of drinking water of sheep range from 0.9‰ to -0.4‰. These values suggest that caprines were primarily drinking from more evaporated sources than cattle, possibly rivers, though because caprines today are usually kept closer to the homestead, they may have been watered at smaller pools of water. The estimated mean $\delta^{18}O$ value of drinking water of the goat is +2.9‰, indicating it ingested water from a different source than did the sheep.

Interpretation of Stable Carbon Isotope Ratios

The Loita Plains region, where the site of Narosura is located, is also a primarily *Themeda triandra* grassland, and includes other NADP grasses such as *Digitaria* sp. and *Pennisetum mezianum*. However, NAD grasses including *Cynodon*, *Eragrostis*, and *Sporobolus* are also common. *Acacia* species are also common. On the hills the vegetation consists mostly of a fire community (*Heeria*, *Combretum*, *Tarchonanthus* sp.). Grasses on the hills include NAD taxa *Digitaria sporobolus*, *Eragrostis*, and *Cynodon*, as well as C_3 forbs of families Labiatae and Acanthaceae (Glover, et al. 1962). Given the similarity in grass species in low-altitude areas reported in studies of Central Rift vegetation (Ambrose and Sikes 1991; Kiringe 1990; Maitima 1991), the same averages for C_4 and C_3 plants are used.

The relatively drier environment of the semi-arid Loita Plains today has led Gramly (1975) to suggest seasonal mobility for the occupants of Narosura. The Loita Plains southwest of the Central Rift Valley are also categorized as an arid grassland, today receiving around 700 m of precipitation annually, though this varies considerably from year-to-year (Glover, et al. 1962; Glover, et al. 1964).

Overall, cattle from Narosura have lower $\delta^{13}C$ values relative to cattle from all other archaeological sites in this study, by roughly 1‰, equivalent to an approximately –6% decrease in C_4 consumption. The cattle from Narosura show little variation in $\delta^{13}C$ values among individuals or within individual teeth. Like other archaeological sites in the study, the cattle from Narosura were herded at low elevations year-round. However, the lower $\delta^{13}C$ values may indicate consumption of NAD and PCK grasses in a more arid environment.

Caprines at Narosura show the most inter- and intra-individual variation of all caprines from the archaeological sites in this study (Figure 11.18). Two specimens, NS *Ovis* 1 and NS *Ovis* 4, show constant $\delta^{13}C$ and $\delta^{18}O$ values over time, but NS *Capra* 1 and NS *Ovis* 3 show significant variability in $\delta^{13}C$ values, which is not clearly correlated with changes in $\delta^{18}O$ values. The marked rise in $\delta^{13}C$ values in the last 10 mm of enamel closest to the ERJ in NS *Ovis* 3 M2 suggests a migration *from* a higher altitude to a lower–lying area with a higher percentage of C_4 grasses. NS *Capra* 1 M3 shows a clear seasonal cycle in the C_4 contribution to diet, so it is possible that this individual was herded to different areas seasonally, a hypothesis supported by the markedly different estimated $\delta^{18}O$ value of drinking water. It is also possible that the individual was consuming seasonally available C_4 plants during wet seasons.

Athi-Kapiti Plains Sites

GvJm44 Cattle

Cattle from the site of GvJm44, or Vaave Makongo, at Lukenya Hill on the Athi-Kapiti Plains, show significant inter- and intra-tooth variation in $\delta^{18}O$ values, with an average of 2.4 ± 1.2‰ and range from 4.3‰ to -0.5‰. The specimen showing the highest range of variation (2.8‰) is GvJm44 *Bos* 4 M3. Only GvJm44 *Bos* 3 shows a seasonal pattern of variation (Figure 11.19).

The $\delta^{13}C$ values average 3.3 ± 0.5‰. Only GvJm44 *Bos* 3 M3 shows a range of variation over 1‰. The other cattle specimens show remarkably constant and high $\delta^{13}C$ values, ranging from 4.4‰ to 2.3‰ among all specimens, indicating a 100 – 91% C_4 contribution to the diet. While mean values of C_4 and C_3 plants have been measured for Nairobi National Park (Cerling, et al. 2003), the value of C_4 plants is -11.8, and when corrected by +1.4‰ to compensate for the fossil fuel effect, this estimate differs by only 0.2‰ from values for the Central Rift Valley. Therefore, the same values are used to estimate the percent contribution of C_4 plants in the diets of animals from the plains sites. Carbon isotope ratios do not vary with changes in oxygen isotope values.

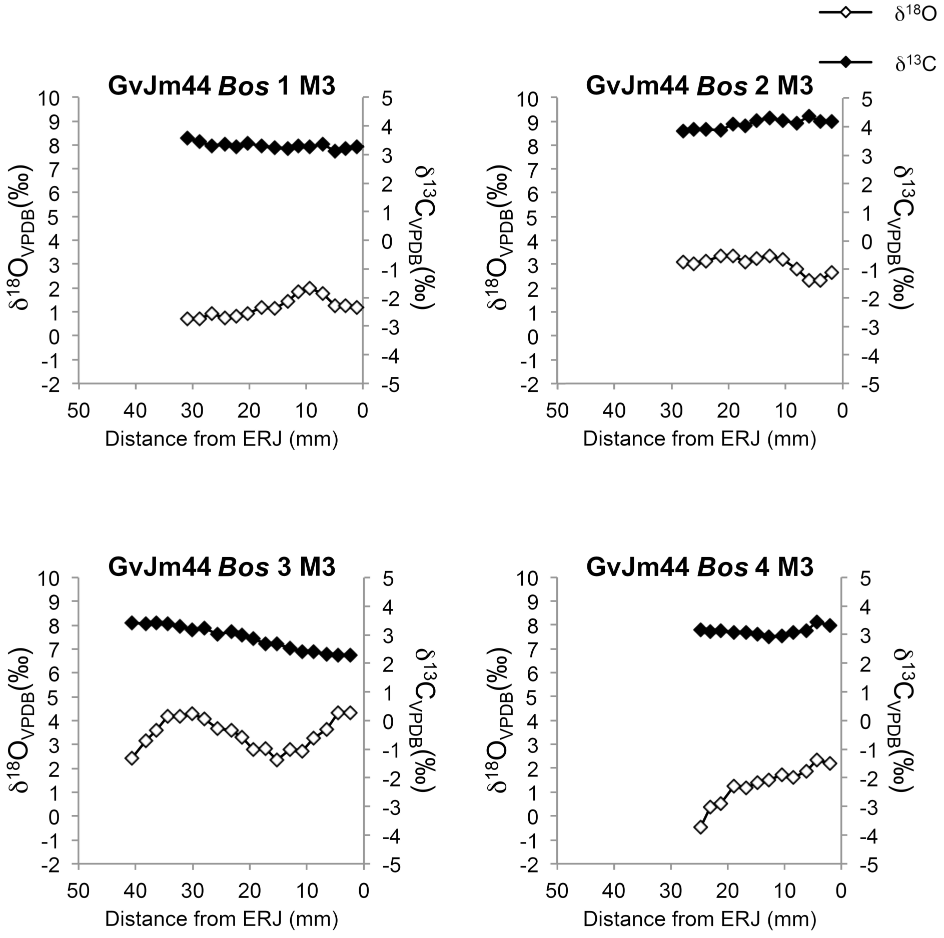


Figure 11.19: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from GvJm44. ERJ= Enamel-root junction.

GvJm52 Cattle

Cattle from GvJm52, also from Lukenya Hill, have δ^{18}O values, averaging 2.5 ± 0.6‰, ranging from 3.6‰ to 0.8‰. The δ^{18}O values of all specimens overlap over time, and all specimens show over 1.2‰ variation, with GvJm52 showing over 2‰ variation. GvJm52 *Bos* 1 and *Bos* 3 show evidence for seasonal variation, but *Bos* 2 and *Bos* 4 do not show a clear seasonal signal (Figure 11.20).

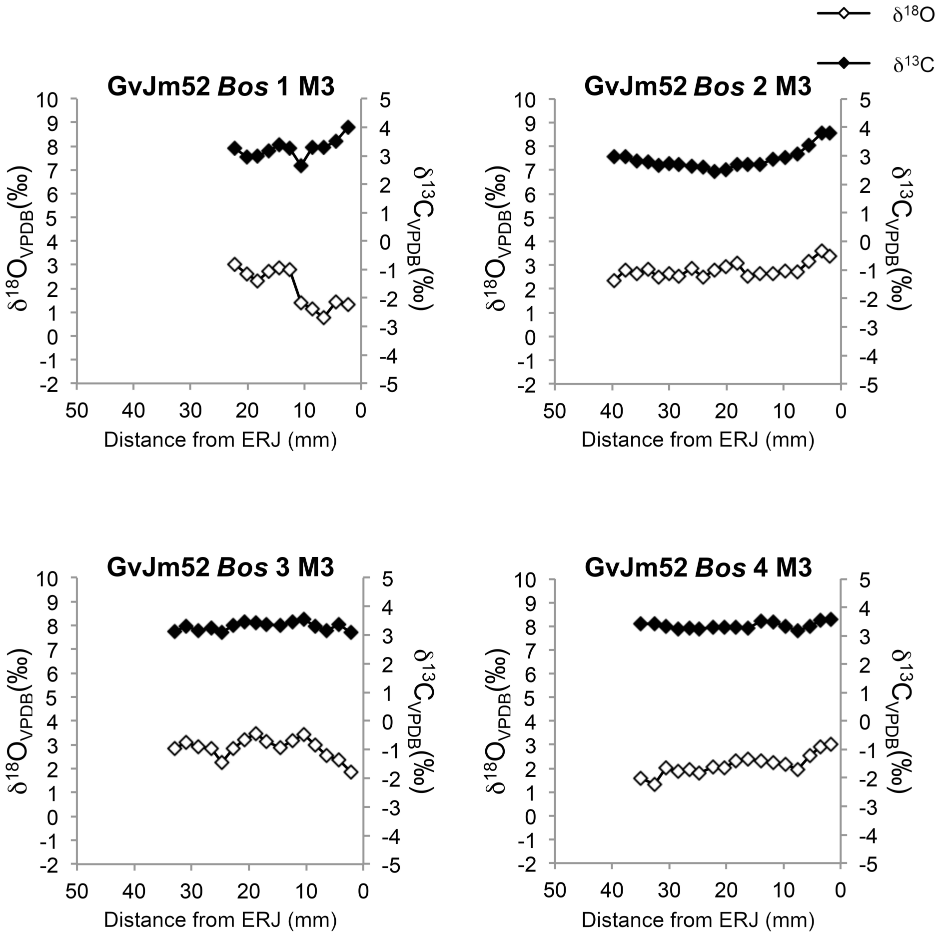


Figure 11.20: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from GvJm52. ERJ= Enamel-root junction.

Cattle δ^{13}C values are constant over span sampled, with an average of 3.2 ± 0.3‰, ranging from 4.0‰ to 2.5‰, indicating a 100 – 92% C_4 contribution to diet. For GvJm52 *Bos* 2, *Bos* 3, and *Bos* 4, δ^{13}C values positively covary (though showing relatively low variation) with δ^{18}O values. In contrast, GvJm52 *Bos* 1 M3 δ^{13}C values increase as δ^{18}O values decrease.

GvJm52 Caprines

Caprines from GvJm52 show significant inter- and intra-tooth variation in oxygen isotope composition, with an average $\delta^{18}O$ value of 5.0 ± 1.3‰ (Figure 11.21). All specimens overlap in $\delta^{18}O$ values, except for GvJm52 *Capra* 1, which has an average of 7.2‰, ranging from 8.0‰ to 6.5‰. The other caprines have values ranging from 5.6‰ to 3.1‰. GvJm52 *Capra* 1, as well as GvJm52 *Ovis* 1 and GvJm52 *O/C* 2, show strong evidence for seasonal variation in $\delta^{18}O$ values; while GvJm52 *Ovis* 2 also shows variation, it is not clearly cyclical.

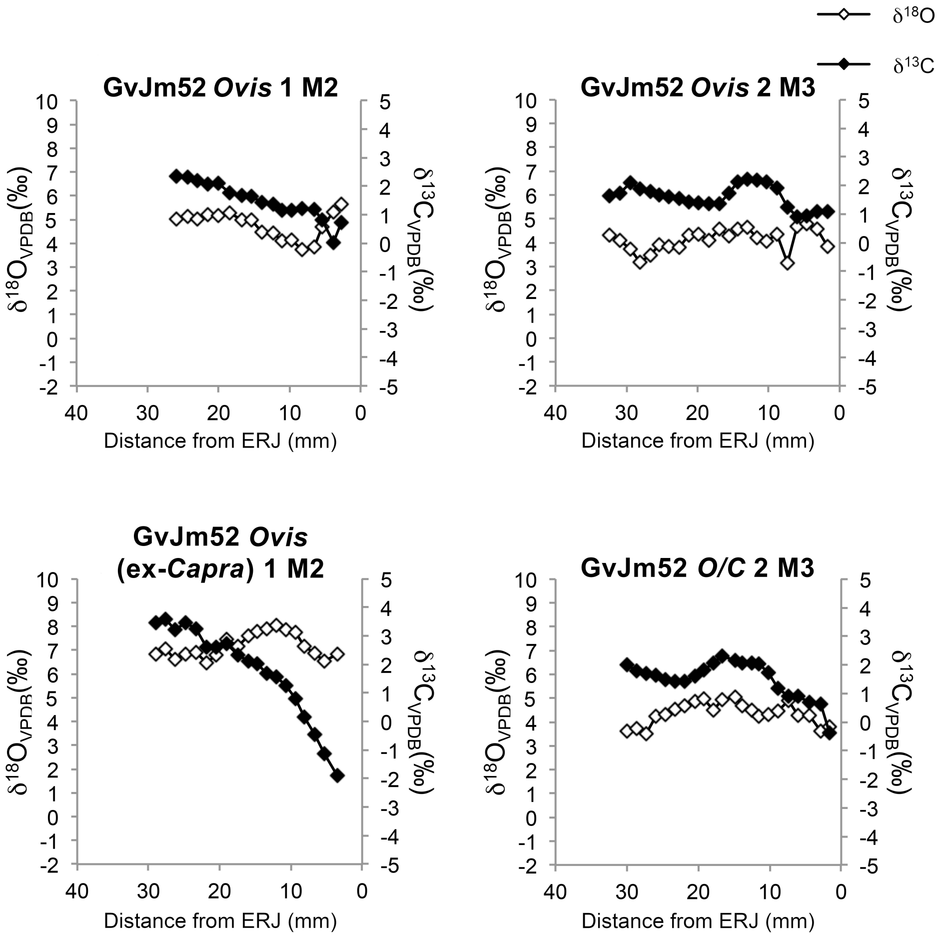


Figure 11.21: Results from carbon and oxygen isotope analysis of enamel of caprine specimens from GvJm52. ERJ= Enamel-root junction.

All specimens have overlapping $\delta^{13}C$ values except for the lowest values of GvJm52 *Ovis* ex-*Capra* 1 M2, which occur toward the ERJ. The average $\delta^{13}C$ value for all specimens is 1.6 ± 0.9‰, ranging from 3.6‰ to -1.9‰ (both from GvJm52 *Ovis (*ex-*Capra*) 1), showing a 99 – 63% C_4 contribution to diet. Based upon the relatively high carbon isotope values, all actually appear to be sheep (Balasse and Ambrose 2005a).

Specimens GvJm52 *Ovis* 2 and GvJm52 o/c 2 show seasonal changes in δ^{13}C values. GvJm52 *Ovis* 1 and GvJm52 *Capra* 1 both show a dramatic decrease in δ^{13}C values over time, which is not correlated with changes in δ^{18}O values.

Interpretation of Stable Oxygen Isotope Ratios

On the Athi-Plains, GvJm44 and GvJm52 are two sites from Lukenya Hill. Nearby Nairobi is wetter, currently receiving 980 mm of precipitation annually (Kenya Meteorological Service). The Athi River's source waters come from the Aberdare Forest, and it also drains the area around Nairobi. Many seasonal streams also exist in the area. The cattle from the two sites show quite similar averages and ranges, reflecting herding in a similar habitat. At Lukenya Hill rainfall seldom exceeds 500 mm per year.

Estimates of the δ^{18}O value of drinking water of the cattle specimens range from -0.1‰ to -1.9‰. To my knowledge, no measurements of the oxygen isotope composition of water sources in the immediate area exist, aside from water samples collected in the Tsavo-Athi drainage, some 200 km away from Lukenya Hill, measure -3.7‰ ± 1.3‰ (Passey and Cerling 2002). A sample from the Athi River, 49 km east of Machakos district has a value of -3‰, and the Nairobi River has a value of -5.6‰ (Levin, et al. 2009). These, as well as measurements from other water sources in the study region, consistently show that large lakes exhibit the highest δ^{18}O values, above 0.0‰, while large rivers have lower values, and springs and small streams can have the lowest values. Cattle from the Lukenya Hill sites were likely drinking from rivers.

The clear seasonal variation of $\delta^{18}O$ values in some specimens (e.g. GvJm44 Bos 3, GvJm52 Bos 1) but not others (e.g. GvJm52 *Bos* 2) may be a consequence of interannual variability in seasonal variation in precipitation over the lifetimes of different animals. Alternatively, it is possible that some animals may have been herded elsewhere during the time of tooth formation and later moved to the Lukenya Hill area. Whether this isotopic variation is a consequence of yearly shifting mobility strategies of one herder or exchange between different groups, is not demonstrable with isotopic methods.

GvJm52 caprines have a mean $\delta^{18}O$ value of 5.0 ± 1.3‰, similar to caprines from the other sites in different environs. Specimens GvJm52 *Ovis* 2 and GvJm52 *o/c* 2 show a seasonal changes in $\delta^{13}C$ values over time. In both cases, $\delta^{13}C$ values decrease with increasing $\delta^{18}O$ values, indicating sheep feeding upon more C_3 plants during dry seasons. GvJm52 *Ovis* 1 and GvJm52 *Ovis* (ex-*Capra*) 1 both show a dramatic decrease in $\delta^{13}C$ values over time, and this is *not* associated with changes in $\delta^{18}O$ values. In particular, the marked decrease in $\delta^{13}C$ values GvJm52 *Ovis* (ex-*Capra*) 1 suggests mobility to higher elevations. Estimates of $\delta^{18}O$ values of drinking water of sheep range from -0.4‰ to -0.7‰. Only GvJm52 *Ovis* (ex-*Capra*) 1 has positive $\delta^{18}O$ values, with a mean of 1.2‰, indicating it was watered at different sources than the other individuals in the sample during formation of the tooth. Given the high $\delta^{18}O$ values in that specimen, it is possible that particularly dry conditions prompted the herder to move the herd to higher elevations to access adequate pasture for the animals.

Interpretation of Stable Carbon Isotope Ratios

The three archaeological sites located on the Athi-Kapiti and Loita Plains are situated in environments without major topographic changes in their vicinities. Both GvJm44 and GvJm52 are located close to Lukenya Hill. The Athi-Kapiti plains region, stretching east from Nairobi, is a large, mesic grassland with riparian forests. With elevations between 1000 – 1500 m, it is a near 100% C4 grassland (Tieszen, Senyimba, et al. 1979). NADP grasses dominate, and common species include *Themeda triandra*, *Hyparrhenia* sp., *Digitaria macroblephara, Bothriochloa insulpta* (Boutton, et al. 1988a; Hattersley and Browning 1981), and others such as *Pennisetum mezianum*, which is preferred less by herbivores than *T. triandra* (Tieszen, Hein, et al. 1979). Acacias comprise most of the woody growth.

The cattle from GvJm44 have very high and stable $\delta^{13}C$ values, with an estimated 100 – 91% contribution of C_4 plants to the diet. These consistently high values over the entire course of tooth mineralization indicate that, like the livestock from the Central Rift Valley sites, the cattle on the Athi-Kapiti Plains were herded at low elevations over the whole year. Caprines analyzed from the Lukenya Hill sites are limited to those from GvJm52. In contrast to caprines from Central Rift Valley sites, GvJm52 sheep show a great deal of inter- and intra-individual variation in $\delta^{13}C$ values. In GvJm52 *Ovis* 2 and GvJm52 *o/c* 2, $\delta^{13}C$ values covary with $\delta^{18}O$ values, indicating an increased reliance on C_3 vegetation or NAD and PCK grasses in arid seasons. Two specimens show a steady decrease in $\delta^{13}C$ values despite changes in

$\delta^{18}O$ values (GvJm52 *Ovis* 1 and GvJm52 *Capra* 1). The significant change from 3.6‰ to -1.9‰ in GvJm52 *Capra* 1, which is likely a sheep, based on its $\delta^{13}C$ values (Balasse and Ambrose 2005a), suggests mobility to higher elevations. However, the other specimens show year-round herding at low elevations.

Evidence for Bimodal Rainfall Patterns

Some caprines show patterns of rising and falling $\delta^{18}O$ values along the length of the crown. Today, the bimodal rainfall pattern in East Africa allows year-round lactation of the cattle, permitting pastoralists to rely nearly entirely upon milk as a food source (Dahl and Hjort 1976; Western and Finch 1986). Marshall (1990c) suggested that the onset of the bimodal rainfall pattern characteristic of most of Kenya allowed specialized pastoralism to take place. Evidence for this precipitation pattern is sparse, indicated primarily by the contrast between one clear rainy season visible from the Naivasha core from 9,200 until 2500 BP, followed by a sequence of indistinct laminations, likely reflecting the presence of two rainy seasons (Richardson and Richardson 1972). Recent work by Upex (2009) suggests that the bimodal pattern, detectable as peaks of hypoplasias along the tooth that broadly align with dry seasons, was in place at least 2,500 BP, and is detectable in caprines from Narosura and Lemek North East.

Evidence for a bimodal pattern in the modern specimens from this study is only detectable in one tooth, the second molar from GvJhB100 *Ovis* 1, though the rainfall pattern from the time of tooth growth and mineralization has a slight bimodal pattern, most evident in $\delta^{13}C$ values (Figure 11.4). However, no such pattern was found in Balasse and Ambrose's (2005b) study of livestock from Elmenteitan archaeological sites in the Central Rift Valley.

Several archaeological caprine teeth in this study do exhibit some evidence for a bimodal precipitation pattern. Specimens from sites in the Central Rift Valley and the Athi-Kapiti plains show this pattern, including CIC- *Ovis* 4, CI-M *Ovis* 2, CI-M *Ovis* 3, NDA *Capra* 1 M2, NDA *Ovis* 1 M2; and GvJm52 *Bos* 1 M3, and GvJm52 *Bos* 3 M3, respectively.

Teeth showing evidence for a bimodal rainfall pattern may be contrasted with caprine teeth exhibiting a clear unimodal pattern of variation. Figure 11.22 shows two teeth from one sheep from the site of Cheia in Romania (Tornero, et al. 2013). The duration of an entire annual cycle is indicated by the grey arrow, though a complete cycle is not evident in CHE *Ovis* 1 M2.

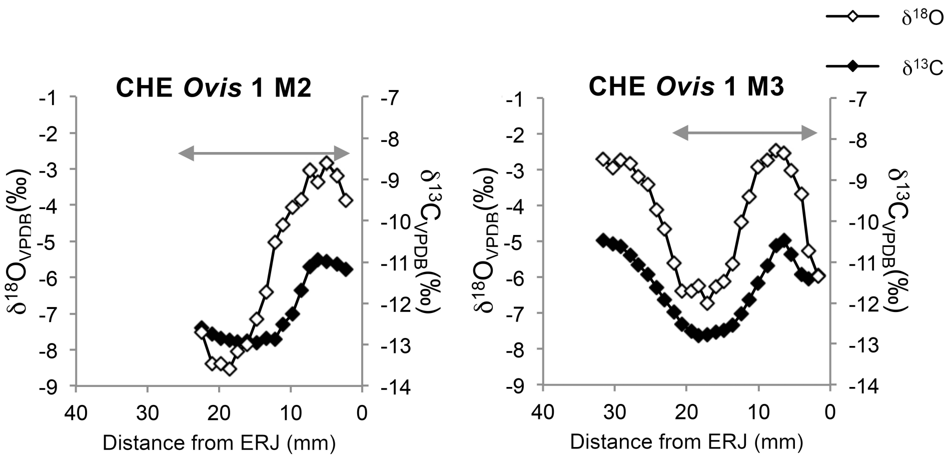


Figure 11.22: Results from carbon and oxygen isotope analysis of enamel of cattle specimens from GvJm52. ERJ= Enamel-root junction.

The Kenyan archaeological specimens exhibiting possible evidence for a bimodal rainfall pattern are shown in Figure 11.23. Because of the degree of variation in rainfall both within and between years, $\delta^{18}O$ values over the course of tooth growth may not show a strong sinusoidal pattern, with the same $\delta^{18}O$ values exhibited each dry or rainy season. However, in the case of the Kenyan archaeological material, we may visually identify multiple peaks and valleys in the sequence of $\delta^{18}O$ values along the tooth crown that signal the presence of two dry and two rainy seasons within the length of a tooth crown that roughly corresponds to a year of growth. For example, around 36 mm of the tooth crown of sheep second molars is formed in a year (Balasse, Obein, et al. 2012).

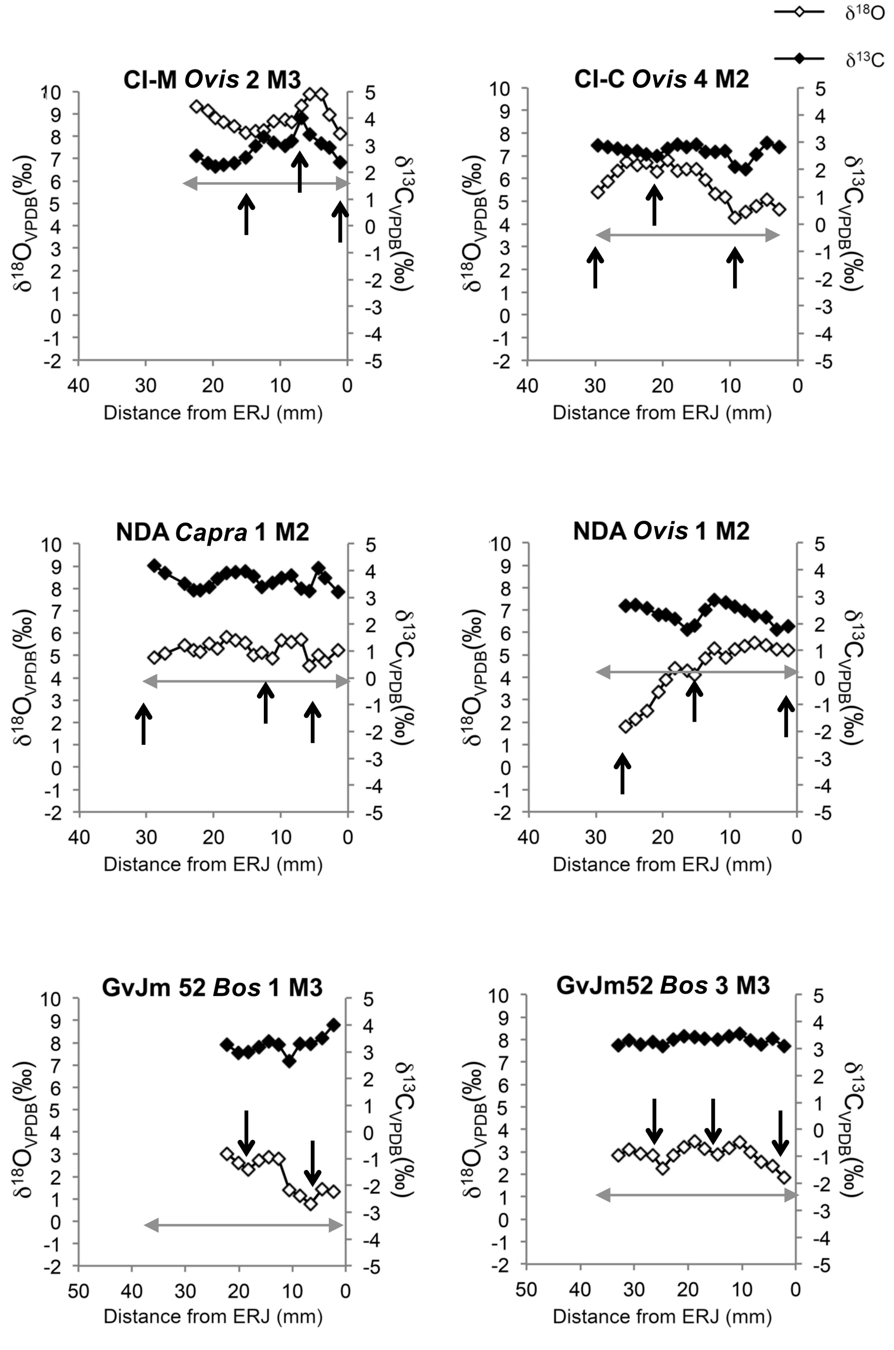


Figure 11.23: Cattle and caprine specimens from this study that exhibit evidence for a bimodal rainfall pattern. Grey arrows indicate the length of crown that should at minimum display a year-long cycle. Black arrows indicate dips in $\delta^{18}O$ values, indicating a rainy season.

Not all specimens show evidence for a bimodal rainfall pattern, and this is likely due to the degree of interannual variability in precipitation. However, the pattern in some specimens indicates that this rainfall pattern was indeed present 2500 years ago in the Central Rift Valley and Athi-Kapiti Plains.

Summary

The consistently low $\delta^{13}C$ values reveal that both cattle and caprines from SPN sites, the single Eburran 5b locality, and Prolonged Drift were not seasonally herded to higher altitudes, seasonally or otherwise. Similar results have been reported by Balasse and Ambrose (2005b) for Elmenteitan sites. This emphasis on herding at low elevations is interesting, as it suggests that the Rift Valley and neighboring plains many have been productive enough to support pastoralism year-round. If there were no need to move animals seasonally to higher elevations, livestock would have been spared long journeys into mountainous areas. Herders relying on cattle for milk would have avoided avoid such trips, as cattle who move long distances have lower milk yields (Coppolillo 2000). Thus, the isotopic values may reflect the optimal solution for grazing, even in the case of Narosura, in circumstances of relatively low human and livestock population densities. This will be discussed further in Chapter 13.

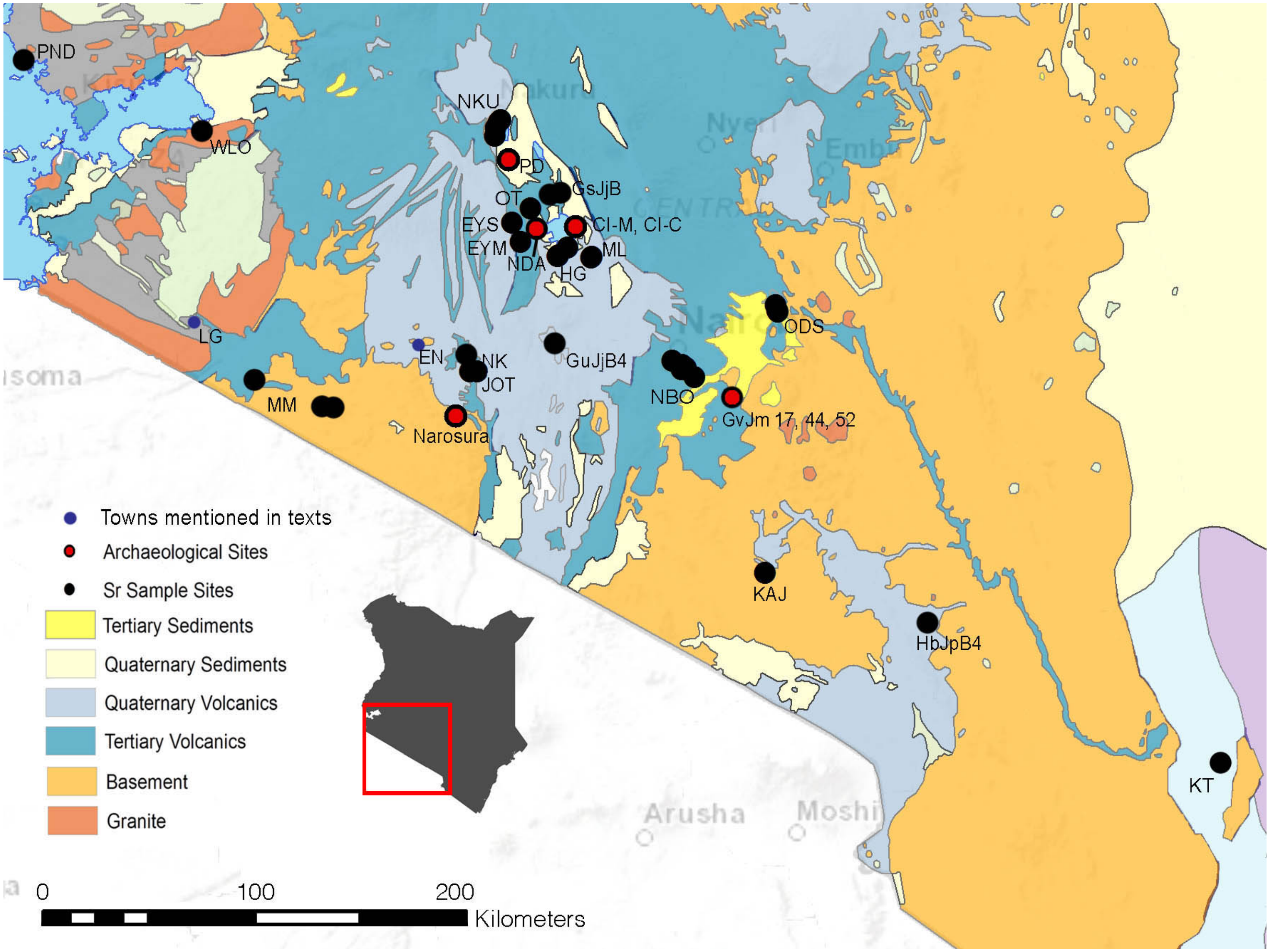
In general, while all cattle from plains sites show consistently high $\delta^{13}C$ values, caprines from these sites are more variable. This could be due to several factors. First, the longer mineralization time of cattle tooth enamel may result in some attenuation of seasonal isotopic signals. Second, it is also more likely that caprines, especially sheep, are consuming a variety of plants that vary in their combined $\delta^{13}C$ values over the course of the year, while the cattle are consuming only grass. Another source of variation may be a consequence of cattle and caprines having been herded in different areas. Cattle may have been strategically shifted to optimal grazing areas, while the hardier caprines may have been herded in other, relatively marginal, environments. Caprines often remain close to homesteads rather than making long distance migrations with more valuable large livestock (Dahl and Hjort 1976). If animals with more specialized diets, such as cattle, are consistently moved to more productive areas, they may also exhibit fewer signs of seasonal changes in vegetation quality as well as aridity (Western 1982). The consistently high $\delta^{13}C$ values for all livestock samples suggests that major seasonal movements to higher elevations did not occur among all livestock species, but minor differences in $\delta^{13}C$ values may suggest some divergences in herding strategies.

Unlike evidence for altitudinal mobility, evidence for exchange of livestock is much more difficult to detect. Differences in the patterns of carbon and oxygen isotope values in some specimens from a single site may be a consequence of interannual variability in seasonal precipitation. Alternatively, it is possible that some animals may have been herded elsewhere during the time of tooth formation and later moved to the site local. Whether a consequence of yearly shifting mobility strategies of one herder or exchange between different groups, is not detectable using these isotopic methods.

