The Resilience of Agro-pastoral Communities in High Altitude Central Tibet: Zooarchaeological and Stable Isotope Investigations at Bangga, 3000–2200 BP

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The Resilience of Agro-Pastoral Communities in High Altitude Central Tibet: Zooarchaeological and Stable Isotope Investigations at Bangga, 3000–2200 BP
by
Zhengwei Zhang

A dissertation presented to
The Graduate School of Washington University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

May 2022
St. Louis, Missouri
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Zhengwei Zhang

Washington University in St. Louis
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ABSTRACT OF THE DISSERTATION

The Resilience of Agro-Pastoral Communities in High Altitude Central Tibet: Zooarchaeological and Stable Isotope Investigations at Bangga, 3000–2200 BP

by

Zhengwei Zhang

Doctor of Philosophy in Anthropology

Washington University in St. Louis, 2022

Associate Professor Xinyi Liu, Chair

Professor Fiona Brigid Marshall, Co-Chair

Our understanding of the development of high-altitude adaptations worldwide has been enriched by recent anthropological research. Study of life on the Tibetan Plateau—dubbed “the Roof of the World”—has highlighted specific challenges of seasonal availability of food and extreme weather systems. Recent archaeological studies have revealed that pastoralism has a long history of resilience on the extreme high altitude Tibetan Plateau. However, specific risks to early flocks on the Tibetan Plateau and ways that herders managed their animals to mitigate these have not been well explored. Dated to 3000–2200 Cal BP, the archaeological settlement of Bangga represents one of the earliest pastoral communities in high altitude central Tibet. Faunal assemblage at Bangga offers the rare opportunity to examine these issues. In this research, I use zooarchaeological and stable isotopic analyses to address these missing aspects of understanding regarding pastoralist high altitude adaptations, in two different ways.

First, to address the enduring challenge of identifying and discriminating among Tibetan wild bovids and domestic animals, I developed new method for identifying and discriminating
takin (*Budorcas taxicolor*) from yak (*Bos grunniens*), cattle (*Bos taurus*), gaur (*Bos gaurus*), and water buffalo (*Bubalus bubalis*) in archaeofaunal assemblages. This research provided a reproducible method for distinguishing takin from other large bovids in this region. The osteomorphological criteria established in this study are important to future archaeological investigations of early usage of wild bovids and the emergence and development of pastoralism on the Tibetan Plateau.

Second, to examine two broad research questions: 1) How environmental challenges might have threatened the survival of early pastoralists at the high altitudinal regions of the Tibetan Plateau? 2) How early central Tibetan pastoralists managed their livestock to cope with environmental pressures? I analyzed mortality profiles and enamel isotope compositions of sheep and goat remains Bangga. The mortality profile revealed that most sheep at Bangga (64.28%, n=27) died within the first year of their life. Recent herd mortality metadata from Tibet and simulations suggest that within this high-risk context of Tibetan Plateau, the archaeological mortality profile from Bangga was most likely the outcome of environmentally-driven lamb mortality. Contextual archaeological and isotopic data for corrauling and foddering at Bangga indicate specific ancient disease and nutritional risks associated with periodic confinement and lack of access to pasture. Comparison with archaeological sites from other regions of the plateau and its vicinities document similar high mortality at other high altitude sites, but not at lower elevations, drawing attention to high altitude risk. Together, these findings indicate that high juvenile mortality presented a threat for ancient herders who suffered from serious environmental pressures on the Tibetan Plateau. Research on the sequential stable carbon and oxygen isotope compositions in tooth enamel of sheep and goats from Bangga shed light on ways that these early central Tibetan pastoralists maintained their pastoral life under such environmental pressure. The
sequential stable carbon and oxygen isotopic data show clear evidence of human control over
diet and drinking water of their livestock. Sheep and goats at Bangga were provisioned with
ground water and significant amounts of cultigens (likely barley and millet) seasonally or all year
around, but there is no clear isotopic patterning suggesting seasonal movements along altitudinal
gradients. These results demonstrate that central Tibetan agropastoralists three thousand years
ago practiced a specialized livestock management strategy together with sophisticated cultivation
systems, to assure year-round food for their livestock in order to survive in the extreme Tibetan
Plateau environment.

This research revealed ways that early pastoralists of central Tibet were able to increase
resilience to periodic stresses and to survive, despite the inhospitable and unpredictable
environment. As a result of the rare opportunity that well preserved animal bones from Bangga
provided for of systematic zooarchaeological analyses, sequential stable oxygen and carbon
isotope analyses, and the availability of regional ethnographic records, this research is the first to
reveal details of animal-based subsistence strategies of some of the earliest central Tibetan
pastoral groups. This research also provides complementary data to better interpret other
archaeological materials from this region and will ultimately expand our knowledge of the
process of peopling the Tibetan Plateau, shedding light on resilience of human communities’ in
extreme environments worldwide.
Chapter 1: Introduction

Recent anthropological and archaeological research has greatly refined our understanding of early adaptations to high-altitude environments in several continents, including East and Central Asia, East Africa, and South America. Study of life on the Tibetan Plateau—dubbed “the Roof of the World”—has revealed specific challenges regarding strategies for securing a reliable food supply. Today more than 90% of people in the modern day Tibetan Autonomous Region practice pastoralism to varied degrees (Cheng et al., 1984, pp. 99-101), but it is rather difficult for herders on the Tibetan Plateau to maintain their pastoral lifeways. Herders on the Tibetan Plateau and in other extreme environments worldwide (e.g. Mekuyie et al., 2018; Thornton et al., 2009; Opiyo et al., 2014), face risks of the seasonal availability of pasture and extremely seasonal weather system (Guo et al., 2018, pp. 112-115; Naidong, 2006, pp. 353-354; Xin & Chen, 2013; Xin et al., 2013). Surviving on the plateau requires resilience to the particular stresses of seasonal pasture shortage and extreme weather. Resilience is defined here as a group’s ability to maintain a fundamentally similar subsistence system after shocks of unexpected challenges to survival, following ecological and social perspectives (Longstaff, 2005; Mekuyie et al., 2018; Holling and Meffe, 1996). In a pathbreaking quantitative study conducted in southern Ethiopia, designed to predict the future resilience of contemporary pastoral households, Mekuyie et al. (2018) developed a resilience index by identifying specific factors influencing household resilience, including those that fell into generalized and specialized strategies. Factors used to estimate dimensions of resilience (resilience index) included assets (e.g. livestock owned, labor), adaptive capacity (e.g. mobility, herd splitting, extent of cultivation), social safety nets (e.g. food
from external source), access to public services, income and food access, and stability (Mekuyie et al. 2018). As one of the first to attempt to quantify multiple factors influencing herder resilience and to model future resilience, this study is relevant to thinking about ancient as well as modern herders. This study emphasized that both generalizing and specializing strategies can be used simultaneously to strengthen resilience, through assets and adaptive capacity, for example. Most of the factors identified as important to future outcomes have ancient correlates that can be considered in modelling or hypothesizing the potential for ancient households to survive shocks given herd holdings, agricultural participation or social settings at varied times and places.

Hypothetical options for ancient herders in Tibet to generalize subsistence could have included increasing land under cultivation, increased hunting or trading, for example. Increasing labor inputs, heavier reliance on specific animals, increased seasonal movements among varied pastures, or increased labor inputs through foddering or watering livestock and increased fertilization would also have improved adaptive capacity and the survivorship of herds and minimized the loss occurred through more specialized practices such as dependence on sheep.

Generalizing and specializing approaches are common strategies employed to increase resilience globally (Adger, 2000; Bruneau et al., 2003; Fernandez-Gimenez et al., 2011; Goldstein & Beall, 1990; Huang et al., 1981; Herrero et al., 2016; Klein et al., 2003; Rhoades & Thompson, 1975). Given the risks of snowstorms, shortages of winter fodder, and predation on the Tibetan Plateau strategies for increasing contemporary herder resilience are particularly relevant for thinking about survival of ancient settlers in these extreme environments.

There has been considerable recent momentum in understanding of prehistoric human ecology in the high altitude environments (>3500 m a.s.l.) of the Tibetan Plateau, and the
implications are profound for understanding the human past on a more global scale. The earliest evidence of human activity on high elevational areas of Tibetan Plateau can be dated to 40,000 ~ 30,000 Cal BP (Zhang et al., 2018). Recent studies at Chusang in central Tibet have highlighted the possibility of permanent occupation at high altitudes by hunting-gathering groups in the early Holocene (Meyer et al., 2017). During the late Holocene, the region witnessed increases in site numbers, in particular, associated with the archaeological evidence of agropastoralism marked by use of both indigenous resources and newly introduced non-native cultigens and livestock between 4200-3000 BP. Multi-resource pastoral economies that corresponded with the occupation of previously unoccupied, uninhabitable higher altitude environments relied on herd animals such as yak (Bos grunniens), cattle (Bos taurus), horse (Equus caballus), sheep (Ovis aries), and goat (Capra hircus) (Chen et al., 2015; d’Alpoim Guedes et al., 2013; Dong et al., 2016; Fu, 2001; Fu, 2008; Li, 2012; Lü, 2016; Ren, 2017; Song et al., 2017; Tong et al., 2015; Tong et al., 2014; Wang, 2017; Zhang & Lü, 2017; Zhang et al., 2015; Zhou, 1999). Among these herd animals, yak is the only species that is indigenous to the high altitudinal Tibetan Plateau. Currently available archaeobotanical data suggests that these early pastoralists of the northeastern, eastern, central, and western high elevation regions of the Tibetan Plateau incorporated millet, wheat, and barley cultivation at varied scales (d’Alpoim Guedes, 2015; d’Alpoim Guedes et al., 2015; d’Alpoim Guedes et al., 2013; Dong et al., 2016; Fu, 2001; Fu, 2008; Gao et al., 2021; Ren et al., 2020; Song et al., 2021; Song et al., 2017; Tang et al., 2021). Similar multi-resource economies had developed during the third millennium BC at various lower environments adjacent to the Tibetan Plateau, particularly along the Inner Asian Mountain Corridor and northwest India (e.g. Chen et al., 2015; Flad, 2007; Frachetti, 2012; Olsen et al., 2006; Outram et al., 2009; Patel & Meadow, 2017). It is not unreasonable to assume that the
agropastoral lifeways were developed within this context, and that non-native cultigens and livestock (e.g. barley, millet, cattle, horse, goat and sheep) were introduced from to Tibetan Plateau from lower environments. The pathway of those movements is yet obscure but the timing of the appearance of pastoralists on the Tibetan Plateau is becoming increasingly clear, as well as the plant and animal taxa on which people depended. Much less is known about the survival of introduced herd animals and the development of novel resilient agropastoral systems in the range of high altitude environments of Tibetan Plateau. Investigation of this question has been obscured by a lack of systematic zooarchaeological study of faunal remains from early pastoral settlement on the high elevation (>3500 m a.s.l.) regions of the Tibetan Plateau.