CHAPTER 12: STABLE STRONTIUM ISOTOPE ANALYSES: RESULTS AND INTERPRETATION

In this chapter I present results and interpretations of stable strontium isotope analysis on livestock tooth enamel. As with the $\delta^{18}O$ and $\delta^{13}C$ patterns presented above, it is useful to examine the $^{87}Sr/^{86}Sr$ ratios of modern livestock with known life histories as a comparative sample. In particular, it is important to test whether movements between geologic substrates in the study area do indeed manifest in differences in $^{87}Sr/^{86}Sr$ ratios. Next, I present results of isotopic analyses of modern and archaeological faunal remains for a strontium isoscape. The results of the strontium isotope analysis of archaeological livestock tooth enamel are presented in the latter half of this chapter. Similar to the organization of the previous chapter, I interpret herding patterns based upon mobility of livestock across geologic substrates within each main region of study: the Central Rift Valley, the Loita Plains, and the Athi-Kapiti Plains, as each of these areas exhibit a different geologic setting (Figure 12.1).

Figure 12.1: Geologic map of study area with sites and sample locations. Codes for sample locations outlined in Table 1. Codes for modern livestock locations: EN= Ewaso Ngiro town; LG = Lolgorien.



PND
WLO
NKU
PD
GsJjB
OT
EYS
CI-M, CI-C
EYM
NDA
ML
HG
ODS
LG
EN
NK
JOT
GuJjB4
NBO
GvJm 17, 44, 52
MM
Narosura
KAJ
HbJpB4
KT
Nakuru
Nyeri
Embu
CENTRAL
Narok
Arusha
Moshi
Musoma
● Towns mentioned in texts
● Archaeological Sites
● Sr Sample Sites
Tertiary Sediments
Quaternary Sediments
Quaternary Volcanics
Tertiary Volcanics
Basement
Granite
0
100
200
Kilometers

Table 12.1: Sample locations, tissue type, antiquity, and $^{87}Sr/^{86}Sr$ ratios for each sample. Codes are listed in Figure 12.1

Site Code	**Site Name**	**Sample**	**Tissue**	**Age**	**Final $^{87}Sr/^{86}Sr$**	**Estimated uncertainty**
PND	Pundo	PND Trag 1 M1	Enamel	Arch.	0.70912	±0.00003
		PND HYST 1 I1	Enamel	Arch.	0.71037	±0.00004
WLO	Wadh Lang'o	WLO Red 1	Enamel	Arch.	0.71051	±0.00004
		WLO Red 2	Enamel	Arch.	0.70903	±0.00003
		WLO Red 3	Enamel	Arch.	0.71047	±0.00004
		WLO Red 4	Enamel	Arch.	0.71028	±0.00004
MM	Maasai Mara	MM-1	Bone	Modern	0.70791	±0.00006
		MM-6	Bone	Modern	0.70865	±0.00004
		MM-8.1	Bone	Modern	0.70843	±0.00005
		MM-8.2	Bone	Modern	0.70857	±0.00006
		MM-8.4	Bone	Modern	0.70860	±0.00004
NK	Narok	NK-1	Enamel	Modern	0.70645	±0.00003
		NK-2	Bone	Modern	0.70668	±0.00003
JOT	Boma: J. Ole Tumpuya	JOT-1	Enamel	Modern	0.70646	±0.00003
NKU	Nakuru National Park	NKU-4a	Bone	Modern	0.70631	±0.00003
		NKU-4b	Enamel	Modern	0.70644	±0.00003
GsJjB	GsJjB	GsJjB12 PRO 1 P3	Enamel	Modern	0.70750	±0.00003
		GsJjB316 MAD P3	Enamel	Modern	0.70664	±0.0001
		GsJjB326 PRO 1 M1	Enamel	Modern	0.70751	±0.00003

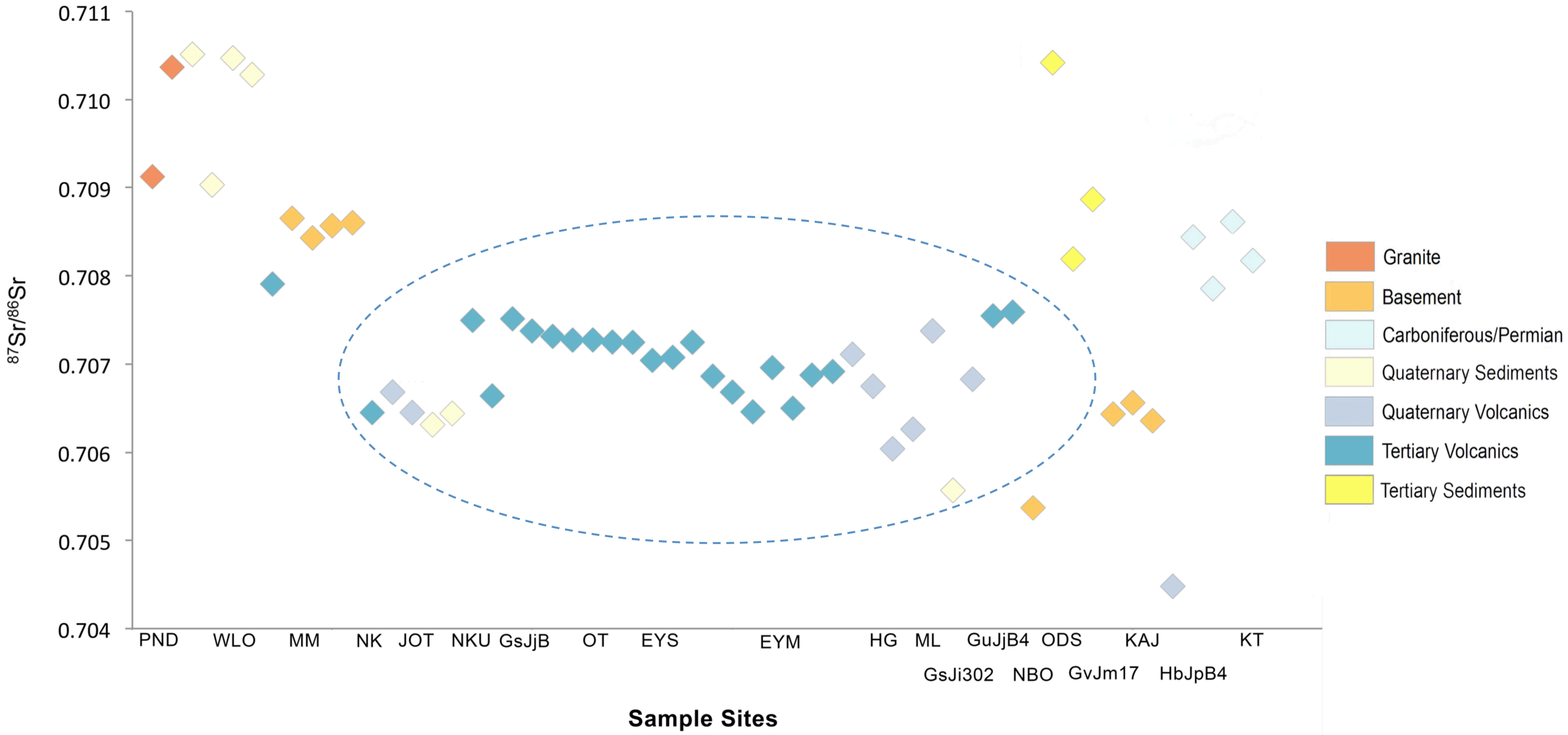
Table 12.1 continued

Site Code	**Site Name**	**Sample**	**Tissue**	**Age**	**Final $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$**	**Estimated uncertainty**
OT	Ol Tepesi	OT PRO 1 I1	Enamel	Arch.	0.70738	±0.00003
		OT PRO 2 I1	Enamel	Arch.	0.70732	±0.00003
		OT PRO 3 I1	Enamel	Arch.	0.70727	±0.00003
		OT PRO 4 I1	Enamel	Arch.	0.70727	±0.00003
		OT PRO 5 I1	Enamel	Arch.	0.70725	±0.00003
		OT HET 1	Enamel	Modern	0.70725	±0.00003
EYS	Enkapune Ya Sauli	EYS PRO 1 I1	Enamel	Arch.	0.70704	±0.00003
		EYS RED 1 P2	Enamel	Arch.	0.70708	±0.00003
		EYS RED 2 P4	Enamel	Arch.	0.70725	±0.00003
EYM	Enkapune Ya Muto	EYM Tac 1 I1	Enamel	Arch.	0.70686	±0.00004
		EYM Tac 2 I1	Enamel	Arch.	0.70668	±0.00004
		EYM Tac 3 I1	Enamel	Arch.	0.70646	±0.00003
		EYM Tac 4 I1	Enamel	Arch.	0.70696	±0.00003
		EYM Tac 5 I1	Enamel	Arch.	0.70650	±0.00003
		EYM Oto 1 I1	Enamel	Arch.	0.70688	±0.00004
		EYM Oto 2 I1	Enamel	Arch.	0.70691	±0.00004
HG	Hell’s Gate National Park	HG-1A	Bone	Modern	0.70711	±0.00003
		HG-1B	Enamel	Modern	0.70675	±0.00003
		GtJjB79 PRO 1 M3	Bone	Modern	0.70604	±0.00003
		GtJjB55.1 PRO 1 I1	Bone	Modern	0.70626	±0.00003

Table 12.1continued

Site Code	Site Name	Sample	Tissue	Age	Final ^{87}Sr/^{86}Sr	Estimated uncertainty
ML	Mt. Longonot National Park	ML-1	Bone	Modern	0.70738	±0.00004
GsJi302	West of Lake Naivasha	GsJi302	Enamel	Modern	0.70557	±0.00004
GuJjB4	Suswa lava tube	GuJjB4 PRO 1 I1	Enamel	Modern	0.70683	±0.00003
NBO	Nairobi National Park	NBO-1	Bone	Modern	0.70755	±0.00004
		NBO-4A	Bone	Modern	0.70759	±0.00004
ODS	Ol Donyo Sabuk	ODS 3A	Enamel	Modern	0.70537	±0.00003
GvJm 17	Lukenya Hill	GvJm17 Rod 4	Enamel	Modern	0.71042	±0.00004
		GvJm17 Rod 6	Enamel	Modern	0.70819	±0.00004
		GvJm17 Rod 7	Enamel	Modern	0.70887	±0.00004
KAJ	Kajiado District	KAJ Aco Fem 4-7	Bone	Modern	0.70643	±0.00004
		KAJ Aco Fem 20-23	Bone	Modern	0.70656	±0.00004
		KAJ Aco Fem 24-27	Bone	Modern	0.70636	±0.00003
HbJpB4	Umani springs, near Kibwezi	TRAG 1 P3	Enamel	Modern	0.70448	±0.00003
KT	Kathuva	KT MAD 1 M2	Enamel	Arch.	0.70844	±0.00004
		KT MAD 2 M3	Enamel	Arch.	0.70786	±0.00004
		KT MAD 3 M3	Enamel	Arch.	0.70862	±0.00004
		KT MAD 4 M3	Enamel	Arch.	0.70817	±0.00005

Figure 12.2: Plot of $^{87}Sr/^{86}Sr$ ratios of microfauna from sample sites presented in Figure 12.1. Samples from Central Rift Valley locations are surrounded by the dashed line.


0.711
0.710
0.709
0.708
0.707
0.706
0.705
0.704
$^{87}Sr/^{86}Sr$
PND
WLO
MM
NK
JOT
NKU
GsJjB
OT
EYS
EYM
HG
ML
GuJjB4
ODS
KAJ
KT
GsJi302
NBO
GvJm17
HbJpB4
Sample Sites
Granite
Basement
Carboniferous/Permian
Quaternary Sediments
Quaternary Volcanics
Tertiary Volcanics
Tertiary Sediments

The $^{87}Sr/^{86}Sr$ ratios of microfauna show clear similarities with the underlying geology of the collection sites. Similar to reports by Rogers, et al. (2000) samples closer to the most recent Pleistocene Holocene volcanics of the Central Rift Valley exhibit some of the lowest ratios, under 0.7070, while samples closer to the older Tertiary volcanics, formed in the Miocene and Pliocene (France 1987) on the sides of the rift exhibit slightly higher $^{87}Sr/^{86}Sr$ ratios ranging from 0.7065 to 0.7075, including samples from Ol Tepesi and Enkapune Ya Sauli (Figure 12.2, Table 12.1).

Archaeofaunal remains from two localities near Lake Victoria were sampled. All samples from the site of Wadh Lang'o were collected from Quaternary sediments from Lake Victoria and some samples were from a geologic area that was surrounded by a completely different system. However, all values are quite high, averaging 0.71007 ± 0.0007 (1σ), indicating that the dominant geology of the Neoarchean Nyanzian system is contributing most of the bioavailable strontium in the area. Similarly high values, ranging from 0.7102–0.7236, have been reported for the Archaean Kavirondian system, also a component of the Tanzanian craton (Bell and Dodson 1981). Samples from the site of Pundo, situated on the Nyanzian system have similarly high values.

To the south, samples from Maasai Mara, situated on the Precambrian rocks of the Mozambique Belt, have high $^{87}Sr/^{86}Sr$ ratios, ranging from 0.70791 to 0.70860. These relatively high ratios show that, even if there is some effect of young volcanic ash transported by the predominantly east-to-west blowing winds, this effect does not completely override the local strontium signal of the basement rocks.

East of the Central Rift, samples also exhibit higher values. Samples from Nairobi National Park, situated on Pliocene volcanics, range from 0.70755 to 0.70759.

Just southeast of Nairobi, on the boarder of Miocene volcanics and the Precambrian Mozambique Belt, samples from Lukenya Hill yield higher $^{87}Sr/^{86}Sr$ ratios, averaging 0.70916 ± 0.00114 (1σ), demonstrating the influence of the older basement rocks. Farther southeast samples are rare. Samples from Kajiado District north of Lake Amboseli, and the one from near Kibwezi both exhibit quite low $^{87}Sr/^{86}Sr$ ratios (0.70636 to 0.70656 and 0.70448 for the sample locations, respectively). The Kajiado samples display higher values likely due to the combined influence of the older Bukoban system basement rock as well as the Pleistocene and Holocene volcanics in the region. The sample from near Kibwezi exhibits a lower strontium isotope ratio due to the Holocene volcanics forming the Chyulu range to the southwest (Figure 12.1, 12.2) This value is in line with strontium isotope ratios for the Amboseli Lake Basin and Plio-Pleistocene basalts from Kilimanjaro, which range from 0.7047 to 0.7049 (Koch, et al. 1995), indicating quite low ratios for the region. The same study notes a $^{87}Sr/^{86}Sr$ ratio of 0.7067 for the Proterozoic gneiss north of the Amboseli basin. Finally, samples from Kathuva, display high $^{87}Sr/^{86}Sr$ ratios, ranging from 0.70786 to 0.70862, reflective of the Carboniferous-Lower Permian geology of the sample location (France 1987).

Strontium Isotope Analysis of Modern Livestock Tooth Enamel

The results from the strontium stable isotope analysis are shown below in Figure 12.3 and Appendix 2. The cow GvJhB113 was born south of Ewaso Ngiro town. The town is situated near Holocene and Miocene volcanics near the border of the Precambrian Mozambique belt region (Figure 12.1). The exact location of the cow's birth is unknown, so it is possible that it was born in an area characterized by either younger volcanics or old basement rock. It died near Narok town, which is situated on young volcanics. The cow's mother was from Lolgorien, which is situated on Precambrian Nyanzan system. Along the crowns of the three molars, substantial variation in $^{87}Sr/^{86}Sr$ ratios exists (Figure 12.3). The higher strontium isotope ratios of the M_1 (0.70997 to 0.70905) may be due to transmission from the mother during pregnancy and lactation, as other studies have shown remobilization of skeletal high mass elements, like lead, during pregnancy and post pregnancy periods (Gulson, et al. 1998; Gulson, et al. 2003). However, because the second molar also exhibits high $^{87}Sr/^{86}Sr$ ratios (0.7098) in the cervical half of the crown, which forms by the time weaning is completed, the must have animal resided in an area with older geology. The most cervically located sample on the crown of the M_2 has a $^{87}Sr/^{86}Sr$ ratio of 0.70840, which is in line with values recorded for Maasai Mara (Figure 12.2, Table 12.1). The gradual decrease in strontium isotope ratios over time in the third molar indicates movement of the animal to the younger volcanics of the Narok area. This specimen does indeed demonstrate that analysis of $^{87}Sr/^{86}Sr$ ratios can be used to track movement of animals across geologically differing landscapes in Kenya.

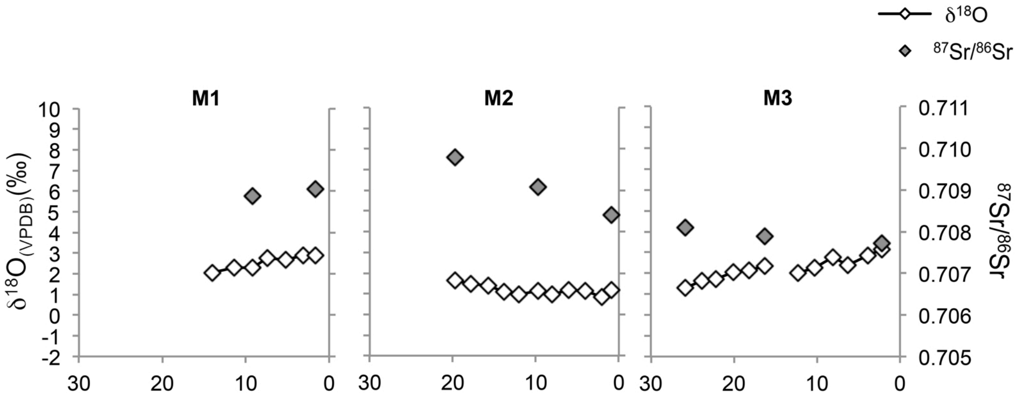
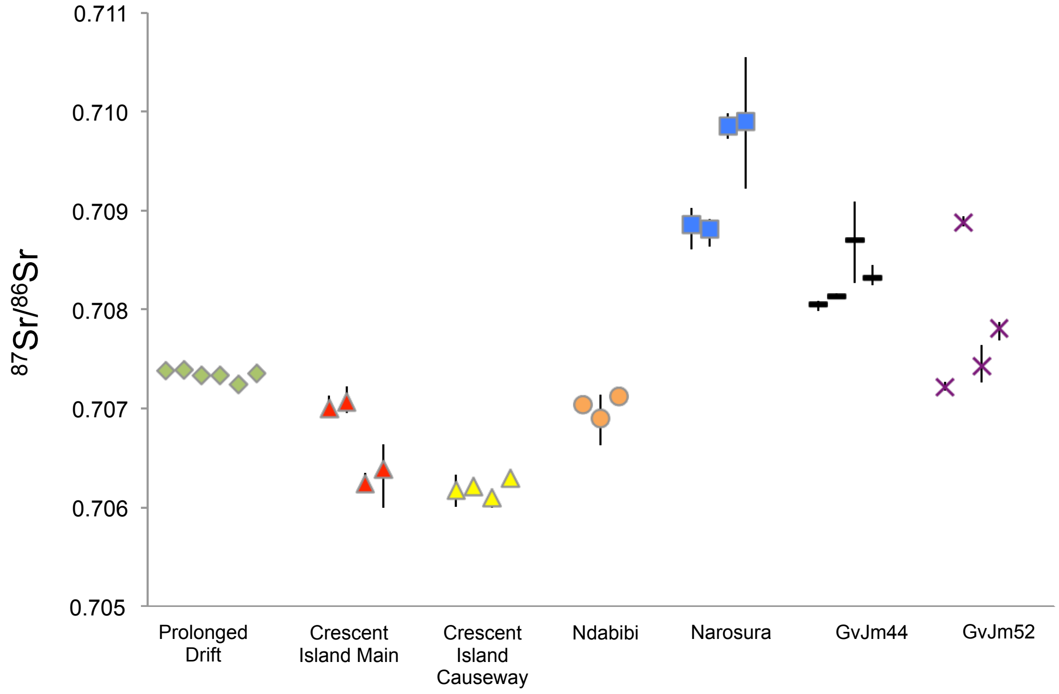


Figure 12.3: Plots of oxygen isotope ratios and strontium isotope ratios of the first, second, and third molar of the modern cattle specimen, GvJhB113.

Strontium Stable Isotope Analysis of Archaeological Livestock Tooth Enamel

The same archaeological livestock specimens analyzed for their carbon and oxygen isotope composition were subjected to strontium isotope analysis. Due to expense, only 3 to 5 enamel samples, representing extremes in $\delta^{18}O$ and $\delta^{13}C$ values, and spaced evenly along the tooth crown, were analyzed for their strontium $^{87}Sr/^{86}Sr$ ratios. However, this approach can still show seasonal or longer term variation (Balasse, et al. 2002). Most figures show $^{87}Sr/^{86}Sr$ ratios plotted against $\delta^{18}O$ values, though in some cases $^{87}Sr/^{86}Sr$ ratios are plotted against $\delta^{13}C$ values when the two show correlated changes over time. The means and ranges of variation of $^{87}Sr/^{86}Sr$ ratios are shown for cattle and caprines at each site in Figure 12.4 for broad comparisons.

Overall, my work reveals that many specimens show little strontium isotope variation, but that there is significant variation between Central Rift Valley sites and the sites on the plains, and in some cases, substantial variation between individuals within a single site. These differences will be further clarified by assessment of seasonal variations in each site below.



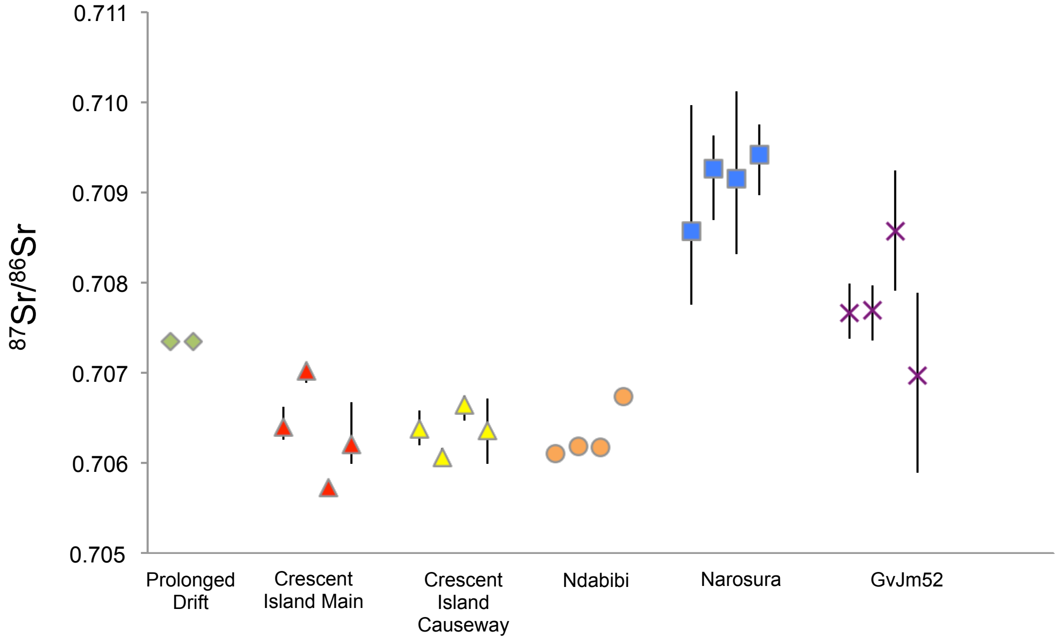


Figure 12.4: Upper chart shows mean and variation of ^{87}Sr/^{86}Sr ratios of cattle from all sites. Lower chart shows mean and variation of ^{87}Sr/^{86Sr} ratios from caprines at all sites.

Central Rift Valley Sites

The Central Rift Valley is dominated by young volcanics. The Crescent Island Main and Crescent Island Causeway sites are both situated on the east side of Lake Naivasha on Holocene alluvium, as is Ndabibi, on the west side of the lake on the Ndabibi Plain. Prolonged Drift is situated farther north, on the floodplain of the Nderit River, southwest of Lake Nakuru, surrounded by Holocene volcanics.

Crescent Island Main

Cattle

The cattle at Crescent Island Main have an average strontium isotope ratio of 0.70668 ± 0.00039 (1σ) with a range of 0.70599 to 0.70722. The specimens do not all overlap in their ^{87}Sr/^{86}Sr ratios. CI-M *Bos* 1 M3 and CI-M *Bos* 2 M3 both display values ranging from 0.70692 to 0.70722 (Figure 12.5), but they do not display similar trends over time, with ratios increasing in CI-M *Bos* 1 M3 and ratios increasing and then decreasing in CI-M *Bos* 2 M3. CI-M *Bos* 3 M3 and CI-M *Bos* 4 M3 both overlap in ^{87}Sr/^{86}Sr ratios, with ratios much lower than in the first two specimens. CI-M *Bos* 3 M3 has values that remain very constant over time, showing a range of variation of just 0.00017. CI-M *Bos* 4 M3 displays the most variation in ^{87}Sr/^{86}Sr ratios over time, 0.00064, and values appear to covary with δ^{18}O values in the occlusal half of the tooth as both values increase over time.

The strontium isotope ratios in the cattle specimens from Crescent Island Main are similar to those at Nakuru, Hell's Gate, Enkapune Ya Muto, with values characteristic of the Pleistocene and Holocene volcanics predominantly west and south of Lake Naivasha. Higher $^{87}Sr/^{86}Sr$ ratios characteristic of samples from Enkapune Ya Sauli and Ol Tepesi are also displayed in these specimens, suggesting a quite broad herding environment within the Central Rift Valley (Figure 12.1, 12.2, Table 12.1).

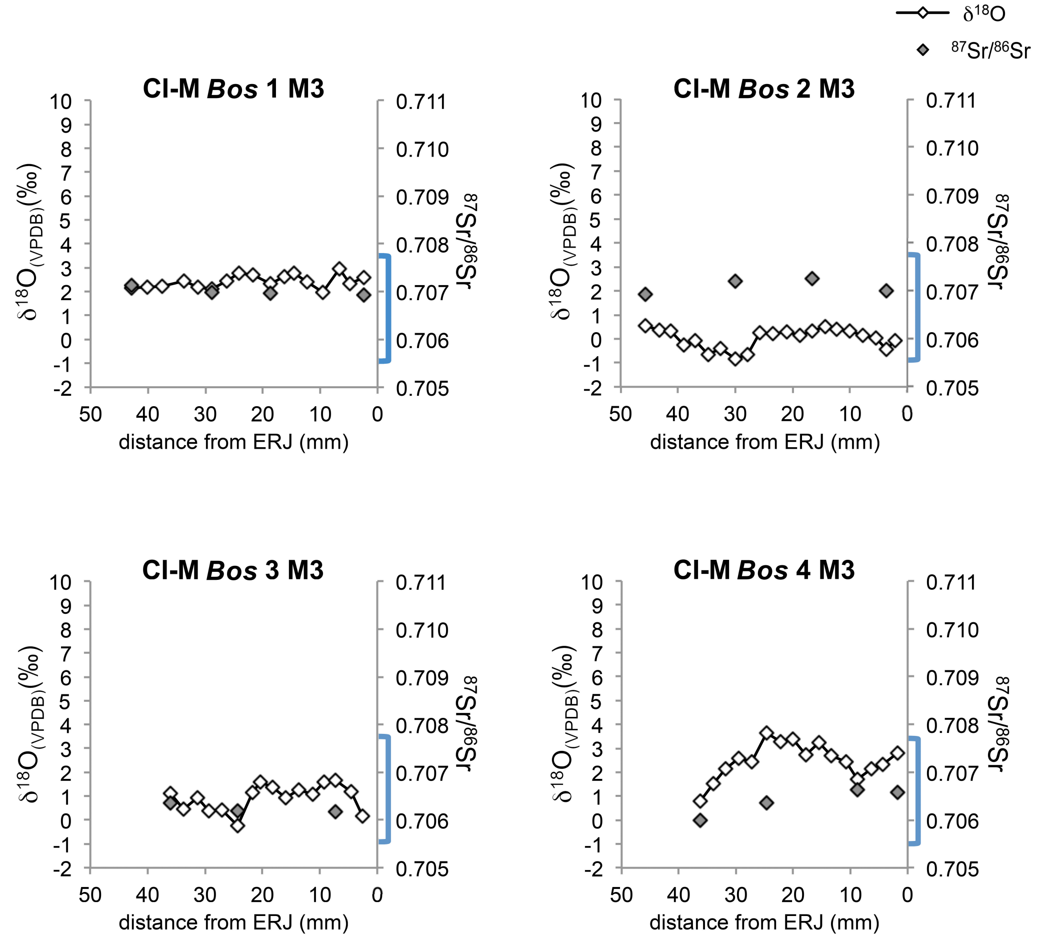


Figure 12.5: Results from strontium and oxygen isotope analysis of enamel of cattle specimens from Crescent Island Main. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Caprines

The sheep at Crescent Island Main have an average strontium isotope ratio of 0.70628 ± 0.00051 (1σ), with a range of 0.70568 to 0.70711. This range of values overlaps considerably with that of the cattle specimens from the same site. However, not all sheep display overlapping $^{87}Sr/^{86}Sr$ ratios. CI-M *Ovis* 2 M3 has very low ratios with little variation over time, ranging from 0.70568 to 0.70579 (Figure 12.6). CI-M *Ovis* 3 has low values in the occlusal 30 mm of the tooth, and the sample in the last 10 mm of the tooth has a much higher value, as $\delta^{18}O$ values simultaneously decrease. CI-M *Ovis* 4 M3 shows no correlated changes in $^{87}Sr/^{86}Sr$ ratios with $\delta^{18}O$ values, as the specimen exhibits a range of ratios from 0.70626 to 0.70662, with values decreasing over time. CI-M *Ovis* 1 M3 exhibits the highest $^{87}Sr/^{86}Sr$ ratios, with ratios varying from 0.70689 to 0.70711. In sum, the $^{87}Sr/^{86}Sr$ ratios of all Crescent Island caprine specimens, like those of the cattle at Crescent Island Main, show herding in the Central Rift Valley.

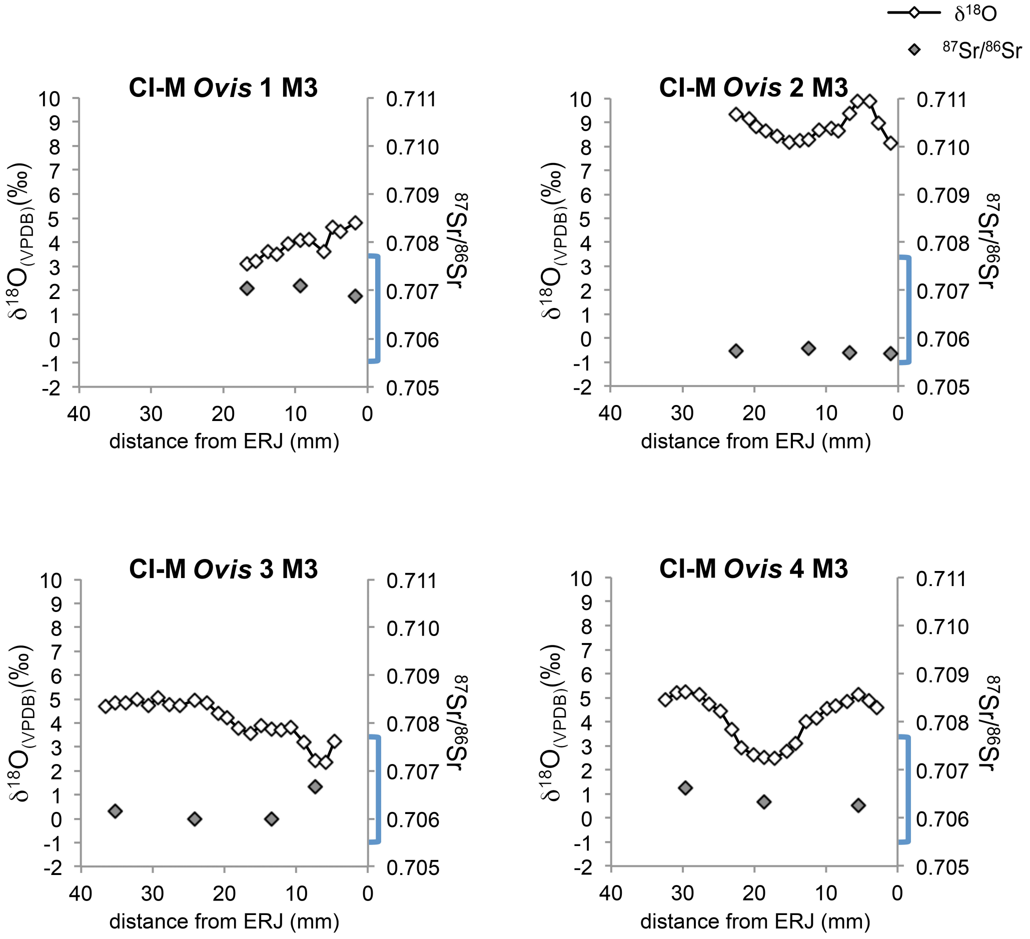


Figure 12.6: Results from strontium and oxygen isotope analysis of enamel of caprine specimens from Crescent Island Main. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Crescent Island Causeway

Cattle

The cattle from Crescent Island Causeway, like those at Crescent Island Main, exhibit low ^{87}Sr/^{86}Sr ratios, with much less inter-individual variation than exhibited in Crescent Island Main. The average ^{87}Sr/^{86}Sr ratio for all specimens is 0.70619 ± 0.00011 (1σ), with values ranging from 0.70626 to 0.70636. None of the specimens showed any evidence for correlated changes in δ^{18}O values. CI-C *Bos* 1 M2 shows the most variation in $^{87}Sr/^{86}Sr$ ratios, with a rise in ratios in the occlusal 30 mm of the tooth, and a lower value in the last 10 mm of the tooth. The other teeth showed a range of variation of $^{87}Sr/^{86}Sr$ ratios under 0.0002 (Figure 12.7).

The $^{87}Sr/^{86}Sr$ ratios of the cattle specimens indicates herding confined to one region, likely in areas dominated by Pleistocene and Holocene volcanics around Crescent Island and west and south of Lake Naivasha (Figure 12.1, 12.2).

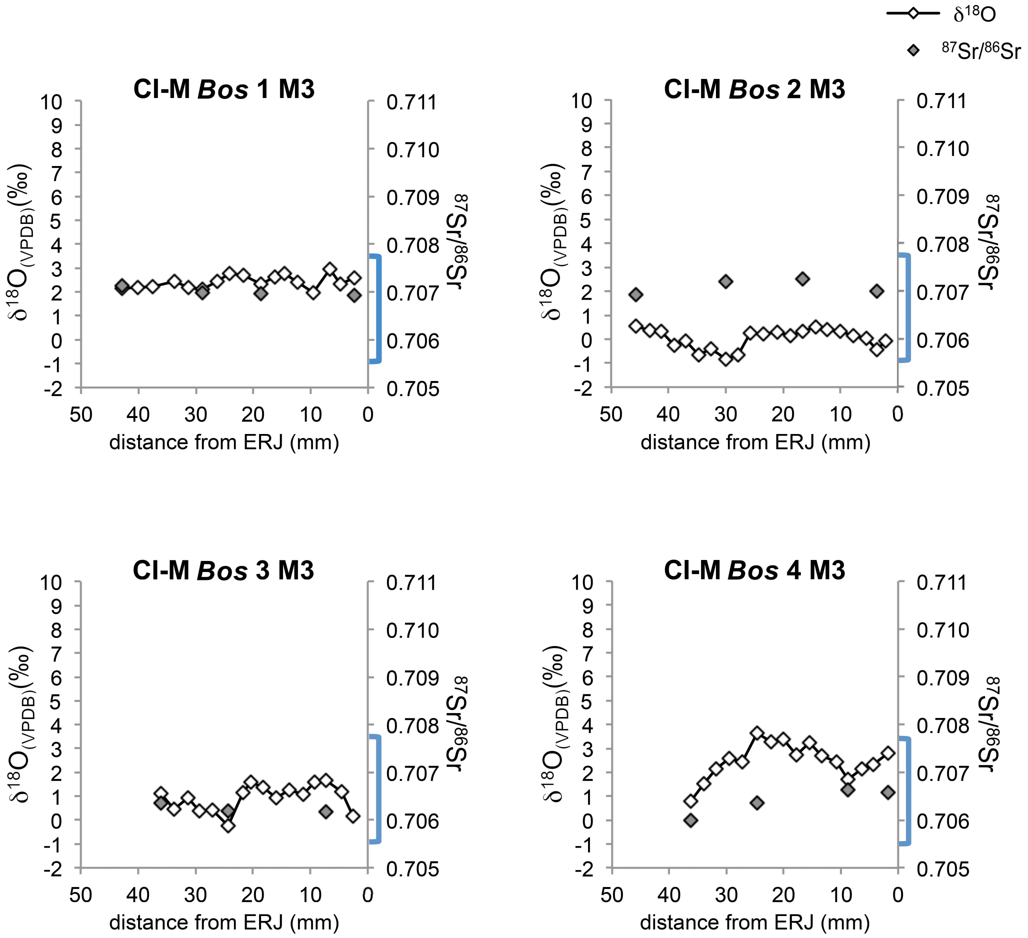


Figure 12.7: Results from strontium and oxygen isotope analysis of enamel of cattle specimens from Crescent Island Causeway. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Caprines

The sheep from Crescent Island Causeway show more variation in $^{87}Sr/^{86}Sr$ ratios than the cattle from the site. Ratios average 0.70636 ± 0.00028 (1σ), with a range of 0.70599 to 0.70672. All specimens show some overlap in ratios. CI-C *Ovis* 1 M3 exhibits a sinusoidal pattern in $^{87}Sr/^{86}Sr$ ratios, which does not appear to covary with $\delta^{18}O$ values (Figure 12.8). CI-C *Ovis* 4 exhibits the most variation, with a sharp increase in $^{87}Sr/^{86}Sr$ ratios matched by a decrease in $\delta^{18}O$ values. CI-C *Ovis* 2 M3 and CI-C *Ovis* 3 M3 both show a slight decrease in $^{87}Sr/^{86}Sr$ ratios over the course of tooth growth.

The $^{87}Sr/^{86}Sr$ ratios displayed in the caprine specimens show a much wider range than those of the cattle specimens, likely indicating movements into areas influenced by the older volcanics of the Miocene and Pliocene on the eastern flank of the Central Rift Valley. For example, the sinusoidal pattern of $^{87}Sr/^{86}Sr$ ratios in CI-C *Ovis* 1 M3 indicates a seasonal basis in mobility to different geologic substrates. However, the range of values is so narrow, 0.70620 to 0.70658, indicating that the sheep was not herded great distances, remaining within the young Quaternary volcanics of the Central Rift Valley. CI-C *Ovis* 4 M2 also shows more substantial variation, still remaining within the range of young Quaternary volcanics of the Central Rift Valley.

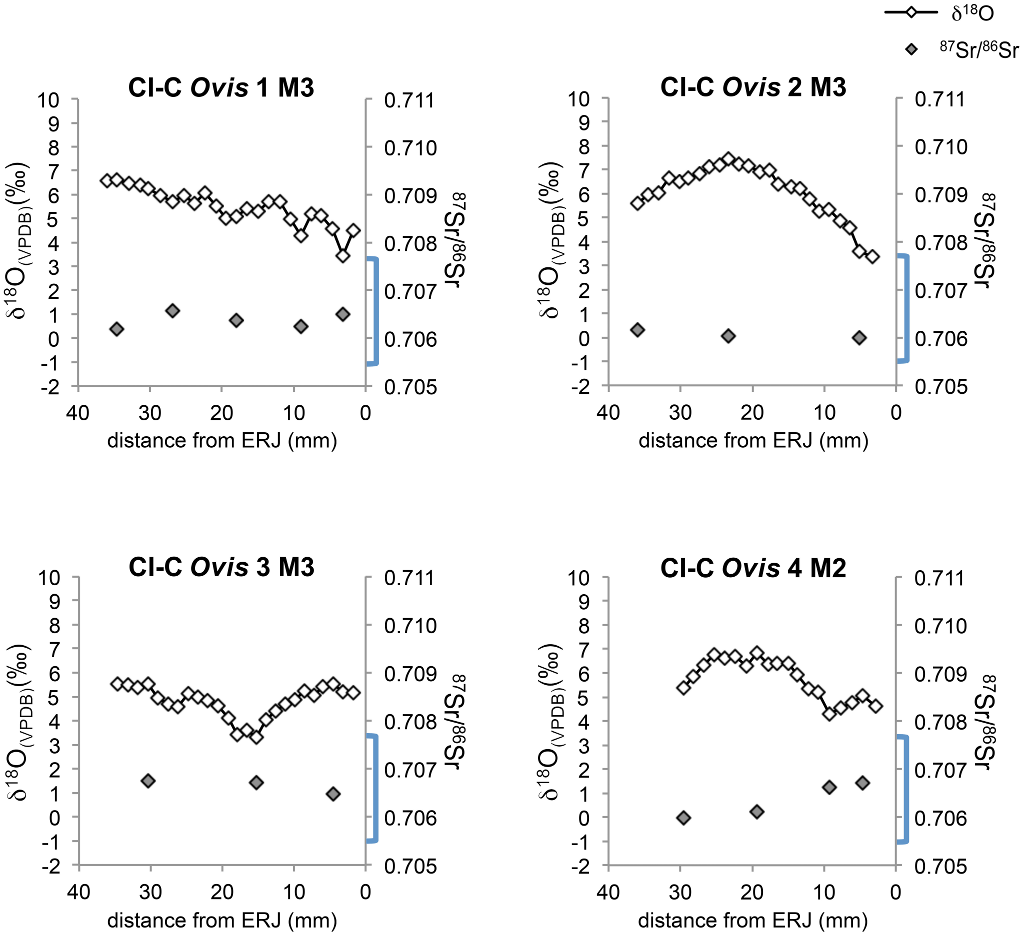


Figure 12.8: Results from strontium and oxygen isotope analysis of enamel of caprine specimens from Crescent Island Causeway. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Ndabibi

Cattle

At Ndabibi, cattle specimens exhibit ^{87}Sr/^{86}Sr ratios ranging from 0.70662 to 0.70714, with an average of 0.70696 ± 0.00022 (1σ). NDA *Bos* 3 M3 exhibits very little variation in ^{87}Sr/^{86}Sr ratios, with an average of 0.70696 ± 0.00022, ranging from 0.70662 to 0.70714 (Figure 12.9). NDA *Bos* 2 M1 displays slightly lower values than the other two specimens, ranging from 0.70662 to 0.70670, while NDA *Bos* 1 and NDA *Bos* 3 all have ratios higher than 0.70697. Only NDA *Bos* 1 M1 has a range of variation exceeding the fourth decimal place, at 0.0013. Because the teeth were highly worn, it is not possible to determine if fluctuations occur on a seasonal basis, but overall, as with the $\delta^{13}C$ and $\delta^{18}O$ values of the specimens, not much variation exists (see Figure 8.7). Only NDA *Bos* 1 M1 shows a pattern of increasing values in all stable isotopes analyzed over the course of tooth growth.

The range of $^{87}Sr/^{86}Sr$ ratios of Ndabibi cattle is very close to the range exhibited by cattle at Crescent Island Main, indicating that the animals were herded in similar environments.

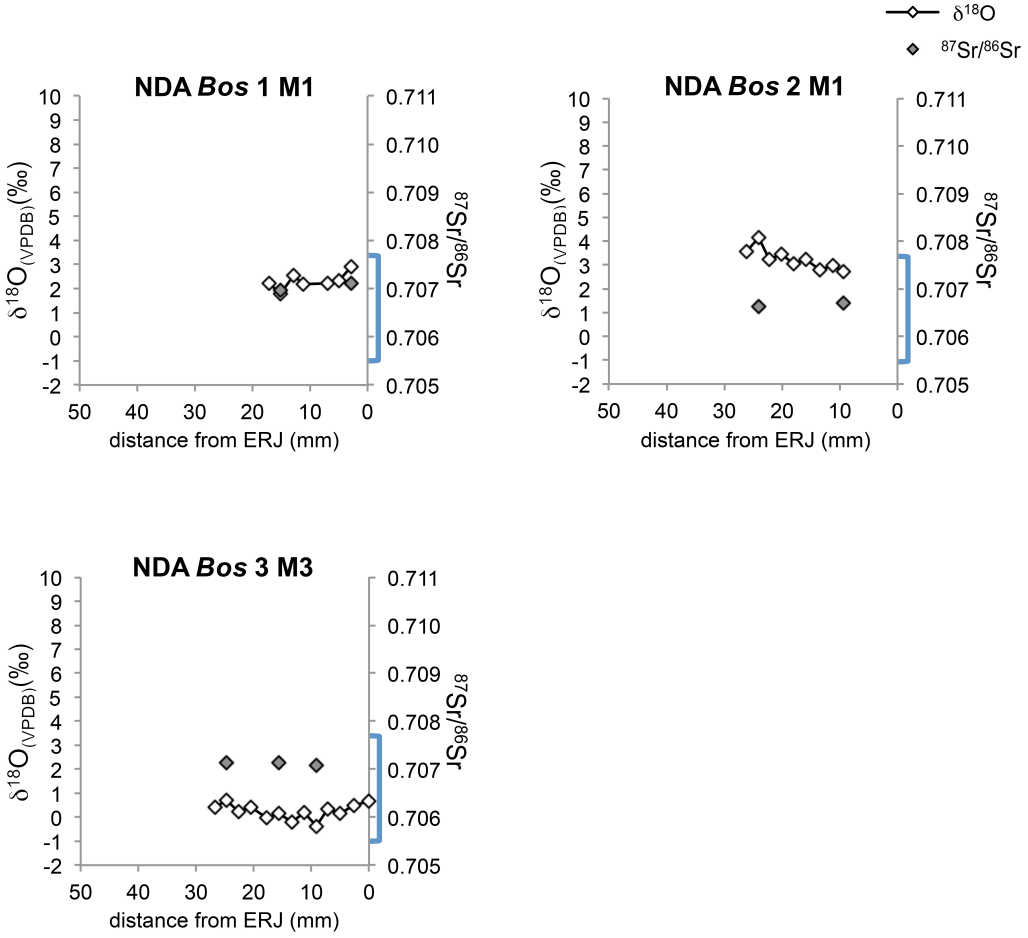


Figure 12.9: Results from strontium and oxygen isotope analyses of enamel of cattle specimens from Ndabibi. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Caprines

The caprines at Ndabibi have a combined average $^{87}Sr/^{86}Sr$ ratio of 0.70632 ± 0.00027 (1σ), ranging from 0.70606 to 0.70624. NDA o/c 1 M3 and NDA *Ovis* 1 both exhibit substantial variation in $\delta^{18}O$ values, but no correlated changes in strontium isotope ratios exist in those specimens. In fact, no specimen shows a range of variation in $^{87}Sr/^{86}Sr$ ratios beyond 0.0004 (Figure 12.10).

The $^{87}Sr/^{86}Sr$ ratios of the caprine specimens are lower than those of the cattle at the site, suggesting small livestock were herded in a more restricted region, likely around the site locale, perhaps extending southwest from Lake Naivasha in areas characterized by Quaternary volcanics and sediments (Figure 12.1, 12.2).

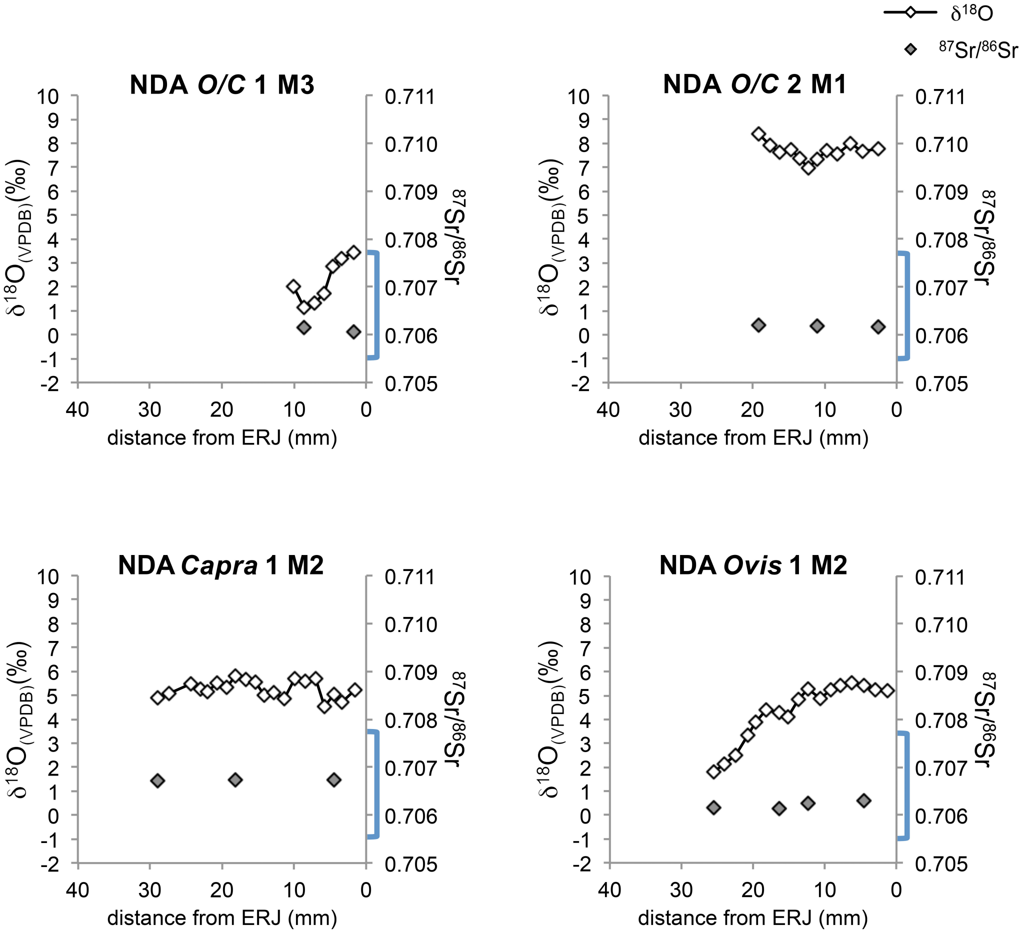


Figure 12.10: Results from strontium and oxygen isotope analyses of enamel of caprine specimens from Ndabibi. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Prolonged Drift

Cattle

The six cattle from Prolonged Drift show very little variation, with an average $^{87}Sr/^{86}Sr$ ratio of 0.70734 ± 0.00006 (1σ), ranging from 0.70717 to 0.70742. This is the lowest standard deviation in the study. Only one specimen, PD *Bos* 5 M3, shows a range of variation in $^{87}Sr/^{86}Sr$ ratios in the fourth decimal place, at 0.00014. That specimen also has the lowest $^{87}Sr/^{86}Sr$ ratios at the site, and does not overlap with any other specimens aside from PD *Bos* 4 M3 (Figure 12.11).

These ratios are higher than those reported for the specimens in other Central Rift Valley sites. The $^{87}Sr/^{86}Sr$ ratios do match some of the microfaunal samples collected closer to the eastern margins of the Rift Valley from Ol Tepesi, which is situated on Tertiary volcanics of the Miocene and Pliocene (Figure 12.1, 12.2), which extend between Lakes Naivasha and Elmenteita, indicating animals were herded very close to the site over the course of tooth development.

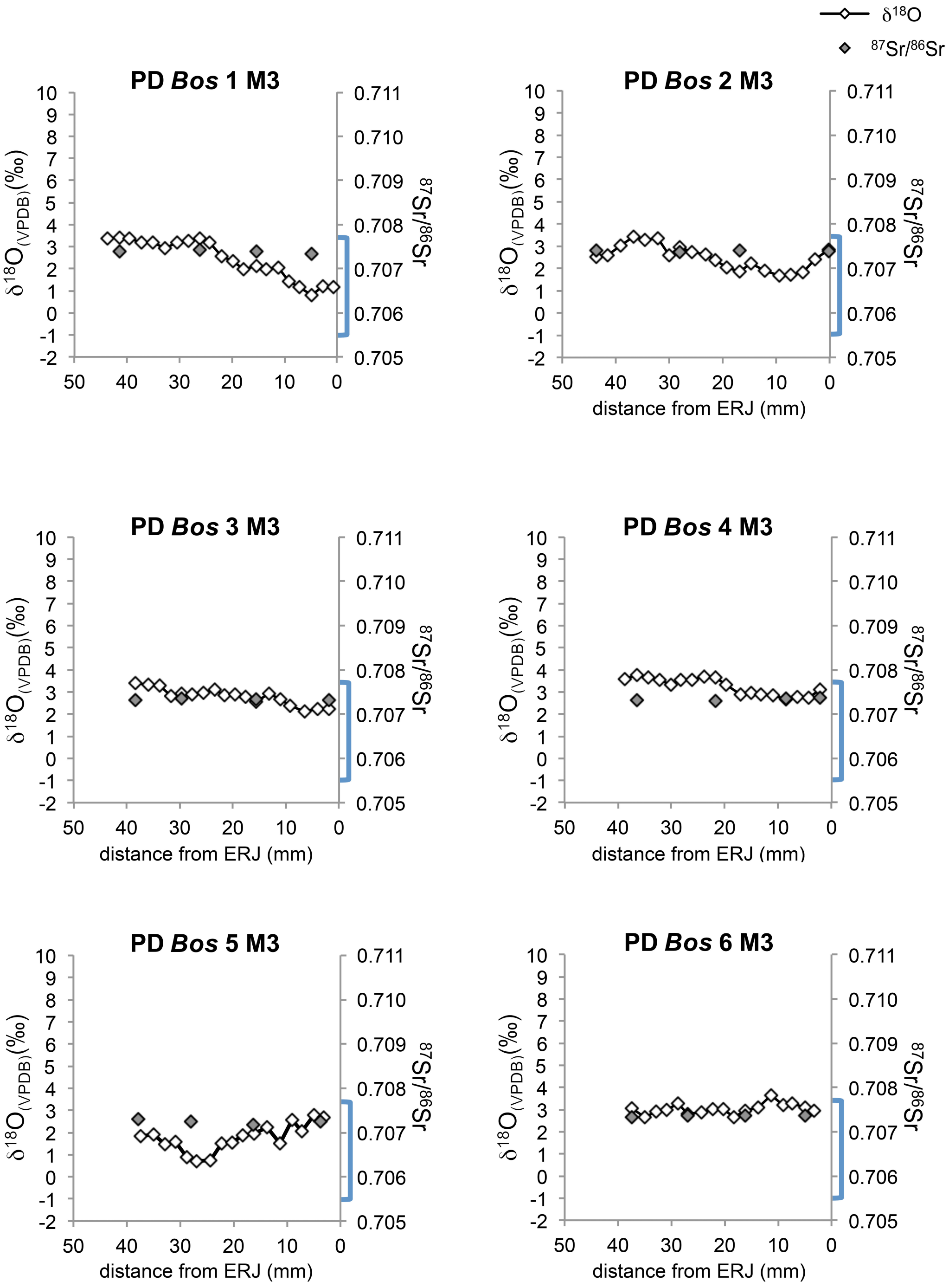


Figure 12.11: Results from strontium and oxygen isotope analyses of enamel of cattle specimens from Prolonged Drift. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Caprines

Similar to the cattle from the site, the two caprines from Prolonged Drift show almost no variation in $^{87}Sr/^{86}Sr$ ratios within or between specimens, with an average of 0.70734 ± 0.00002 (1σ), and a range from 0.70731 to 0.70736. Neither specimen exhibits a range of variation over 0.00004. The close similarity in $^{87}Sr/^{86}Sr$ confirms that the two specimens are likely from the same individual (Figure 12.12), as suggested by the near identical carbon and oxygen isotope values (Figure 11.16).

Caprines exhibit the same mean of strontium isotope ratios as cattle, indicating herding in the same environment.

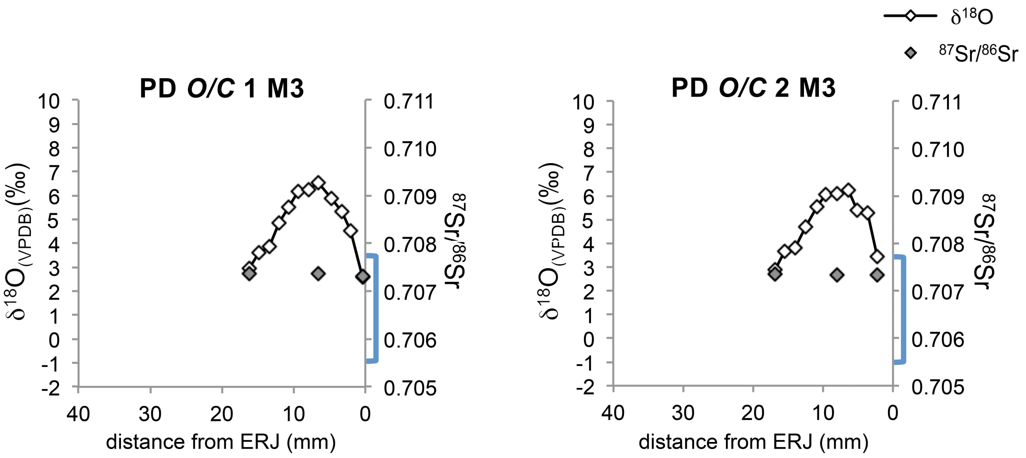


Figure 12.12: Results from strontium and oxygen isotope analyses of enamel of caprine specimens from Prolonged Drift. ERJ= Enamel-root junction. Blue marker on strontium axis indicates local Central Rift strontium signature.

Interpretation

Overall, livestock from sites in the Central Rift Valley were herded in the Central Rift Valley. Because so many locations were sampled in the Central Rift Valley, it is possible to identify differences in herding patterns *within* the region.

Crescent Island Main and Crescent Island Causeway, two sites in close proximity with considerable faunal assemblages, show some striking differences in the isotopic patterns of livestock. The cattle from Crescent Island Causeway, an Eburran 5b site, were herded in a much more constricted region than those at nearby Crescent Island Main, as demonstrated by a narrow range of strontium isotope ratios. Caprines from the Causeway site, too, show much less variation in $^{87}Sr/^{86}Sr$ ratios, with livestock herded predominantly in the Pleistocene and Holocene volcanics of the Central Rift Valley. In contrast, cattle and caprines from Crescent Island Main, an SPN site, display a much wider range $^{87}Sr/^{86}Sr$ ratios, indicative of herding animals within a broader area.

The variability of isotopic patterns between cattle at Crescent Island Main is likely the result of inter-annual changes in herding locations, which can be considerable among modern pastoralists (McCabe 1994; McCabe 2004). All cattle sampled from the site fall into the Older Juvenile and Young Adult age classes. Unfortunately, it is not possible to identify yearly cohorts in animals of that age, so it is possible that some of the animals were obtained through exchange, but such trade would have been local. This also applies for the cattle at Crescent Island Causeway, which represent individuals ranging in age classes from Young Juvenile to Mature

Adult. The caprines at Crescent Island Main do show some significant inter-individual differences in isotopic patterns. All except for CI-M *Ovis* 4 M3 (classed as Young Adult) are classed as Older Juveniles. Therefore, it is possible that CI-M Ovis 2 M3, which has unusually high $\delta^{18}O$ values, was obtained through exchange from other pastoralists also herding animals on young volcanics. Caprines from Crescent Island Causeway do not differ substantially from one another in their $\delta^{18}O$ values, and all individuals fall into the Mature Adult age class, so it is not possible to know if the were born in the same year, but it is likely that any variation in isotopic pattern represents yearly changes in precipitation and herding strategies in a local area.

Ndabibi, another SPN site, has cattle that display $^{87}Sr/^{86}Sr$ ratios within a similar range as those from Crescent Island Main, indicating a similar herding environment that includes most of the Central Rift Valley. Oxygen isotope values of the cattle show range of values overlapping with those from Crescent Island Main and Crescent Island Causeway. All of the Ndabibi cattle are estimated to have died as Young Adults, and it is possible that the variation in isotopic patterns reflects normal mobility patterns typical of this part of the Central Rift. Oxygen isotope values of the caprines from Ndabibi show a similar pattern, with values overlapping those at the Crescent Island sites. However, the caprines from Ndabibi show much less variation in strontium isotope ratios, with ratios characteristic of the site environment. This may be evidence of caprines being kept near a homestead, while cattle were herded farther away to better pastures.

The strontium isotope ratios for the Prolonged Drift cattle specimens range from 0.70717 to 0.70742, ratios are higher than those reported for the specimens in other Central Rift Valley sites (Figure 12.4). The strontium isotope ratios match some of the microfaunal samples collected closer to the eastern margins of the Rift Valley, including Ol Tepesi and the GsJjB samples north of Lake Naivasha, all of which are situated on or near Upper Miocene volcanics. The lack of variation between *and* within individual cattle, as well as caprines (both sets of taxa have the same mean of 0.70734), suggests that these animals were all herded together in the same environment, All of the sampled specimens are roughly the same age based upon occlusal wear (Age Class Older Juvenile to Young Adult, see Chapter 8). The consistency in strontium isotope ratios among the specimens at this site suggests that the animals were herded together, and that herding strategies were *very* consistent from year-to-year.

Loita Plains Site

The site of Narosura is situated on the edge of the semi-arid Loita Plains, near the border of the younger volcanics of the Central Rift Valley and the much older Precambrian basement rocks of the Tanzanian craton (Figure 12.1).

Narosura

Cattle

Strontium isotope ratios of cattle specimens at Narosura average 0.70928 ± 0.00061 (1σ), with values ranging from 0.70861 to 0.71055. Each individual displays a different pattern of ^{87}Sr/^{86}Sr ratios (Figure 12.13). NS *Bos* 4 M3 exhibits the most variation (0.0013) in ^{87}Sr/^{86}Sr ratios, which increase over the course of tooth growth as oxygen isotope values decrease. This specimen also has the highest ^{87}Sr/^{86}Sr ratio, followed by NS *Bos* 3 M3, which displays ^{87}Sr/^{86}Sr ratios that rise and then fall over the course of tooth growth, reflecting the inverse pattern displayed in δ^{18}O values. NS *Bos* 1 M3 displays a steady drop in ^{87}Sr/^{86}Sr ratios as oxygen isotope ratios increase over the course of tooth growth, and NS *Bos* 2 M3 displays a subtle sinusoidal pattern over time, but correlated changes in δ^{18}O values are not apparent.

Strontium isotope ratios are much higher in cattle at Narosura than cattle in the Central Rift Valley sites. All of the specimens have at least *some* strontium ^{87}Sr/^{86}Sr isotope ratios that are higher than the maximum value of 0.70865 recorded at Maasai Mara (Figure 12.2). The higher range of variation in ^{87}Sr/^{86}Sr ratios in the Narosura cattle specimens may be due to higher mobility among herders at Narosura, or higher variation in the ^{87}Sr/^{86}Sr ratios of the Precambrian rocks of the Mozambique Belt of southwest of the site (Figures 12.1, 12.2).

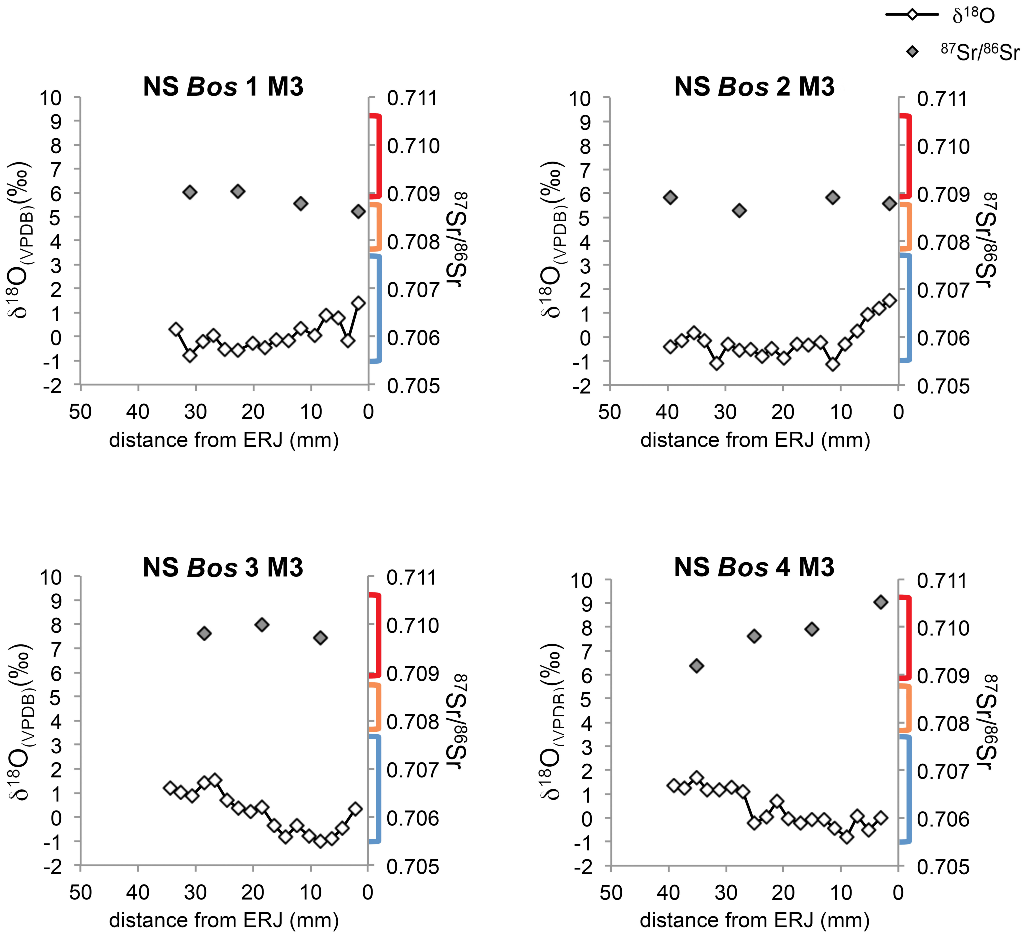


Figure 12.13: Results from strontium and oxygen isotope analyses of enamel of cattle specimens from Narosura. ERJ= Enamel-root junction. Blue marker on strontium axis indicates Central Rift strontium signature. Orange and red markers on strontium axis indicate ^{87}Sr/^{86}Sr ratios for Maasai Mara and east shore of Lake Victoria, respectively.

Caprines

The caprines at Narosura exhibit quite high ^{87}Sr/^{86}Sr ratios, averaging 0.70913 ± 0.00076 (1σ), with a range of 0.70775 to 0.71012. These specimens have the greatest standard deviation of all sites in this study. Strontium isotope ratios vary considerably along the tooth of each specimen, with some exhibiting a strong sinusoidal pattern and others showing a weaker pattern (Figure 12.14). Both a goat, NS *Capra* 1 M3 and a sheep, NS *Ovis* 4 M3, show sinusoidal patterns. In the sheep, ^{87}Sr/^{86}Sr ratios are very high in near the occlusal end of the tooth, drop, and then rising again near the cervical end. The reverse pattern manifests in the goat, although the ratios show much more variation. The two other sheep specimens show quite similar patterns, with the first two samples farthest from the ERJ displaying a slight drop in ^{87}Sr/^{86}Sr ratios over time, while samples in the 18-20 mm of the tooth closest to the ERJ display a rise in ^{87}Sr/^{86}Sr ratios over time. In NS *Ovis* 3 M3, this pattern covaries with δ^{13}C values, but no such correlated pattern occurs in NS *Ovis* 1 M3.

Values in NS *Ovis* 1 M3 and NS *Capra* 1 M3 have *some* values that are lower than the maximum value of 0.70865 at Maasai Mara, but *all* ^{87}Sr/^{86}Sr ratios of NS *Ovis 3* M3 and NS *Ovis* 4 M3 are higher than that maximum value, indicating, as with Narosura cattle, herding farther west into older Precambrian rocks over the lifespans of the animals, rather than movement towards the younger volcanics of the Central Rift Valley.

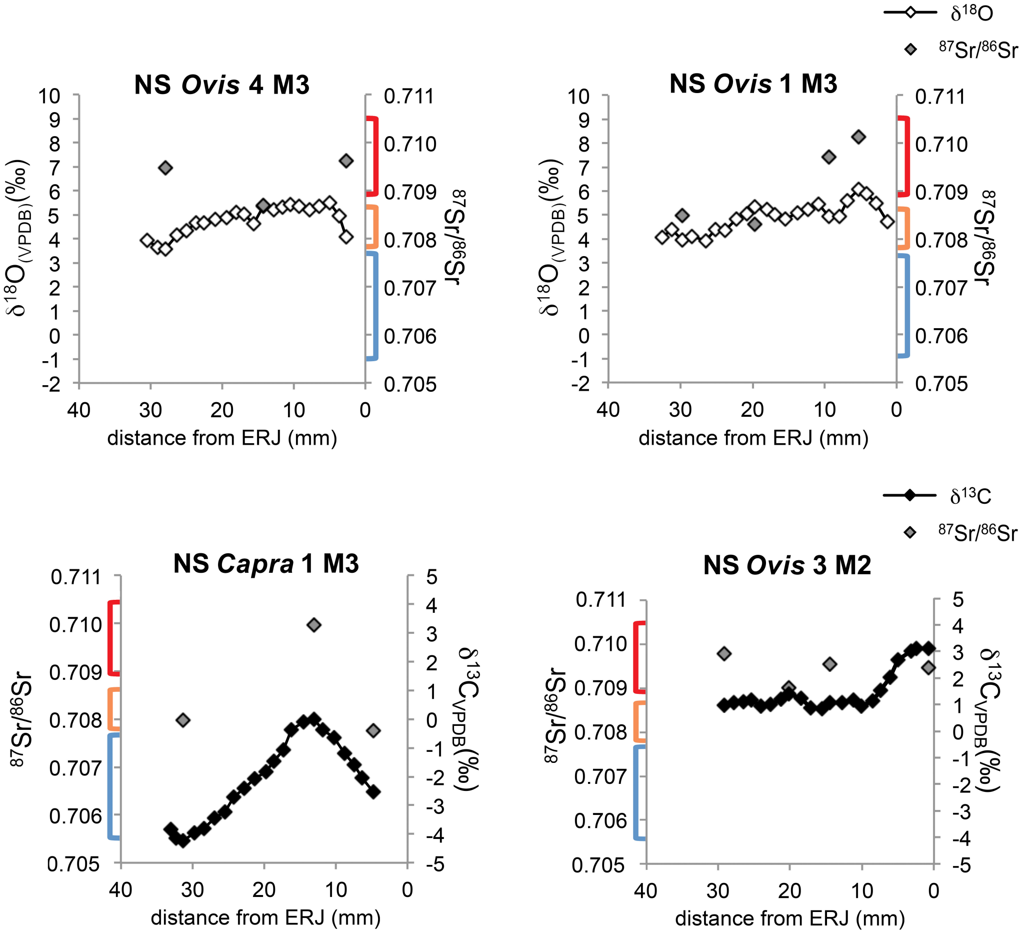


Figure 12.14: Results from strontium and oxygen isotope analyses (NS Ovis 4 M3 and Ovis 1 M3, above), and from strontium and carbon isotope analyses (NS Capra 1 M3 and NS Ovis 3 M2, below) of enamel of caprine specimens from Narosura. ERJ= Enamel-root junction. Blue marker on strontium axis indicates Central Rift strontium signature. Orange and red markers on strontium axis indicate $^{87}Sr/^{86}Sr$ ratios for Maasai Mara and east shore of Lake Victoria, respectively.