In this dissertation I shift the research focus from the timing of the development of Tibetan pastoralism, to explore the mechanisms by which animal herds were managed in extreme environments through analysis of the archaeological faunal assemblage from the high altitude pastoral settlement of Bangga (~3800 m a.s.l.). Previous studies at Bangga have suggested that the site was occupied by agro-pastoralists between ~3000-2000 Cal BP, which makes it one of only a few prehistoric settlements documenting long-term occupation on the high elevation (>3500 m a.s.l.) regions of the Tibetan Plateau (Liu et al., 2016; Lü, 2016; Lü et al., 2021). My research addresses the missing piece of the story by investigating how early herders and their herds survived and contributed to development of novel resilient agropastoral systems at high altitudes. Well-preserved faunal specimens, especially domesticated sheep remains retrieved from Bangga, provide an exceptional opportunity to investigate the details of lifeways of early pastoralists in high elevational central Tibet and to explore strategies of herd management.

In this research, I use zooarchaeological and stable isotopic analyses to address two broad research questions: 1) How environmental challenges might have threatened the survival of early
pastoralists at the high altitudinal regions of the Tibetan Plateau? 2) How early central Tibetan pastoralists managed their livestock to cope with environmental pressures? This project also contributes methodologically to the zooarchaeology of the Tibetan Plateau through development of comparative osteomorphological criteria for distinguishing regional large wild and domestic bovids such as takin and large Bovini including cattle and yak. By answering questions regarding extreme environmental challenges and strategies of livestock management, the study has broad implications for regions beyond the study area and sheds light on our understanding of ways that human communities’ may have increased resilience in extreme environments worldwide.

In the following section, I review potential environmental challenges that might threaten the survival of early Tibetan herders and their herds. I will also summarize ethnographically recorded strategies that enable recent resilient Tibetan herders to cope with environmental challenges. These records will allow for the construction of relational analogies (Sensu: Wylie, 1985) for interpreting archaeological data in this study.

1.1 Environmental challenges for pastoralists on the Tibetan Plateau and ethnographically recorded strategies to coping with environmental challenges

More than 90% of people in the modern day Tibetan Autonomous Region practice pastoralism to some degree (Cheng et al., 1984, pp. 99-101) but it is rather difficult for even experienced herders to maintain their pastoral lifeways under extreme conditions of the Tibetan Plateau. Due to effect of the high altitude, Tibetan livestock herds have a relatively low reproduction rate and
slow herd growth. For instance, ewes on the Tibetan Plateau usually only give birth to one lamb once a year compared to lower areas where they often can bear two per year (Yang et al., 1993). Meanwhile, natural losses of livestock on the Tibetan Plateau are rather high, which makes the maintenance of herd size challenging. Highly variable and unpredictable ecological factors, including low temperature, extreme weather, epidemic animal diseases, and wild predators, can decimate the whole herd in a short period of time (Cheng et al., 1984, pp. 50-51; Guo et al., 2018; Huber, 2005, 2012; Miller, 2000; Xin & Chen, 2013). Ethnographic and historical records indicate that high natural loss of livestock among recent and modern pastoral communities on the Tibetan Plateau was common. Natural loss rate of infant livestock on the Tibetan Plateau can be as high as 70% (County, 2010, p. 379). Even in more recent times, a snowstorm and consequent serious shortage of food and fuel may kill more than 90% of lambs and kids of a herd within one month (City, 2004, p. 68). Since the climate system of central Tibet has been relatively stable since the mid-late Holocene (Tang et al., 2000), these natural threats were potential risks for Tibetan herders in the archaeological past.

Maintaining a pastoral lifeway on the Tibetan Plateau in the past thus required resilience to the particular stresses of seasonal food shortage and extreme weather. Resilience can be viewed as a group’s ability to remain stable when facing unexpected challenges to survival (Longstaff, 2005). A good starting point for understanding prehistoric Tibetan pastoralists’ animal-based subsistence strategies is found in the wealth of available ethnographic and historic materials from this region, which allows for the construction of relational analogies (Sensu: Wylie, 1985) useful to interpretation of archaeological data in this study. Ethnographic research has revealed the central role of a combination of generalized subsistence and specialized livestock management
strategies in developing resilient lifeways for recent pastoralists in a range of different ecological conditions on the Tibetan Plateau.

Generalized subsistence strategies include utilizing diverse food resources of a broad range of wild and domestic animal species and agricultural products for both human and their herds. Diversity is also achieved by practicing a multi-species grazing system (Miller, 1999), where contemporary Tibetan pastoralists make use of multiple domesticated animals—including cattle, yak, yak-cattle hybrids, sheep, goats, horses, mules, donkeys (*Equus asinus*), pigs (*Sus domestica*), and chickens (*Gallus gallus domesticus*)—to satisfy their everyday needs for food, hides, and transport (Bauer, 2010; Goldstein & Beall, 1990; Thargyal, 2007). Such a system also serves as a risk management strategy to deal with unpredictable losses affecting particular livestock species. In the face of serious seasonal fodder shortage, hunting can be easily practiced locally. The subsistence hunting of various wild animals by modern Tibetan pastoralists includes deer and blue sheep (*Pseudois nayaur*), goral (*Naemorhedus goral*), tahr (*Hemitragus jemlahicus*), and Tibetan wild sheep (*Ovis ammon*). Tibetan wild ass also constitutes a significant food source for Tibetan pastoralists, especially in winter (Fox & Dorji, 2009; Goldstein & Beall, 1990; Huber, 2005; Næss & Bårdsen, 2016). In addition, hunting can supply Tibetan pastoralists not only with additional protein and fat, but also with hides, hair, and horns that are converted for everyday use and for marketable goods (Corrigan, 2017, pp. 31-45; Goldstein & Beall, 1990; He, 2008; Huber, 2012).

Integrating pastoral subsistence into diverse subsistence strategies, especially agriculture, is another significant approach to broaden Tibetan herders’ food resource. Though pastoralism is widely practiced on the Tibetan Plateau, only around 30% of communities in Tibet purely rely on pastoralism today (Cheng et al., 1984, pp. 99-100). People in other communities rely on
agriculture at varied degrees and cultivate barley, wheat, rapeseed, potato, maize, pea, and buckwheat.

Though generalized subsistence strategies that utilize both pastoral, agricultural, and wild recourses are important for securing food supplies year round, specialized livestock management strategies are also indispensable for Tibetan herders and their herds to survival extreme weathers and other high altitudinal environmental challenges. Specialized livestock management strategies practiced by recent Tibetan herders potentially include dependence on a smaller range of animals and are commonly characterized by intensification of labor inputs to protect the herds including seasonal movements with their livestock among different pastures and intentionally penning and foddering of livestock. Utilizing multiple seasonal pastures mitigate the impact of seasonal pastural resource shortage, however requires pastoralists to engage in seasonal movements either vertically between higher and lower elevations (Rhoades & Thompson, 1975), horizontally across the landscape (Goldstein & Messerschmidt, 1980), or both (Thargyal, 2007). Though the exact number of seasonal pastures used by contemporary pastoralists are varied, the majority move to higher areas in the summer and to lower or warmer areas in winter (Goldstein & Beall, 1990; Miller, 1999; Tan, 2017; Thargyal, 2007). Further, contemporary Tibetan pastoralists also split their livestock into herd-cohorts by species, sex, usage, or age and graze them at different microniches based on the particular needs of the herd (Cheng et al., 1984, p. 65; Goldstein & Beall, 1990, p. 61). Agricultural products, on the other hand, provide people with stable food year-round on Tibetan Plateau and also supplement animal graze and browse from the pastures through provisioning of cut fodder. Barley, wheat, and buckwheat grains and by-products of produce of these cereals are commonly foddered to livestock. In addition, plants, such as turnip (Brassica rapa), oat straw (Avena sativa), burclover (Medicago sativa), that can or cannot be
direct consumed by people are also cultivated as fodder at some areas of Tibetan Plateau (Huang et al., 1981, pp. 19-22). Wild plants are also harvested and stored by recent Tibetan herders (Goldstein & Beall, 1990, pp. 72-79). Stored fodders are particularly useful to mitigate impact of shortage of pasture resource in winter (Gele et al., 2002, pp. 420-438). In addition, penning has also been well recorded as helpful to increase survivorship of livestock, especially newborn individuals, in cold temperature and extreme weather (Huang et al., 1981, pp. 94-95).

1.2 Project Orientation and Objectives

To investigate strategies used by early herders to survive challenges of the extreme environments of the high altitude plateau I develop zooarchaeological methods of identification, examine questions of sheep natural mortality, culling, foddering and other strategies of herd management within the context of all lines of evidence from the site of Bangga at central Tibet. In this section, I summarize the environmental context of the Bangga area today, and subsistence strategies of present day herders at Bangga to provide insights into opportunities and challenges faced by earlier herders in this landscape and specific propositions to examine through archaeological data. I also review current available archaeological data from Bangga and the broader central Tibet area.

1.2.1 Environmental Context

The site of Bangga and the modern village are located on an alluvial fan on the western flank of a hill ranging between 3700 and 4800 m a.s.l. Even though central Tibet is one of warmest
regions of the plateau, large diurnal temperature variation and unbalanced seasonal precipitation still make this area a challenging location for year-round occupation. A temperature of 10 degrees C in the day can be followed by -6 degrees C nighttime in the winter, and noon highs of 24 degrees C are followed by night-time lows of 10 degrees C in the summer. Rainfall at the Chonggye valley is unbalanced between different seasons. Under the influence of the Indian Ocean summer monsoon, rainfall is concentrated between June and September, with an average precipitation of 80mm/month. Thunderstorms, hail, torrential rains, and flooding occur frequently in the summer, while the rest of the year is rather arid and windy, with an average precipitation of only 6mm/month and average relative humidity of 30% (Song et al., 2013).