The Loita Plains: Interpretation

The livestock at Narosura exhibit the highest strontium isotope ratios in the study. Strontium isotope ratios are much higher in cattle at Narosura than cattle in the

Central Rift Valley sites. Two of the specimens have $^{87}Sr/^{86}Sr$ ratios that are all higher than the maximum value of 0.70865 recorded at Maasai Mara. Nearly all of the samples of caprine tooth enamel display $^{87}Sr/^{86}Sr$ ratios that are higher than the maximum value at Maasai Mara. The higher range of variation in strontium isotope ratios in the Narosura cattle specimens may be due to higher mobility among herders at Narosura, or greater variation in the $^{87}Sr/^{86}Sr$ ratios of the Precambrian rocks of the Mozambique Belt southwest of the site. More sampling of microfauna from the area must be carried out to explore this further. However, it is important to note that there is no evidence for the sampled livestock moving to areas characterized by low $^{87}Sr/^{86}Sr$ ratios, such as the Central Rift Valley. This is particularly interesting, because Narosura's lithic assemblage is primarily obsidian from Njorowa Gorge sources just south of Lake Naivasha (at Hell's Gate National Park), and to a far lesser extent Sonanchi sources situated west of Lake Naivasha, between the lake and the Mau Escarpment (Merrick and Brown 1984).

The differences between the cattle and caprines suggest some differences in the management of the two groups of livestock, with caprines showing more variation in $^{87}Sr/^{86}Sr$ ratios than do cattle. This may be due to herding practices, with caprines moved more frequently across the landscape, while cattle were herded in one area for longer periods of time. The longer mineralization time of cattle teeth, further discussed below, may also be a factor in this pattern. We should also take the diet of the animals into account, as the rooting depth of plants may have an effect on their $^{87}Sr/^{86}Sr$ ratios (Dambrine, et al. 1997; Miller, et al. 1993). However, both goats and sheep exhibit similar ranges of ^{87}Sr/^{86}Sr ratios, regardless of their δ^{13}C values. Therefore, it is more likely that any correlating variations in both δ^{13}C values and ^{87}Sr/^{86}Sr ratios must be due to movements to regions characterized by different geologies *and* vegetation.

No convincing strontium isotope evidence for exchange of cattle over great distances exists at Narosura. The specimen with the highest range of variation, NS *Bos* 4 M3, has a slightly younger occlusal wear pattern than the other specimens, so interannual changes in herding patterns at Narosura may be the cause of this difference in specimens. While the extent of isotopic variation in southwest Kenya is still relatively unclear, the very high ^{87}Sr/^{86}Sr ratio of the cervical sample in that specimen, 0.71055, is in the range of microfauna from sample locations near Lake Victoria (Figures 12.1, 12.2), suggesting that the animal was herded very far from Narosura's location. Similarly, caprines from Narosura show evidence for periodic herding in regions with ^{87}Sr/^{86}Sr ratios characteristic of the Lake Victoria area. However, such extreme values are not necessarily indicative of exchange. Two specimens, NS *Ovis* 4 M3 and NS *Capra* 1 M3 show a seasonal pattern of strontium isotope ratios, indicating that herding to regions with extremely high ^{87}Sr/^{86}Sr ratios was a seasonal practice in some years. All specimens but NS *Ovis* 4 M3 exhibit the same tooth wear stage "G" (Grant 1982), but the range of chronological ages associated with this tooth wear stage is too great to identify whether these animals were born the same year. Therefore, we cannot rule out interannual shifts in herding patterns among the pastoralists at Narosura.

Athi-Kapiti Plains Sites

GvJm44

Both GvJm 44 and GvJm 52 are situated at Lukenya Hill, an augen gneiss inselberg on the Athi-Kapiti plains (Baker 1954). The inselberg is surrounded by Tertiary volcanics and sediments to the west, and Precambrian rocks to the east (Figure 12.1).

Cattle

Combined, ^{87}Sr/^{86}Sr ratios of cattle specimens at GvJm44 range from 0.70798 to 0.70909, with an average of 0.70828 ± 0.00030 (1σ). Both GvJm44 *Bos* 1 M3 and GvJm44 *Bos* 2 M3 exhibit very little variation in strontium isotope ratios (Figure 12.15). In contrast, GvJm44 *Bos* 3 M3 and GvJm44 *Bos* 4 display marked variation in ^{87}Sr/^{86}Sr ratios. Oxygen isotope values from these specimens show more significant variation over time as well. Strontium isotope ratios in GvJm44 *Bos* 3 M3 covary with δ^{18}O values over the 35 mm of the tooth closest to the ERJ. Strontium isotope ratios display a similar pattern of covariance in GvJm44 *Bos* 4 M3, but the pattern is more subtle.

The microfauna sampled from Lukenya Hill yielded an average ^{87}Sr/^{86}Sr ratio of 0.70916 ± 0.00114 (1σ). All of the cattle specimens analyzed show ^{87}Sr/^{86}Sr ratios within that range, indicating the animals were herded locally over the course of tooth growth.

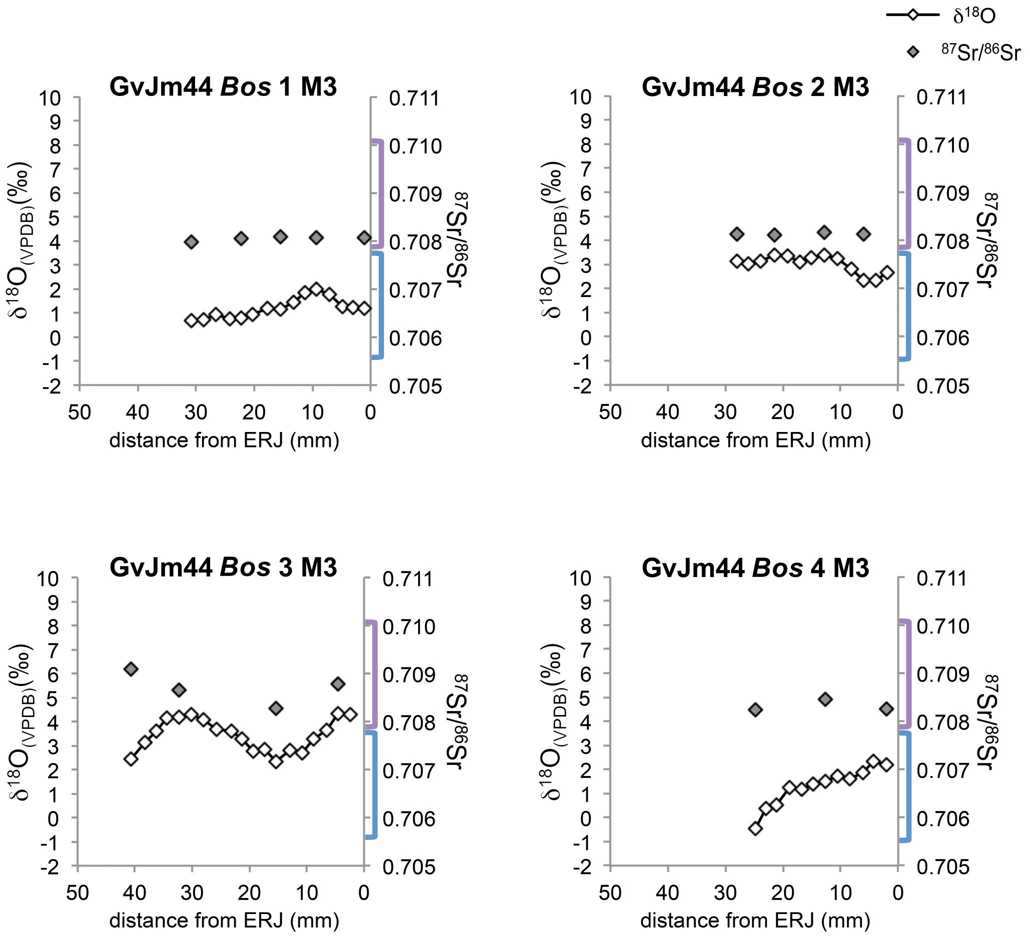


Figure 12.15: Results from strontium and oxygen isotope analyses of enamel of cattle specimens from GvJm44. ERJ= Enamel root junction. Blue marker on strontium axis indicates Central Rift strontium signature. Purple marker on strontium axis indicates ^{87}Sr/^{86}Sr ratios for Lukenya Hill area.

GvJm52

Cattle

Combined, ^{87}Sr/^{86}Sr ratios for the cattle specimens from GvJm52 range from 0.70718 to 0.70894, with an average of 0.70780 ± 0.00063 (1σ). Both GvJm42 *Bos* 1 M3 and GvJm52 *Bos* 2 M3 exhibit ranges of variation no greater than 0.00010.

GvJm52 *Bos* 3 M3 shows the highest range of variation, with ^{87}Sr/^{86}Sr ratios gradually increasing over the course of tooth growth from 0.70726 to 0.70765 (Figure 12.16). GvJm52 *Bos* 4 M3 displays higher values that exhibit a subtle seasonal pattern. No correlated changes in δ^{18}O or δ^{13}C values are evident.

Two of the cattle specimens, GvJm52 *Bos* 1 and GvJm52 *Bos* 3, exhibit strontium isotope ratios outside of the range indicated by microfauna collected in the area. Rather, their ranges (0.70718–0.70727 and 0.70726–0.70765, respectively) are in line with specimens collected in Nairobi. It is possible that the animals were herded in that area. The two other specimens, GvJm52 *Bos* 2 and GvJm52 *Bos* 4, exhibit ^{87}Sr/^{86}Sr ratios within the range established for the Lukenya Hill local (Figures 12.1, 12.2), indicating a more local herding history during the time those teeth were formed.

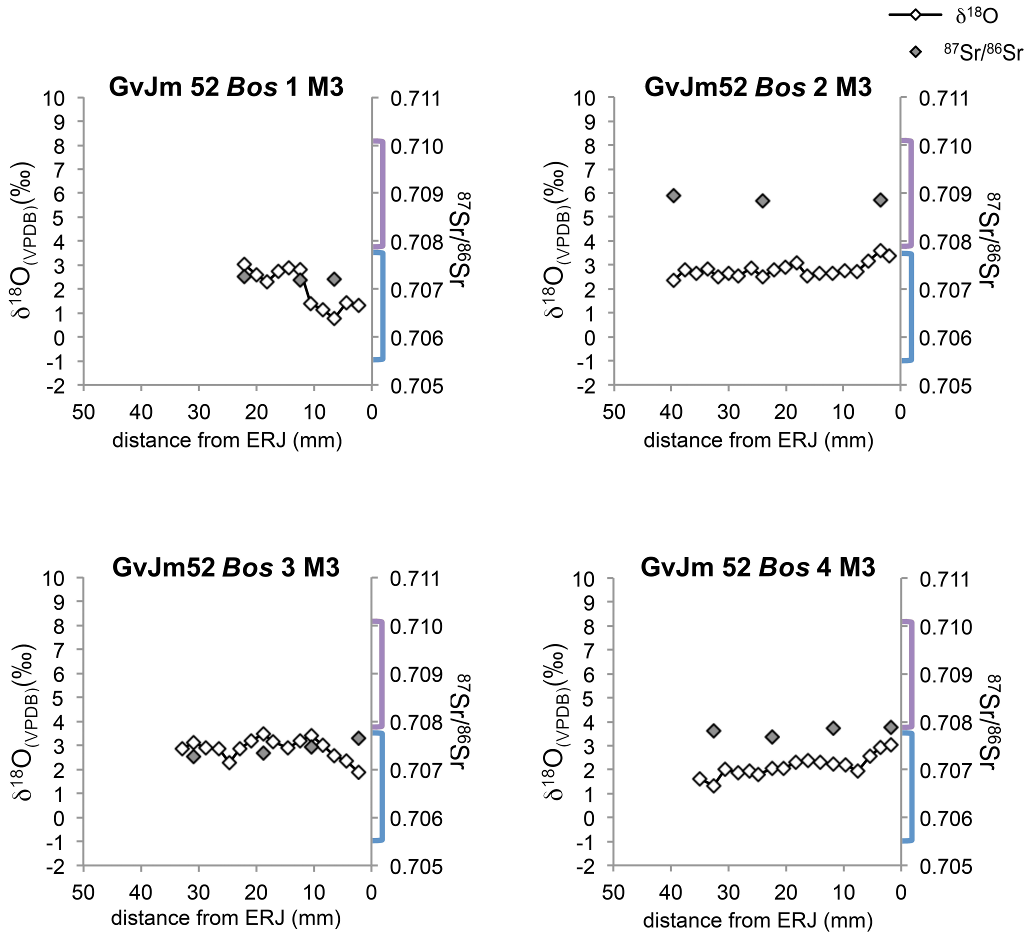


Figure 12.16: Results from strontium and oxygen stable isotope analyses of enamel of cattle specimens from GvJm52. ERJ= Enamel root junction. Blue marker on strontium axis indicates Central Rift strontium signature. Purple marker on strontium axis indicates $^{87}Sr/^{86}Sr$ ratios for Lukenya Hill area.

Caprines

The sheep and goats from GvJm52 show varied patterns in their $^{87}Sr/^{86}Sr$ ratios. The average ratio for the specimens is 0.70772 ± 0.00075 (1σ). GvJm52 *Ovis* (ex-*Capra*) 1 M2, GvJm52 o/c 2 M3 and GvJm52 *Ovis* 1 M2 (carbon not pictured here, see Figure 11.21) show $^{87}Sr/^{86}Sr$ ratios increasing as $\delta^{13}C$ values decrease. GvJm52 *Ovis* 2 M3 does as well, but the variation is subtle (Figure 12.17).

Similar to the cattle from GvJm52, the caprines from the site show movement between areas characterized by low $^{87}Sr/^{86}Sr$ ratios and the Lukenya Hill area. The rise and fall in $^{87}Sr/^{86}Sr$ ratios in GvJm52 *Ovis* 1 M2 indicates a pattern of seasonal mobility. That individual spent the time of initial crown formation in regions characterized by young volcanics, either on the Tertiary volcanics of the Central Rift or the Plio-Pleistocene basalts east and north of the Amboseli basin. As the tooth grew the animal was herded to regions characterized by much higher $^{87}Sr/^{86}Sr$ ratios (0.70789), presumably the Lukenya Hill area, before moving into areas characterized by lower strontium isotope ratios again, before returning to the Lukenya Hill area where it died (Figure 12.17). GvJm52 *Ovis* 2 M3 and GvJm52 o/c 2 M3 also show a sinusoidal pattern, though the amplitude of variation is not as high. The steady rise in strontium isotope ratios over time in GvJm52 *Ovis* (ex-*Capra*) 1 M2 may be indicative of longer term movement to the Lukenya Hill area from regions characterized younger volcanics.

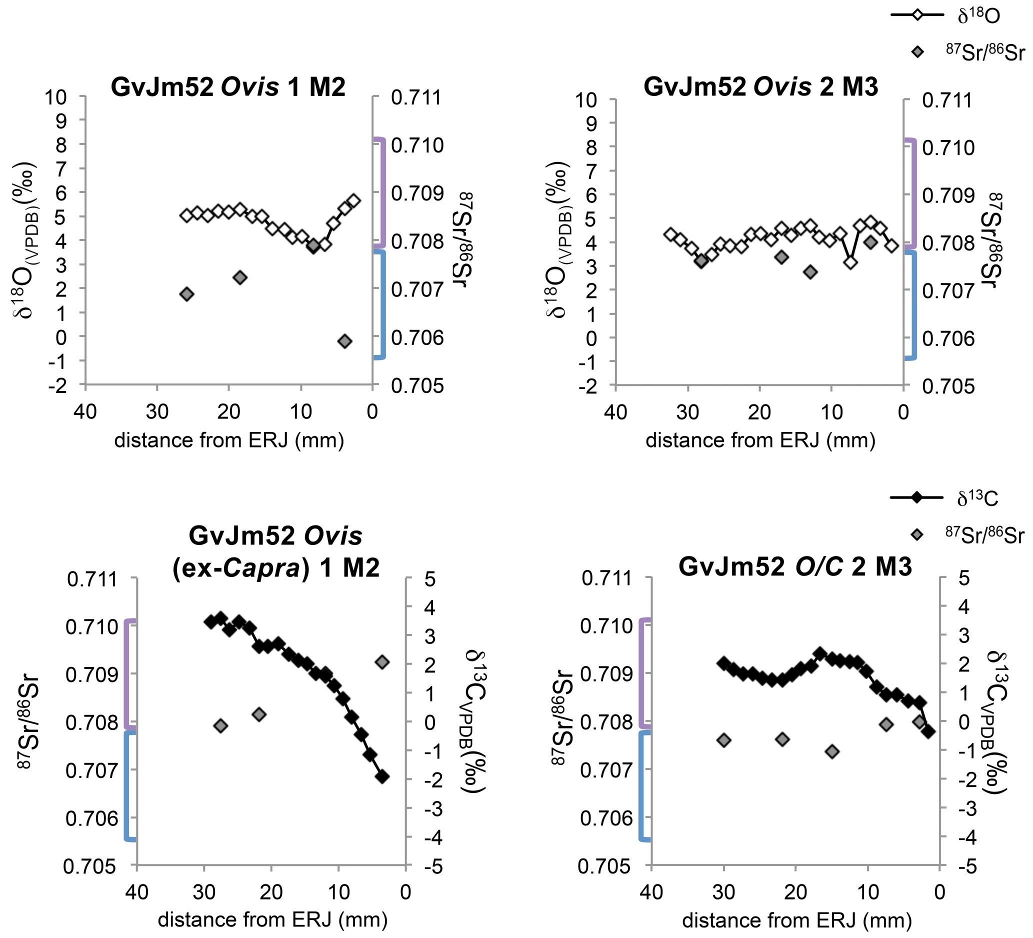


Figure 12.17: Results from strontium and oxygen stable isotope analyses (GvJm52 *Ovis* 1 M2 and GvJm52 *Ovis* 2 M3, above) and strontium and carbon stable isotope analyses (GvJm52 *Ovis* (ex-*Capra*) 1 M2 and GvJm52 o/c 2 M3, below) of enamel of caprine specimens from GvJm52. ERJ= Enamel root junction.

Interpretation

The cattle from GvJm44 have strontium isotope ratios largely characteristic of the Lukenya Hill area, indicating that animals were herded locally. In the case of GvJm44 Bos 3 M3 and, to a lesser extent, GvJm44 Bos 4 M3, strontium isotope ratios mostly covary with oxygen isotope values, suggesting that some local movements had a seasonal basis (Figure 12.16). GvJm44 Bos 3 M3 has higher strontium isotope ratios than the other three specimens from the site. This could be because the animal was obtained from other herders in the region, or due to interannual changes in herding routes, as GvJm44 Bos 3 M3 is has a much younger tooth wear stage (classed as Older Juvenile) than the other specimens, which are classed as either Mature Adults or Aged.

It is notable that two of the cattle from GvJm52 show some evidence for mobility between Lukenya Hill and the Central Rift Valley. The specimens show ^{87}Sr/^{86}Sr ratios below the level characteristic of Lukenya Hill, similar to those of microfauna from Nairobi National Park. The increasing ^{87}Sr/^{86}Sr ratios over the course of tooth growth in GvJm52 Bos 3 M3 indicate movement of the animal from the younger volcanics of the Central Rift Valley to the Nairobi area, around 40 km away, before it died at Lukenya Hill. It is possible that the lower ^{87}Sr/^{86}Sr ratios reflect movement southeast of Lukenya Hill to the Amboseli region, but obsidian from another pastoral site at Lukenya Hill, GvJm47, is dominated by Eburru sources, indicating some link between Lukenya and the Central Rift Valley. All specimens except GvJm52 *Bos* 3 M3 and GvJm52 *Bos* 4 M3 display different tooth wear stages, so interannual changes in herding strategies could be responsible for the differences in ^{87}Sr/^{86}Sr ratios between specimens.

Some caprines from GvJm52 show significant variation, also indicating movement back and forth between areas characterized by low ^{87}Sr/^{86}Sr ratios and the Lukenya Hill locale, particularly GvJm52 Ovis 1 M2, which shows a full cycle of movement (Figure 12.17). All the GvJm52 caprines show increases in ^{87}Sr/^{86}Sr ratios with correlated decreases in δ^{13}C values, suggesting that perhaps the caprines were feeding on more browse while in the Lukenya Hill area, though cattle at the site exhibit very high δ^{13}C values regardless, again pointing to different management strategies for cattle. It is possible that increased browsing by caprines is responsible for lowering the ^{87}Sr/^{86}Sr ratios if rooting depth of plants has an impact on the strontium isotope composition of the leaves. Very high δ^{13}C values of cattle specimens, ranging from 2.5 to 4‰, are associated with samples with ^{87}Sr/^{86}Sr ratios ranging from 0.70718 to 0.70894. Very high ^{87}Sr/^{86}Sr ratios (0.70924) in GvJm52 *Ovis* (ex-*Capra*) 1 M2 are associated with a low δ^{13}C value of -1.9‰. Sampling of fauna that consume different types of vegetation in the area is necessary to further explore this issue.

Finally, to address the issue of exchange, caprine specimens from GvJm52 all exhibit different tooth wear stages, so it is possible that the inter-individual differences in ^{87}Sr/^{86}Sr ratios may be due to changes in mobility strategies by the herders, though exchange of animals cannot be ruled out.

Summary

Given the broad distribution of archaeological sites with common ceramic traditions and lithic industries across the landscape, many archaeologists have assumed that these early pastoral populations were highly mobile. Other lines of evidence, including shared features and dimensions of cattle teeth in Elmenteitan and

SPN sites, as noted by Marshall and Gifford-Gonzalez, point to cattle possibly moving between Elmenteitan and Savanna Pastoral Neolithic ethnic boundaries (Gifford-Gonzalez 1998). Obsidian trade networks also appear to cover great distances (Merrick and Brown 1984). However, isotopic analyses of the cattle and caprines from the sites in this study do not point to high levels of mobility among early pastoralists. Overall, livestock from sites situated in the Central Rift Valley were herded in the Central Rift Valley. Livestock from Narosura, in the Loita Plains, were herded locally and into areas with very high strontium isotope ratios. Only livestock from Lukenya Hill show evidence of herding animals locally and into the Central Rift Valley.

Cattle exhibit more similarity in strontium isotope ratios within individuals than do caprines. This may be due to a few factors. First, this is likely a consequence of the longer mineralization time in cattle teeth, which may dampen the amplitude of the isotopic signal (Balasse, et al. 2002; Montgomery, et al. 2010). Only GvJm44 *Bos* 3 M3 and NS *Bos* 2 M3 (Figure 12.13, Figure 12.15) display seasonal patterns of $^{87}Sr/^{86}Sr$ ratios, and the amplitude of variation is not as high as compared to caprines at Narosura or GvJm52 (Figure 12.14, Figure 12.17).

A second factor is that caprines may have been moved more extensively than cattle. Cattle are more valuable to East African pastoralists today, and do yield less milk if moved long distances (Coppolillo 2000). Pastoralists may have kept cattle herds more locally in prime grazing areas, as indicated by their more constant and very high $\delta^{13}C$ values, while caprines were herded in more marginal regions, though evidence for increased browsing by sheep is not present in the Central Rift Valley sites. This strategy may have been practiced by pastoralists on the plains that flank both sides of the Central Rift Valley, as a way of coping with dystrophic soils. Such a practice would contrast greatly with modern herding strategies, which involve keeping caprines close to the homestead and often moving cattle to distant, better pastures.

Little conclusive evidence exists for exchange of livestock among far-flung pastoral groups. Exchange of livestock among pastoral groups has been widely documented ethnographically. Dahl and Hjort (1976) estimated that up to 40% of a given Maasai cattle herd were distributed among pastoralist friends. Isotopic evidence indicates that, if livestock were traded between herding groups, then these exchanges were based upon local relationships. The findings presented above provide just one window on the herd management strategies of early pastoralists. The next chapter considers hypoplasia data and slaughter patterns in conjunction with isotopic evidence in a discussion of early pastoralism in south-central Kenya.

CHAPTER 13: DISCUSSION

In this chapter I integrate the data from carbon, oxygen, and strontium isotope analyses, with the results from the mortality and hypoplasia study. This information provides a window into seasonal and longer-term pastoral mobility, exchange of livestock, herd management tactics 3000-1200 years ago. As in the previous chapters, I discuss each geographic region separately to address herding strategies at each site. I then turn to a broader discussion of pastoral production in Kenya.

Central Rift Valley Sites

Carbon isotope analysis shows that overall early pastoralists in the study area did not herd their livestock to higher elevations. Balasse and Ambrose (2005b) reported similar findings in their analyses of livestock dentitions from Elmenteitan sites in the Central Rift Valley.

The $^{87}Sr/^{86}Sr$ ratios indicate that livestock from the two Crescent Island sites were herded locally. The oxygen isotope values overall are much higher in Crescent Island Causeway livestock. Crescent Island Main was occupied earlier than Crescent Island Causeway (Table 9.1). It is possible that the drier environment during the time in which Crescent Island Causeway was occupied required herders to remain closer to Lake Naivasha, a permanent water source, while Crescent Island Main herders, occupying the site during a moister period, would have been able to herd animals in a wider geographic range. However, animals from both sites have very high $\delta^{13}C$

values, indicating that grasses were abundant and that conditions were not so dry as to cause livestock to consume browse to supplement their diets.

The $\delta^{18}O$ values of the Ndabibi caprines varies significantly, but strontium isotopes analysis clearly indicates no massive movements. Because the interannual variability of water $\delta^{18}O$ values is so high, it is most likely that the differences in oxygen isotope values likely reflects variation in local precipitation and humidity, especially if the animals are drinking from smaller bodies of water, rather than signaling mobility. The caprines from Ndabibi represent different age classes, and therefore it is not possible to rule out local interannual variability in precipitation or exchange of some animals to the site, as might be the case with the Crescent Island Main caprines.

In contrast, among the cattle from Crescent Island Main and Crescent Island Causeway, the Mature Adult mortality is higher than that in the Aged class. This suggests a herding strategy in which males were slaughtered after being allowed to achieve maximum weight, and females were not kept very long beyond their reproductive prime, perhaps no older than 12 years (Jones and Sadler 2012a). This strategy suggests an emphasis on both meat and milk, and a concentration on herd growth, favoring younger females that are more likely to calve yearly.

The cattle from Prolonged Drift show very little variation oxygen, carbon, or strontium isotope values, indicating that all cattle were kept in the same environment throughout the time of tooth growth. Because there is little inter-individual variation in the cattle specimens, it is possible that the sampled individuals were all from one year cohort or that herding strategies did not vary much from year to year.

The hypoplasia data show that the cattle from Prolonged Drift were very healthy early on in their lives, with hypoplasias increasing later in life. The age at death profiles are quite similar to other SPN sites, including Crescent Island Main and GvJm44, both of which also show peaks in slaughter of cattle as they reach maximum weight, and a substantial proportion of Aged individuals as well. These data suggest that the domesticates at Prolonged Drift were managed by herders living in relatively unstressed conditions.

The slaughter patterns, and hypoplasia data, may be further evaluated in light of the artifact assemblages from Prolonged Drift. The large lithic assemblage, with 250,000 pieces of flaked obsidian, comprising just 10% of the Feature 15 midden contains many microliths and endscrapers, suggesting extensive hide processing (Gifford, et al. 1980; Gifford-Gonzalez, personal communication 2015). A recent reassessment of the lithic assemblage suggests the possible representation of two industries, the Elmenteitan and Eburran 5 (S. Goldstein personal communication 2015). Furthermore, Ambrose (personal communication 2014) has suggested that the undecorated ceramics at the site may be Elmenteitan. One possible explanation of the mixture of lithic traditions and industries at the site is that it was occupied by more than one ethnic/economic group. Interactions between foragers and herders have been documented ethnographically, and in a variety of contexts that include exchange relationships, clientship, intermarriage, etc. It is possible that this single component site represents some facet of interaction between these groups, involving a congregation geared towards the opportunistic hunting and processing seasonally available resources, particularly wildebeest, which are numerous at the site. The high proportion of wild fauna at Prolonged Drift indicates a fluidity in subsistence strategies among pastoral populations. The presence of cattle with relatively few hypoplasias early in their lives, may suggest that particularly high-quality cattle were brought to the site by pastoralists, perhaps as gifts. We may interpret the patterns at Prolonged Drift as further evidence for the maintenance of distinct, yet interdependent ethnic and economic groups.

Narosura

Looking at the combination of strontium, carbon, and oxygen isotope evidence from Narosura, the slightly lower carbon isotope values across individuals at Narosura, relative to other sites, may be due to increased consumption of NADP and PCK grasses, or increased consumption of browse in a drier environment. The lower nutrient content of the soils on older basement rocks may prompt animals to take in more browse (S. Ambrose, personal communication, 2015; Bell 1982). A few caprines do show evidence for higher $\delta^{13}C$ values, but because one is a goat, browsing is likely the source of that trend. The other sampled caprines are sheep, and their $\delta^{13}C$ values are still within the range recorded for modern sheep.

The strontium isotope ratios from both cattle and caprines at the site are quite variable, both within and between individuals. If this variability is not a consequence of a variable geologic substrate, it suggests that herders moved livestock more extensively in this region than did herders in the Central Rift Valley. It is possible that herders at Narosura had to move livestock longer distances to access available water and pastures.

How far livestock, particularly caprines exhibiting high strontium isotope ratios characteristic of the Lake Victoria area, were moved, is still uncertain. While we do not know the degree of variation in southwest Kenya yet, some caprines show a sinusoidal pattern of strontium isotope ratios, indicating that herding to regions with extremely high $^{87}Sr/^{86}Sr$ ratios was a seasonal practice in some years. The fact that these livestock were not herded into areas characterized by lower strontium isotope ratios, like the Central Rift Valley, where other sites with Narosura ware and SPN lithics are found, is intriguing. In fact, the Lake Victoria basin is part of the geographic range of Elmenteitan and Kanysore sites. The domestic assemblages of late Kansyore sites are largely composed of caprines (Prendergast 2010). Future analyses of livestock from Kanysore sites should be undertaken to explore possible trade between Elmenteitan and Narosuran herders and Kansyore-using and –making populations.

Yet another reason may exist for increased mobility. Southwestern Kenya is also home to many Elmenteitan sites, and it is possible that herders from Narosura had to negotiate movements of livestock with respect to herders of the Elmenteitan tradition, therefore increasing their mobility. Obsidian studies have shown that SPN and Elmenteitan groups maintained distinct cultural boundaries, at least in terms of lithic acquisition and trade (Merrick and Brown 1984; Robertshaw 1991). It is possible that herding grounds also remained separate and that livestock were not exchanged between the two groups.

While the exact reason for increased mobility is unclear, herd health and demographic data lend another line of evidence for the ecologic and economic circumstances of herders at the site. Age-at-death data show that, in contrast to other Narosuran sites with substantial MNIs, cattle were slaughtered slightly earlier, before they reached maximum weight. Evidence also exists that some cattle at Narosura were kept alive well past their reproductive prime (represented by very advanced tooth wear stages). The very large caprine assemblage indicates relatively early slaughter of presumably males. Such a strategy is usually employed by herders with limited resources. The hypoplasia data show that livestock from Narosura were relatively healthier than those at other analyzed sites, possibly owing to early culling of males to reserve resources for female livestock and humans. Considered together, these data suggest that the herding conditions at Narosura were slightly less optimal than those in the Central Rift Valley.

Athi-Kapiti Plains Sites

All cattle from the Lukenya Hill sites show evidence for exclusive herding in low elevation areas. Caprines from GvJm52, however, do exhibit higher δ^{13}C values in some cases. One specimen, a sheep, does show a marked decline in δ^{13}C values corresponding with a rise in strontium isotope ratios. Taken together this may be evidence of exchange, though further examination of how rooting depth of plants may affect their strontium isotope ratios is needed (see Chapter 12).

Some specimens at Lukenya Hill, particularly GvJm52, show evidence for herding in areas characterized by lower strontium isotope ratios, similar to values for the Nairobi area. Situated approximately 40 km away from Lukenya Hill, this distance is not unreasonable for herders to travel seasonally (Nyariki, et al. 2009) seasonally. McCabe (1994; 2004), for example, notes remarkable variability in mobility between the herd owners in any given year, as well as variability from one year to the next for individuals. The seasonal variability in ^{87}Sr/^{86}Sr ratios of some GvJm52 caprines also signals that seasonal movements between the Lukenya Hill area and regions characterized by younger volcanics was not uncommon.

No hypoplasia data were collected from Lukenya Hill specimens (largely due to consolidant on many of the specimens). However, mortality data do indicate the herding circumstances at the sites. GvJm52 has a pattern unlike the other sites, with a peak in cattle mortality at the Young Juvenile Age class and one at the Mature Adult age class. Due to low sample sizes, the mortality patterns of cattle and caprines at GvJm52 cannot be interpreted with much certainty, though like the other sites, every age stage for cattle (but infant) is represented here.

Mortality patterns for cattle from GvJm44, like Prolonged Drift and the Crescent Island sites, show a peak at the Older Juvenile age class, which is associated with mortality at maximum weight (see also at Crescent Island Main, Crescent Island Causeway, Prolonged Drift). While mortality does rise with the Mature Adult age class, evidence also exists for cattle kept alive until old age. Some of these aged cattle are represented by very advanced tooth wear stages, and likely represent female cattle kept well past their reproductive prime. Together these patterns suggest herding in an unstressed environment. It is possible that more extensive mobility of herders at Lukenya Hill, with frequent movements onto volcanic soils in the Nairobi region, permitted herders to maintain large herds of cattle.

Summary of seasonal mobility

Overall, the stable isotope analyses indicate that livestock were not moved extensively across the landscape. Stable carbon isotope analyses show that most livestock were herded exclusively in low elevation grasslands, with few individuals exhibiting strontium isotope evidence for movements to geologically distinct regions. Oxygen isotope evidence from this study provides further evidence that a bimodal rainfall pattern was in place by the time specialized pastoralism took hold in south-central Kenya. As noted by Marshall (1990c), this would have permitted pastoralists to rely exclusively on herd animals for subsistence. I hypothesize that before the encroachment of iron-using and –producing agricultural populations into the area, pasture and water resources were abundant so that, especially in the Central Rift Valley, extensive movements were not necessary to maintain livestock herds. Studies and ethnographic accounts show that cattle that are moved extensively yield less milk (Coppolillo 2000; Dahl and Hjort 1976).

The two regions where some evidence for increased mobility exists, the Loita Plains and Athi-Kapiti Plains, are located on old basement rocks, and soils in these areas have lower nutrient contents. I have suggested that this may be one contributing factor to the increase in mobility in these areas. The herders at Narosura, however, did not move livestock into regions characterized by younger volcanics, but moved animals farther west staying on the basement complex of the Tanzanian craton. These divergent mobility strategies may reflect of differences in social networks. It is possible that herders at GvJm44 and GvJm52 maintained relationships with groups in the Central Rift Valley, while those at Narosura interacted with Elmenteitan or Kansyore groups.

Summary of exchange

It is intriguing that stable isotope analyses of livestock from these early pastoralist sites largely do not exhibit evidence for substantial movements across the landscape. Due to the widespread distribution of pastoral sites, particularly those with Narosura ware, many archaeologists have hypothesized that the herding populations would have been highly mobile (Prendergast and Mutundu 2010). The analyses presented here show that this was simply not the case.

The question of whether livestock were exchanged between herders remains. Even for livestock from Narosura, in which drastic changes in strontium isotope composition are seen over time, these patterns are seasonal. Estimates of the percentage of animals exchanged between herders is quite high (Dahl and Hjort

1976). Today livestock are a major medium of exchange among pastoralists. However, the data here show that this was not true in the past, as I found no evidence of early herders trading livestock with far-flung exchange partners. Of course, perhaps those livestock were not sampled. It should be noted that no teeth exhibiting a distinctive reduced third lobe were sampled (Gifford-Gonzalez 1998), and analysis of these specimens may provide evidence for exchange, as the reduced lobe can be a consequence of inbreeding. If livestock were not the major medium of exchange, other items were. Merrick and Brown’s (1984) obsidian XRF study shows that the material was widely exchanged. New obsidian characterization studies can further clarify exchange relationships (Brown, et al. 2013). Still, the presence of neonatal wildebeest, active carriers of the fatal wildebeest-derived malignant catarrhal fever, at sites like Prolonged Drift (Gifford-Gonzalez and Kimengich 1984) would have posed a significant threat to cattle herds in the area. In instances of local disasters, such as disease outbreaks, raiding, or localized drought, herders may activate stock loan or gift friendships to rebuild herds or resort to raiding (Dahl and Hjort 1976; Spencer 1965; Waller and Sobania 1994). It is possible that local exchange relationships may have been sufficient for herders to cope with periodic livestock losses.

While this work does substantially clarify the mobility and herd management strategies of ancient herders, the conclusions summarized above introduce some intriguing questions. In the final chapter I outline the conclusions offered from these analyses, lingering questions, and avenues for future research.

CHAPTER 14: CONCLUSION

In the previous chapters I have shown, through stable isotope analysis of sequentially sampled livestock teeth, that Central Kenya's earliest pastoralists definitely did not practice altitudinal mobility characteristic of historically documented herders. Similarly, strontium isotope evidence shows that in most cases herders did not move their animals long distances, nor is there evidence for exchange of livestock between far-flung groups. These results indicate that the mobility patterns seen among East African pastoralists today were not in place 3000 to 1200 years ago. It is likely that before the growth of pastoral populations and the encroachment of iron-using and –producing peoples into the region, population densities were low enough that pastoralists did not need to move their animals altitudinally to access seasonally available pastures.

Overall, the age-at-death profiles presented here show an emphasis on maintaining large herds. Cattle were kept alive for longer spans of their lifetimes, and at most sites males were allowed to reach maximum weight before slaughter. These culling strategies suggest that land and forage were abundant in relation to the standing herd of cattle. One of the research questions posed in the beginning of this work that remains unanswered is how pastoralism spread. Results from artifactual, isotopic and zooarchaeological analyses of cattle from Prolonged Drift suggest that the site was occupied by more than one ethnic/economic group. The circumstances at this site do give a window into one aspect of the interactions between economically separate, yet interdependent foragers and herders of the region.

These data strongly indicate that ethnographic studies, while certainly a useful starting point, do not necessarily reflect practices of herders one to two millennia ago, before the introduction of agriculture into the region. In particular, the social and ecological context in which these pastoral groups were managing herds is different from anything documented historically, and therefore detailed zooarchaeological and isotopic analyses as presented here are necessary to identify subtle differences in herd management strategies and provide a more textured view of the economic shifts among pastoral populations over time. However, more ethnographic and archaeological studies of pastoral populations in East Africa are necessary to further the understanding of the long-term social and economic history of the region.

Several avenues for further research may clarify the economic decisions and interactions among herders and foragers. While substantial work exists detailing livestock productivity in East Africa, future ethnographic research focusing on the proportion of aged cows in modern herds would provide a more nuanced view of herding strategies. Ethnoarchaeological studies of hypoplasias in modern cattle populations with known life histories in a variety of herding environments in East Africa are also needed to provide a comparison to the archaeological data to accurately assess the health of ancient cattle populations.

Archaeologically, a reanalysis of the ceramics at Prolonged Drift is warranted, particularly since the initial classifications were made only when SPN wares had been recently identified. Petrographic analyses of ceramics could also shed more light on production, exchange, and interactions among different groups.

More work is necessary to refine the strontium isoscape. In particular, more samples from the Athi Plains region would lend a more detailed view on the herding patterns of the occupants of the Lukenya Hill sites, which here show evidence for herding between the plains and the younger volcanics of the Central Rift Valley. In addition, more samples from the Mara area will be required to gain a better picture of the mobility patterns of herders at Narosura and other early herding sites in that area. Given the number of other pastoral sites in this region, this will be crucial for identifying mobility strategies for Elmenteitan herders as well.

In addition increased sampling west of the Central Rift, towards Lake Victoria, is another area in need of sampling. Domestic livestock are present at late Kansyore sites including at Wadh Lang'o as early as 2458 – 2032 cal. BC. (Prendergast 2010) as well as at Usenge 3 and Gogo Falls (Lane, et al. 2007). Future work examining the mobility strategies and livestock exchange patterns of Kansyore-users and -makers would shed light on the transition from foraging to herding in this region, as well as herding strategies in this different environment and cultural setting.

The strontium isoscape should also be expanded into northern Tanzania. Recent work by Prendergast, et al. (2014) has shown that the dates for Narosura sites are indeed quite early. Investigations into herding practices at these sites could clarify whether livestock were moved within long distances between herders, or seasonally. The diverse geology around Lake Eyasi in particular would be a worthwhile starting point.

Because most radiocarbon dates for the sites discussed in this study are decades-old, conventional determinations, often on questionable materials, several AMS dates should be obtained for each site. The standard deviations are quite large for the original dates reported for the sites, and a better chronology could shed light on differences in herding strategies over time. Sites included in this study span centuries, and there would have certainly been climatic shifts over that time span. Furthermore, a substantial difference exists between the $\delta^{18}O$ values at the two Crescent Island sites, and precise AMS dating would clarify whether the trends in $\delta^{18}O$ values were due to climatic changes over time, or differences in herding strategies.

Finally, zooarchaeological and isotopic analyses of livestock from Iron Age sites would provide insight into the shifts in herding and mobility strategies pastoral populations had to negotiate as farming populations moved into East Africa. As noted above, the herd management tactics employed by early pastoralists do not fully align with those recorded in ethnohistoric accounts. However, by the time these ethnographies were published, significant changes had occurred due to the influence of colonialism, yet the impacts of such contacts were usually never discussed (Stahl 2001, but see Stenning 1959). Future studies of herding practices in the Iron Age would clarify whether the management tactics practiced by pastoralists today developed long ago with the introduction of agriculture, or whether they emerged during the colonial period, which greatly impacted pastoralists' livelihoods (Waller and Sobania 1994).

The divergence between herding practices of modern and ancient pastoralists shows the need for fine-grained zooarchaeological and isotopic analyses to elucidate mobility, livestock management and exchange relationships. The data presented here reveal that landscape use among early herders was much different before the entry of agricultural populations, and that exchange patterns differed significantly as well, both aspects of pastoral production remaining on the local scale. These findings are seemingly at odds with the patterns of obsidian acquisition and exchange patterns, as well as the distribution of ceramic wares across a vast geographic range. These disparate patterns may suggest that, while livestock were clearly economically important to early herders, they were not the pervasive medium of exchange documented so extensively among pastoralists today.

In sum, this study clarifies some of the mobility and herd management tactics of early pastoralists in Kenya. Through detailed analyses of fauna, subtle differences in the patterns in pastoral production can be brought to light. The above suggestions for further research would further enhance our understanding of shifts in the patterns of herding practices and spread of food production throughout East Africa as well as the relationships between herding and foraging groups.

APPENDIX 1: OXYGEN, CARBON, AND STRONTIUM ISOTOPE VALUES OF ARCHAEOLOGICAL LIVESTOCK TOOTH ENAMEL

Table A1.1: Oxygen, carbon, and strontium isotope values of CI-M *Bos* 1 M3.

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**	**$^{87}Sr/^{86}Sr$**
CI-M *Bos* 1 M3-1	42.8	3.0	2.2	0.70713
CI-M *Bos* 1 M3-2	40.1	2.7	2.2	
CI-M *Bos* 1 M3-3	37.5	2.8	2.2	
CI-M *Bos* 1 M3-4	33.8	3.0	2.5	
CI-M *Bos* 1 M3-5	31.3	2.5	2.2	
CI-M *Bos* 1 M3-6	28.8	2.7	2.1	0.70698
CI-M *Bos* 1 M3-7	26.3	2.8	2.5	
CI-M *Bos* 1 M3-8	24.1	2.8	2.8	
CI-M *Bos* 1 M3-9	21.7	3.0	2.7	
CI-M *Bos* 1 M3-10	18.7	2.9	2.3	0.70697
CI-M *Bos* 1 M3-11	16.3	3.0	2.6	
CI-M *Bos* 1 M3-12	14.5	3.1	2.8	
CI-M *Bos* 1 M3-13	12.3	2.9	2.4	
CI-M *Bos* 1 M3-14	9.6	2.7	2.0	
CI-M *Bos* 1 M3-15	6.7	3.0	2.9	
CI-M *Bos* 1 M3-16	4.8	2.5	2.3	
CI-M *Bos* 1 M3-17	2.4	3.0	2.6	0.70692

Table A1.2: Oxygen, carbon, and strontium isotope values of CI-M Bos 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
Cl-M *Bos* 2 M3-1	45.7	3.5	0.6	0.70693
Cl-M *Bos* 2 M3-2	43.2	3.4	0.4	
Cl-M *Bos* 2 M3-3	41.3	3.4	0.3	
CI-M *Bos* 2 M3-4	39	3.2	-0.3	
Cl-M *Bos* 2 M3-5	37	3.4	-0.1	
Cl-M *Bos* 2 M3-6	34.7	3.4	-0.6	
Cl-M *Bos* 2 M3-7	32.6	3.5	-0.4	
CI-M *Bos* 2 M3-8	30	3.3	-0.8	0.7072
Cl-M *Bos* 2 M3-9	27.8	3.5	-0.6	
Cl-M *Bos* 2 M3-10	25.7	3.6	0.2	
Cl-M *Bos* 2 M3-11	23.4	3.3	0.2	
Cl-M *Bos* 2 M3-12	21	3.3	0.3	
Cl-M *Bos* 2 M3-13	18.7	3.3	0.2	
Cl-M *Bos* 2 M3-14	16.6	3.3	0.3	0.70725
Cl-M *Bos* 2 M3-15	14.3	3.4	0.5	
Cl-M *Bos* 2 M3-16	12.3	3.4	0.4	
Cl-M *Bos* 2 M3-17	10	3.0	0.3	
Cl-M *Bos* 2 M3-18	7.8	3.1	0.1	
Cl-M *Bos* 2 M3-19	5.5	3.1	0.0	
Cl-M *Bos* 2 M3-20	3.7	2.8	-0.4	0.70699
Cl-M *Bos* 2 M3-21	2.1	3.2	-0.1	

Table A1.3: Oxygen, carbon, and strontium isotope values CI-M *Bos* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-M *Bos* 3 M3-1	36.1	3.2	1.1	0.70635
CI-M *Bos* 3 M3-2	33.8	3.0	0.5	
CI-M *Bos* 3 M3-3	31.4	3.0	0.9	
CI-M *Bos* 3 M3-4	29.3	2.8	0.4	
CI-M *Bos* 3 M3-5	27.1	3.0	0.4	
CI-M *Bos* 3 M3-6	24.3	2.8	-0.2	0.70619
CI-M *Bos* 3 M3-7	21.7	3.2	1.2	
CI-M *Bos* 3 M3-8	20.4	3.3	1.6	
CI-M *Bos* 3 M3-9	18.2	3.3	1.4	
CI-M *Bos* 3 M3-10	15.9	3.2	0.9	
CI-M *Bos* 3 M3-11	13.6	3.4	1.3	
CI-M *Bos* 3 M3-12	11.3	3.4	1.1	
CI-M *Bos* 3 M3-13	9.2	3.5	1.6	
CI-M *Bos* 3 M3-14	7.3	3.7	1.7	0.70618
CI-M *Bos* 3 M3-15	4.6	3.7	1.2	
CI-M *Bos* 3 M3-16	2.5	3.5	0.2	

Table A1.4: Oxygen, carbon, and strontium isotope values of CI-M *Bos* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-M *Bos* 4 M3-1	36.3	2.4	0.8	0.70599
CI-M *Bos* 4 M3-2	33.9	2.5	1.5	
CI-M *Bos* 4 M3-3	31.9	2.4	2.1	
CI-M *Bos* 4 M3-4	29.6	2.6	2.6	
CI-M *Bos* 4 M3-5	27.3	2.6	2.4	
CI-M *Bos* 4 M3-6	24.6	2.7	3.6	0.70636
CI-M *Bos* 4 M3-7	22.2	2.8	3.3	
CI-M *Bos* 4 M3-8	20	2.7	3.4	
CI-M *Bos* 4 M3-9	17.8	2.9	2.7	
CI-M *Bos* 4 M3-10	15.5	3.0	3.2	
CI-M *Bos* 4 M3-11	13.3	2.9	2.7	
CI-M *Bos* 4 M3-12	10.8	3.0	2.5	
CI-M *Bos* 4 M3-13	8.8	3.1	1.7	0.70663
CI-M *Bos* 4 M3-14	6.4	3.0	2.2	
CI-M *Bos* 4 M3-15	4.4	3.3	2.3	
CI-M *Bos* 4 M3-16	1.7	3.3	2.8	0.70657

Table A1.5: Oxygen, carbon, and strontium isotope values of CI-M *Ovis* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-M *Ovis* 1 M3-1	16.7	3.6	3.1	0.70705
CI-M *Ovis* 1 M3-2	15.5	3.5	3.2	
CI-M *Ovis* 1 M3-3	13.8	3.3	3.6	
CI-M *Ovis* 1 M3-4	12.6	3.1	3.5	
CI-M *Ovis* 1 M3-5	11	2.9	3.9	
CI-M *Ovis* 1 M3-6	9.3	2.7	4.1	0.70711
CI-M *Ovis* 1 M3-7	8.1	2.7	4.1	
CI-M *Ovis* 1 M3-8	6.1	2.5	3.6	
CI-M *Ovis* 1 M3-9	4.8	2.5	4.6	
CI-M *Ovis* 1 M3-10	3.7	2.7	4.4	
CI-M *Ovis* 1 M3-11	1.7	3.0	4.8	0.70689

Table A1.6: Oxygen, carbon, and strontium isotope values of CI-M *Ovis* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-M *Ovis* 2 M3-1	22.5	2.6	9.3	0.70574
CI-M *Ovis* 2 M3-2	20.7	2.3	9.1	
CI-M *Ovis* 2 M3-3	19.7	2.2	8.8	
CI-M *Ovis* 2 M3-4	18.4	2.3	8.6	
CI-M *Ovis* 2 M3-5	16.8	2.3	8.4	
CI-M *Ovis* 2 M3-6	15.1	2.5	8.2	
CI-M *Ovis* 2 M3-7	13.7	3.0	8.2	
CI-M *Ovis* 2 M3-8	12.5	3.3	8.3	0.7057
CI-M *Ovis* 2 M3-9	11	3.1	8.7	
CI-M *Ovis* 2 M3-10	9.3	3.0	8.7	
CI-M *Ovis* 2 M3-11	8.3	3.2	8.6	
CI-M *Ovis* 2 M3-12	6.8	4.0	9.4	0.70569
CI-M *Ovis* 2 M3-13	5.6	3.4	9.9	
CI-M *Ovis* 2 M3-14	3.9	3.1	9.9	
CI-M *Ovis* 2 M3-15	2.7	2.9	9.0	
CI-M *Ovis* 2 M3-16	1.1	2.4	8.1	0.70578

Table A1.7: Oxygen, carbon, and strontium isotope values of CI-M *Ovis* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-M *Ovis* 3 M3-1	36.6	3.4	4.7	
CI-M *Ovis* 3 M3-2	35.2	3.3	4.8	0.70616
CI-M *Ovis* 3 M3-3	33.8	3.4	4.8	
CI-M *Ovis* 3 M3-4	32.2	3.3	5.0	
CI-M *Ovis* 3 M3-5	30.6	3.4	4.7	
CI-M *Ovis* 3 M3-6	29.2	3.6	5.0	
CI-M *Ovis* 3 M3-7	27.7	3.3	4.8	
CI-M *Ovis* 3 M3-8	26.2	3.5	4.7	
CI-M *Ovis* 3 M3-9	24.1	3.8	4.9	0.70599
CI-M *Ovis* 3 M3-10	22.4	3.7	4.8	
CI-M *Ovis* 3 M3-11	20.9	3.6	4.4	
CI-M *Ovis* 3 M3-12	19.6	3.7	4.2	
CI-M *Ovis* 3 M3-13	18	3.6	3.8	
CI-M *Ovis* 3 M3-14	16.4	3.6	3.5	
CI-M *Ovis* 3 M3-15	14.9	3.2	3.9	
CI-M *Ovis* 3 M3-16	13.4	3.1	3.7	0.70599
CI-M *Ovis* 3 M3-17	12.1	3.1	3.7	
CI-M *Ovis* 3 M3-18	10.7	3.3	3.8	
CI-M *Ovis* 3 M3-19	8.9	3.3	3.2	
CI-M *Ovis* 3 M3-20	7.4	3.6	2.4	0.70667
CI-M *Ovis* 3 M3-21	5.9	3.4	2.3	
CI-M *Ovis* 3 M3-22	4.7	3.2	3.2	

Table A1.8: Oxygen, carbon, and strontium isotope values of CI-M *Ovis* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-M *Ovis* 4 M3-1	32.4	3.1	4.9	
CI-M *Ovis* 4 M3-2	30.8	3.2	5.2	
CI-M *Ovis* 4 M3-3	29.6	3.0	5.3	0.70662
CI-M *Ovis* 4 M3-4	27.7	2.7	5.1	
CI-M *Ovis* 4 M3-5	26.3	2.5	4.7	
CI-M *Ovis* 4 M3-6	24.7	2.5	4.4	
CI-M *Ovis* 4 M3-7	23.2	2.3	3.7	
CI-M *Ovis* 4 M3-8	21.8	1.9	2.9	
CI-M *Ovis* 4 M3-9	20.1	1.9	2.6	
CI-M *Ovis* 4 M3-10	18.6	2.0	2.5	0.70663
CI-M *Ovis* 4 M3-11	17.2	2.1	2.5	
CI-M *Ovis* 4 M3-12	15.5	2.1	2.8	
CI-M *Ovis* 4 M3-13	14.2	2.0	3.1	
CI-M *Ovis* 4 M3-14	12.8	2.2	4.0	
CI-M *Ovis* 4 M3-15	11.3	2.3	4.2	
CI-M *Ovis* 4 M3-16	9.8	2.1	4.5	
CI-M *Ovis* 4 M3-17	8.6	2.0	4.6	
CI-M *Ovis* 4 M3-18	7	2.4	4.8	
CI-M *Ovis* 4 M3-19	5.4	2.5	5.1	0.70626
CI-M *Ovis* 4 M3-20	4	2.5	4.9	
CI-M *Ovis* 4 M3-21	2.9	2.8	4.6	

Table A1.9: Oxygen, carbon, and strontium isotope values of CI-C *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Bos* 1 M2-1	36.6	2.9	3.9	0.70601
CI-C *Bos* 1 M2-2	34.5	3.3	3.4	
CI-C *Bos* 1 M2-3	32.4	3.1	3.4	
CI-C *Bos* 1 M2-4	30.5	3.3	3.2	
CI-C *Bos* 1 M2-5	28.6	3.4	3.2	
CI-C *Bos* 1 M2-6	26.9	3.3	3.2	
CI-C *Bos* 1 M2-7	24.6	3.6	3.7	
CI-C *Bos* 1 M2-8	22.8	3.5	3.4	0.70618
CI-C *Bos* 1 M2-9	20.9	3.6	3.8	
CI-C *Bos* 1 M2-10	19.1	3.6	4.0	
CI-C *Bos* 1 M2-11	17.1	3.7	4.1	
CI-C *Bos* 1 M2-12	15.4	3.6	4.2	
CI-C *Bos* 1 M2-13	13.5	3.6	4.4	0.70633
CI-C *Bos* 1 M2-14	11.6	3.6	4.3	
CI-C *Bos* 1 M2-15	10.4	3.7	4.3	
CI-C *Bos* 1 M2-16	8.2	3.8	4.3	
CI-C *Bos* 1 M2-17	6	3.7	4.4	
CI-C *Bos* 1 M2-18	4.3	3.7	4.1	
CI-C *Bos* 1 M2-19	2.2	4.0	5.0	0.70619

Table A1.10: Oxygen, carbon, and strontium isotope values of CI-C *Bos* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Bos* 2 M3-2	30.6	3.8	4.0	0.7063
CI-C *Bos* 2 M3-3	28.2	3.7	3.9	
CI-C *Bos* 2 M3-4	26.2	3.6	4.5	
CI-C *Bos* 2 M3-5	23.9	3.7	4.4	
CI-C *Bos* 2 M3-6	21.6	3.8	5.0	0.7062
CI-C *Bos* 2 M3-7	19.2	3.8	4.7	
CI-C *Bos* 2 M3-8	16.9	3.7	4.9	
CI-C *Bos* 2 M3-9	14.7	3.8	4.7	
CI-C *Bos* 2 M3-10	12.6	3.9	4.8	
CI-C *Bos* 2 M3-11	10.3	3.7	4.2	0.70613

Table A1.11: Oxygen, carbon, and strontium isotope values of CI-C *Bos* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Bos* 3 M3-1	42.5	2.7	4.4	
CI-C *Bos* 3 M3-2	40.5	3.3	5.2	
CI-C *Bos* 3 M3-3	38.6	3.3	5.4	0.70612
CI-C *Bos* 3 M3-4	36.4	3.3	5.1	
CI-C *Bos* 3 M3-5	34.4	3.3	4.8	
CI-C *Bos* 3 M3-6	32.5	3.2	5.0	
CI-C *Bos* 3 M3-7	30.6	3.3	4.7	
CI-C *Bos* 3 M3-8	28.5	3.2	4.3	
CI-C *Bos* 3 M3-9	26.5	3.2	4.5	
CI-C *Bos* 3 M3-10	24.3	3.1	4.5	0.70618
CI-C *Bos* 3 M3-11	22.3	3.0	3.7	
CI-C *Bos* 3 M3-12	20.2	2.9	4.1	
CI-C *Bos* 3 M3-13	18.3	2.8	4.0	
CI-C *Bos* 3 M3-14	16.2	2.7	4.1	
CI-C *Bos* 3 M3-15	14	2.5	3.9	
CI-C *Bos* 3 M3-16	12	2.4	3.9	
CI-C *Bos* 3 M3-17	9.4	2.3	3.7	
CI-C *Bos* 3 M3-18	6.9	2.1	3.8	
CI-C *Bos* 3 M3-19	4.4	1.9	3.7	0.706
CI-C *Bos* 3 M3-20	2.4	2.1	4.3	

Table A1.12: Oxygen, carbon, and strontium isotope values of CI-C *Bos* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Bos* 4 M3-1	44.1	3.5	4.2	0.70636
CI-C *Bos* 4 M3-2	42.2	3.5	4.1	
CI-C *Bos* 4 M3-3	40.1	3.6	3.9	
CI-C *Bos* 4 M3-4	38	3.6	3.8	
CI-C *Bos* 4 M3-5	36	3.5	3.5	
CI-C *Bos* 4 M3-6	33.6	3.3	3.2	
CI-C *Bos* 4 M3-7	31.4	3.5	3.3	
CI-C *Bos* 4 M3-8	29.2	3.5	3.0	
CI-C *Bos* 4 M3-9	27.2	3.6	3.0	
CI-C *Bos* 4 M3-10	25.1	3.7	3.3	
CI-C *Bos* 4 M3-11	22.9	3.5	2.6	
CI-C *Bos* 4 M3-12	21	3.8	2.3	0.70626
CI-C *Bos* 4 M3-13	19	3.8	2.6	
CI-C *Bos* 4 M3-14	16.5	4.0	2.3	
CI-C *Bos* 4 M3-15	14.5	3.9	2.7	
CI-C *Bos* 4 M3-16	12.4	3.9	3.0	
CI-C *Bos* 4 M3-17	9.7	3.9	3.2	
CI-C *Bos* 4 M3-18	7.4	4.0	3.5	
CI-C *Bos* 4 M3-19	4.9	4.0	3.4	
CI-C *Bos* 4 M3-20	2.3	3.9	3.9	0.70627

Table A1.13: Oxygen, carbon, and strontium isotope values of CI-C *Ovis* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Ovis* 1 M3-1	36	3.7	6.6	
CI-C *Ovis* 1 M3-2	34.6	3.6	6.6	0.7062
CI-C *Ovis* 1 M3-3	32.9	3.6	6.5	
CI-C *Ovis* 1 M3-4	31.4	3.2	6.4	
CI-C *Ovis* 1 M3-5	30.2	3.2	6.2	
CI-C *Ovis* 1 M3-6	28.5	3.1	6.0	
CI-C *Ovis* 1 M3-7	26.9	2.9	5.7	0.70658
CI-C *Ovis* 1 M3-8	25.3	2.7	5.9	
CI-C *Ovis* 1 M3-9	23.8	2.7	5.6	
CI-C *Ovis* 1 M3-10	22.4	2.4	6.1	
CI-C *Ovis* 1 M3-11	20.8	2.2	5.5	
CI-C *Ovis* 1 M3-12	19.4	2.0	5.0	
CI-C *Ovis* 1 M3-13	18	1.9	5.1	0.70636
CI-C *Ovis* 1 M3-14	16.5	2.1	5.4	
CI-C *Ovis* 1 M3-15	15	2.1	5.3	
CI-C *Ovis* 1 M3-16	13.5	2.2	5.7	
CI-C *Ovis* 1 M3-17	11.9	2.4	5.7	
CI-C *Ovis* 1 M3-18	10.4	2.6	5.0	
CI-C *Ovis* 1 M3-19	9	3.4	4.3	0.70624
CI-C *Ovis* 1 M3-20	7.6	3.3	5.2	
CI-C *Ovis* 1 M3-21	6.2	3.1	5.1	
CI-C *Ovis* 1 M3-22	4.6	3.2	4.6	
CI-C *Ovis* 1 M3-23	3.2	3.2	3.5	0.70649
CI-C *Ovis* 1 M3-24	1.7	3.5	4.5	

Table A1.14: Oxygen, carbon, and strontium isotope values of CI-C *Ovis* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Ovis* 2 M3-1	36	2.4	5.6	0.70616
CI-C *Ovis* 2 M3-2	34.5	2.2	5.9	
CI-C *Ovis* 2 M3-3	33	2.1	6.0	
CI-C *Ovis* 2 M3-4	31.6	2.1	6.6	
CI-C *Ovis* 2 M3-5	30.2	2.0	6.5	
CI-C *Ovis* 2 M3-6	28.9	2.1	6.7	
CI-C *Ovis* 2 M3-7	27.3	2.4	6.8	
CI-C *Ovis* 2 M3-8	26	2.3	7.1	
CI-C *Ovis* 2 M3-9	24.6	2.2	7.2	
CI-C *Ovis* 2 M3-10	23.4	2.3	7.4	0.70603
CI-C *Ovis* 2 M3-11	21.9	2.3	7.2	
CI-C *Ovis* 2 M3-12	20.5	2.2	7.1	
CI-C *Ovis* 2 M3-13	19	2.1	6.9	
CI-C *Ovis* 2 M3-14	17.7	2.0	7.0	
CI-C *Ovis* 2 M3-15	16.4	2.2	6.4	
CI-C *Ovis* 2 M3-16	14.6	2.0	6.3	
CI-C *Ovis* 2 M3-17	13.4	2.0	6.2	
CI-C *Ovis* 2 M3-18	12.1	2.2	5.8	
CI-C *Ovis* 2 M3-19	10.7	2.2	5.3	
CI-C *Ovis* 2 M3-20	9.4	2.1	5.3	
CI-C *Ovis* 2 M3-21	7.8	2.1	4.9	
CI-C *Ovis* 2 M3-22	6.5	2.1	4.6	
CI-C *Ovis* 2 M3-23	5.1	1.8	3.6	0.706
CI-C *Ovis* 2 M3-24	3.3	2.1	3.4	

Table A1.15: Oxygen, carbon, and strontium isotope values of CI-C *Ovis* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Ovis* 3 M3-1	34.6	2.5	5.5	
CI-C *Ovis* 3 M3-2	33.1	2.5	5.5	
CI-C *Ovis* 3 M3-3	31.8	2.6	5.4	
CI-C *Ovis* 3 M3-4	30.4	2.7	5.5	0.70675
CI-C *Ovis* 3 M3-5	29	2.7	5.0	
CI-C *Ovis* 3 M3-6	27.5	3.1	4.7	
CI-C *Ovis* 3 M3-7	26.2	3.0	4.6	
CI-C *Ovis* 3 M3-8	24.8	3.2	5.1	
CI-C *Ovis* 3 M3-9	23.4	3.2	5.0	
CI-C *Ovis* 3 M3-10	22.1	3.3	4.8	
CI-C *Ovis* 3 M3-11	20.6	3.3	4.6	
CI-C *Ovis* 3 M3-12	19.2	3.3	4.1	
CI-C *Ovis* 3 M3-13	17.9	3.5	3.4	
CI-C *Ovis* 3 M3-14	16.6	3.7	3.6	
CI-C *Ovis* 3 M3-15	15.2	3.8	3.3	0.70671
CI-C *Ovis* 3 M3-16	13.9	3.7	4.1	
CI-C *Ovis* 3 M3-17	12.5	3.7	4.4	
CI-C *Ovis* 3 M3-18	11.2	3.3	4.7	
CI-C *Ovis* 3 M3-19	9.9	3.2	4.9	
CI-C *Ovis* 3 M3-20	8.5	3.2	5.2	
CI-C *Ovis* 3 M3-21	7.2	2.8	5.0	
CI-C *Ovis* 3 M3-22	6	2.5	5.4	
CI-C *Ovis* 3 M3-23	4.5	2.8	5.5	0.70647
CI-C *Ovis* 3 M3-24	3.2	2.8	5.2	
CI-C *Ovis* 3 M3-25	1.7	2.7	5.2	

Table A1.16: Oxygen, carbon, and strontium isotope values of CI-C *Ovis* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
CI-C *Ovis* 4 M2-1	29.6	2.9	5.4	0.70599
CI-C *Ovis* 4 M2-2	28.2	2.8	5.9	
CI-C *Ovis* 4 M2-3	26.7	2.8	6.3	
CI-C *Ovis* 4 M2-4	25.3	2.7	6.8	
CI-C *Ovis* 4 M2-5	23.8	2.7	6.6	
CI-C *Ovis* 4 M2-6	22.4	2.6	6.7	
CI-C *Ovis* 4 M2-7	20.8	2.5	6.3	
CI-C *Ovis* 4 M2-8	19.3	2.8	6.8	0.70612
CI-C *Ovis* 4 M2-9	17.8	2.9	6.4	
CI-C *Ovis* 4 M2-10	16.5	2.8	6.4	
CI-C *Ovis* 4 M2-11	15	2.9	6.4	
CI-C *Ovis* 4 M2-12	13.7	2.6	5.9	
CI-C *Ovis* 4 M2-13	12.2	2.6	5.3	
CI-C *Ovis* 4 M2-14	10.8	2.7	5.2	
CI-C *Ovis* 4 M2-15	9.3	2.1	4.3	0.70662
CI-C *Ovis* 4 M2-16	7.7	2.0	4.5	
CI-C *Ovis* 4 M2-17	6.1	2.6	4.8	
CI-C *Ovis* 4 M2-18	4.6	3.0	5.1	0.70672
CI-C *Ovis* 4 M2-19	2.8	2.8	4.6	

Table A1.17: Oxygen, carbon, and strontium isotope values of NDA *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA *Bos* 1 M1-1	17.1	3.3	2.2	
NDA *Bos* 1 M1-2	15.1	2.9	1.8	0.70697
NDA *Bos* 1 M1-3	12.9	3.3	2.5	
NDA *Bos* 1 M1-4	11.2	3.2	2.2	
NDA *Bos* 1 M1-5+6	7	3.4	2.2	
NDA *Bos* 1 M1-7	4.9	3.6	2.3	
NDA *Bos* 1 M1-8	2.8	3.7	2.9	0.7071

Table A1.18: Oxygen, carbon, and strontium isotope values of NDA *Bos* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA *Bos* 2 M1-1	26.1	2.2	3.6	
NDA *Bos* 2 M1-2	24.1	2.4	4.2	0.70662
NDA *Bos* 2 M1-3	22.2	2.4	3.2	
NDA *Bos* 2 M1-4	20.1	2.7	3.4	
NDA *Bos* 2 M1-5	18	2.7	3.1	
NDA *Bos* 2 M1-6	15.8	2.6	3.2	
NDA *Bos* 2 M1-7	13.5	2.8	2.8	
NDA *Bos* 2 M1-8	11.2	2.7	3.0	
NDA *Bos* 2 M1-9	9.4	2.9	2.7	0.7067

Table A1.19: Oxygen, carbon, and strontium isotope values of NDA *Bos* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA Bos 3 M3-1	26.7	2.4	0.4	
NDA Bos 3 M3-2	24.8	2.5	0.7	0.70714
NDA Bos 3 M3-3	22.6	2.6	0.2	
NDA Bos 3 M3-4	20.5	2.7	0.4	
NDA Bos 3 M3-5	17.8	2.8	0.0	
NDA Bos 3 M3-6	15.7	2.9	0.2	0.70714
NDA Bos 3 M3-7	13.4	2.8	-0.2	
NDA Bos 3 M3-8	11.3	2.9	0.2	
NDA Bos 3 M3-9	9.1	2.4	-0.4	0.70708
NDA Bos 3 M3-10	7.1	2.1	0.4	
NDA Bos 3 M3-11	5.1	2.2	0.2	
NDA Bos 3 M3-12	2.6	2.4	0.5	
NDA Bos 3 M3-13	0	3.2	0.7	

Table A1.20: Oxygen, carbon, and strontium isotope values of NDA *Capra* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA *Capra* 1 M2-1	28.9	4.2	4.9	0.70672
NDA *Capra* 1 M2-2	27.3	3.9	5.1	
NDA *Capra* 1 M2-3	24.3	3.5	5.5	
NDA *Capra* 1 M2-4	23	3.3	5.2	
NDA *Capra* 1 M2-5	22	3.3	5.2	
NDA *Capra* 1 M2-6	20.7	3.4	5.5	
NDA *Capra* 1 M2-7	19.4	3.7	5.3	
NDA *Capra* 1 M2-8	18.1	3.9	5.8	0.70674
NDA *Capra* 1 M2-9	16.7	3.9	5.7	
NDA *Capra* 1 M2-10	15.3	4.0	5.6	
NDA *Capra* 1 M2-11	14.1	3.8	5.0	
NDA *Capra* 1 M2-12	12.8	3.4	5.1	
NDA *Capra* 1 M2-13	11.3	3.5	4.9	
NDA *Capra* 1 M2-14	9.9	3.7	5.7	
NDA *Capra* 1 M2-15	8.4	3.8	5.6	
NDA *Capra* 1 M2-16	7	3.3	5.7	
NDA *Capra* 1 M2-17	5.8	3.2	4.5	
NDA *Capra* 1 M2-18	4.4	4.1	5.0	0.70674
NDA *Capra* 1 M2-19	3.4	3.7	4.7	
NDA *Capra* 1 M2-20	1.5	3.2	5.2	

Table A1.21: Oxygen, carbon, and strontium isotope values of NDA *O/C* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA *O/C* 1 M3-1	10.1	3.5	2.0	
NDA *O/C* 1 M3-2	8.6	3.2	1.1	0.70614
NDA *O/C* 1 M3-3	7.2	3.1	1.3	
NDA *O/C* 1 M3-4	5.9	3.2	1.7	
NDA *O/C* 1 M3-5	4.7	3.1	2.9	
NDA *O/C* 1 M3-6	3.4	2.5	3.2	
NDA *O/C* 1 M3-7	1.7	2.2	3.5	0.70606