Thirty-two species of wild mammals and more than 300 species of birds have been recorded in central Tibet—among these are fox, wolf, Tibetan wild ass (Asinus kiang), musk deer (Moschus sianicus), Tibetan gazelle (Procapra picticaudata), blue sheep (Pseudois nayaur), argali (Ovis ammon), and wooly hare (Lepus oiostolus), which all could serve as sources of meat and hides for early inhabitants in central Tibet. (Feng et al., 1986; Zheng et al., 1983)

1.2.2 Modern Subsistence Strategies at Bangga

Today people living at the Bangga village year-round practice a generalized form of agro-pastoralism. Agriculture and pastoralism contribute to the Bangga village economy in roughly equal measure. They cultivate wheat, barley, rapeseed, potato, pea, and buckwheat on the bottom of the Chonggye valley and raise multiple species of domesticated animals, including cattle, sheep, goat, horse, pig, dog, and chicken. In a relatively specialized animal husbandry system, more than 75% of their livestock is composed of sheep and goat (Naidong, 2006, pp. 373-374),
but Bangga villagers also kept yak until recent decades. An ethnographic survey that I conducted in collaboration with archaeologists from Sichuan University and central Tibet local archaeological institutes in 2017 and 2018, revealed that modern central Tibet villagers raise these livestock for varied purposes. Cattle are kept mainly for milk, sheep and goats for milk, wool, and meat, and horses are used for transportation and ploughing. Residents also separate and herd their livestock by grazing requirements. Cattle and horses are fed in close proximity to households with fodder consisting of clover, dog tail grass, and the stems of various crops. Sheep and goat are taken to graze daily to pastures outside the village, the choice of which depends on the seasonal availability of grasses. In summer/fall (June ~ Oct.), when temperatures are warmer, a higher-altitude pasture (~4200 masl) 2.5 km to the north of the village is used. In winter/spring (Nov. ~ May, birth season of sheep and goat at Bangga village) when temperatures are colder and higher elevations are susceptible to frost, people take animals to a lower-altitude pasture (~3800 masl) less than 1 km to the south. Given their different altitudinal and climatic conditions, distinct plant species flourish in different pastures. The main plant food of sheep and goat at the winter pasture are mesothermal xeric grasses and shrubs, such as *Sophora moorcroftian.* The summer pasture is alpine and subalpine steppe, dominated by *Stipa purpurea, Carex* sp., *Pennisetum flaccidum,* and *Artemisia* sp.

1.2.3 Previous Archaeological Studies of Central Tibet and the Bangga Site

The sites of Qugong (~3700~2350 Cal BP) and Changguogou (~3550~2750 Cal BP) are some of the only sites where subsistence related evidence has been so far reported for central Tibet in the Second millennium BC (14C Laboratory of the Archaeological Science and Techniques)
A single faunal assemblage has been analyzed, that from Qugong (Zhou, 1999). To date, qualitative interpretations have been published for this site with quantitative data awaited. Based on large proportions of the Qugong faunal assemblage attributed to yak and sheep, as well as the relatively small body size of Qugong yak, Zhou (1999) argued that the Qugong inhabitants were yak and sheep herders. However, dog and wild animals—which included red deer, musk deer, boar, Tibetan wild ass, and birds—were also reported from Qugong. The relative effort expended on herding and hunting is hard to gauge, however, in the absence of quantitative data. No zooarchaeological studies have been conducted at Changguogou, but paleobotanical analyses from this site revealed that prehistoric central Tibetan inhabitants made use of foxtail millet as well as cereals and pulses that originated in southwest Asia (barley, wheat, and pea) (Fu, 2001).

Figure 1. 1 Location and geography of Bangga (1. Bangga; 2. Changguogou; 3. Qugong; 4. Chusang)

Currently, the excavations at Bangga (Figure 1.2) offer the only opportunity to explore prehistoric central Tibetan animal-based subsistence strategies in depth, complemented by
archaeobotanical investigations. The site of Bangga is located at an altitude of 3800 m a.s.l. on the east side of the Chonggye valley—a broad U-shaped valley that branches to the Yarlung valley to the southwest in central Tibet. The site is named after the modern Tibetan village Bangga, which is located only 50 m to the south of the site. Bangga was discovered and first excavated in 1985 by the archaeological survey team lead by the Cultural Relics Management Committee of the Tibetan Autonomous Region (1986). Subsequent excavations of Bangga were directed by Shargan Wangdue, Linhui Li, and Huimin Zhao between 2000 and 2002 (Li, 2001; Wangdui, 2001) and again in 2015-2018 by Shargan Wangdue and Hongliang Lu (Li, 2001; Lü et al., 2020; Lü et al., 2021). Bangga is an agro-pastoral settlement dated to as early as 3000 Cal BP (Liu et al., 2017; Liu et al., 2016; Lü, 2016). The estimated range of Bangga is over 3000 m², with more than 400 m² excavated to date. The site is composed of irregular stone structures associated with stone-constructed hearths, post holes, and pits dated to around 3000 to 2200 Cal BP. At least one stone structure is likely a corral, in which a large quantity of sheep and goat dung was preserved (Figure 1.2). Over 12,000 well preserved faunal remains have been recovered from Bangga during the field seasons between 2000 and 2002, and between 2015 and 2018 and are the subject of this study. Archaeobotanical studies at Bangga have so far revealed that the Bangga community also practiced farming with six-row hulled barley—a frost tolerant hardy crop—being the primary focus of the cultivation activities. Wheat and buckwheat were also present at the site but in low ubiquity (Tang et al., 2021).
Previous excavators postulated that Bangga was occupied by agro-pastoralists. This is drawn from three lines of evidence: (1) the stone domestic structures at Bangga are similar in shape to those used by contemporary Tibetan pastoralists who practice both livestock husbandry and hunting; (2) Some polished stone tools recovered from Bangga were interpreted as related to crop harvesting and processing; and (3) faunal remains from the site were attributed to sheep and goat (Li, 2001; Region, 1986; Wangdui, 2001). No systematic zooarchaeological study was conducted at that time.
1.2.4 Preliminary analysis of faunal assemblage from Bangga

Prior to this dissertation, I conducted an earlier study of 5772 faunal specimens from Bangga (2760 from excavations in 2000-2002, and 3010 from the 2015 excavation). My initial findings showed that the assemblage is dominated by domesticated sheep and goat, with small proportion of cattle/yak, horse, and fewer hare (*Lepus oiostolus*), pika (*Ochotona* sp.), Tibetan gazelle (*Procapra picticaudata*), musk deer (*Moschus* sp.), and rodents (Table 1.1). This preliminary assessment of the Bangga material provides support for previous hypotheses (Li, 2001; Region, 1986; Wangdui, 2001) that Bangga is occupied by people who kept domestic herd animals.

Analysis of faunal remains from 2016-2018 were interrupted by COVID-19 pandemic. Prior to the pandemic, I sorted all faunal remains from the 2016-2018 field seasons into skeletal elements. My observation confirmed that the taxonomic composition of 2016-2018 faunal assemblage is consistent with that of 2000-2002 and 2015 assemblages. Domesticated sheep and goat are the most abundant taxa, with cattle/yak, horse, hare, pika, musk deer, and rodents also present. In addition, a few bird and fish bones were retrieved.

Table 1.1 Results of preliminary taxonomic identification of faunal assemblage from Bangga

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Common name</th>
<th>2000-2002 excavation</th>
<th>2015 excavation</th>
<th>Total NISP</th>
<th>Total Non-identifiable specimens</th>
<th>Total Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Canis cf. familiaris</em></td>
<td>dog (?)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Equus caballus</em></td>
<td>domesticated horse</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Moschus</em> sp.</td>
<td>musk deer</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Bos</em> spp.</td>
<td>cattle/yak</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Procapra picticaudata</em></td>
<td>Tibetan gazelle</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caprinae</td>
<td>mostly domesticated sheep/goat</td>
<td>196</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Lepus</em> sp.</td>
<td>hare</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-identifiable specimens</td>
<td></td>
<td>2503</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-total</td>
<td></td>
<td>2760</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Moschus</em> sp.</td>
<td>musk deer</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Bos</em> spp.</td>
<td>cattle/yak</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caprinae</td>
<td>mostly domesticated sheep/goat</td>
<td>135</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cricetidae</td>
<td>rodent</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-identifiable specimens</td>
<td></td>
<td>2869</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-total</td>
<td></td>
<td>3010</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total NISP</td>
<td></td>
<td>398</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Non-identifiable specimens</td>
<td></td>
<td>5372</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Specimens</td>
<td></td>
<td>5770</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the following chapters of this dissertation, I employ zooarchaeological and stable isotopic analyses to develop new methods and to address the questions of how environmental challenges described here (Section 1.1) might have threatened the survival of early pastoralists at the high altitudinal regions of the Tibetan Plateau and how early central Tibetan pastoralists managed their livestock to cope with environmental pressures. This research is the first to provide detailed information on animal-based subsistence strategies of early pastoralists on high altitude Tibetan Plateau. This project also contributes to fundamental methods for regional faunal analysis through developing new method for taxonomic identification of local large bovid remains, proposing a new theoretical sheep mortality model for interpreting ancient livestock management strategies on the Tibetan Plateau, and providing a comparative reference set of tooth enamel carbonate stable isotopic data for the south and east Tibetan Plateau and the broader Indian summer monsoon region.

1.3 Dissertation organization

This dissertation uses a three-article format. Besides this introduction chapter, it includes three separate co-authored articles, which I intend to submit to peer-reviewed journals for publication, and a discussion & conclusion chapter. Below I provide information on each chapter.

Chapter 2: Comparative Osteomorphological Criteria for Differentiating Takin (Budorcas taxicolor) from Yak (Bos grunniens), Cattle (Bos taurus), Gaur (Bos gaurus), and Water Buffalo (Bubalus bubalis) using Mandibular Teeth and Post-crania
In this chapter, I consider comparative osteomorphological criteria for distinguishing the mandibular teeth and post-cranial elements of takin (*Budorcas taxicolor*) from those of four Bovidae taxa common in the Tibetan Plateau: yak (*Bos grunniens*), taurine cattle (*Bos taurus*), gaur (*Bos gaurus*), and water buffalo (*Bubalus bubalis*). Through systematic study of a total of 80 mandibles and 68 post cranial skeletal elements of these five species curated across four institutions in China and the United States, this research tested previously published osteomorphological criteria and proposes a set of new criteria. These new insights enable differentiations of closely related large bovids that have habited in the region during the Holocene. The results show that takin can be distinguished from yak, cattle, gaur, and water buffalo using various characteristics of mandibular teeth and post-cranial elements. Such criteria concerning takin has not been previously documented. In providing a reproducible method for distinguishing takin from other large bovids in this region, the osteomorphological criteria established in this study have potential impacts on the future zooarchaeological research in Tibetan Plateau. We draw scholarly attention to aiding in efforts that seek to curb the illegal trade of products made of takin and gaur bones.

This chapter will be submitted to as an invited contribution to a special issue, Effects of Novel Environments on Domesticated Species, in *Frontiers in Ecology and Evolution*. Fan Li and Fiona Marshall are co-authors of this article. Co-author roles: Conceptualization- Z. Zhang, Fan Li, and Fiona Marshall; Data collection- Z. Zhang; Data analysis- Z. Zhang; Writing- Z. Zhang wrote the original draft, Fiona Marshall and Fan Li edited the draft.
Chapter 3: High lamb mortality at Bangga and environmental risks for early herders in Central Tibet, 3000–2200 Cal BP

To address the question about how environmental challenges might threaten the survival of early pastoralists at the high altitudinal regions of the Tibetan Plateau, in this chapter, I reconstruct mortality profile for sheep herd at Bangga, analyzing a relatively large sample of 42 sheep (*Ovis aries*) left mandibles excavated from the site. Our results suggest that most of sheep at Bangga (64.28%, n= 27) died within the first year of their life. This mortality profile resembles Payne’s model of a milk oriented specialized kill-off pattern commonly used by zooarchaeologists. As a result of comparisons of Bangga’s sheep mortality profile with the sheep mortality model simulated in this study, and metadata from local livestock management, and regional ethnographical records, and archaeological evidence from broader area, we argue, however, that high lamb mortality at Bangga more likely reflects natural mortality. This is supported by evidence from the site for environmental risks evidenced by penning, a response to extreme conditions, and associated with crowding and disease. Comparative data also reveal high juvenile mortality at one of the few known early high altitude occupations and not at lower altitude settlements. These findings provide some of the first contextualized evidence for environmental challenges that early pastoralists and their herds experienced during their adaptation to the high Tibetan Plateau.

This chapter is intended for submission to the *International Journal of Osteoarchaeology*.

Hailun Xu, Fiona Marshall, Shargan Wangdue, Xinzhou Chen, Li Tang, Xuan Gao, Jixiang Song, Hongliang Lü, and Xinyi Liu are co-authors of this paper. Co-author roles: Conceptualization- Z. Zhang; Excavation and samples acquisition- Z. Zhang, Shargan Wangdue, Xinzhou Chen, Li Tang, Hailun Xu, Jixiang Song, Xinyi Liu, Hongliang Lü; Data collection- Z.
Chapter 4: Feeding sheep and goat in the second-first millennium BC central Tibet: Insights from stable Carbon and Oxygen isotopic analysis

In this article, I explore herding strategies employed by prehistoric communities who lived in high altitude environments of the Tibetan Plateau using materials from Bangga (c. 3000 - 2100 Cal BP), one of the earliest agropastoralist sites in central Tibet. I analyzed stable carbon and oxygen isotope compositions from sequentially sampled tooth enamel of ten archaeological sheep and goats. In addition, I collected teeth of fourteen extent sheep and goat raised near Bangga and analyzed the enamel specimens in order to establish isotopic baselines for archaeological interpretations. The results show unambiguous evidence of human control over diet and drinking water of domestic sheep and goats at this time in central Tibet. The data suggest that some sheep and goat were provisioned all year around with ground water and both C₃ and C₄ cultigens, likely barley and millet. Other animals show seasonal dietary input with C₄ plants in an almost C₄-free environments due to the altitude effect. This suggests either millet foddering over summers or that the animals were taken to saltmarsh environments. These results demonstrate that unlike present-day pastoralists—who mainly cope with seasonal rangeland resource shortages through seasonal movements between upland and lowland pastures — 3,000 years ago people in this area practiced a different form of herd management involving a more elaborate foddering and watering system. This resonates with the archaeobotanical (and plant isotope) observations from Bangga, indicating that in order to assure year-round food/water
supply in this extreme environment, the prehistoric Bangga community employed a type of strategy that can be characterized as redundancy. Villagers relied on resource diversity to certain extent, but relied on high intensity of labor inputs into targeted resource including sheep/goat and barley.

This chapter is intended for submission to the *Journal of Archaeological Science*. Petra Vaiglova, Shargan Wangdue, Xinzhou Chen, Li Tang, Hailun Xu, Jixiang Song, Hongliang Lü, and Xinyi Liu are co-authors of this paper. Co-author roles: Conceptualization- Z. Zhang and Xinyi Liu; Excavation and samples acquisition- Z. Zhang, Shargan Wangdue, Xinzhou Chen, Li Tang, Hailun Xu, Jixiang Song, Hongliang Lü; Data collection- Z. Zhang; Data analysis- Z. Zhang, Xinyi Liu, and Petra Vaiglova; Writing- Z. Zhang wrote the original draft, Xinyi Liu, Petra Vaiglova, Shargan Wangdue, Xinzhou Chen, Li Tang, Hailun Xu, Jixiang Song, and Hongliang Lü edited the draft.
1.4 References


Ren, L. (2017). *A study on animal exploitation strategies from the late Neolithic to Bronze Age in northeastern Tibetan Plateau and its surrounding areas, China* Lanzhou University.


Chapter 2: Comparative Osteomorphological Criteria for Differentiating Mandibular Teeth and Post-cranial Skeletons of Takin (*Budorcas taxicolor*) from Bovini species on Tibetan Plateau

Zhengwei Zhang, Fan Li, Fiona Marshall

**Abstract:** Domesticated large bovids, including yak (*Bos grunniens*) and cattle (*Bos taurus*) are indispensable to everyday life of present people groups living on the Tibetan Plateau. When and how early people on the Tibetan Plateau begin to make use of domesticated yak and cattle and how cattle, which were initially domesticated in low altitudinal environments, adapted to the new high altitudinal Tibetan Plateau is poorly known. Investigation of these questions is impeded by the difficulty of distinguishing large domestic Bovidae in archaeological sites, from indigenous wild large bovids such as takin (*Budorcas taxicolor*) and gaur (*Bos gaurus*). In this paper, we present comparative osteomorphological criteria for distinguishing the mandibular teeth and post-cranial elements of takin from four large bovids common on the Tibetan Plateau: domesticated yak, taurine cattle, gaur, and water buffalo (*Bubalus bubalis*). Through the comparative and systematic study of a total of 80 mandibles and 68 skeletons representing modern specimens curated across five institutions in China and the United States, this research tested previously published osteomorphological criteria and proposes a set of new criteria for differentiating large bovids from the Tibetan Plateau. The results show that takin can be easily differentiated from yak, cattle, gaur, and water buffalo using characteristics of mandibular teeth and post-cranial elements. In providing a reproducible method for distinguishing takin from
other large bovids in this region, the osteomorphological criteria established in this study will be important to future archaeological investigations on early usage of domesticated yak and cattle on the Tibetan Plateau, in addition to aiding in efforts that seek to curb the illegal trade of products made of wild Bovidae bones.

2.1 Introduction

Hunting and herding of large bovids has played a significant role in recent human survival at high altitudes on the Tibetan Plateau (Chen et al., 2020; Cheng et al., 1984; Dong et al., 2016; Goldstein & Beall, 1990; Ren, 2017; Wang et al., 2020; Wang, 2017; Zhang, 2016; Zhang et al., 2019). However, we know little about past human relations with iconic plateau animals, such as yak (*Bos grunniens* Linnaeus, 1766) or takin (*Budorcas taxicolor* Hodgson, 1850). As a browser, takin (also known as “cattle chamois”, Order Artiodactyla, Family Bovidae, Subfamily Caprinae) have a broad range across the plateau and are adapted to forests, shrublands and subalpine meadows between 1000-5000 m a.s.l. (Castelló, 2016; Song et al., 2008) (Table 1). Best documented in the northwest and southeast Tibetan Plateau and Himalayan regions during the historic period, Takin migrate seasonally between high (> 2500 m a.s.l.) and low altitude areas primarily for food, but also to visit salt licks (Wu et al., 1990; Zeng et al., 2008). Takin have been widely hunted in recent centuries for meat, hides, as well as for trade and for social and ritual purposes (Aiyadurai et al., 2010; Chen et al., 2020; Feng et al., 1986: p.234; Guo, 2004; Rao et al., 2011). Ethnographic records make it clear that people of the southeast Tibetan Plateau and Himalayan regions have had a long history of interactions with wild takin and know its behavior well. Active in relatively big herds of 10 to 50 individuals, takin could create obvious paths during their regular seasonal
migrations. This made takin more readily tracked and successfully hunted. Several studies record mass hunting, with sometimes more than ten takin individuals trapped at one time (Guo, 2004; Wu et al., 1990, pp. 77-88). Large bovids remains have been frequently discovered from archaeological sites on the Tibetan Plateau (e.g. Dong et al., 2016; He & Chen, 2006; Huang & Leng, 1985; Zhang et al., 2019) but evidence relevant to the use of takin by past people on the Tibetan Plateau is rather scarce (Dong et al., 2016). This is due, in part, to the difficulty of taxonomic identification of large bovid bones excavated from sites on the Tibetan Plateau and specific challenges of differentiating takin from other relatively large bovids with overlapping distributions. Although members of the Caprinae subfamily, due to their size, takin can be confused with large bovids including wild yak (Bos mutus Przewalski, 1883), domesticated yak, cattle (Bos taurus Linnaeus, 1758 and Bos indicus Linnaeus, 1758), gaur (Bos gaurus Smith, 1827), gayal/mithan (domesticated/semi-domesticated gaur, Bos frontalis Lambert, 1804), wild water buffalo (Bubalus arnee Kerr, 1792), and domesticated water buffalo (Bubalus bubalis Linnaeus, 1758) (Table 2.1 and Figure 2.1).

Recent application of promising biomolecular methods (i.e. ZooMS and ancient DNA analyses) have contributed to taxonomic identification of archaeological faunas and been particularly useful in analysis of fragmentary or indeterminate specimens. Sampling for these studies is still reliant, however on baseline osteomorphological taxonomic analyses, which characterize variation (e.g. taxonomic, body part, taphonomic) in large zooarchaeological assemblages. Osteomorphological analysis are irreplaceable in field zooarchaeological studies, nondestructive, portable, and no/low-cost. However, building research scaffolds for baseline osteomorphological analyses of wild taxa of the Tibetan Plateau is challenging. Due to over-hunting large wild bovids are vulnerable or even threatened with local extinction in the region (Buzzard & Berger, 2016; Duckworth et al., 2016; Kaul et al., 2019; Song et al., 2008) and
necessary conservation restrictions on collecting skeletal remains make it difficult for regional institutes to build comparative reference collections of wild Tibetan mammals. To lay the foundation for regional zooarchaeological research, and to create a baseline for further biomolecular analyses, studies are needed of the comparative osteomorphology of large bovids from the Tibetan Plateau held in varied global museum and research institute collections.