Table A1.22: Oxygen, carbon, and strontium isotope values of NDA *O/C* 2 M1

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA *O/C* 2 M1-1	19.1	3.0	8.4	0.70621
NDA *O/C* 2 M1-2	17.6	2.8	7.9	
NDA *O/C* 2 M1-3	16.2	2.8	7.6	
NDA *O/C* 2 M1-4	14.7	2.9	7.8	
NDA *O/C* 2 M1-5	13.5	2.8	7.4	
NDA *O/C* 2 M1-6	12.3	2.4	7.0	
NDA *O/C* 2 M1-7	11.1	2.5	7.3	0.70619
NDA *O/C* 2 M1-8	9.7	2.4	7.7	
NDA *O/C* 2 M1-9	8.3	2.6	7.6	
NDA *O/C* 2 M1-10	6.4	2.8	8.0	
NDA *O/C* 2 M1-11	4.7	2.5	7.7	
NDA *O/C* 2 M1-12	2.6	2.6	7.8	0.70616

Table A1.23: Oxygen, carbon, and strontium isotope values of NDA *Ovis* 1 M2

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NDA *Ovis* 1 M2-1	25.5	2.7	1.8	0.70615
NDA *Ovis* 1 M2-2	24.1	2.7	2.1	
NDA *Ovis* 1 M2-3	22.4	2.6	2.5	
NDA *Ovis* 1 M2-4	20.7	2.3	3.3	
NDA *Ovis* 1 M2-5	19.6	2.3	3.9	
NDA *Ovis* 1 M2-6	18.2	2.2	4.4	
NDA *Ovis* 1 M2-7	16.4	1.8	4.3	0.70614
NDA *Ovis* 1 M2-8	15.2	1.9	4.1	
NDA *Ovis* 1 M2-9	13.7	2.5	4.8	
NDA *Ovis* 1 M2-10	12.3	2.9	5.3	0.70624
NDA *Ovis* 1 M2-11	10.6	2.8	4.9	
NDA *Ovis* 1 M2-12	9.2	2.6	5.2	
NDA *Ovis* 1 M2-13	7.8	2.5	5.4	
NDA *Ovis* 1 M2-14	6.3	2.3	5.5	
NDA *Ovis* 1 M2-15	4.6	2.2	5.4	0.7063
NDA *Ovis* 1 M2-16	3	1.8	5.3	
NDA *Ovis* 1 M2-17	1.3	1.9	5.2	

Table A1.24: Oxygen, carbon, and strontium isotope values of PD *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *Bos* 1 M3-1	43.7	2.9	3.4	
PD *Bos* 1 M3-2	41.4	2.9	3.4	0.70739
PD *Bos* 1 M3-3	39.5	2.8	3.4	
PD *Bos* 1 M3-4	37.2	2.7	3.2	
PD *Bos* 1 M3-5	35	2.5	3.2	
PD *Bos* 1 M3-6	32.7	2.5	2.9	
PD *Bos* 1 M3-7	30.5	2.5	3.2	
PD *Bos* 1 M3-8	28.3	2.6	3.3	
PD *Bos* 1 M3-9	26.1	2.6	3.4	0.70742
PD *Bos* 1 M3-10	24.2	2.6	3.2	
PD *Bos* 1 M3-11	22	2.3	2.6	
PD *Bos* 1 M3-12	19.8	2.2	2.3	
PD *Bos* 1 M3-13	17.8	2.1	2.0	
PD *Bos* 1 M3-14	15.3	2.0	2.1	0.70739
PD *Bos* 1 M3-15	13.5	1.9	2.0	
PD *Bos* 1 M3-16	11.2	2.0	2.0	
PD *Bos* 1 M3-17	9.2	2.2	1.4	
PD *Bos* 1 M3-18	7.1	2.5	1.2	
PD *Bos* 1 M3-19	4.8	2.5	0.8	0.70733
PD *Bos* 1 M3-20	2.7	2.6	1.2	
PD *Bos* 1 M3-21	0.7	2.8	1.2	

Table A1.25: Oxygen, carbon, and strontium isotope values of PD *Bos* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *Bos* 2 M3-1	43.6	2.9	2.5	0.7074
PD *Bos* 2 M3-2	41.5	2.8	2.6	
PD *Bos* 2 M3-3	39.1	3.0	3.0	
PD *Bos* 2 M3-4	36.7	3.3	3.4	
PD *Bos* 2 M3-5	34.6	3.3	3.3	
PD *Bos* 2 M3-6	32.2	3.4	3.4	
PD *Bos* 2 M3-7	30.1	3.0	2.6	
PD *Bos* 2 M3-8	28	3.3	3.0	0.70736
PD *Bos* 2 M3-9	25.8	3.6	2.7	
PD *Bos* 2 M3-10	23.2	3.6	2.6	
PD *Bos* 2 M3-11	21.4	3.7	2.4	
PD *Bos* 2 M3-12	19.3	3.6	2.0	
PD *Bos* 2 M3-13	16.9	3.5	1.9	0.7074
PD *Bos* 2 M3-14	14.7	3.7	2.2	
PD *Bos* 2 M3-15	12.1	3.5	1.9	
PD *Bos* 2 M3-16	9.5	3.4	1.7	
PD *Bos* 2 M3-17	7.3	3.4	1.7	
PD *Bos* 2 M3-18	5.1	3.2	1.8	
PD *Bos* 2 M3-19	2.8	3.3	2.4	
PD *Bos* 2 M3-20	0.2	3.7	2.9	0.70739

Table A1.26: Oxygen, carbon, and strontium isotope values of PD *Bos* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *Bos* 3 M3-1	38.3	2.9	3.4	0.70732
PD *Bos* 3 M3-2	35.9	3.1	3.3	
PD *Bos* 3 M3-3	33.8	3.0	3.3	
PD *Bos* 3 M3-4	31.7	2.9	2.8	
PD *Bos* 3 M3-5	29.6	3.0	2.9	0.70735
PD *Bos* 3 M3-6	27.6	3.0	2.9	
PD *Bos* 3 M3-7	25.5	3.0	3.0	
PD *Bos* 3 M3-8	23.4	3.0	3.1	
PD *Bos* 3 M3-9	21.5	3.0	2.9	
PD *Bos* 3 M3-10	19.6	2.9	2.9	
PD *Bos* 3 M3-11	17.6	2.9	2.8	
PD *Bos* 3 M3-12	15.6	2.8	2.6	0.70734
PD *Bos* 3 M3-13	13.2	2.8	2.9	
PD *Bos* 3 M3-14	11	2.8	2.7	
PD *Bos* 3 M3-15	9.2	2.6	2.4	
PD *Bos* 3 M3-16	6.5	2.7	2.1	
PD *Bos* 3 M3-17	4	2.4	2.2	
PD *Bos* 3 M3-18	1.9	2.1	2.2	0.70732

Table A1.27: Oxygen, carbon, and strontium isotope values of PD *Bos* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *Bos* 4 M3-1	38.7	3.4	3.6	
PD *Bos* 4 M3-2	36.5	3.4	3.8	0.70732
PD *Bos* 4 M3-3	34.3	3.2	3.6	
PD *Bos* 4 M3-4	32.2	3.3	3.5	
PD *Bos* 4 M3-5	30.1	3.3	3.3	
PD *Bos* 4 M3-6	28.3	3.4	3.6	
PD *Bos* 4 M3-7	26.2	3.5	3.6	
PD *Bos* 4 M3-8	23.9	3.3	3.7	
PD *Bos* 4 M3-9	21.7	3.4	3.7	0.7073
PD *Bos* 4 M3-10	19.7	3.5	3.3	
PD *Bos* 4 M3-11	17.1	3.5	2.9	
PD *Bos* 4 M3-12	15	3.6	3.0	
PD *Bos* 4 M3-13	13.2	3.6	2.9	
PD *Bos* 4 M3-14	10.9	3.4	2.9	
PD *Bos* 4 M3-15	8.6	3.4	2.7	0.70735
PD *Bos* 4 M3-16	6.4	3.3	2.8	
PD *Bos* 4 M3-17	4.3	3.4	2.7	
PD *Bos* 4 M3-18	2.1	3.8	3.1	0.70737

Table A1.28: Oxygen, carbon, and strontium isotope values of PD *Bos* 5 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *Bos* 5 M3-1	37.8	3.1	1.8	0.70731
PD *Bos* 5 M3-2	35.5	2.9	1.9	
PD *Bos* 5 M3-3	33.7	2.8	1.5	
PD *Bos* 5 M3-4	31.8	2.5	1.6	
PD *Bos* 5 M3-5	30	2.7	0.9	
PD *Bos* 5 M3-6	28	2.7	0.7	0.70725
PD *Bos* 5 M3-7	26.4	2.7	0.7	
PD *Bos* 5 M3-8	24.6	2.6	1.5	
PD *Bos* 5 M3-9	22.7	2.5	1.5	
PD *Bos* 5 M3-10	20.8	2.4	1.9	
PD *Bos* 5 M3-11	18.6	2.6	2.0	
PD *Bos* 5 M3-12	16.4	2.6	2.3	0.70717
PD *Bos* 5 M3-13	14.4	2.4	1.8	
PD *Bos* 5 M3-14	12.4	2.9	2.6	
PD *Bos* 5 M3-15	9.9	2.9	2.2	
PD *Bos* 5 M3-16	7.9	3.1	2.8	
PD *Bos* 5 M3-17	5.8	3.2	2.7	
PD *Bos* 5 M3-18	3.8	3.3	3.1	0.70724
PD *Bos* 5 M3-19	1.6	3.4	2.4	

Table A1.29: Oxygen, carbon, and strontium isotope values of PD *Bos* 6 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *Bos* 6 M3-1	37.4	2.9	3.0	0.70732
PD *Bos* 6 M3-2	35	3.0	2.7	
PD *Bos* 6 M3-3	32.8	3.1	2.9	
PD *Bos* 6 M3-4	30.9	3.2	3.0	
PD *Bos* 6 M3-5	28.7	3.3	3.3	
PD *Bos* 6 M3-6	26.9	3.2	2.8	0.70736
PD *Bos* 6 M3-7	24.4	3.2	2.9	
PD *Bos* 6 M3-8	22.3	3.4	3.0	
PD *Bos* 6 M3-9	20.3	3.3	3.0	
PD *Bos* 6 M3-10	18.3	3.2	2.6	
PD *Bos* 6 M3-11	16.1	3.2	2.9	0.70736
PD *Bos* 6 M3-12	13.7	3.4	3.1	
PD *Bos* 6 M3-13	11.3	3.5	3.6	
PD *Bos* 6 M3-14	9.1	3.4	3.2	
PD *Bos* 6 M3-15	7.3	3.8	3.3	
PD *Bos* 6 M3-16	5	3.8	3.1	0.70737
PD *Bos* 6 M3-17	3.2	3.4	2.9	

Table A1.30: Oxygen, carbon, and strontium isotope values of PD *O/C* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *O/C* 1 M3-1	16.2	1.1	3.0	0.70736
PD *O/C* 1 M3-2	14.8	1.1	3.6	
PD *O/C* 1 M3-3	13.4	0.7	3.9	
PD *O/C* 1 M3-4	12	0.4	4.9	
PD *O/C* 1 M3-5	10.7	0.4	5.5	
PD *O/C* 1 M3-6	9.3	0.3	6.2	
PD *O/C* 1 M3-7	7.9	0.4	6.2	
PD *O/C* 1 M3-8	6.5	1.0	6.5	0.70736
PD *O/C* 1 M3-9	4.7	0.5	5.9	
PD *O/C* 1 M3-10	3.3	1.0	5.3	
PD *O/C* 1 M3-11	2.1	1.3	4.5	
PD *O/C* 1 M3-12	0.4	1.1	2.6	0.70731

Table A1.31: Oxygen, carbon, and strontium isotope values of PD *O/C* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
PD *O/C* 2 M3-1	16.9	1.1	2.9	0.70736
PD *O/C* 2 M3-2	15.5	1.0	3.7	
PD *O/C* 2 M3-3	14	0.8	3.8	
PD *O/C* 2 M3-4	12.5	0.4	4.7	
PD *O/C* 2 M3-5	10.9	0.5	5.5	
PD *O/C* 2 M3-6	9.6	0.5	6.1	
PD *O/C* 2 M3-7	8	0.7	6.1	0.70733
PD *O/C* 2 M3-8	6.4	0.8	6.2	
PD *O/C* 2 M3-9	5.1	0.7	5.4	
PD *O/C* 2 M3-10	3.6	1.2	5.3	
PD *O/C* 2 M3-11	2.2	1.1	3.4	0.70734

Table A1.32: Oxygen, carbon, and strontium isotope values of NS *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NS *Bos* 1 M3-1	33.4	1.6	0.3	
NS *Bos* 1 M3-2	31	1.0	-0.8	0.70901
NS *Bos* 1 M3-3	28.7	1.4	-0.2	
NS *Bos* 1 M3-4	26.9	1.5	0.0	
NS *Bos* 1 M3-5	24.9	1.5	-0.5	
NS *Bos* 1 M3-6	22.6	1.5	-0.6	0.70902
NS *Bos* 1 M3-7	20.1	1.6	-0.3	
NS *Bos* 1 M3-8	17.9	1.5	-0.5	
NS *Bos* 1 M3-9	16	1.6	-0.1	
NS *Bos* 1 M3-10	13.9	1.5	-0.2	
NS *Bos* 1 M3-11	11.8	1.8	0.3	0.70878
NS *Bos* 1 M3-12	9.4	1.5	0.0	
NS *Bos* 1 M3-13	7.3	2.0	0.9	
NS *Bos* 1 M3-14	5.2	1.8	0.8	
NS *Bos* 1 M3-15	3.6	1.6	-0.2	
NS *Bos* 1 M3-16	1.7	2.3	1.4	0.7086

Table A1.33: Oxygen, carbon, and strontium isotope values of NS *Bos* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NS *Bos* 2 M3-1	39.5	1.7	-0.4	0.70891
NS *Bos* 2 M3-2	37.5	1.9	-0.2	
NS *Bos* 2 M3-3	35.4	2.3	0.2	
NS *Bos* 2 M3-4	33.6	2.3	-0.1	
NS *Bos* 2 M3-5	31.5	2.2	-1.1	
NS *Bos* 2 M3-6	29.6	2.1	-0.3	
NS *Bos* 2 M3-7	27.6	2.5	-0.6	0.70863
NS *Bos* 2 M3-8	25.6	2.5	-0.5	
NS *Bos* 2 M3-9	23.7	2.2	-0.8	
NS *Bos* 2 M3-10	22	2.4	-0.5	
NS *Bos* 2 M3-11	19.8	1.9	-0.9	
NS *Bos* 2 M3-12	17.6	2.1	-0.3	
NS *Bos* 2 M3-13	15.7	2.1	-0.3	
NS *Bos* 2 M3-14	13.5	1.9	-0.2	
NS *Bos* 2 M3-15	11.4	1.8	-1.1	0.70891
NS *Bos* 2 M3-16	9.3	2.2	-0.3	
NS *Bos* 2 M3-17	7.2	2.4	0.3	
NS *Bos* 2 M3-18	5.3	2.4	0.9	
NS *Bos* 2 M3-19	3.4	2.7	1.2	
NS *Bos* 2 M3-20	1.5	3.3	1.5	0.70878

Table A1.34: Oxygen, carbon, and strontium isotope values of NS *Bos* 3 M3

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**	**$^{87}Sr/^{86}Sr$**
NS *Bos* 3 M3-1	34.4	2.5	1.2	
NS *Bos* 3 M3-2	32.5	2.8	1.0	
NS *Bos* 3 M3-3	30.6	2.5	0.9	
NS *Bos* 3 M3-4	28.5	2.6	1.4	0.70981
NS *Bos* 3 M3-5	26.6	2.5	1.5	
NS *Bos* 3 M3-6	24.5	2.4	0.7	
NS *Bos* 3 M3-7	22.6	2.5	0.4	
NS *Bos* 3 M3-8	20.4	2.4	0.2	
NS *Bos* 3 M3-9	18.4	2.5	0.4	0.70999
NS *Bos* 3 M3-10	16.3	2.6	-0.4	
NS *Bos* 3 M3-11	14.3	2.3	-0.8	
NS *Bos* 3 M3-12	12.4	2.5	-0.4	
NS *Bos* 3 M3-13	10.2	2.5	-0.8	
NS *Bos* 3 M3-14	8.3	2.3	-1.0	0.70973
NS *Bos* 3 M3-15	6.3	2.6	-0.9	
NS *Bos* 3 M3-16	4.4	2.5	-0.4	
NS *Bos* 3 M3-17	2.2	2.4	0.3	

Table A1.35: Oxygen, carbon, and strontium isotope values of NS *Bos* 4 M3

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**	**$^{87}Sr/^{86}Sr$**
NS *Bos* 4 M3-1	39.1	2.0	1.4	
NS *Bos* 4 M3-2	37.2	1.7	1.2	
NS *Bos* 4 M3-3	35.1	1.8	1.7	0.70919
NS *Bos* 4 M3-4	33.3	1.8	1.2	
NS *Bos* 4 M3-5	31.1	1.8	1.2	
NS *Bos* 4 M3-6	29	1.8	1.3	
NS *Bos* 4 M3-7	27	1.6	1.1	
NS *Bos* 4 M3-8	25.1	1.3	-0.2	0.70981
NS *Bos* 4 M3-9	22.9	1.7	0.0	
NS *Bos* 4 M3-10	21.1	1.9	0.7	
NS *Bos* 4 M3-11	19.1	1.8	0.0	
NS *Bos* 4 M3-12	17	1.4	-0.2	
NS *Bos* 4 M3-13	15	1.5	-0.1	0.70996
NS *Bos* 4 M3-14	13	1.8	-0.1	
NS *Bos* 4 M3-15	11.1	1.4	-0.4	
NS *Bos* 4 M3-16	8.9	1.5	-0.8	
NS *Bos* 4 M3-17	7.1	1.7	0.1	
NS *Bos* 4 M3-18	5.2	1.8	-0.5	
NS *Bos* 4 M3-19	3	2.5	0.0	0.71053

Table A1.36: Oxygen, carbon, and strontium isotope values of NS *Ovis* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NS *Ovis* 1 M3-1	32.5	2.8	4.1	
NS *Ovis* 1 M3-2	31.2	3.1	4.4	
NS *Ovis* 1 M3-3	29.8	3.1	3.9	0.70848
NS *Ovis* 1 M3-4	28.4	2.9	4.1	
NS *Ovis* 1 M3-5	26.5	2.8	3.9	
NS *Ovis* 1 M3-6	25.2	2.9	4.4	
NS *Ovis* 1 M3-7	23.8	3.2	4.4	
NS *Ovis* 1 M3-8	22.3	3.5	4.8	
NS *Ovis* 1 M3-9	20.8	3.8	5.0	
NS *Ovis* 1 M3-10	19.7	3.6	5.3	0.70831
NS *Ovis* 1 M3-11	18	3.5	5.2	
NS *Ovis* 1 M3-12	16.9	3.3	5.0	
NS *Ovis* 1 M3-13	15.4	3.2	4.8	
NS *Ovis* 1 M3-14	13.7	3.3	5.1	
NS *Ovis* 1 M3-15	12.3	3.1	5.2	
NS *Ovis* 1 M3-16	10.8	3.0	5.5	
NS *Ovis* 1 M3-17	9.4	2.9	4.9	0.7097
NS *Ovis* 1 M3-18	8	3.0	4.9	
NS *Ovis* 1 M3-19	6.8	3.2	5.6	
NS *Ovis* 1 M3-20	5.3	3.1	6.1	0.71012
NS *Ovis* 1 M3-21	4.2	2.9	5.9	
NS *Ovis* 1 M3-22	2.8	3.2	5.5	
NS *Ovis* 1 M3-23	1.3	3.3	4.7	

Table A1.37: Oxygen, carbon, and strontium isotope values of NS *Ovis* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NS *Capra* 1 M3-1	33	-3.9	5.2	
NS *Capra* 1 M3-2	32.3	-4.1	5.5	
NS *Capra* 1 M3-3	31.3	-4.2	5.3	0.70798
NS *Capra* 1 M3-4	29.7	-4.0	5.0	
NS *Capra* 1 M3-5	28.4	-3.8	4.9	
NS *Capra* 1 M3-6	27	-3.4	4.6	
NS *Capra* 1 M3-7	25.5	-3.2	4.5	
NS *Capra* 1 M3-8	24.3	-2.7	4.6	
NS *Capra* 1 M3-9	22.8	-2.4	4.8	
NS *Capra* 1 M3-10	21.3	-2.1	5.1	
NS *Capra* 1 M3-11	19.8	-1.8	4.8	
NS *Capra* 1 M3-12	18.6	-1.5	5.2	
NS *Capra* 1 M3-13	17.3	-1.1	4.5	
NS *Capra* 1 M3-14	16.2	-0.4	4.9	
NS *Capra* 1 M3-15	14.5	-0.1	5.2	
NS *Capra* 1 M3-16	13.1	0.0	5.9	0.70997
NS *Capra* 1 M3-17	11.8	-0.4	5.7	
NS *Capra* 1 M3-18	10.2	-0.7	5.9	
NS *Capra* 1 M3-19	8.8	-1.2	5.5	
NS *Capra* 1 M3-20	7.5	-1.6	5.8	
NS *Capra* 1 M3-21	6.3	-2.1	6.3	
NS *Capra* 1 M3-22	4.8	-2.5	5.6	0.70775

Table A1.38: Oxygen, carbon, and strontium isotope values of NS *Ovis* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NS *Ovis* 3 M2-1	29.1	1.0	6.6	0.70975
NS *Ovis* 3 M2-2	27.8	1.1	6.7	
NS *Ovis* 3 M2-3	26.5	1.1	6.6	
NS *Ovis* 3 M2-4	25.4	1.2	6.8	
NS *Ovis* 3 M2-5	24	0.9	6.5	
NS *Ovis* 3 M2-6	22.7	1.0	7.0	
NS *Ovis* 3 M2-7	21.3	1.2	7.0	
NS *Ovis* 3 M2-8	20.1	1.4	7.1	0.70897
NS *Ovis* 3 M2-9	18.5	1.2	6.9	
NS *Ovis* 3 M2-10	17.1	0.9	6.6	
NS *Ovis* 3 M2-11	15.6	0.8	6.6	
NS *Ovis* 3 M2-12	14.4	1.1	6.2	0.70952
NS *Ovis* 3 M2-13	12.8	1.1	6.5	
NS *Ovis* 3 M2-14	11.2	1.2	6.6	
NS *Ovis* 3 M2-15	10.1	0.9	6.6	
NS *Ovis* 3 M2-16	8.5	1.1	6.6	
NS *Ovis* 3 M2-17	7.4	1.5	6.1	
NS *Ovis* 3 M2-18	6.1	2.0	6.3	
NS *Ovis* 3 M2-19	5	2.7	6.2	
NS *Ovis* 3 M2-20	3.2	3.0	6.7	
NS *Ovis* 3 M2-21	2.4	3.1	6.5	
NS *Ovis* 3 M2-22	0.8	3.1	6.8	0.70944

Table A1.39: Oxygen, carbon, and strontium isotope values of NS *Ovis* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
NS *Ovis* 4 M3-1	30.5	1.6	3.9	
NS *Ovis* 4 M3-2	29	1.8	3.7	
NS *Ovis* 4 M3-3	27.9	1.6	3.6	0.70948
NS *Ovis* 4 M3-4	26.4	1.6	4.2	
NS *Ovis* 4 M3-5	25	1.5	4.3	
NS *Ovis* 4 M3-6	23.7	1.4	4.7	
NS *Ovis* 4 M3-7	22.6	1.5	4.7	
NS *Ovis* 4 M3-8	21	1.3	4.8	
NS *Ovis* 4 M3-9	19.4	1.4	4.9	
NS *Ovis* 4 M3-10	18.1	1.5	5.1	
NS *Ovis* 4 M3-11	16.9	1.8	5.0	
NS *Ovis* 4 M3-12	15.6	1.4	4.6	
NS *Ovis* 4 M3-13	14.3	1.5	5.4	0.70869
NS *Ovis* 4 M3-14	12.8	1.5	5.2	
NS *Ovis* 4 M3-15	11.6	1.8	5.3	
NS *Ovis* 4 M3-16	10.5	1.8	5.4	
NS *Ovis* 4 M3-17	9.3	2.2	5.3	
NS *Ovis* 4 M3-18	7.8	2.5	5.2	
NS *Ovis* 4 M3-19	6.4	2.0	5.4	
NS *Ovis* 4 M3-20	5	2.1	5.5	
NS *Ovis* 4 M3-21	3.7	2.1	5.0	
NS *Ovis* 4 M3-22	2.7	2.5	4.1	0.70963

Table A1.40: Oxygen, carbon, and strontium isotope values of GvJm44 *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm44 *Bos* 1 M3-1	30.8	3.6	0.7	0.70798
GvJm44 *Bos* 1 M3-2	28.7	3.4	0.7	
GvJm44 *Bos* 1 M3-3	26.6	3.3	0.9	
GvJm44 *Bos* 1 M3-4	24.2	3.3	0.8	
GvJm44 *Bos* 1 M3-5	22.2	3.3	0.8	0.70805
GvJm44 *Bos* 1 M3-6	20.3	3.4	0.9	
GvJm44 *Bos* 1 M3-7	17.8	3.3	1.2	
GvJm44 *Bos* 1 M3-8	15.5	3.2	1.2	0.70809
GvJm44 *Bos* 1 M3-9	13.2	3.2	1.4	
GvJm44 *Bos* 1 M3-10	11.3	3.3	1.8	
GvJm44 *Bos* 1 M3-11	9.3	3.3	2.0	0.70806
GvJm44 *Bos* 1 M3-12	7.1	3.4	1.8	
GvJm44 *Bos* 1 M3-13	4.9	3.1	1.3	
GvJm44 *Bos* 1 M3-14	3	3.2	1.2	
GvJm44 *Bos* 1 M3-15	1.1	3.3	1.2	0.70807

Table A1.41: Oxygen, carbon, and strontium isotope values of GvJm44 *Bos* 2 M3

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**	**$^{87}Sr/^{86}Sr$**
GvJm44 *Bos* 2 M3-1	28	3.8	3.1	0.70812
GvJm44 *Bos* 2 M3-2	26.1	3.9	3.0	
GvJm44 *Bos* 2 M3-3	23.9	3.9	3.1	
GvJm44 *Bos* 2 M3-4	21.4	3.9	3.4	0.70812
GvJm44 *Bos* 2 M3-5	19.2	4.1	3.4	
GvJm44 *Bos* 2 M3-6	17.1	4.0	3.1	
GvJm44 *Bos* 2 M3-7	15.1	4.2	3.3	
GvJm44 *Bos* 2 M3-8	12.8	4.3	3.4	0.70816
GvJm44 *Bos* 2 M3-9	10.5	4.2	3.2	
GvJm44 *Bos* 2 M3-10	8.1	4.1	2.8	
GvJm44 *Bos* 2 M3-11	5.9	4.4	2.3	0.70813
GvJm44 *Bos* 2 M3-12	3.9	4.2	2.4	
GvJm44 *Bos* 2 M3-13	1.9	4.2	2.7	

Table A1.42: Oxygen, carbon, and strontium isotope values of GvJm44 *Bos* 3 M3

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**	**$^{87}Sr/^{86}Sr$**
GvJm44 *Bos* 3 M3-1	40.7	3.4	2.4	0.70909
GvJm44 *Bos* 3 M3-2	38.2	3.4	3.1	
GvJm44 *Bos* 3 M3-3	36.3	3.4	3.6	
GvJm44 *Bos* 3 M3-4	34.4	3.4	4.2	
GvJm44 *Bos* 3 M3-5	32.3	3.3	4.2	0.70865
GvJm44 *Bos* 3 M3-6	30.1	3.2	4.3	
GvJm44 *Bos* 3 M3-7	28	3.2	4.1	
GvJm44 *Bos* 3 M3-8	25.7	3.0	3.7	
GvJm44 *Bos* 3 M3-9	23.2	3.1	3.6	
GvJm44 *Bos* 3 M3-10	21.3	3.0	3.3	
GvJm44 *Bos* 3 M3-11	19.4	2.9	2.8	
GvJm44 *Bos* 3 M3-12	17.3	2.7	2.8	
GvJm44 *Bos* 3 M3-13	15.3	2.7	2.3	0.70827
GvJm44 *Bos* 3 M3-14	12.9	2.5	2.8	
GvJm44 *Bos* 3 M3-15	10.8	2.4	2.7	
GvJm44 *Bos* 3 M3-16	8.8	2.4	3.3	
GvJm44 *Bos* 3 M3-17	6.6	2.3	3.6	
GvJm44 *Bos* 3 M3-18	4.5	2.3	4.3	0.70878
GvJm44 *Bos* 3 M3-19	2.4	2.3	4.3	

Table A1.43: Oxygen, carbon, and strontium isotope values of GvJm44 *Bos* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm44 *Bos* 4 M3-1	24.8	3.2	-0.5	0.70825
GvJm44 *Bos* 4 M3-2	23	3.1	0.4	
GvJm44 *Bos* 4 M3-3	21.2	3.1	0.5	
GvJm44 *Bos* 4 M3-4	18.9	3.1	1.2	
GvJm44 *Bos* 4 M3-5	16.7	3.1	1.2	
GvJm44 *Bos* 4 M3-6	14.7	3.0	1.4	
GvJm44 *Bos* 4 M3-7	12.7	2.9	1.5	0.70845
GvJm44 *Bos* 4 M3-8	10.5	3.0	1.7	
GvJm44 *Bos* 4 M3-9	8.4	3.1	1.6	
GvJm44 *Bos* 4 M3-10	6.2	3.1	1.9	
GvJm44 *Bos* 4 M3-11	4.3	3.4	2.3	
GvJm44 *Bos* 4 M3-12	2	3.3	2.2	0.70826

Table A1.44: Oxygen, carbon, and strontium isotope values of GvJm52 *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Bos* 1 M3-1	22.2	3.3	3.0	0.70727
GvJm52 *Bos* 1 M3-2	20.1	3.0	2.6	
GvJm52 *Bos* 1 M3-3	18.2	3.0	2.3	
GvJm52 *Bos* 1 M3-4	16.3	3.2	2.7	
GvJm52 *Bos* 1 M3-5	14.4	3.4	2.9	
GvJm52 *Bos* 1 M3-6	12.5	3.2	2.8	0.70718
GvJm52 *Bos* 1 M3-7	10.6	2.6	1.4	
GvJm52 *Bos* 1 M3-8	8.6	3.3	1.1	
GvJm52 *Bos* 1 M3-9	6.5	3.3	0.8	0.7072
GvJm52 *Bos* 1 M3-10	4.4	3.5	1.4	
GvJm52 *Bos* 1 M3-11	2.3	4.0	1.3	

Table A1.45: Oxygen, carbon, and strontium isotope values of GvJm52 *Bos* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Bos* 2 M3-1	39.6	3.0	2.3	0.70894
GvJm52 *Bos* 2 M3-2	37.7	3.0	2.8	
GvJm52 *Bos* 2 M3-3	35.6	2.8	2.6	
GvJm52 *Bos* 2 M3-4	33.7	2.8	2.8	
GvJm52 *Bos* 2 M3-5	31.8	2.7	2.5	
GvJm52 *Bos* 2 M3-6	30	2.7	2.7	
GvJm52 *Bos* 2 M3-7	28.3	2.7	2.5	
GvJm52 *Bos* 2 M3-8	26.1	2.7	2.9	
GvJm52 *Bos* 2 M3-9	24.1	2.6	2.5	0.70884
GvJm52 *Bos* 2 M3-10	22.1	2.4	2.8	
GvJm52 *Bos* 2 M3-11	20.1	2.5	2.9	
GvJm52 *Bos* 2 M3-12	18.1	2.7	3.1	
GvJm52 *Bos* 2 M3-13	16.3	2.7	2.5	
GvJm52 *Bos* 2 M3-14	14.1	2.7	2.6	
GvJm52 *Bos* 2 M3-15	11.9	2.9	2.6	
GvJm52 *Bos* 2 M3-16	9.8	2.9	2.7	
GvJm52 *Bos* 2 M3-17	7.6	3.1	2.7	
GvJm52 *Bos* 2 M3-18	5.6	3.4	3.2	
GvJm52 *Bos* 2 M3-19	3.4	3.8	3.6	0.70885
GvJm52 *Bos* 2 M3-20	2	3.8	3.4	

Table A1.46: Oxygen, carbon, and strontium isotope values of GvJm52 *Bos* 3 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Bos* 3 M3-1	32.9	3.1	2.8	
GvJm52 *Bos* 3 M3-2	30.9	3.3	3.1	0.70726
GvJm52 *Bos* 3 M3-3	28.8	3.2	2.9	
GvJm52 *Bos* 3 M3-4	26.5	3.3	2.8	
GvJm52 *Bos* 3 M3-5	24.7	3.1	2.3	
GvJm52 *Bos* 3 M3-6	22.8	3.3	2.8	
GvJm52 *Bos* 3 M3-7	20.8	3.5	3.2	
GvJm52 *Bos* 3 M3-8	18.7	3.4	3.5	0.70734
GvJm52 *Bos* 3 M3-9	17	3.4	3.2	
GvJm52 *Bos* 3 M3-10	14.5	3.3	2.9	
GvJm52 *Bos* 3 M3-11	12.4	3.5	3.2	
GvJm52 *Bos* 3 M3-12	10.4	3.5	3.4	0.70746
GvJm52 *Bos* 3 M3-13	8.4	3.3	3.0	
GvJm52 *Bos* 3 M3-14	6.5	3.1	2.6	
GvJm52 *Bos* 3 M3-15	4.3	3.4	2.4	
GvJm52 *Bos* 3 M3-16	2.2	3.1	1.9	0.70765

Table A1.47: Oxygen, carbon, and strontium isotope values of GvJm52 *Bos* 4 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Bos* 4 M3-1	35	3.4	1.6	
GvJm52 *Bos* 4 M3-2	32.6	3.4	1.3	0.70782
GvJm52 *Bos* 4 M3-3	30.6	3.3	2.0	
GvJm52 *Bos* 4 M3-4	28.4	3.2	1.9	
GvJm52 *Bos* 4 M3-5	26.4	3.3	1.9	
GvJm52 *Bos* 4 M3-6	24.8	3.2	1.8	
GvJm52 *Bos* 4 M3-7	22.4	3.3	2.1	0.70768
GvJm52 *Bos* 4 M3-8	20.4	3.3	2.0	
GvJm52 *Bos* 4 M3-9	18.3	3.3	2.3	
GvJm52 *Bos* 4 M3-10	16.2	3.3	2.4	
GvJm52 *Bos* 4 M3-11	14	3.5	2.3	
GvJm52 *Bos* 4 M3-12	11.8	3.5	2.2	0.70787
GvJm52 *Bos* 4 M3-13	9.6	3.3	2.2	
GvJm52 *Bos* 4 M3-14	7.5	3.2	1.9	
GvJm52 *Bos* 4 M3-15	5.4	3.3	2.6	
GvJm52 *Bos* 4 M3-16	3.6	3.6	2.9	
GvJm52 *Bos* 4 M3-17	1.7	3.6	3.0	0.70788