Figure 2. Approximate distributions of extant large Bovids of the Tibetan Plateau and vicinity. Data from: Buzzard & Berger, 2016; Duckworth et al., 2016; Gilbert et al., 2018a, 2018b; Kaul et al., 2019; Simoons, 1968; Song et al., 2008; Zhang, 1989. Cattle are found throughout the region.

This research builds on the few previous studies that mention osteomorphological characteristics for distinguishing cranial and a few post-cranial skeletal elements of takin from other members of the bovini (e.g. Gentry, 1992; Lydekker, 1907; von den Driesch, 1995; Vrba & Schaller, 2000; Wu et al., 1990). These have shown high potential for differentiating varied large
bovids on the Tibetan Plateau, but more comprehensive studies are needed that include takin and other taxa and larger sample sizes (see: Lyman, 2019). In this paper, we present comparative osteomorphological criteria for distinguishing takin mandibular teeth and post-cranial skeletons from four regionally common Bovini species: yak, taurine cattle, gaur, and water buffalo. We pooled and tested previously published osteomorphological criteria for differentiating closely related regional large bovids and proposes a set of new criteria through systematic study of 80 mandibles and 68 skeletons of modern takin, yak, gaur, and water buffalo at five institutes in China and United States (Table 2.2 and Appendix 1).

Table 2.1 Body size and habitat information for large Bovidae of the Tibetan Plateau and Himalaya.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Latin name</th>
<th>Body size and weight*</th>
<th>Altitudinal range of habitats</th>
<th>Habitat types</th>
<th>Geographic range on the Tibetan Plateau</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takin</td>
<td>Budorcas taxicolor</td>
<td>BL: 170–220 cm. SH:100–140 cm. Wt.: 150–350 kg.</td>
<td>1000 – 4000 m asl</td>
<td>Forest, shrubland, grassland</td>
<td>South and southeastern Tibetan Plateau</td>
<td>(Castelló, 2016; Song et al., 2008)</td>
</tr>
<tr>
<td>Wild yak</td>
<td>Bos mutus</td>
<td>BL: 220–385 cm. SH: 130–200 cm. Wt.: 535–1000 kg.</td>
<td>3000 – 6100 m asl</td>
<td>Grassland, desert</td>
<td>– the whole plateau</td>
<td>(Buzzard &amp; Berger, 2016; Castelló, 2016; Feng et al., 1986)</td>
</tr>
<tr>
<td>Yak</td>
<td>Bos grunniens</td>
<td>BL: 145–218 cm. SH: 106–129 cm. Wt.: 197–593 kg.</td>
<td>2000 – 5000 m asl</td>
<td>Grassland, desert</td>
<td>– the whole plateau</td>
<td>(Huang et al., 1981; Shi et al., 2010)</td>
</tr>
<tr>
<td>Gaur</td>
<td>Bos gaurus</td>
<td>BL: 250–330 cm. SH: 170–220 cm. Wt.: 700–1000 kg.</td>
<td>0 – 2800 m asl</td>
<td>Forest, savanna, grassland</td>
<td>Southeast Tibetan Plateau</td>
<td>(Castelló, 2016; Duckworth et al., 2016)</td>
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<tr>
<td>Mithan/gayal</td>
<td>Bos frontalis</td>
<td>BL: 250 cm. SH: 120–170 cm. Wt.: 350–560 kg.</td>
<td>0 – 3000 m asl</td>
<td>Forest, savanna, grassland</td>
<td>Southeast Tibetan Plateau, Southern slope of Himalaya Mountains</td>
<td>(Castelló, 2016; Simoons, 1968)</td>
</tr>
<tr>
<td>Taurine cattle</td>
<td>Bos taurus</td>
<td>BL: 110–124 cm. SH: 96–106 cm. Wt.: 170–201 kg.</td>
<td>0–4500 m asl</td>
<td>Grassland, desert</td>
<td>– the whole plateau, except north Tibet</td>
<td>(Huang et al., 1981; Shi et al., 2010)</td>
</tr>
<tr>
<td>Zebu cattle</td>
<td>Bos indicus</td>
<td>BL: 150–250 cm. SH: 86–106 cm. Wt.: 150–200 kg.</td>
<td>0– at least 3400 m asl</td>
<td>Grassland, wetlands, forest, woodland</td>
<td>Southern slope of Himalaya Mountains, Southeast Tibetan Plateau</td>
<td>(Castelló, 2016; Huang et al., 1981)</td>
</tr>
<tr>
<td>Domesticated Water buffalo</td>
<td>Bubalus bubalis</td>
<td>BL: 240–300 cm. SH: 133–142 cm. Wt.: 450–1000 kg.</td>
<td>0 – 5000 m asl</td>
<td>Grassland, wetlands, forest, woodland</td>
<td>Southern slope of Himalaya Mountains, Southeast Tibetan Plateau</td>
<td>(Castelló, 2016; Epstein, 1977)</td>
</tr>
<tr>
<td>Asian wild water buffalo</td>
<td>Bubalus arnee</td>
<td>BL: 240–300 cm. SH: 150–190 cm. Wt.: 700–1200 kg.</td>
<td>0 – 1500 m asl</td>
<td>Grassland, wetlands, forest, savanna</td>
<td>Southern slope of Himalaya Mountains</td>
<td>(Castelló, 2016; Kaul et al., 2019)</td>
</tr>
</tbody>
</table>

Note: *BL=Body length, SH=Shoulder height, Wt=Weight.
2.2 Methods and materials

The baseline for this study was provided by review of previously published osteomorphological criteria for differentiating takin from other large bovid, including domesticated yak (Vrba & Schaller, 2000), cattle (Wu et al., 1990), and European bison (*Bison bonasus*) (Gentry, 1992). Criteria from the global osteological literature on differentiation among bovids and the Bovini following paleontological and zooarchaeological perspectives (e.g. Balkwill & Cumbaa, 1992; Gee, 1993; Higham, 1975; Lawrence, 1951; Olsen, 1960; Peters, 1986; von den Driesch, 1995) that might be useful for Tibetan taxa were also considered.

We studied mandibular teeth and post-cranial skeletal elements of modern takin (18 mandibles and 4-13 skeletons), domesticated yak (18 mandibles and 13-35 skeletons), gaur (15 mandibles and 6 skeletons), cattle (19 mandibles and 17-22 skeletons), and water buffalo (14 mandibles and 7-9 skeletons) at the American Museum of Natural History (AMNH), the National Museum of Natural History at the Smithsonian Institution (NMNH), the Field Museum (FMNH), the Henan Provincial Institute of Cultural Heritage and Archaeology (Henan), and the Shaanxi Provincial Institute of Archaeology (Shaanxi) (Appendix 1). Specimens were mostly historic, collected during the 19-20th Centuries. Taxonomies are debated for many of the taxa studied but here we follow zooarchaeological convention (Gentry et al., 2004) for domestic taxa, and the International Commission on Zoological Nomenclature. The strength of this sample is that it represents a significant portion of known world holdings for Tibetan taxa. Weaknesses are, that some elements are better represented than others (Table 2.2). We sampled all possible specimens, working with what was available samples are adequate though not extensive. Although we focused on wild caught or shot animals, without destructive ancient DNA testing
(which is currently not possible), undetected hybridization could also not be ruled out. This is an issue encountered by most scholars of Bovid osteomorphology (Marshall per com. 2020). As a result, the goal of the study was to identify clear trends that are evident in the sample as a whole.

In terms of anatomical nomenclature used, we primarily follow Gentry (1992), palaeontological convention, and the *Nomina Anatomica Veterinaria* (2017). We started by systematically comparing a few (one ~ two) specimens from each species—complying with the limitations of different institutions regarding how many specimens could be taken out from cabinets at one time—to create a set of pilot criteria (two to nine distinguishable characters) that would allow discrimination of each takin element from elements of other taxa including yak, cattle, and gaur. We then examined all remaining specimens to interrogate pilot criteria.

Twenty two elements were studied for each taxon, excluding only the cranium, ribs, some post-cervical vertebra, and phalanges. We included most carpals and tarsals because these small dense bones are often recovered in sites, have a history of successful discrimination among bovids but are often excluded from identification studies. Metric data was collected on all measurable specimens following Von den Driesch (1976). Our notation system for pilot criteria was straightforward, designed to recognize clear results rather than degrees. To synthesize our observations, we used quantification tools introduced by Hanot and Bochaton (2018). These include: the Number of Observations (N Obs), the Number of Attributions (NA), the Number of Correct attributions (NC), the Percentage of Assessment (PA=NA/N Obs*100, reflects the difficulty of defining the certain character clearly and the variability of the criterion), and the Correct Identification Rate (CIR=NC/NA*100, reflects the reliability of the criterion). In this paper we report only criteria with total PA and CIR both higher than or equal to 80%.
Table 2. Number of examined elements that exhibited reliable identification characteristics

<table>
<thead>
<tr>
<th></th>
<th>Takin</th>
<th>Yak</th>
<th>Cattle</th>
<th>Gaur</th>
<th>Water buffalo</th>
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<tr>
<td></td>
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<td>♂</td>
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<td>♂</td>
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<tr>
<td></td>
<td>Subtot al</td>
<td>U</td>
<td>Subtot al</td>
<td>U</td>
<td>Subtot al</td>
<td>U</td>
</tr>
<tr>
<td>Mandible</td>
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<td>1</td>
<td>2</td>
<td>0</td>
<td>18</td>
<td>2</td>
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<tr>
<td>Scapula</td>
<td>3</td>
<td>1</td>
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<td>6</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Humerus</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Scaphoid</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>10</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Lunate</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>10</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Magnum</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>11</td>
<td>2</td>
<td>6</td>
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<tr>
<td>Metacarpal</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>15</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Tibia</td>
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<td>1</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Fibula</td>
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<td>1</td>
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<td>2</td>
<td>6</td>
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<tr>
<td>Astragalus</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td>2</td>
<td>6</td>
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<tr>
<td>Cuboid-Navicular</td>
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<td>7</td>
<td>1</td>
<td>13</td>
<td>2</td>
<td>6</td>
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<tr>
<td>Metatarsal</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>14</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

2.3 Results

We found reliable criteria (with two to seven distinguishable characters) for mandibular teeth and eleven postcranial elements: scapula, humerus, radius, magnum (carpale II+III), unciform (carpale IV), lunate (carpi intermediate), scaphoid (carpi radiale), metacarpal, femur, tibia, fibula (malleolus lateralis), metatarsal, navicular-cuboid (centroquartale), and calcaneus, astragalus. We did not find reliable identification criterion for ulna, cuneiform (carpae ulnare), and patella examined in this study. There were only three atlas and four axis specimens available in collections we visited so these two elements were excluded in this study. Here we describe the most robust criteria.
Mandibular teeth (Figure 2.2)

TE1. The buccal outlines of lower molars (NObs=75, PA=99%, CIR=100%): In occlusal view, the outlines of the buccal side of takin molars are more pointed (as shown in landmark TE1 in fig 2) (NObs of takin=23, PA=96%, CIR=100%) than Bovini species, which are more bowed or rounded (fig 2) (NObs of Bovini=52, PA=100%, CIR=100%).

TE2. The Lower Fourth Premolar (NObs=70, PA=86%, CIR=100%): The metaconid of takin (NObs of takin=23, PA=96%, CIR=100%) joins or almost joins the paraconid and form a closed rectangle but is open on P4 of Bovini species (NObs of Bovini =47, PA=81%, CIR=100%).

TE3. The lower Third Premolar (NObs=74, PA=97%, CIR=99%): Metaconid and paraconid of P3 of takin forms a restricted “U” shape (NObs of takin=23, PA=96%, CIR=95%) but form an open “V” shape on Bovini species (NObs of Bovini =51, PA=98%, CIR=100%).
Figure 2. 2 Mandibular teeth of takin and Bovini (*Bos grunniens* on the figure)

**Scapula (Figure 2.3)**

SC1. A medial notch is present in the lateral border of the glenoid cavity in the four Bovini species but absent in takin (NObs=77, PA=87%, CIR=96%). This characteristic has previously been proposed by Peters (1986) for distinguishing *Bos primigenius f. taurus* and *Syncerus caffer*.

SC2. The outline of glenoid cavity is more oval in four Bovini species but more rounded in takin (NObs=77, PA=97%, CIR=100%).

SC3. The lateral border of glenoid cavity and the coracoid process in takin are continuous but are discontinuous in four Bovini species (NObs=77, PA=100%, CIR=100%).
HM1. The proximal border of greater trochanter exhibits a more flared single notch in takin than in four Bovini species (NObs=52, PA=88%, CIR=91%).

HM2. The posterior border of medial condyle is flat in takin but is curved in four Bovini species (NObs=56, PA=100%, CIR=100%).

Lunate (Figure 2.5)

LN1. In view of articular surface for scaphoid, two distal small articular facets are much reduced in takin than on four Bovini species (NObs=58, PA=100%, CIR=79%).

LN2. In distal view, the outline of distal articular facet in is more rectangular in takin but more irregular in four Bovini species (NObs=59, PA=100%, CIR=100%).

**Scaphoid (Figure 2.6)**

SP1. In view of the articular surface for the lunate, distal small articular facets are much reduced in takin and only cover the anterior end. The same articular facets are more prominent in four Bovini species.
Budorcas taxicolor  

Bos grunniens

Figure 2. 6 Scaphoid of takin and Bovini (Bos grunniens on the figure)

Magnum (Figure 2.7)

MG1. In proximal view, a deep depression is present on the posterior border of medial articular facet in takin but nearly absent in four Bovini species (NObs=62, PA=100%, CIR=98%).

MG2. In posterior view, the proximal articular facet is much reduced in takin. The proximal articular facets are farther extended distally on four Bovini species (NObs=62, PA=87%, CIR=89%).

Metacarpal (Figure 2.9)

MC1. The overall shape of the takin metacarpal is the stoutest in all five species (Figure 2.8). This character has been previous described by Wu et al. (1990) as characteristic for distinguishing takin and cattle, and by Vrba and Schaller (2000) as characteristic for distinguishing takin and yak (NObs=63, PA=100%, CIR=100%).
Figure 2. 8 Comparison of measurements of metacarpal of takin and Bovini species

MC2. The notch between proximal articular facets is much reduced or nearly absent in takin compared to the four Bovini species (NObs=62, PA=98%, CIR=93%).

MC3. The anterior longitudinal groove is much shallower in takin than in the four Bovini species (NObs=62, PA=97%, CIR=95%).

MC4. In posterior view, the projection of trochlea is considerable farther extended in takin than in four Bovini species (NObs=65, PA=97%, CIR=100%).

Tibia (Figure 2.10)

TB1. The craniolateral notches in takin are much more restricted than in four Bovini species (NObs=52, PA=81%, CIR=88%).

TB2. The caudolateral border of the lateral condyle in takin is flat but is curved in four Bovini species (NObs=55, PA=98%, CIR=98%).
Figure 2. 10 Tibia of takin and Bovini (Bos taurus on the figure)

Malleolus lateralis (Figure 2.11)

ML3. In lateral view, the anterior and posterior borders on malleolus lateralis of takin form a more flared outline than on four Bovini species (NObs=53, PA=96%, CIR=82%).
Figure 2. 11 Malleolus lateralis of takin and Bovini (\textit{Bos grunniens} on the figure)

\textbf{Cuboid-Navicular (Figure 2.12)}

CN1. The length of the articular facet for calcaneum in takin is much shorter than in four Bovini species (NObs=68, PA=99\%, CIR=100\%).
Figure 2.12 Navicular-Cuboid of takin and Bovini (*Bos grunniens* on the figure).

Metatarsal (Figure 2.14)

MT1. The overall shape of metatarsal of takin is the stoutest among all five species (NObs=63, PA=100%, CIR=100%) (Figure 2.13).
Figure 2. 13 Comparison of measurements of metatarsal of takin and Bovini species

MT2. The anterior longitudinal groove is much shallower in takin than in four Bovini species (NObs=64, PA=100%, CIR=98%).
MT3. In posterior view, the projection of trochlea is considerable farther extended in takin than in four Bovini species (NObs=63, PA=100%, CIR=100%).

![Image of metatarsal bones](image)


### 2.4 Discussion and conclusion

Wild and domesticated large bovids, such as takin, gaur, yak, and cattle, have been important for the survival of people on high altitude Tibetan Plateau and Himalaya region, as emphasized by ethnographical records (e.g. Gele et al., 2002; Goldstein & Beall, 1990; Schaller, 2000, pp. 284-323; Simoons, 1968; Wu et al., 1990). But the time depth of these relationships is not well understood. Zooarchaeological evidence regarding when and how early pastoralists on
the Tibetan Plateau began to make use of domesticated yak and cattle, and how they utilized large wild members of the family Bovidae is also sparse. Zooarchaeological investigations have been impeded by the difficulty of taxonomic identification of excavated and often fragmentary archaeological large bovid remains from the Tibetan Plateau, where osteomorphological criteria for distinguishing skeletal elements of local mammal taxon have been barely established. In this study we propose the first comprehensive osteomorphological criteria for identifying teeth and post-cranial elements of takin, which were widely hunted by hunters on the Tibetan Plateau and Himalayan region and for differentiating them from four large bovids that were commonly present in the region.

Complete and fragmentary takin skeletal elements can be readily differentiated from elements of the yak, cattle, gaur, and water buffalo using characteristics described in this paper. Twenty-two new characteristics for distinguishing takin skeletal elements from Bovini species on Tibetan Plateau include: TE1, TE2, and TE3 on mandibular teeth; SC1, SC2, and SC3 on scapula; HM1 and HM2 on humerus; LN1 and LN2 on lunate; SP1 on scaphoid; MG1 and MG2 on magnum; MC2, MC3 and MC4 on metacarpal; TB1 and TB2 on Tibia; ML1 on fibula (malleolus lateralis); CN1 on cuboid-navicular; MT2 and MT3 on metatarsal. We also examined two characteristics that were previous suggested as useful for distinguishing takin from other large bovids, including MC1 for metacarpal and MT1 for metatarsal. Our results confirmed the reliability of these characteristics for distinguishing takin from all four Bovini species examined. Other characteristics described by previous studies that could be used to distinguish teeth and postcranial skeletons of takin from Bovini species were not systematic assessed in this study due to limited sample size of some elements, conditions of some specimens (e.g. mounted or pathological), and the permitted and affordable amount of time that we could stay at each
collection. Those undoubted worth future attention include five characteristics mentioned by Vrba and Schaller (2000, pp. 203-222), that have potential to distinguishing takin element from domesticated yak: (1) Basal pillars on lower molars are absent on takin but present on yak; (2) The anterior and posterior extremities of central enamel cavities of lower molars are narrow and pointed without central constriction or of simple shape on takin, but are moderately rounded with an approach to central constriction on yak; (3) The hollow at the top of the posterior surface of the metatarsal is reduced on takin, but not reduced on yak; (4) Mediolateral compression of the metatarsal shaft is reduced on takin, but not reduced on yak; (5) The flanges distally on the anterior metatarsal are reduced on takin, but not reduced on yak.

In conclusion, this study provides a reproducible method for distinguishing takin from other large bovids in this region. The osteomorphological criteria established here hold great promise for future archaeological investigations of changing hunting patterns through time and across the Tibetan Plateau. Success in distinguishing takin, which were known as a common prey of recent local hunters, as mentioned by ethnographies (e.g. Guo, 2004; Wu et al., 1990), from other large bovids in this region will also facilitate studies of early usage of domesticated cattle and on the Tibetan Plateau and yak domestication. Beyond their application in archaeology, our study will contribute to conservation of threatened species. Over-hunting has been one of the main threats for survival of takin, who’s population are in decreasing and have been listed as vulnerable by IUCN (Song et al., 2008). Identifying products made of takin skeletal elements from wildlife markets is important to curb the illegal trade of takin products. Nondestructive method proposed by our study can be readily applied to identify products made of takin from domesticated cattle, yak, and water buffalo.
2.5 References


Duckworth, J. W., Sankar, K., Williams, A. C., Samba Kumar, N., & Timmins, R. J. (2016). *Bos gaurus*.


Ren, L. (2017). *A study on animal exploitation strategies from the late Neolithic to Bronze Age in northeastern Tibetan Plateau and its surrounding areas, China Lanzhou University*.