Table A1.48: Oxygen, carbon, and strontium isotope values of GvJm52 *Ovis* 1 M2

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Ovis* 1 M2-1	25.9	2.4	5.0	0.70689
GvJm52 *Ovis* 1 M2-2	24.4	2.3	5.1	
GvJm52 *Ovis* 1 M2-3	23	2.2	5.0	
GvJm52 *Ovis* 1 M2-4	21.5	2.1	5.2	
GvJm52 *Ovis* 1 M2-5	20.1	2.1	5.2	
GvJm52 *Ovis* 1 M2-6	18.5	1.8	5.3	0.70723
GvJm52 *Ovis* 1 M2-7	16.8	1.7	5.0	
GvJm52 *Ovis* 1 M2-8	15.4	1.6	5.0	
GvJm52 *Ovis* 1 M2-9	13.9	1.4	4.5	
GvJm52 *Ovis* 1 M2-10	12.3	1.4	4.4	
GvJm52 *Ovis* 1 M2-11	11.1	1.2	4.1	
GvJm52 *Ovis* 1 M2-12	9.8	1.1	4.1	
GvJm52 *Ovis* 1 M2-13	8.3	1.2	3.7	0.70789
GvJm52 *Ovis* 1 M2-14	6.6	1.2	3.8	
GvJm52 *Ovis* 1 M2-15	5.4	0.8	4.7	
GvJm52 *Ovis* 1 M2-16	3.9	0.0	5.3	0.70589
GvJm52 *Ovis* 1 M2-17	2.7	0.7	5.6	

Table A1.49: Oxygen, carbon, and strontium isotope values of GvJm52 *Ovis* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Ovis* 2 M3-1	32.4	1.6	4.3	
GvJm52 *Ovis* 2 M3-2	31	1.7	4.1	
GvJm52 *Ovis* 2 M3-3	29.5	2.1	3.7	
GvJm52 *Ovis* 2 M3-4	28.1	1.9	3.2	0.70761
GvJm52 *Ovis* 2 M3-5	26.7	1.8	3.5	
GvJm52 *Ovis* 2 M3-6	25.4	1.7	3.9	
GvJm52 *Ovis* 2 M3-7	24.1	1.6	3.8	
GvJm52 *Ovis* 2 M3-8	22.6	1.5	3.8	
GvJm52 *Ovis* 2 M3-9	21.2	1.4	4.3	
GvJm52 *Ovis* 2 M3-10	19.9	1.4	4.3	
GvJm52 *Ovis* 2 M3-11	18.4	1.4	4.1	
GvJm52 *Ovis* 2 M3-12	16.9	1.4	4.6	0.70767
GvJm52 *Ovis* 2 M3-13	15.6	1.7	4.3	
GvJm52 *Ovis* 2 M3-14	14.3	2.1	4.6	
GvJm52 *Ovis* 2 M3-15	13	2.2	4.7	0.70738
GvJm52 *Ovis* 2 M3-16	11.7	2.2	4.2	
GvJm52 *Ovis* 2 M3-17	10.3	2.1	4.1	
GvJm52 *Ovis* 2 M3-18	8.8	1.9	4.4	
GvJm52 *Ovis* 2 M3-19	7.4	1.2	3.1	
GvJm52 *Ovis* 2 M3-20	6	0.9	4.7	
GvJm52 *Ovis* 2 M3-21	4.6	0.9	4.8	0.70798
GvJm52 *Ovis* 2 M3-22	3.2	1.1	4.6	
GvJm52 *Ovis* 2 M3-23	1.7	1.1	3.8	

Table A1.50: Oxygen, carbon, and strontium isotope values of GvJm52 *Ovis* (ex-*Capra*) 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-1	29	3.5	6.8	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-2	27.6	3.6	7.0	0.70791
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-3	26.3	3.2	6.6	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-4	24.8	3.5	6.8	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-5	23.3	3.2	6.9	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-6	21.9	2.6	6.5	0.70814
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-7	20.5	2.6	6.8	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-8	19	2.7	7.4	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-9	17.4	2.3	7.2	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-10	16	2.1	7.6	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-11	14.7	2.0	7.8	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-12	13.4	1.7	7.9	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-13	12	1.6	8.0	0.709
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-14	10.7	1.3	7.9	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-15	9.4	0.8	7.8	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-16	8.1	0.2	7.2	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-17	6.7	-0.4	6.9	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-18	5.3	-1.1	6.6	
GvJm52 *Ovis* (ex-*Capra*) 1 M2 M2-19	3.5	-1.9	6.8	0.70924

Table A1.51: Oxygen, carbon, and strontium isotope values of GvJm52 *O/C* 2 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJm 52 *O/C* 2 M3-1	30	2.0	3.6	0.70759
GvJm 52 *O/C* 2 M3-2	28.6	1.8	3.7	
GvJm 52 *O/C* 2 M3-3	27.3	1.7	3.5	
GvJm 52 *O/C* 2 M3-4	26	1.6	4.2	
GvJm 52 *O/C* 2 M3-5	24.6	1.5	4.3	
GvJm 52 *O/C* 2 M3-6	23.3	1.4	4.5	
GvJm 52 *O/C* 2 M3-7	21.9	1.4	4.7	0.70762
GvJm 52 *O/C* 2 M3-8	20.5	1.6	4.9	
GvJm 52 *O/C* 2 M3-9	19.3	1.8	5.0	
GvJm 52 *O/C* 2 M3-10	17.9	2.1	4.5	
GvJm 52 *O/C* 2 M3-11	16.7	2.3	4.9	
GvJm 52 *O/C* 2 M3-12	14.9	2.1	5.0	0.70736
GvJm 52 *O/C* 2 M3-13	13.9	2.1	4.7	
GvJm 52 *O/C* 2 M3-14	12.5	2.1	4.5	
GvJm 52 *O/C* 2 M3-15	11.5	2.0	4.2	
GvJm 52 *O/C* 2 M3-16	10.2	1.7	4.3	
GvJm 52 *O/C* 2 M3-17	8.8	1.2	4.5	
GvJm 52 *O/C* 2 M3-18	7.4	0.9	4.9	0.70793
GvJm 52 *O/C* 2 M3-19	6	0.9	4.3	
GvJm 52 *O/C* 2 M3-20	4.4	0.7	4.3	
GvJm 52 *O/C* 2 M3-21	2.9	0.6	3.6	0.70797
GvJm 52 *O/C* 2 M3-22	1.6	-0.4	3.8	

APPENDIX 2: CARBON, OXYGEN, AND STRONTIUM ISOTOPE VALUES OF MODERN LIVESTOCK

Table A2.1: Oxygen, carbon, and strontium isotope values of GvJhB113 *Bos* 1 M1

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJhB113 *Bos* 1 M1-1	14	-1.3	2.1	
GvJhB113 *Bos* 1 M1-1	11.4	-1.2	2.3	
GvJhB113 *Bos* 1 M1-3	9.2	-1.0	2.3	0.70887
GvJhB113 *Bos* 1 M1-4	7.4	-0.9	2.8	
GvJhB113 *Bos* 1 M1-5	5.2	-0.8	2.7	
GvJhB113 *Bos* 1 M1-6	3.1	-0.8	2.9	
GvJhB113 *Bos* 1 M1-7	1.6	-0.6	2.9	0.70905

Table A2.2: Oxygen, carbon, and strontium isotope values of GvJhB113 *Bos* 1 M2

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJhB113 *Bos* 1 M2-1	19.7	0.2	1.7	0.7098
GvJhB113 *Bos* 1 M2-2	17.8	0.2	1.5	
GvJhB113 *Bos* 1 M2-3	15.7	0.3	1.4	
GvJhB113 *Bos* 1 M2-4	13.8	0.1	1.1	
GvJhB113 *Bos* 1 M2-5	12	0.2	1.0	
GvJhB113 *Bos* 1 M2-6	9.7	0.3	1.1	0.7091
GvJhB113 *Bos* 1 M2-7	8	0.3	1.0	
GvJhB113 *Bos* 1 M2-8	6.1	0.1	1.2	
GvJhB113 *Bos* 1 M2-9	4.1	0.2	1.1	
GvJhB113 *Bos* 1 M2-10	2.1	0.1	0.8	
GvJhB113 *Bos* 1 M2-11	0.9	0.1	1.2	0.7084

Table A2.3: Oxygen, carbon, and strontium isotope values of GvJhB113 *Bos* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**	**^{87}Sr/^{86}Sr**
GvJhB113 *Bos* 1 M3-1	25.9	-0.5	1.3	0.7081
GvJhB113 *Bos* 1 M3-2	23.9	-0.7	1.6	
GvJhB113 *Bos* 1 M3-3	22.2	-0.8	1.7	
GvJhB113 *Bos* 1 M3-4	20.1	-0.9	2.0	
GvJhB113 *Bos* 1 M3-5	18.2	-1.3	2.1	
GvJhB113 *Bos* 1 M3-6	16.3	-1.3	2.3	0.7079
GvJhB113 *Bos* 1 M3-7	14.6			
GvJhB113 *Bos* 1 M3-8	12.3	-1.4	2.0	
GvJhB113 *Bos* 1 M3-9	10.3	-1.5	2.3	
GvJhB113 *Bos* 1 M3-10	8.1	-1.4	2.8	
GvJhB113 *Bos* 1 M3-11	6.3	-1.7	2.4	
GvJhB113 *Bos* 1 M3-12	3.9	-1.8	2.9	
GvJhB113 *Bos* 1 M3-13	2.2	-1.9	3.1	0.7077

Table A2.4: Oxygen and carbon isotope values of GvJhB110 *Ovis* 1 M1

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**
GvJhB110 *Ovis* 1 M1-1	10	-0.4	3.4
GvJhB110 *Ovis* 1 M1-2	8.4	-1.4	3.1
GvJhB110 *Ovis* 1 M1-3	6.8	-1.0	3.0
GvJhB110 *Ovis* 1 M1-4	5.2	-1.3	3.4
GvJhB110 *Ovis* 1 M1-5	3.9	-2.5	3.6
GvJhB110 *Ovis* 1 M1-6	2.7	-2.4	4.4
GvJhB110 *Ovis* 1 M1-7	1.7	-2.7	4.5

Table A2.5: Oxygen and carbon isotope values of GvJhB110 *Ovis* 1 M2

Sample	**mm from ERJ**	**$\delta^{13}C$ (‰)**	**$\delta^{18}O$ (‰)**
GvJhB110 *Ovis* 1 M2-1	17.8	-4.0	4.7
GvJhB110 *Ovis* 1 M2-2	16.4	-4.2	5.2
GvJhB110 *Ovis* 1 M2-3	14.6	-4.5	5.6
GvJhB110 *Ovis* 1 M2-4	13.4	-4.9	5.5
GvJhB110 *Ovis* 1 M2-5	12.2	-5.3	6.5
GvJhB110 *Ovis* 1 M2-6	11	-5.6	6.6
GvJhB110 *Ovis* 1 M2-7	9.3	-5.5	6.7
GvJhB110 *Ovis* 1 M2-8	8.1	-5.3	6.4
GvJhB110 *Ovis* 1 M2-9	6.9	-4.9	6.8
GvJhB110 *Ovis* 1 M2-10	5.3		
GvJhB110 *Ovis* 1 M2-11	3.7	-3.3	7.1
GvJhB110 *Ovis* 1 M2-12	2.5	-2.9	6.5
GvJhB110 *Ovis* 1 M2-13	1.5	-2.6	6.5

Table A2.6: Oxygen and carbon isotope values of GvJhB110 *Ovis* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**
GvJhB110 *Ovis* 1 M3-1	26.2	-3.4	6.3
GvJhB110 *Ovis* 1 M3-2	24.9	-3.1	5.9
GvJhB110 *Ovis* 1 M3-3	23.3	-2.9	5.9
GvJhB110 *Ovis* 1 M3-4	22.1	-2.8	6.1
GvJhB110 *Ovis* 1 M3-5	20.4	-2.5	5.9
GvJhB110 *Ovis* 1 M3-6	19.2	-2.5	5.7
GvJhB110 *Ovis* 1 M3-7	18	-2.4	5.6
GvJhB110 *Ovis* 1 M3-8	16.5	-2.5	5.6
GvJhB110 *Ovis* 1 M3-9	15.3	-2.8	5.0
GvJhB110 *Ovis* 1 M3-10	13.6	-2.9	5.0
GvJhB110 *Ovis* 1 M3-11	12.7	-2.8	5.0
GvJhB110 *Ovis* 1 M3-12	11.2	-3.2	5.0
GvJhB110 *Ovis* 1 M3-13	9.9	-3.4	4.9
GvJhB110 *Ovis* 1 M3-14	8.2	-3.8	4.7
GvJhB110 *Ovis* 1 M3-15	6.6	-3.6	4.3
GvJhB110 *Ovis* 1 M3-16	4.8	-3.9	3.9
GvJhB110 *Ovis* 1 M3-17	3.1	-3.5	2.0
GvJhB110 *Ovis* 1 M3-18	1.9	-3.6	4.3

Table A2.7: Oxygen and carbon isotope values of GvJhB100 *Ovis* 1 M1

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**
GvJhB100 *Ovis* 1 M1-1	15.5	-4.6	6.6
GvJhB100 *Ovis* 1 M1-2	14.1		
GvJhB100 *Ovis* 1 M1-3	12.5	-4.4	6.7
GvJhB100 *Ovis* 1 M1-4	11.5	-4.1	6.8
GvJhB100 *Ovis* 1 M1-5	10	-4.0	7.1
GvJhB100 *Ovis* 1 M1-6	8.8	-4.0	7.3
GvJhB100 *Ovis* 1 M1-7	7.8	-3.7	6.9
GvJhB100 *Ovis* 1 M1-8	5.8	-3.2	7.2
GvJhB100 *Ovis* 1 M1-9	4.8	-2.8	6.7
GvJhB100 *Ovis* 1 M1-10	3.8	-2.6	6.4
GvJhB100 *Ovis* 1 M1-11	2.1	-2.3	6.5
GvJhB100 *Ovis* 1 M1-12	0.7	-2.3	6.0

Table A2.8: Oxygen and carbon isotope values of GvJhB100 *Ovis* 1 M2

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**
GvJhB100 *Ovis* 1 M2-1	28.9	-2.0	5.8
GvJhB100 *Ovis* 1 M2-2	27.5	-2.2	5.5
GvJhB100 *Ovis* 1 M2-3	26.1	-2.3	5.1
GvJhB100 *Ovis* 1 M2-4	24.7	-2.1	5.5
GvJhB100 *Ovis* 1 M2-5	23.7	-2.0	5.0
GvJhB100 *Ovis* 1 M2-6	21.8	-2.0	5.0
GvJhB100 *Ovis* 1 M2-7	20.6	-1.9	4.8
GvJhB100 *Ovis* 1 M2-8	19.2	-1.9	4.7
GvJhB100 *Ovis* 1 M2-9	18.1	-1.7	4.7
GvJhB100 *Ovis* 1 M2-10	16.4	-1.5	4.8
GvJhB100 *Ovis* 1 M2-11	14.8	-1.5	4.3
GvJhB100 *Ovis* 1 M2-12	13.2	-1.6	4.3
GvJhB100 *Ovis* 1 M2-13	11.8	-1.8	4.2
GvJhB100 *Ovis* 1 M2-14	10.5	-2.3	4.2
GvJhB100 *Ovis* 1 M2-15	8.7	-2.7	3.4
GvJhB100 *Ovis* 1 M2-16	7.2	-3.0	2.9
GvJhB100 *Ovis* 1 M2-17	6.2	-3.4	3.1
GvJhB100 *Ovis* 1 M2-18	4.7	-3.5	4.3
GvJhB100 *Ovis* 1 M2-19	3.3	-3.2	4.1
GvJhB100 *Ovis* 1 M2-20	1.9	-2.9	4.0
GvJhB100 *Ovis* 1 M2-21	0.6	-3.4	3.6

Table A2.9: Oxygen and carbon isotope values of GvJhB100 *Ovis* 1 M3

Sample	**mm from ERJ**	**δ^{13}C (‰)**	**δ^{18}O (‰)**
GvJhB100 *Ovis* 1 M3-1	37.3	-2.5	3.6
GvJhB100 *Ovis* 1 M3-2	35.8	-2.8	3.3
GvJhB100 *Ovis* 1 M3-3	34.3	-3.1	3.0
GvJhB100 *Ovis* 1 M3-4	32.9	-3.3	3.0
GvJhB100 *Ovis* 1 M3-5	31.5	-3.2	3.1
GvJhB100 *Ovis* 1 M3-6	29.9	-3.2	3.5
GvJhB100 *Ovis* 1 M3-7	28.7	-3.3	3.6
GvJhB100 *Ovis* 1 M3-8	27.1	-3.3	4.0
GvJhB100 *Ovis* 1 M3-9	25.5	-3.4	3.9
GvJhB100 *Ovis* 1 M3-10	24.1	-3.5	3.8
GvJhB100 *Ovis* 1 M3-11	22.8		
GvJhB100 *Ovis* 1 M3-12	21.4	-4.0	4.1
GvJhB100 *Ovis* 1 M3-13	20.2	-3.7	4.0
GvJhB100 *Ovis* 1 M3-14	18.7	-4.6	4.4
GvJhB100 *Ovis* 1 M3-15	17.2	-4.4	4.4
GvJhB100 *Ovis* 1 M3-16	16	-4.5	4.1
GvJhB100 *Ovis* 1 M3-17	14.5	-4.6	4.3
GvJhB100 *Ovis* 1 M3-19	13.2	-3.0	4.4
GvJhB100 *Ovis* 1 M3-20	11.5	-2.3	4.5
GvJhB100 *Ovis* 1 M3-21	10.2	-1.9	3.2
GvJhB100 *Ovis* 1 M3-22	8.8	-1.6	4.3
GvJhB100 *Ovis* 1 M3-23	7.6	-1.6	3.6
GvJhB100 *Ovis* 1 M3-24	6.3	-1.0	2.1

APPENDIX 3: FAUNAL SAMPLES FOR STRONTIUM ISOSCAPE

Table A3.1: List of sample locations with specimen information and $^{87}Sr/^{86}Sr$ ratios

Site Code	Site Name	Sample	Taxon	Tissue	Antiquity	Final $^{87}Sr/^{86}Sr$	Estimated uncertainty	Latitude	Longitude
PND	Pundo	PND Trag 1 M1	*Tragelaphus scriptus*	Enamel	Arch.	0.70912	±0.00003	34.03032	-0.04034
		PND HYST 1 I1	*Hystrix* sp.	Enamel	Arch.	0.71037	±0.00004		
WLO	Wadh Lang'o	WLO Red 1	*Redunca redunca*	Enamel	Arch.	0.71051	±0.00004	34.80228	-0.347784
		WLO Red 2	*Redunca redunca*	Enamel	Arch.	0.70903	±0.00003		
		WLO Red 3	*Redunca redunca*	Enamel	Arch.	0.71047	±0.00004		
		WLO Red 4	*Redunca redunca*	Enamel	Arch.	0.71028	±0.00004		
MM	Maasai Mara	MM-1	Rodentia indet.	Bone	Modern	0.70791	±0.00006	35.02497	-1.41641
		MM-6	Small Mammal indet.	Bone	Modern	0.70865	±0.00004	35.25153	-1.51473
		MM-8.1	Rodentia indet.	Bone	Modern	0.70843	±0.00005	35.24458	-1.51088
		MM-8.2	Rodentia indet.	Bone	Modern	0.70857	±0.00006		
		MM-8.4	Rodentia indet.	Bone	Modern	0.7086	±0.00004		
NK	Narok	NK-1	Small Bovid indet.	Enamel	Modern	0.70645	±0.00003	35.97554	-1.387
		NK-2	Small Mammal indet.	Bone	Modern	0.70668	±0.00003	35.94586	-1.38835
JOT	Boma: J. Ole Tumpuya	JOT-1	*Capra hircus* (local)	Enamel	Modern	0.70646	±0.00003	35.94586	-1.38835
NKU	Nakuru National Park	NKU-4a	*Procavia* sp.	Bone	Modern	0.70631	±0.00003	36.05558	-0.3513
		NKU-4b	Rodentia indet.	Enamel	Modern	0.70644	±0.00003		
GsJjB	GsJjB	GsJjB12 PRO 1 P3	Procaviidae	Enamel	Modern	0.7075	±0.00003	36.33804	-0.645585
		GsJjB316 MAD P3	*Madoqua* kirkii	Enamel	Modern	0.70664	±0.0001	36.25251	-0.643513
		GsJjB326 PRO 1 M1	Procaviidae	Enamel	Modern	0.70751	±0.00003	36.32755	-0.649172
OT	Ol Tepesi	OT PRO 1 I1	*Procavia habessinica*	Enamel	Arch.	0.70738	±0.00003	36.20313	-0.694182
		OT PRO 2 I1	*Procavia habessinica*	Enamel	Arch.	0.70732	±0.00003		
		OT PRO 3 I1	*Procavia habessinica*	Enamel	Arch.	0.70727	±0.00003		
		OT PRO 4 I1	*Procavia habessinica*	Enamel	Arch.	0.70727	±0.00003		
		OT PRO 5 I1	*Procavia habessinica*	Enamel	Arch.	0.70725	±0.00003		
		OT HET 1	*Heterohyrax* sp.	Enamel	Modern	0.70725	±0.00003		

Table A3.1: Continued

Site Code	Site Name	Sample	Taxon	Tissue	Antiquity	Final $^{87}Sr/^{86}Sr$	Estimated uncertainty	Latitude	Longitude
EYS	Enkapune Ya Sauli	EYS PRO 1 I1	Procaviidae	Enamel	Arch.	0.70704	±0.00003	36.12416	-0.754172
		EYS RED 1 P2	*Redunca* sp.	Enamel	Arch.	0.70708	±0.00003		
		EYS RED 2 P4	*Redunca* sp.	Enamel	Arch.	0.70725	±0.00003		
EYM	Enkapune Ya Muto	EYM Tac 1 I1	*Tachyoryctes splendens*	Enamel	Arch.	0.70686	±0.00004	36.16116	-0.836648
		EYM Tac 2 I1	Tachyoryctes splendens	Enamel	Arch.	0.70668	±0.00004		
		EYM Tac 3 I1	Tachyoryctes splendens	Enamel	Arch.	0.70646	±0.00003		
		EYM Tac 4 I1	Tachyoryctes splendens	Enamel	Arch.	0.70696	±0.00003		
		EYM Tac 5 I1	Tachyoryctes splendens	Enamel	Arch.	0.7065	±0.00003		
		EYM Oto 1 I1	*Otomys tropicalis*	Enamel	Arch.	0.70688	±0.00004		
		EYM Oto 2 I1	*Otomys tropicalis*	Enamel	Arch.	0.70691	±0.00004		
HG	Hell’s Gate National Park	HG-1A	Rodentia indet.	Bone	Modern	0.70711	±0.00003	36.31882	-0.89495
		HG-1B	Rodentia indet.	Enamel	Modern	0.70675	±0.00003		
		GtJjB79 PRO 1 M3	Procaviidae	Bone	Modern	0.70604	±0.00003		
		GtJjB55.1 PRO 1 I1	Procaviidae	Bone	Modern	0.70626	±0.00003		
ML	Mt. Longonot National Park	ML-1	Rodentia indet.	Bone	Modern	0.70738	±0.00004	36.46262	-0.90182
GsJi302	West of Lake Naivasha	GsJi302	*Tachyoryctes* splendens	Enamel	Modern	0.70557	±0.00004	36.27003	-0.766554
GuJjB4	Suswa lava tube	GuJjB4 PRO 1 I1	Procaviidae	Enamel	Modern	0.70683	±0.00003	36.35195	-1.154167
NBO	Nairobi National Park	NBO-1	*Otomys* sp.	Bone	Modern	0.70755	±0.00004	36.84801	-1.37815
		NBO-4A	Small Mammal indet.	Bone	Modern	0.70759	±0.00004	36.85077	-1.36052
ODS	Ol Donyo Sabuk	ODS 3A	*Procavia* sp.	Enamel	Modern	0.70537	±0.00003	37.24628	-1.10667
GvJm 17	Lukenya Hill	GvJm17 Rod 4	Rodentia indet.	Enamel	Modern	0.71042	±0.00004	37.07674	-1.447638
		GvJm17 Rod 6	Rodentia indet.	Enamel	Modern	0.70819	±0.00004		
		GvJm17 Rod 7	Rodentia indet.	Enamel	Modern	0.70887	±0.00004		
KAJ	Kajiado District	KAJ Aco Fem 4-7	*Acomys* sp.	Bone	Modern	0.70643	±0.00004	37.20275	-2.2465333
		KAJ Aco Fem 20-23	*Acomys* sp.	Bone	Modern	0.70656	±0.00004		
		KAJ Aco Fem 24-27	*Acomys* sp.	Bone	Modern	0.70636	±0.00003		

Table A3.1: Continued

Site Code	**Site Name**	**Sample**	**Taxon**	**Tissue**	**Antiquity**	**Final ^{87}Sr/^{86}Sr**	**Estimated uncertainty**	**Latitude**	**Longitude**
HbJpB4	Umani springs, near Kibwezi	TRAG 1 P3	*Tragelaphus* sp.	Enamel	Modern	0.70448	±0.00003	37.91338	-2.454474
KT	Kathuva	KT MAD 1 M2	Madoqua kirkii	Enamel	Arch.	0.70844	±0.00004	39.16667	-3.066667
		KT MAD 2 M3	*Madoqua kirkii*	Enamel	Arch.	0.70786	±0.00004		
		KT MAD 3 M3	*Madoqua kirkii*	Enamel	Arch.	0.70862	±0.00004		
		KT MAD 4 M3	*Madoqua kirkii*	Enamel	Arch.	0.70817	±0.00005		

APPENDIX 4: HYPOPLASIA AND AGE-AT-DEATH DATA

Table A4.1: Crescent Island Main Cattle.

cat no.	taxon name	Elem	Part	Side	Wear Stage	Age Grp.	Crown compl	Max crown ht.	Mes loph Hypo	Ds loph hypo	3rd loph hypo	Type	Sev
21-24-3	BOSTA	LM1	Co	R	erpt.	Infant	no	broken		-	-		
21-55-4	BOSTA	LM1	Co	L	B	Infant	No	broken		-	-		
22-70-2	BOSTA	LM1	FR	L	B	Infant	no	broken		-	-		
21-44-5	BOSTA	LM1	Co	L	C	YJ	No	42.9					
21-32-6	BOSTA	LM1	Co	R	J	OJ	y	31.1	-	-			
22-66-2	BOSTA	LM1	Co	R	J	OJ	y	32.1	23.1	21.7		line	1
21-21-5	BOSTA	LM1	Co	R	J	OJ	y	31.6	12.6	15.5		depr.	1
21-21-5	BOSTA	LM1	Co	R	J			31.6	4.6	7.3		Line	2
21-21-5	BOSTA	LM1	Co	R	J			31.6	3.5	6.1		Line	3
21-21-5	BOSTA	LM1	Co	R	J			31.6	0.5	2.9		Line	2
21-21-5	BOSTA	LM1	Co	R	J			31.6	-	1.5		Line	2
21-11-5	BOSTA	LM1	Co	L	K	YA	y	31.4	broken				
21-28-3	BOSTA	LM1	Co	L	K	YA	y	28.3	-	-	-		
21-31-3	BOSTA	LM1	Co	L	K	YA	y	32.9	14.2	16			
21-44-5	BOSTA	LM1	FR	L	K	YA	y	12.2	-	-			
21-32-6	BOSTA	LM1	Co	R	K	YA	y	21.1	broken	-			
21-38-4	BOSTA	LM1	Co	R	K	YA	y	32.8	-	-			
21-39-2	BOSTA	LM1	Co	L	L	OA	y	26.6	-	-			
21-30-4	BOSTA	LM1	FR	R	L	OA	y	broken	-	-	-		
21-30-4	BOSTA	LM1	Co	R	L	OA	y	13.5	-	-	-		
21-30-4	BOSTA	LM1	CO	R	M	Aged	y	9.4	-	-	-		
21-27-3	BOSTA	LM1	Co	R	M	Aged	y	5	-	-	-		
21-19-2	BOSTA	LM1	Co	L	M	Aged	y	broken		-			
21-39-7	BOSTA	LM2	Co	R	Erupt	YJ	broken	broken					
21-31-5	BOSTA	LM2	Co	L	B	YJ	N	49.8					
21-17-2	BOSTA	LM2	Co	R	G	OJ	y	broken	25.3			line	2
21-7-4	BOSTA	LM2	FR	R	G	OJ	y	46.2					
21-43-5	BOSTA	LM2	Co	R	G	OJ	y	46.7	-	7.8		line	1
21-28-4	BOSTA	LM2	Co	R	g	OJ	y	45.1	-	-			
21-30-4	BOSTA	LM2	Co	R	G	OJ	y	44.3	27.6				
21-30-4	BOSTA	LM2	Co	R	G			44.3	19.3-12.2				

Table A4.1: Crescent Island Main Cattle.

cat no.	taxon name	Elem	Part	Side	Wear Stage	Age Grp.	Crown compl	Max crown ht.	Mes loph Hypo	Ds loph hypo	3rd loph hypo	Type	Sev
21-30-4	BOSTA	LM2	Co	R	G			44.3	8.8	n/a			
21-30-4	BOSTA	LM2	Co	R	G			44.3	3.1-0	n/a			
21-45-3	BOSTA	LM2	Co	L	G	OJ	y	42.4	17.5-13.3	20.2-18.2		Line	4b
21-45-3	BOSTA	LM2	Co	L	G		y	42.4	8.5	10.2		Line	2
21-45-3	BOSTA	LM2	Co	L	G			42.4	-	6.4		Line	1
21-44-5	BOSTA	LM2	Co	L	G	OJ	y	24.7	10.6	11.8	-	depr.	1
21-44-5	BOSTA	LM2	Co	L	G			24.7	5.7	7	-	depr.	1
21-29-4	BOSTA	LM2	Co	R	J	YA	y	41.2	11.8	13.6		depr.	2
21-29-4	BOSTA	LM2	Co	R	J			41.2	9	11.1		Line	1
21-29-4	BOSTA	LM2	Co	R	J			41.2	4.5	5.8		Line	2
21-3-3	BOSTA	LM2	Co	R	J	YA	y	43.4	4.6	n/a		Line	1
21-3-3	BOSTA	LM2	Co	R	J			43.4	2.8	n/a		Line	1
21-8-4	BOSTA	LM2	Co	L	J	YA	y	46.7	10.5	9.5		depr.	1
21-8-4	BOSTA	LM2	Co	L	J			46.7	7.6	6.1		Line	1
21-8-4	BOSTA	LM2	Co	L	J			46.7	5.6	4.4		Line	2
21-8-4	BOSTA	LM2	Co	L	J			46.7	1.6	2.5		Line	4
21-31-3	BOSTA	LM2	Co	L	J	YA	y	39.7	3.3	4.5		Line	1
21-10-3	BOSTA	LM2	Co	L	K	OA	y	35.5	5.9	5		line	1
21-14-4	BOSTA	LM2	Co	L	K	OA	y	29	13.6	14		Line	1
21-14-4	BOSTA	LM2	Co	L	K			29	6.5	7.2		Line	2
21-14-4	BOSTA	LM2	Co	L	K			29	4.7	4.8		Line	1
21-54-6	BOSTA	LM2	Co	L	K	OA	y	28.9	-	-			
21-36-3	BOSTA	LM2	Co	L	K	OA	y	42.8	-	-			
21-17-2	BOSTA	LM2	Co	R	K	OA	y	23.3	-	-			
21-27-3	BOSTA	LM2	Co	R	K-L	OA	y	18.4	4.3	4.7		line	3
21-48-3	BOSTA	LM2	Co	R	K	OA	y	38.3	26.6	25.4		depr	1
21-54-4	BOSTA	LM2	Co	R	K	OA	y	28.1	-	-	-		
No number	BOSTA	LM2	FR	L	L	Aged	y	16	-	-			
No number (No F.P.T)	BOSTA	LM3	Co	indet	Erupt	YJ	no	broken		-			
21-43-4	BOSTA	LM3	Co	R	A/B	OJ	no	n/a		33.3	27.1	line	2
21-23-3	BOSTA	LM3	Co	L	E	OJ	y	broken	23.4	19.8	n/a	line	4
21-23-3	BOSTA	LM3	Co	L	E			broken	12.8	broken	n/a	line	4
21-46-4	BOSTA	LM3	Co	L	D	OJ	y	56.3	28.5	27.5	29.1	line	2
21-27-3	BOSTA	LM3	Co	L	F	OJ	y	broken	33.8	35.8	broken	Line	1
21-27-3	BOSTA	LM3	Co	L	F			broken	29.6	31.1		Line	1

Table A4.1: Crescent Island Main Cattle.

cat no.	taxon name	Elem	Part	Side	Wear Stage	Age Grp.	Crown compl	Max crown ht.	Mes loph Hypo	Ds loph hypo	3rd loph hypo	Type	Sev
21-51-5	BosTA	LM3	Co	R	F	OJ	y	49.6	-	-	-		
21-53-3	BOSTA	LM3	Co	L	G	YA	y	36.2	16.7	19.1	20.7	line	1
21-6-4	BOSTA	LM3	Co	L	G	YA	y	35.8	-	-	-		
21-6-5	BOSTA	LM3	Co	L	G	YA	y	51.6	-	-	-		
21-31-3	BOSTA	LM3	Co	L	G	YA	y	45.4	-	-	-		
21-36-3	BOSTA	LM3	Co	L	G	YA	y	51.4	21.9	25.9	26.6	line	3
21-36-3	BOSTA	LM3	Co	L	G		y	51.4	12.5	14.2	15.1	Line	2
21-36-3	BOSTA	LM3	Co	L	G		y	51.4	-	9	10.6	Line	1
21-37-4	BOSTA	LM3	Co	L	G	YA	y	53.4	39.4-34.1	45.2-41.8	n/a	line	4b
21-37-4	BOSTA	LM3	Co	L	G			53.4	27.3	32.6		Line	2
21-37-4	BOSTA	LM3	Co	L	G			53.4	10.2	14.7		Line	2
21-51-3	BOSTA	LM3	Co	L	G	YA	y	54.5	7.2	12.1	14.5	line	1
21-51-3	BOSTA	LM3	Co	L	G			54.5	-	5.5	8	line	1
21-51-3	BOSTA	LM3	Co	L	G			54.5	-	2	3.2	line	1
21-31-3	BOSTA	LM3	Co	R	G	YA	y	broken				line	1
21-38-3	BOSTA	LM3	Co	R	G	YA	y	43.1	19.6	-	-	line	1
21-41-3	BOSTA	LM3	Co	R	G	YA	y	41.6	-	-	-		
21-11-3	BOSTA	LM3	Co	R	G	YA	y	40.4	-	-	-		
21-46-3	BOSTA	LM3	Co	L	J	OA	y	35.9	16.8	19.3	-	Line	1
21-35-4	BOSTA	LM3	Co	L	J	OA	y	30.6	9.5	12.5	14.8	Line	3
21-35-4	BOSTA	LM3	Co	L	J		y	30.6	5.9	7.1	6.8	Line	1
21-28-4	BOSTA	LM3	Co	L	J	OA	y	40.9	11.4	16.5	-	Line	2
21-28-4	BOSTA	LM3	Co	L	J			40.9	1.3	4.4	5.7	line	2
21-30-4	BOSTA	LM3	Co	R	J	OA	y	35.7	-	-	-		
21-32-3	BOSTA	LM3	Co	R	J	OA	y	40.4	11.9	11.3	n/a	line	1
21-42-5	BOSTA	LM3	Co	R	J	OA	y	36.1	15.5	15.3	13.1	line	1
21-25-3	BOSTA	LM3	co	L	K	Aged	y	37.1	-	-	-		
21-36-3	BOSTA	LM3	Co	R	K	Aged	y	40.8	7.8	13.4	n/a	Line	1
21-36-3	BOSTA	LM3	Co	R	K			40.8	5.9	10.5		Line	1

Table A4.2: Crescent Island Main Caprines.