Wang, Y. (2017). *Identifying the beginnings of Sheep Husbandry in Western China* University of


Chapter 3 High lamb mortality at Bangga and environmental risks for early herders in Central Tibet, 3000–2200 Cal BP

Zhengwei Zhang, Hailun Xu, Shargent Wangdue, Xinzhou Chen, Li Tang, Xuan Gao, Jixiang Song, Hongliang Lü, Xinyi Liu, Fiona Marshall

Abstract: Pastoralism has a long history of resilience on the extreme high altitude Tibetan Plateau. However, the specific risks faced by early flocks on the Plateau and ways that herders managed their animals to mitigate these have not been well explored. Dated to the first millennium BC, the archaeological settlement of Bangga represents one of the early agro-pastoral communities in high altitude central Tibet, offering a rare opportunity to examine these issues. Mortality profiles have been a powerful tool for reconstructing livestock herding strategies from archaeological sites. Here, we used dental eruption and wear to reconstruct sheep mortality profiles from early levels at Bangga. In order to contextualize archaeological livestock mortality data from Tibetan Plateau we also simulated sheep natural mortality levels using data for recent Tibetan herders. The mortality profiles from Bangga revealed that 64.28% (n= 27) of the sheep died within the first year of their life. In a case of equifinality, this profile is consistent with Payne’s Anatolian models for specialized management for milk. However, our data show that the same profile may also be the product of low culling levels and high natural lamb death rates. Herd mortality metadata from Tibet and simulations suggest that within this high-risk context, specialization is a less probable interpretation than environmentally-driven lamb mortality. Contextual archaeological and isotopic data for corralling and foddering at Bangga indicate specific ancient disease and nutritional risks associated with periodic confinement and
lack of access to pasture. Comparison with sites from other regions of the plateau and its vicinities document similar high mortality at Shidaqiu, but not at lower elevations, drawing attention to high altitude risk. Together, these findings indicate that high juvenile mortality presented a threat for ancient herders who suffered from serious environmental pressures on the Tibetan Plateau.

Keywords: archaeofaunal mortality profile, pastoralism, Tibetan Plateau, zooarchaeology

3.1 Introduction

Pastoralism has a long history of resilience on the Tibetan Plateau with recent archaeological evidence dates development of agro-pastoralism in the region to the mid Second millennium BC and reliance on introduced animals including sheep (*Ovis aries*), goat (*Capra hircus*), horse (*Equus caballus*), and taurine cattle (*Bos taurus*) and the Tibetan Plateau domesticate yak (*Bos grunniens*) as well as cultivation. Current zooarchaeological and archaeobotanical data suggests that the early agro-pastoralists of the northeastern, southern, and western Tibetan Plateau depended on sheep and other herd animals and cereal cultivation with varying degree of dependence on wild resources (Chen et al., 2015; d’Alpoim Guedes et al., 2013; Dong et al., 2016; Fu, 2001; Fu, 2008; Lü, 2016; Song et al., 2017; Tong et al., 2015; Tong et al., 2014; Zhang & Lü, 2017; Zhang et al., 2015; Zhou, 1999). The time and routes of movements of crops and animal domesticates are increasingly well documented, with sheep appearing in central Tibet no later than 3500 cal BP (Gao et al., 2021; Zhou, 1999). Less is known about the response of introduced animals like sheep and goat to the high altitude plateau environments, and the ways in which that herders managed their flocks in those challenging conditions.
Mortality profiles have long been a powerful tool for reconstructing livestock herding strategies from archaeological sites and archaeologists have drawn attention to contrasting patterns indicative of generalized and more specialized strategies, with high juvenile culling usually taken as an indication that herds were managed for milk or meat (e.g. Payne, 1973; Vigne & Helmer, 2007). Environmental pressures confronted by early herders and their flocks on the Tibetan Plateau have been highlighted, however, in a pioneering study conducted at the site of Shidaqiu on the eastern rim of the Tibetan Plateau. He et al. (2012) reported on unusually high kid death (81.25% of 16 goat mandibles) (~2500 m a.s.l., ~ 220 BCE - AD 220). The researchers relate this unusual patterning to unpredictable external challenges, such as disease and/or seasonal fodder shortage during winter. Ultimately, herders survived on the Tibetan Plateau, but this research has emphasized the need for further investigation of development of resilient pastoral strategies on the plateau. Such understanding can be achieved through studies of larger faunal assemblages from high elevations and examination of management strategies and herd survivorship. To date, most archaeological faunal assemblages from high altitude environments (>3500 m asl) are derived from burial contexts (e.g. Tong et al., 2015; Tong et al., 2014; Zhang et al., 2015). We lack zooarchaeological records that represent non-mortuary contexts and systematic excavations of settlements are rare in the Tibetan Plateau (Aldenderfer & Moyes, 2004; Aldenderfer & Zhang, 2004; Institute of Archaeology & Bureau of Cultural Relics, 1999; Lü, 2007).

Bangga (~ 3800 m a.s.l), an agro-pastoral settlement dating to c. 3000–2200 cal. BP, represents one of the early such communities in high altitude central Tibet (Figure 3.1). The large faunal assemblage preserved at the site provides a unique opportunity for systematic exploration of how early pastoralist herding systems and animal management developed in the
challenging novel environments of central Tibet. People at Bangga cultivated barley and wheat and relied on domestic herd animals including sheep and goat, with some horses, cattle/yak (Lü et al., 2021; Tang et al., 2021). In this study, we explore ancient herd management strategies on the Tibetan Plateau and their relationship to the degree of environmental pressure confronted by the early pastoralists on the high altitudinal Tibetan Plateau through an examination of archaeological sheep mortality profile at Bangga.

Mortality profiles of livestock in archaeological sites provide a direct indication of how people managed and exploited their livestock in ancient pastoral and agricultural systems. Interpretations of archaeological age profiles have been informed by theoretical expectations and empirically based models of culling patterns, such as Payne’s (1973) pathbreaking characterizations of milk, meat, or wool oriented management based on ethnographic data from Turkish herders. Specialized pastoral production has been identified in early pastoral settlements in central and east Asia (e.g. Ananyevskaya et al., 2021; Li et al., 2014; You et al., 2016). However, research has also shown that other factors, notably natural mortality, are capable of producing archaeological mortality profiles similar to those expected for specialized culling (Boschin, 2020; Cribb, 1984, 1987; Greenfield et al., 1988; Halstead, 1998; Kelly, 1985; Marciniak, 2014; Mutundu, 2005). As a result, Sasson and Greenfield (2014) have drawn attention to the need for consideration of local ethnographical and ethological information and use of regionally grounded models (e.g. Dahl & Hjort, 1976; Payne, 1973; Redding Jr, 1981; Shahrani, 2002, pp. 87–117; Vigne & Helmer, 2007). To date, such approaches are not widespread, but this is particularly important for analysis of populations living in the extreme conditions like the Tibetan Plateau where natural loss of livestock can be very high due to altitude and climatic stresses. To interpret mortality profiles in high altitude Tibetan Plateau at
the site of Bangga in this paper we complement analysis of archaeological sheep mortality profiles at Bangga with collection of ethnographic and historic data on herd management and natural mortality in Tibet and develop locally grounded simulation models for sheep mortality profiles.

Figure 3.1 Locations of archaeological sites mentioned in this chapter
3.2 Background

3.2.1 Environmental challenges for survival of small bovids on the Tibetan Plateau

Grasslands cover nearly 70% of the land area of Tibet, making pastoralism the most important subsistence strategy of Tibetan people today, with reliance on sheep, goat, yak, cattle, and horses and herding strategies integrated with cultivation and trade (Cheng et al., 1984, pp. 33-71). With an average altitude of 4320 m a.s.l., however, the Tibetan Plateau presents challenges in the for pastoralists due to highly seasonal pasture resources, prolonged frosts (-13.4 ~ 5 °C during the winter and spring), and unpredictable extreme weather events (Song et al., 2013, pp. 44-61; Zhang et al., 2021). Survival on the Tibetan Plateau is challenging for wild and domestic small bovids, particularly young individuals. High level of natural juvenile mortalities are frequently recorded in zoological surveys of wild small bovids on the Tibetan Plateau and Himalayan region. For example, Schaller (2000, pp. 94-108) reports that as many as 27-58% of blue sheep (*Pseudois nayaur*) herds died on the Tibetan Plateau between birth and two years old due to malnutrition, disease, and predation. Similar high juvenile mortality of ~50-60% has also been observed among Kashmir markhor (*Capra falconeri*) in the Himalaya region (Schaller, 1977, pp. 127-137). For small bovids living in these regions in general, snowstorms and other extreme weather during calving season and the first winter seem to be particularly dangerous to neonates. Approximately 50% of neonatal Tibetan antelope (*Pantholops hodgsoni*) have been reported to have died within two months after birth (Schaller, 2000, pp. 41-79). The environmental factors that threaten survival of wild young small bovid also threaten survival of domesticated lamb and
kid on the Tibetan Plateau. According to ethnographical and historic records on livestock of recent Tibetan pastoral communities, lambs and kids are susceptible to low temperature, extreme weather, and epidemic animal diseases (Cheng et al., 1984, pp. 50-51; Guo et al., 2018; Huber, 2005, 2012; Miller, 2000; Shahrani, 2002, pp. 87–117; Xin & Chen, 2013). Even with modern husbandry technology (e.g. stabling, veterinary care), lambs and kids from a whole area can be completely decimated by a serious snowstorm (City, 2004, p. 68). These regional environmental circumstances suggest that previous widely used zooarchaeological theoretical sheep/goat mortality models (e.g. Dahl & Hjort, 1976; Payne, 1973; Redding Jr, 1981; Vigne & Helmer, 2007) generated from husbandry systems in less extreme environments might underestimate the contribution of natural killed lambs and kids in regional archaeological mortality profiles. To evaluate ancient strategies of herd management on the Tibetan Plateau and natural pressures that early herders confronted in the region we develop locally grounded models based on regional ethnographic and historic data on herd management and natural mortality among Tibetan pastoral communities.

3.2.2 Central Tibet and excavations at Bangga

Central Tibet is one of the cultural and economic centers of the Tibetan Plateau. Despite rich historic records with regards to regional economy in historical periods (e.g. Wang & Chen, 2014, pp. 111-199), there are only two published sites, Qugong (~3700~2350 Cal BP) and Changguogou (~3550~2750 Cal BP), which provide insights into prehistoric subsistence (14C Laboratory of the Archaeological Science and Techniques Experiment and Research Center, 1996; Fu, 2001; Gao et al., 2021; He, 1994; Institute of Archaeology & Bureau of Cultural Relics, 1999; Liu & Zhao, 1999; Liu et al., 2017; Liu et al., 2016; Lü, 2016). Qugong is the only
site with published faunal information (Zhou 1999). Based on a high quantity of sheep bones and and small sized yak bones, Zhou (1999) argued that the Qugong’s inhabitants were yak and sheep herders who also hunted (e.g. red deer, musk deer, boar, Tibetan wild ass, and birds).