cat no.	taxon name	Elem.	Part	Side	Wear Stage	Age Group	Crown compl	Max crown ht.	Mes loph Hypo	Ds loph hypo	3^{rd} loph hypo	Type	Sev
21-50-1	CAPRI	LM1	Co	L	H	YA			2.2	3.2		line	3/4a
21-5-4	CAPRI (sheep)	LM2	Co	L	D	OJ	N	n/a	-	-			
21-48-3	CAPRI (sheep?)	LM2	Co	L	G	YA	y	n/a	11.2	13.8		line	1
21-48-3	CAPRI (sheep?)	LM2	Co	L	G				5.7	7.1		line	3
21-48-3	CAPRI (sheep)	LM2	Co	L	G				4.3	4.5		line	3
21-4-2	CAPRI (sheep)		Co	L	H	OA			4.3	6.1		line	4a
21-4-2	CAPRI (sheep)	LM2	Co	L	H				2.7	3.3		line	4a
21-39-4	CAPRI (sheep)	LM2	Co	R	H	OA	y	broken	7.8-11.6			line	4a
21-53-3	CAPRI-cf. Sheep	LM3	FR	L	D	OA	indet	broken	-				
21-23-5	Caprini-cf. sheep	LM3	Co	L	G	OA	y	23.1	1.8	6.1	5.1	line	2
No #	Caprini (sheep)	LM3	Co	L	G	OA	y	30.5	9.2	12.3	13	pitting	3
21-54-4	Caprini (sheep)	LM3	Co	R	G	OA	y	23.2	-	2	2.5		
21-44-5	Caprini (sheep)	LM3	Co	R	G	OA	Y	37.7	7.5	7.9	9.7	Line	2
21-44-5	Caprini (sheep)	LM3	Co	R	G			37.7	6.7	6.7	8	Line	3
21-44-5	Caprini (sheep)	LM3	Co	R	G			37.7	4.4	5.3	6.5	Line	3
21-44-5	Caprini (sheep)	LM3	Co	R	G			37.7	1.9	2.3	3.3	Line	3
21-10-4	CAPRI-sheep	LM3	FR	R	G	OA	y	broken	not present	5.8	5.6	line	3
21-10-4	CAPRI-sheep	LM3	FR	R	G			broken	not present	2.6	2	line	3
21-48-3	CAPRI (goat)	LM1	Co	R	U	Infant	no	n/a	-	-			
21-50-1	CAPRI (goat)	LM1	Co	L	H	YA	y	20.2	10.2-5.8	10.5-6.8		line	4b
21-35-3	CAPRI-goat	LM1	Co	R	F	OJ	y	23.5	11.2	11.8		line	2
21-35-3	CAPRI-goat	LM1	Co	R	F				2.3	3		line	2
21-38-4	CAPRI cf. Goat	LM2	Co	R	E	OJ	no	n/a	-	-			

Table A4.3: Crescent Island Causeway Cattle

cat no.	Letter	taxon name	Element	Side	Unit	Level	Wear Stage	Age Class
642	A	BOSTA	Ldp4	R	TP9	Feature Horizon, Photo series 6	E	infant
814	B	BOSTA	LM1	R	TP9A	Feature Horizon, Photo series 2	Half	infant
840	B	BOSTA	LM1	L	TP9A	Feature Horizon, Photo series 3	A	infant
623		BOSTA	LM1	R		Feature Horizon, Photo series 5	G	YJ
474	A	BOSTA	LM1	L	TP9	Feature Horizon, Photo series 5	K	YA
1237	A	BOSTA	LM1	L	TP9A	Feature Horizon, Photo series 3	K	YA
705		BOSTA	LM1	L	TP9A	20-25	K	YA
280		BOSTA	LM1	L	TP2	40-50	K	YA
808	D	BOSTA	LM1	R	TP9A	Feature Horizon, Photo series 2	K	YA
1159	A	BOSTA	LM1	R	TP9A	Feature Horizon, Photo series 4	K	YA
2665		BOSTA	LM1	R	TP1 Area	Surface	K	YA
580	D	BOSTA	LM1	R	TP9B	Feature Horizon, Photo series 7	M	Aged
1381	A	BOSTA	LM1	R	TP9A	Feature Horizo, no photo	M	Aged
1239	D	BOSTA	LM1	L	TP9A	Feature Horizon, Photo series 3	O	Aged
1627	C	BOSTA	LM1	R	TP9B	Feature Horizon, Photo series 4	O	Aged
1480		BOSTA	LM2	R	TP9B	Feature Horizon, Photo series 5	A	YJ
2406	B	BOSTA	LM2	R	TP8	Surface	C	YJ
474	B	BOSTA	LM2	L	TP9	Feature Horizon, Photo series 5	G	OJ
1237	B	BOSTA	LM2	L	TP9A	Feature Horizon, Photo series 3	G	OJ
1159	B	BOSTA	LM2	R	TP9A	Feature Horizon, Photo series 4	J	YA
300		BOSTA	LM2	R	TP4	20-30	J	YA
2669		BOSTA	LM2	R	Area A	Surface	K	MA
1840		BOSTA	LM2	R	TP9C	Feature Horizo, no photo	K	MA
580	E	BOSTA	LM2	R	TP9B	Feature Horizon, Photo series 8	K-L	MA
1381	B	BOSTA	LM2	R	TP9A	Feature Horizo, no photo	K-L	MA
2620		BOSTA	LM2	L	TP8	40-50	K	MA
811		BOSTA	LM2	L	TP9A	Feature Horizon, Photo series 2	K	MA
1239	E	BOSTA	LM2	L	TP9A	Feature Horizon, Photo series 3	L	Aged
1627	D	BOSTA	LM2	R	TP9B	Feature Horizon, Photo series 4	L	Aged
2640		BOSTA	LM3	R	General	Surface	F-G	YA
2075		BOSTA	LM3	L	Near TP7	Surface	G	YA
474	C	BOSTA	LM3	L	TP9	Feature Horizon, Photo series 5	G	YA
1161		BOSTA	LM3	L	TP9C	Feature Horizon, Photo series 2	G	YA
1159	C	BOSTA	LM3	R	TP9A	Feature Horizon, Photo series 4	G	YA
931		BOSTA	LM3	R	TP9B	10-20 cm, photo series 1-4	G	YA
2635		BOSTA	LM3	R	TP9	0-10	G cf.	YA
2621		BOSTA	LM3	R	TP9C	20 cm	J	MA
2441		BOSTA	LM3	R	TP9	Surface	K	Aged
2442		BOSTA	LM3	R	TP9	Surface	K	Aged
1239	F	BOSTA	LM3	L	TP9A	Feature Horizon, Photo series 3	L	Aged
1523		BOSTA	LM3	R	TP9B	Feature Horizon, Photo series 3	L	Aged

Table A4.4: Crescent Island Causeway Caprines

cat no.	Letter	taxon name	Element	Portion	Side	Unit	Level	Wear Stage	Age Class
1439	B	CAPRI	Ldp4	Co	L	TP9A	Feature H photo series 5	G	YJ
2678		CAPRI	Ldp4	Co	L	TP9B	20-30cm	H	OJ
1130	B	CAPRI	LM1	Co	R	TP9A	Feature Horizon photo series 4	G	OJ
906	A	CAPRI	LM1	Co	L	TP9B	10-20cm	G	OJ
417		CAPRI	LM1	Co (in mandible)	L	TP9	Feature Horizon photo series 3	G	OJ
1490		CAPRI	LM1	Co	L	TP9B	Feature Horizon photo series 5	L	Aged
1695	C	CAPRI	LM1	Co (in mandible)	L	TP9B	Feature H photo series 3	M	Aged
541	A	CAPRI	LM1	Co (in mandible)	L	TP9	Feature Horizon	M	Aged
754		CAPRI	LM1	Fr	L	TP9A	20-25cm	L	Aged
685		CAPRI	LM1	Co	R	TP9A	Photo Series 2	L	Aged
618	D	CAPRI	LM1	Co	R	TP9A	10-20cm	M	Aged
2677		CAPRI	LM2	Co	L	TP9B	20-30cm	E	OJ
906	B	CAPRI	LM2	Co	L	TP9B	10-20cm	E	OJ
1307		CAPRI	LM2	Co	R	TP9A	Feature Horizon photo series 3	E	OJ
1130	C	CAPRI	LM2	Co	R	TP9A	Feature Horizon photo series 5	E	OJ
1624		CAPRI	LM2	Co	L	TP9B	Feature Horizon photo series 4	G	YA
1131	A	CAPRI	LM2	Co	L	TP9A	Feature Horizon photo series 3	G	YA
618	E	CAPRI	LM2	Co	R	TP9A	10-20cm	H	MA
1245	B	CAPRI	LM2	Co	L	TP9A	Feature Horizon photo series 3	H	MA
1640		CAPRI	LM2	Co	L	TP9B	Feature Horizon photo series 4	H	MA
754		CAPRI	LM2	Co	L	TP9A	20-25cm	J	MA
541	B	CAPRI	LM2	Co (in mandible)	L	TP9	Feature Horizon	M	Aged
1130	D	CAPRI	LM3	Co	R	TP9A	Feature Horizon photo series 6	A	YA
2631		CAPRI	LM3	Co	L	TP9	10-20cm	B	YA
1415		CAPRI	LM3	FR	R	TP9A	20-30cm, Feature H photo series 5	C	YA
1598		CAPRI	LM3		L	TP9B-		D	MA
155		CAPRI	LM3		L	TP9A	10-20cm	F	MA
1274		CAPRI	LM3	Co (in mandible)	R	TP9	20-30cm	G	MA
29		CAPRI	LM3	Co	R	n/a	n/a	G	MA
1142		CAPRI	LM3		L	TP9A-	Feature Horizon	G	MA
1602		CAPRI	LM3	Co	L	TP9B	Feature Horizon photo series 3	G	MA
1238		CAPRI	LM3	Co	L	TP9A	Feature Horizon photo series 3	G	MA
1131	B	CAPRI	LM3	Co	L	TP9A	Feature Horizon photo series 3	G	MA
1148		CAPRI	LM3		L	TP9A-	Feature Horizon	G	MA
101186		CAPRI	LM3	Co	R	Tp9B	10-20cm	G	MA
80		CAPRI	LM3	Co	R	TP9	Feature H photo series 1	G	MA
33		CAPRI	LM3	Co	R	n/a	n/a	G	MA
1844		CAPRI	LM3	Co	R	TP9	Feature H photo series 4	G-J	MA
754		CAPRI	LM3	Co	L	TP9A	20-25cm	H	Aged
543		CAPRI	LM3	Co	L	TP9B	Feature Horizon photo series 4	J	Aged

Table A4.5: Ndabibi Cattle

cat no.	Letter	Taxon	Element	Portion	Side	Wear stage	Age Class
373	A	BOSTA	DUP4	CO	R	G	infant
119		BOSTA	LM1	CO	R	L	OA
549		BOSTA	LM3	CO	L	G	YA

Table A4.6: Ndabibi Caprines

cat no.	Letter	Taxon	element	portion	Side	Wear stage	Age Class
321	B	CAPRA	DUP4	CO	L	med wear	YJ
588		CAPRI	LM1	CO	R	G	OJ
332		CAPRI	LM1	CO	L	M	Aged
482	A	CAPRI	LM2	CO	L	G	YA

Table A4.7: Prolonged Drift Cattle

cat no.	taxon name	Element	Part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes loph Hypo	Ds loph hypo	3rd loph hypo	Type	Sev.
1688001	BOSTA	DLP3	CO		F								
2316800	BOSTA	DLP3	CO		A	infant							
1809802	BOSTA	DLP4	FR		A	Infant							
2139300	BOSTA	DLP4	CO		D	Infant							
2154800	BOSTA	DLP4	CO		A	Infant							
2345500	BOSTA	LM1	CO	L	A	Infant	no	indet					
569600	BOSTA	LM1	CO	L	G	YJ	yes	33.9	--	--	--		
2374700	BOSTA	LM1	FR	L	J	OJ	yes	indet					
2262703	BOSTA	LM1	FR	R	J	OJ	yes	broken					
2157804	BOSTA	LM1	CO	L	K	YA	yes	22.9	--	--	--		
1288800	BOSTA	LM1	CO	R	K	YA	yes	19.1	--	--			
2168801	BOSTA	LM1	CO	R	K	YA	yes	21.5	--	--			
2290400	BOSTA	LM1	FR	R	K	YA	yes	indet		n/a			
2369001	BOSTA	LM1	CO	R	K	YA		25.5	n/a	16.0			
3413800	BOSTA	LM1	CO	R	K	YA	yes	21.4	–	9.6		line	1
3413800									4.1	6.9			2
3413800									0.7	2.3			2
1644700	BOSTA	LM1	CO	L	L	OA	yes	13.2	--	--			
1702900	BOSTA	LM1	CO	L	L-ish	OA	Yes	broken					
2168102	BOSTA	LM1	CO	R	M	Aged	yes	15.7	--	--			
2531400	BOSTA	LM1	CO	R	M	Aged	Yes	4.3	--	n/a			
1711800	BOSTA	LM2	CO	R	C	YJ	indet	broken					
2386300	BOSTA	LM2	CO	R	E	YJ	yes	46.7	--	--			
1842401	BOSTA	LM2	CO	L	G	OJ	yes	45.2	--	--	--		
722600	BOSTA	LM2	CO	R	G	OJ	yes	41.6	buccal sfc not present				

Table A4.7: Prolonged Drift Cattle

cat no.	taxon name	Element	Part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes loph Hypo	Ds loph hypo	3^{rd} loph hypo	Type	Sev.
2262700	BOSTA	LM2	FR	R	G?	OJ	yes	broken	--	ds lobe not present			
19458	BOSTA	LM2	POSHF	R	H	OJ	yes	broken		--			
2303800	BOSTA	LM2	CO	R	H	OJ	yes	49	--	--			
1651900	BOSTA	LM2	CO	R	J	YA	yes	32.1	7.6	7.9		line	1
2369002	BOSTA	LM2	CO	R	J	YA		37.3	19.2	23.9		line	2
1897700	BOSTA	LM2	CO	L	K	OA	yes	24.2	--	--			
2157805	BOSTA	LM2	CO	L	K	OA	yes	36.2					
2123600	BOSTA	LM2	CO	R	K	OA	yes	35.9	--	--			
2168802	BOSTA	LM2	CO	R	K	OA	yes	31.9	--	--			
2154700	BOSTA	LM3	CO	L	B	OJ	yes	54.7	28.3	27.9	11.9-	depr.	1
2154700									15.9	18.2	22.3-	depr.	1
2154700									10.0	8.1		line	3
2812200	BOSTA	LM3	CO	L	C	OJ	yes	broken	--	--			
1774900	BOSTA	LM3	CO	L	A	OJ	indet	broken	--				
1643300	BOSTA	LM3	CO	R	E	OJ	yes	53.9	--	--	5.5-3.1	line	4b
1842402	BOSTA	LM3	CO	L	F	OJ	yes	51.9	--	--	--		
1962900	BOSTA	LM3	CO	L	F cf.	OJ	yes	broken	--				
1233401	BOSTA	LM3	CO	L	D-E	OJ	yes	broken	--	--			
3420700	BOSTA	LM3	CO	R	G	YA	yes	45.1	29.7	30.3	lobe missing		
3420700									11.7	9.0	lobe missing		
418401	BOSTA	LM3	CO	R	G cf.	YA	yes	broken		n/a	24.7	line	2
418401									n/a	n/a	12.3-5.1	line	4b
418401									n/a	n/a	3.3	line	4a
1642900	BOSTA	LM3	CO	R	G	YA	yes	broken	4.9	4.7	10.1	line	1
1343700	BOSTA	LM3	CO	R	G	YA	yes	45.2	--	--	--		
2168803	BOSTA	LM3	CO	R	G	YA	yes	38.8	--	--	--		
1769500	BOSTA	LM3	CO	R	G	YA	yes	45.3	8.4	9.3	11.4	line	3
1769500									5.0	4.7	7.5	line	4a
3382400	BOSTA	LM3	CO	L	G	YA	yes	45.2	28.1-21.9	31.7-27.3	–	line	4b
3382400									10.7	15.1	broken	line	2
1931201	Bos	LM3	C0		G	YA	yes	51.6	37.4	42.0	--	line	3
1931201									22.4	28.1	29.6	line	2
1931201									10.8-4.4	13.6-8.0	16.8-7.3	line	4a
1931201									3.1	6.0	5.6	line	3
1931201									1.7	3.4	3.1	line	3
2157806	BOSTA	LM3	CO	L	J	OA	yes	40.7	19.5	21.5	25.3	line	2
2157806									9.5	11.6	10.8	line	1
2157806									3.1	2.8	3.9	line	2
1768700	BOSTA	LM3	CO	R	J	OA	yes	30	15.8	18.4	19.2	line	1
1768700									3.5	3.6	3.9	line	1
2160800	BOSTA	LM3	CO	L	K	Aged	yes	33.2	13.5	14.3	16.5	line	3

Table A4.7: Prolonged Drift Cattle

cat no.	taxon name	Element	Part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes loph Hypo	Ds loph hypo	3rd loph hypo	Type	Sev.
2160800									6.9	8.9	10.3	line	2
2160800									4.3	4.5	6.6	line	3

Table A4.8: Prolonged Drift Caprines

cat no.	taxon name	Tooth	Part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes loph Hypo	Ds loph hypo	3rd loph hypo	Type	Sev.
1736601	CAPRI	UM1	CO	R	E	YJ	yes	29.3	3.4	--		line	3
1736601									2.2	--		line	3
206400	CAPRI	UM1	CO	R	F	OJ	yes	27.4	5.2	--			
206400									3.2	--			
1789104	CAPRI	UM1	CO	R	G	OJ	yes	27.7	16.2	--		Depr.	
1789104									10.1	8.0		Depr.	
1736602	CAPRI	UM2	CO	R	D	OJ	no	37.4	21.8-20.3	21.1-19.6		line	4b
1736602									24.7	24.8		line	4a
1736602									28.0	27.4		line	4a
1736602									32.8	33.1		line	4b
1789105	CAPRI	UM2	CO	R	E	OJ	No	n/a	11.4	10.5		line	2
1789105									4.7	5.3		line	2
2369602	CAPRI	UM2	CO	L	F	YA	indet	broken	--	--			
1784700	CAPRI	UM3	CO	L	G	OA	yes	22.2	3.4	2.3		line	1
2120600	CAPRI	UM3	CO	R	G or H	Aged	yes	19.4	14.0	13.2		line	4a
2120600									8.1	6.9		line	4a
2120600									4.8	3.6		line	4a
2222100	CAPRI	UM3	CO	R	H	Aged	yes	22.8	3.7	2.2		line	2

Table A4.9: Narosura Cattle

cat no.	taxon name	Elem.	part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes cusp Hypo	Ds cusp hypo	3rd loph hypo	Type	Sev.
100509	Bos taurus	DLP4	FR	L	B	Infant							
100229	Bos taurus	DLP4	Co	L	A	Infant							
100221	Bos taurus	DLP4	FR	R	A	Infant							
100575	Bos taurus	DLP4	FR	R	A	Infant							
100226	Bos taurus	DLP4	Co	R	D	Infant							
100224	Bos taurus	DLP4	CO	R	F	Infant							
100511	Bos taurus	DLP4	CO	R	D	Infant							
100222	Bos taurus	DLP4	Co	R	F	Infant							
101321	Bos taurus	DLP4	Co	L	D	Infant							
100527	Bos taurus	DLP4	CO	R	K	YJ							
100228	Bos taurus	DLP4	Co	L	M	YJ							
100225	Bos taurus	DLP4	Co	L	M	YJ							
100582	Bos taurus	LM1	FR	R	A	Infant	No	n/a					
100502	Bos taurus	LM1	FR	R	A	Infant	No	n/a					
100492	Bos taurus	LM1	FR	L	G	YJ		broken					
100507	Bos taurus	LM1	FR	L	K	YA		16.6					
100555	Bos taurus	LM1	FR	L	K	YA		22.1					
100439	Bos taurus	LM1	Co	L	K	YA		21.6					
100451	Bos taurus	LM1	Co	L	K	YA		30.5	2.6	4.1		line	2
100450	Bos taurus	LM1	Co	R	K	YA		18.2					
100448	Bos taurus	LM1	Co	R	K	YA		15.6	2.4	4.4		depr.	1
100470	Bos taurus	LM1	Co	R	K	YA		26.1	14.5	16.3		depr.	1
100554	Bos taurus	LM1	FR	R	L	MA		14.9	0	7.2			
100485	Bos taurus	LM1	FR	R	L	MA		n/a	0				
100442	Bos taurus	LM1	Co	R	L	MA		19.6	14.7	11.9			
100515	Bos taurus	LM1	FR	L	M	Aged		Broken	0				
100584	Bos taurus	LM1	FR	L	M	Aged		Broken	0	0			
100514	Bos	LM1	FR	L	M	Aged		Broken	--	55.8		depr.	2

Table A4.9: Narosura Cattle

cat no.	taxon name	Elem.	part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes cusp Hypo	Ds cusp hypo	3rd loph hypo	Type	Sev.
	taurus												
100571	Bos taurus	LM1	FR	L	N	Aged		10.6	0				
100556	Bos taurus	LM1	FR	L	P	Aged		Broken	0				
100568	Bos taurus	LM1	FR	R	M	Aged		Broken	--	0			
100443	Bos taurus	LM1	Co	R	O	Aged		10.1	0				
101330	Bos taurus	LM1	FR	R	N	Aged		10	--	1.2		pits	2
100569	Bos taurus	LM1	FR	R	P	Aged		6.6	0				
100724	Bos taurus	LM2	Co	L	A	YJ	No	48	18.5	20.2-14.7		pits	4a
100579	Bos taurus	LM2	FR	L	A	YJ	No	n/a					
100711	Bos taurus	LM2	Co	L	D	YJ		51.4					
100454	Bos taurus	LM2	Co	L	F	YJ		broken					
100520	Bos taurus	LM2	Co	L	B	YJ		51.7	55	40.4		line	3
100520									34.2	33.7		line	3
100520									29.6	30		line	2
100520									20.2	23.7		line	1
100520									10.2	10.7		line	2
100722	Bos taurus	LM2	Co	R	A	YJ	No		0	0			
100517	Bos taurus	LM2	FR	R	D	YJ	No		--	15.3		line	1
100517										22		line	1
100444	Bos taurus	LM2	Co	R	YJ		52.9	23.2	23.8		line		1
100444									19.6	19.8		line	2
100444									12.4	12		line	2
100444									7.3	7.7		line	2
100444									3.8	5.6		line	2
100444									2	4.2		line	2
100483	Bos taurus	LM2	FR	L	G	OJ		35.9	–	6.4		line	1
100574	Bos taurus	LM2	FR	L	G	OJ		n/a					
100449	Bos taurus	LM2	Co	L	G	OJ		44	12	11.8		line	1
100449									1.5	2.8		line	1
100440	Bos taurus	LM2	Co	L	G	OJ			9.7	none		line	1
100558	Bos taurus	LM2	FR	R	G	OJ		n/a					
100519	Bos taurus	LM2	Co	R	G	OJ			–	11.9		line	1
100519									6.6	7.7		line	1

Table A4.9: Narosura Cattle

cat no.	taxon name	Elem.	part	Side	Wear Stage	Age Class	Crown comp.	Max crown ht.	Mes cusp Hypo	Ds cusp hypo	3rd loph hypo	Type	Sev.
100519									2.9	3.7		line	2
100436	Bos taurus	LM2	Co	R	K	MA			22.6	20.9		depr.	1
100436									11.9	10.5		line	4a
100436									26.7	23.2		line	2
100467	Bos taurus	LM2	Co	L	K	MA		33.1		6.8		line	2
100467										5.7		line	2
100439	Bos taurus	LM2	Co	L	K	MA		29.2	0				
100446	Bos taurus	LM2	Co	R	K	MA		27.8	2.2	4.9		line	2
100587	Bos taurus	LM2	FR	R	L	Aged		21.2	0	0			
100453	Bos taurus	LM2	Co	R	L	Aged		19.5	0	0			
100488	Bos taurus	LM3	FR	L	A	OJ		50.1	39.6	n/a	n/a	line	2
100723	Bos taurus	LM3	Co	R	A	OJ		broken	0	0	0		
100464	Bos taurus	LM3	CO	R	E	OJ		49.2	n/a	0	0		
100560	Bos taurus	LM3	FR	R	F	OJ		42.6	5.8			pits	3
100560									32.3			line	2
100438	Bos taurus	LM3	Co	R	G	YA		41.4					
100481	Bos taurus	LM3	FR	L	G	YA		broken					
100457	Bos taurus	LM3	Co	R	G	YA		39.6	28.7	none	none	line	2
100457									21.9–20.1	24.6	23.4	line	2
100457									12.2	17.8	20.6	line	2
100457									3.8	8.1	10.5	line	2
100591	Bos taurus	LM3	FR	R	J	MA		Broken					
100938	Bos taurus	LM3	FR	R	J	MA		Broken					
101054	cf. Bos taurus	LM3	FR	L	J	MA		Broken					
100456	Bos taurus	LM3	Co	L	J	MA		44.6	27.6		24.8	line	1
100456									20.6			line	1
100456									11.9	17.2	18.3	line	2
100456									4.1	8.4	8.1	line	2
100437	Bos taurus	LM3	Co	L	K	Aged		31					
100441	Bos taurus	LM3	Co	R	K	Aged		25					
100455	Bos taurus	LM3	FR	R	L	Aged		broken					

Table A4.10: GvJm44 Cattle

cat no.	Letter	taxon name	Element	Part	Side	Unit	Level	Wear Stage	Age Class
5296		Bos	dlp4	co	L	E13-14, S23-24	25-40	L	YJ
3702		Bos	dlp4	co	R	E12-13, S21-22	30-40	E	Infant
3702		Bos	LM1	co	R	E12-13, S21-22	30-40	A	Infant
5281		Bos	LM1	Co	L	E13-14, S23-24	25-40	E	YJ
4521		Bos	LM1	Co	L	E40-41, S 36-37	20-25	G	YJ
5306		Bos	LM1	Co	L	E13-14, S23-24	25-40	G	YJ
5307		Bos	LM1	Co	R	E13-14, S23-324	25-40	G	YJ
6437		Bos	LM1	Co	L	E13-14, S21-22	30-50	H	YJ
857		Bos	LM1	Co	L	E15-16, S22-23	30-40	K	YA
4148		Bos	LM1	Co	L	E38-39, S38-39	30-35	K	YA
5235	c	Bos	LM1	Co	L	E14-15, S24-25	30-40	K	YA
6249		Bos	LM1	Co	R	E12-13, S22-23	? - 45	K	YA
6261		Bos	LM1	FR	R	E12-13, S22-23	30-45	K/L	YA
1025		Bos	LM1	Co	L	E14-15, S23-24	27-40	L	MA
6245		Bos	LM1	Co	L	E12-13, S22-23	30-45	L	MA
3657		Bos	LM1	Co	R	E13-14, S22-23	30-40	L	MA
5501		Bos	LM1	Co	R	E14-15, S22-23	Hor.	L	MA
3711	c	Bos	LM1	Co	R	E12-13, S23-24	30-40	L	MA
1645	b	Bos	LM1	Co	L	E15-16, S22-23	30-40 (feature)	M	Aged
6255		Bos	LM1	FR	L	E12-13, S22-23	30-45	M	Aged
6257		Bos	LM1	FR	L	E12-13, S22023	30-45	M	Aged
3963		Bos	LM1	Co	L	E15-16, S23-24	30-40	N	Aged
3957		Bos	LM1	FR	R	E15-16, S23-24	30-40	M	Aged
5490		Bos	LM1	Co	R	E14-15, S22-23	Horizon	N	Aged
3856		Bos	LM1	Co	R	E15-16, S23-24	30-40	O	Aged
3652	b	Bos	LM2	Co	R	E13-14, S22-23	30-40	K	MA
4148		Bos	LM2	Co	L	E38-39, S38-39	30-35	E	YJ
5257		Bos	LM2	Co	L	E13-14, S23-24	25-40	B	YJ
5287		Bos	LM2	Co	L	E13-14, S23-24	25-40	B	YJ
5277		Bos	LM2	Co	L	E13-14, S23-24	25-40	F	YJ
1043		Bos	LM2	Co	L	E14-15, S23-24	27-40	G	OJ
5492		Bos	LM2	Co	R	E14-15, S22-23	Horizon	G	OJ
3241		Bos	LM2	Co	L	E38-39, S37-38	50-60	H	OJ
3736	b	Bos	LM2	CO	L	E13-14, S22-23	30-40	H	OJ
6748		Bos	LM2	Co	R	E37-38, S43-44	35-40	J	YA
5283		Bos	LM2	Co	L	E13-14, S23-34	25-40	J	YA
3453		Bos	LM2	Co	L	S22-23, E16-17	25-35	J	YA
3804		Bos	LM2	Co	L	E15-16, S23-24	40-50	K	MA
3963		Bos	LM2	Co	L	E12-13, S22-23	30-40	K	MA
5248		Bos	LM2	Co	L	E14-15, S24-25	Below occ. -60	K	MA
5394		Bos	LM2	CO	L	E17-18, S24-25	Featue	K	MA
5517		Bos	LM2	Co	L	E14-13, S22-23	Horizon	K	MA
3657		Bos	LM2	Co	R	E13-14, S22-23	30-40	K	MA

Table A4.10: GvJm44 Cattle

cat no.	Letter	taxon name	Element	Part	Side	Unit	Level	Wear Stage	Age Class
1304		Bos	LM2	Co	L	E14-13, S23-24	27-40	K	MA
5299		Bos	LM2	Co	R	E13-14, S23-24	25-40	K	MA
5501		Bos	LM2	FR	R	E14-15, S22-23	Hor.	K	MA
6239		Bos	LM2	Co	R	E12-13, S22-23	30-40	K	MA
1485		Bos	LM2	Co	L	E15-16, S22-23	30-40	L	Aged
3957		Bos	LM2	Co	R	E15-16, S23-24	30-40	L	Aged
4135		Bos	LM3	Co	L	E38-39, S38-39	25-30	a	OJ
5284		Bos	LM3	Co	L	E13-14, S23-24	25-40	a	OJ
6833		Bos	LM3	FR	L	E37-38, S41-42	35-40	A	OJ
1042		Bos	LM3	Co	L	E14-15, S23-34	27-40	B	OJ
4237		Bos	LM3	Co	R	E39-40, S37-38	25-30	a or b	OJ
6436		Bos	LM3	Co	R	E13-14, S21-22	30-50	A or b	OJ
6440		Bos	LM3	Co	R	S21-22, E13-14	30-50	A or B	OJ
6440		Bos	LM3	Co	R	E13-14, S21-22	30-50	a or b	OJ
4304		Bos	LM3	Co	R	E38-39, S32-33	10-20	b	OJ
3656		Bos	LM3	FR	R	E13-14, S22-23	30-40	B	OJ
1022		Bos	LM3	Co	R	E14-15, S23-24	27-40	C	OJ
4422		Bos	LM3	Co	R	E39-40, S36-37	20-25	C	OJ
3893		Bos	LM3	FR	R	E15-16, S23-24	30-40	D	OJ
2691		Bos	LM3	FR	L	E15-16, S22-23	40-50	E	OJ
6010		Bos	LM3	Co	R	E39-40, S43-44	40-45	E	OJ
3457		Bos	LM3	FR	L	E16-17, S22-23	25-35	F	OJ
4761		Bos	LM3	Co	L	E38-39, S39-40	45-50	F	OJ
5270		Bos	LM3	Co	L	E13-14, S23-24	25-40	F	OJ
3252		Bos	LM3	FR	L	E15-16, S24-25	30-40	G	YA
5340		Bos	LM3	Co	L	E1617, S24-25	Feature	G	YA
1418		Bos	LM3	Co	R	E14-15, S23-24	27-40	G	YA
3219		Bos	LM3	Co	R	E12-13, S21-22	40-50	G	YA
1563		Bos	LM3	FR	L	E15-16, S22-23	30-40	H	MA
3657		Bos	LM3	Co	R	E13-14, S22-23	30-40	H	MA
4755		Bos	LM3	FR	R	E38-39, 39-40	47-50	H	MA
5482		Bos	LM3	Co	R	E14-15, S22-23	Horizon	H	MA
3735		Bos	LM3	Co	L	E13-14, S22-23	30-40	J	MA
3804		Bos	LM3	Co	L	E15-16, S23-24	40-50	J	MA
3963		Bos	LM3	Co	L	E15-16, S23-24	30-40	J	MA
1504		Bos	LM3	Co	R	E15-16, S22-23	30-40	J	MA
6238		Bos	LM3	FR	R	E12-13, S22-23	35-45	J	MA
1038		Bos	LM3	FR	L	n/a	n/a	K	Aged
1461		Bos	LM3	Co	L	E15-16, S22-23	30-40	K	Aged
5247		Bos	LM3	Co	L	E14-15, S24-25	below occ. -60	K	Aged
5517		Bos	LM3	Co	L	E14-13, S22-23	Horizon	K	Aged
6247		Bos	LM3	Co	L	E12-13, S22-23	30-45	K	Aged
1414		Bos	LM3	Co	R	E14-15, S23-24	27-40	K	Aged
3547		Bos	LM3	Co	R	E15-16, S24-25	30-40	K	Aged

Table A4.10: GvJm44 Cattle

cat no.	Letter	taxon name	Element	Part	Side	Unit	Level	Wear Stage	Age Class
3957		Bos	LM3	Co	R	E15-16, S23-24	30-40	K	Aged
5513		Bos	LM3	Co	R	E14-15, S22-23	Horizon	K	Aged
3655	c	Bos	LM1	Co	R	E13-14, S22-23	30-40	L	MA
3655	d	Bos	LM2	Co	R	E13-14, S22-23	30-40	K	MA
3655	e	Bos	LM3	Co	R	E13-14, S22-23	?30-40?	G	YA
5481	a	Bos	LM1	Co	R	E14-15, S22-23	Hor.	K	MA
1044	b	Bos	LM2	Co	R	E14-15, S23-24	27-40	K	MA
1417	c	Bos	LM1	FR	R	E14-15, S22-23	Hor.	cf. L	MA
1417	d	Bos	LM2	Co	R	E14-15, S22-23	Hor.	K	MA
3737	a	Bos	LM2	Co	L	E13-14, S22-23	30-40	L	Aged
3737	b	Bos	LM3	Co	L	E13-14, S22-23	30-40	K	Aged
6233	b	Bos	LM1/2	Co	R	E12-13, S22-23	30-45	K	MA
6233	a	Bos	LM3	Co	R	E12-13, S22-23	30-45	G/H	OJ
1001	b	Bos	LM1	Co	R	E14-15, S23-24	horizon	N	Aged
1001	c	Bos	LM2	Co	R	E14-15, S23-24	horizon	L	Aged
1001	d	Bos	LM3	Co	R	E14-15, S23-24	horizon	K	Aged

GvJm52 Cattle

Table A4.11: GvJm52 Cattle

Spec. No.	Species	Element	Portion	Side	Wear Stage	Age Class
1058	BOSTA	ldp4	Co	R	N	YJ
1572	BOSTA	LM1	Co	R	G	YJ
1835	BOSTA	LM1	Co	R	G	YJ
2552b	BOSTA	LM1	Co	L	K	YA
1006	BOSTA	LM1	Co	R	K	YA
2284	BOSTA	LM2	Co	L	L	MA
1565	BOSTA	LM2	Co	L	K	MA
1691	BOSTA	LM2	Co	L	K	MA
2559	BOSTA	LM3	Co	L	C	OJ
1209	BOSTA	LM3	Co	R	G	YA
1569	BOSTA	LM3	Co	R	J	MA
5003A	BOSTA	LM3	Co	L	K	Aged

Table A4.12 GvJm52 Caprines

Spec. No.	Species	Tooth	Portion	Side	Wear Stage	Age Class
1355	CAPRI	ldp4	Co	R	G	YJ
no #	CAPRI	ldp4	Co	L	F	Infant
2702b	CAPRI	LM1	Co	R	M	Aged
1714	CAPRI	LM1	Co	L	J	MA
1655	CAPRI	LM2	Co	R	H	MA
1201	CAPRINI	LM3	Co	R	F	MA
2245	CAPRA	LM2	Co	L	E	MA

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