Named after a nearby village, the site of Bangga (3800 m a.s.l.) is located at the edge of an alluvial fan in the Qonggyai valley at the foothill of a mountain that goes up to 4800 m a.s.l. Under the influence of the Indian Ocean summer monsoon, rainfall in this area is concentrated between June and September, making drought a serious threat to local agricultural and pastoral production in the rest of year. In addition, catastrophic events such as thunderstorms and flooding occur frequently in the summer, whereas frosts and snowstorms present serious hazards in the winter (L. C. C. C. o. t. C. County, 2010, pp. 91-95; Sun et al., 2021).

The archaeological settlement of Bangga was discovered and first excavated in 1985 by a team lead by the Cultural Relics Management Committee of the Tibetan Autonomous Region (1986). Subsequent excavations of Bangga were conducted between 2000 and 2002 (Li, 2001; Wangdui, 2001) and again in 2015-2018 (Li, 2001; Lü et al., 2020; Lü et al., 2021). The estimated size of the site is over 3000 m², with more than 400 m² excavated to date. The stratigraphy of Bangga could be divided into two phases (early phase, 3000–2200 cal BP and late phase 2200 cal BP to the modern era) (Lü et al., 2021). Only a few artifacts and faunal and botanical remains were retrieved from the late phase. This research focuses on the early phase. Common features in the early phase include irregular stone structures associated with stone installations such as hearths, post holes, and pits dated to around 3000 to 2200 cal. BP (Liu et al., 2017; Liu et al., 2016; Lü, 2016; Lü et al., 2021). Features were likely parts of dwellings with attached areas devoting for livestock. An extensive livestock corral (>15m by 5m) containing a
large quantity of dung pellets distinctive of sheep and goat was documented adjacent to structures on the south side of the site (Figure 3.2).

Figure 3. 2 A. Photo of 2015~2018 excavated area of Bangga, showing site structure and major features (P=pit; PH=post hole; H=hearth). Photo by Hailun Xu. B. Sheep/goat dung pellets from the corral area.

Research to date, suggests that people living at Bangga were among the earliest high altitude pastoralists in the central Tibet (Lü et al., 2021; Tang et al., 2021). A faunal assemblage of over 10,000 specimens was recovered from the site during field seasons 2000-2002 and 2015-2018, the latter conducted by authors of this paper (HL, LT, XZ, ZZ, HX, JS, SW, and XL). Animal remains are generally well preserved. Those retrieved at Bangga 2000–2002 were collected by hand picking, while remains from 2015–2018 excavations were collected by hand picking and screening through 6 mm-sized mesh. Analysis of mammal faunal assemblage from Bangga
conducted by Z. Zhang and X. Gao, showed that the assemblage is dominated by sheep, with lesser numbers of goats, and small proportions of cattle/yak, horse (Lü et al., 2021). Very small numbers of hare (Lepus oiostolus), pika (Ochotona sp.), Tibetan gazelle (Procapra picticaudata), musk deer (Moschus sp.), and rodent specimens were also identified. Archaeobotanical studies at Bangga document that people at Bangga also cultivated barley extensively and wheat and buckwheat at smaller scales, with millet being absent from the site and present elsewhere nearby (Tang et al., 2021). Sequential stable carbon and oxygen isotope analyses performed on sheep and goat mandibular molars reveal that animals were provisioned with ground water and significant amounts of cultigens (likely barley and millet) seasonally or all year around (Zhang et al., in prep). There is no clear isotopic patterning suggesting seasonal movements along altitudinal gradient. Together these data present a picture of agro-pastoralists who herded sheep and goat with cattle/yak and horses in local pastures, provisioned them with water and fodder, relied on local cultivation and did a little hunting. The evident investments to livestock infrastructure made at the settlement (e.g. pens) and the substantial amount of caprine dung accumulation suggests that herd animals spent a significant amount of time at the site, with sheep and goat kept within designated enclosed spaces.

3.3 Method and materials

3.3.1 Ethnographic Data

Herding strategies on the recent Tibetan Plateau are influenced by integration and technology characteristic of the modern world, but many aspects are influenced by environmental factors relevant to thinking about the past. Topographies have changed little and
the climate system of central Tibet has been largely stable since the mid-late Holocene (Tang et al., 2000), resulting in similar environments and herding landscapes. Ethnographical and historic recorded experience of recent Tibetan pastoralists provide useful contexts for interpretation of regional archaeological data and construction of relational analogies (sensu Wylie, 1985). To estimate overall conditions for pastoralism on the Tibetan Plateau, we collected data on recent and historic herd management and mortality on the Tibetan Plateau from ethnographic literature (e.g. Gele et al., 2002; Goldstein & Beall, 1990; Thargyal, 2007) and from local gazetteer (e.g. City, 2004; L. C. C. o. D. D. County, 2010; L. C. C. o. t. C. County, 2010; County, 2011) from 16 areas distributed across the Tibetan Plateau. In compiling metadata we collected four categories of livestock husbandry data:

(1) natural death rate (NDR) of lamb/kid, which is the rate that lambs/kids of a herd that are killed by natural factors before they reach a year old;

(2) adult sheep/goat natural death rate, which is the rate that adult sheep/goat in a herd die a natural death in a certain year;

(3) reproduction rate, which is the proportion of female sheep/goat of a herd that actually give birth during a certain year; and

(4) cropping rate, or marketing rate (“出栏率” in Chinese literatures), which is the proportion of adult sheep/goat of a herd that were intentional culled (slaughtered) or sold in a certain year.

We focused on sheep and goat but in a few cases when specific data were not available, we collected information published for the general category “livestock”, which combines information from sheep/goat, cattle/yak, and horse. Data for sheep/goat in local gazetteers are
usually reported by an administrative unit, which lumps various numbers of villages in an area together. Village scale information might be even more variable, but this was not available.

### 3.3.2 Modeling mortality profiles for sheep herds on the Tibetan Plateau

Our mathematical modelling focused on sheep, which were the dominant domestic animal in the Bangga samples. Following Cribb’s (1987) logic of computer-simulated herd structures in archaeological interpretation, we built models for sheep mortality profiles on the Tibetan Plateau in dynamic terms. The number of sheep of every cohort of our model population changed positively or negatively through the time based on the growth rate of that cohort. The growth rates were determined by birthrates and deathrates of that sheep cohort. This differs from a static model of a single sheep cohort where deathrate is the only parameter specified, which will produce a simple 1:1 relationship between the survivorship curve and the kill-off pattern.

Although dynamic, our model represents a discrete and self-sustaining system and we do not consider possibilities of herd splitting, mixing, and trade among different pastoral communities (Cribb, 1987). We used sheep reproduction and mortality data from recent pastoral communities on the Tibetan Plateau to build our models. Because this is an idealized model used to visualize the impact of varied lamb natural death rates on the final mortality profiles, we consider the lamb natural death rate (NDR) as the only variable in our model and set fixed values based on local records for the adult sheep natural death rates, reproduction rates, and crop rates. To simplify the model, we also set the following conditions based on recorded herder behavior and sheep reproduction information on the Tibetan Plateau (Ding et al., 2016; Gele, 2004):

1. the natural mortality rate is first applied to each adult sheep cohort and then the human slaughtering rate
(2) the natural mortality rate applies to both sexes adult sheep of each cohort equally, but human slaughtering prefers male sheep. Ewes will not be slaughtered if there are enough rams/wethers

(3) the sex ratio of the lamb cohort is 1:1

(4) the reproduction period of ewes is between the first and eighth year of their life

(5) the maximum lifespan of sheep is ten years old

We built the model using the software STELLA with an initial population of 200 female and 200 male lambs under one year old (see Appendix 2 for STELLA script). We use accumulated death data to build each survivorship curve. Each of these hypothetical herds is then run through the program for multiple years until the herd dies out. Or, if the population kept growing, we simulated demographic change up to one hundred years.

### 3.2.3 Identification

Published dental and postcranial morphology and landmarks (Hillson, 2005, p. 140–143; Leslie Jr, 2010; Tong et al., 2008; Wang et al., 2020; Zeder & Pilaar, 2010) and comparative research conducted in collections of the Smithsonian National Museum of Natural History, American Museum of Natural History, and Field Museum were used in identification of small bovid taxa. We focus here on domestic sheep and goat mandibles. Wild bovids are rare in the Bangga fauna, with only Tibetan gazelle (*Procapra picticaudata*) remains clearly identified (Lü et al., 2021).
3.2.4 Reconstruction of mortality profile for sheep and goat in archaeological samples

This study focuses on eruption and wear of sheep mandibular teeth. Post-cranial bones data were not easily accessible due to the pandemic. Mandibular dental groups and age of goat and sheep were initially recorded following Zeder (2006)’s revised method. In order to compare our data with data from other sites, we converted Zeder’s age groups (I–XII for age groups) into the widely used Payne (1973)’s age stages (A–I for age stages) when calculating survivorship curves. We focused further analysis on specimens that could be identified to a single age stage. Specimens assigned to age stages like A/B or > B were not counted. Many recent studies of mortality profiles of ancient sheep and goat also present data that are corrected following Vigne and Helmer (2007). But since Brochier (2013) demonstrated that Vigne and Helmer (2007)’s correction method overestimates the frequencies of first age stages and underestimates the last age stages, we did not employ this approach (available raw data in Appendix 3 would allow this).

Samples sizes influenced our analysis of sheep versus goats at Bangga, leading us to focus on sheep. Lyman (1987) suggested a minimum sample size of 30 individuals for reconstructing a reliable mortality profile. A total of 110 Caprine left mandibles were excavated at Bangga. Of the 110 Caprine left mandibles containing mandibular dentition, 13 could were attributed to goat and 57 to sheep. The remaining 40 mandibles were attributed to sheep/goat. Of the 110 Caprine left mandibles, 64 come from early phase (3000–2200 Cal BP) of the site and could be identified to a single age stage. These included 21 mandibles from the corral, 18 mandibles from the residential area as identified by the excavators (Lü et al. 2021), and the other 25 mandibles from stratigraphic layers overlying the corral and residential areas of the settlement (Appendix 3). Of these 64 ageable mandibles, 11 were goat, 42 sheep, and 11 attributable to domestic caprine
sheep/goat. Since the number of ageable goat mandibles (N=11) from Bangga is small, we present ageing results for all 64 Caprine mandibles in the result section. We focus only on data from sheep mandibles in further analyses. To ensure a large enough sample size for analyses, we lumped sheep mandibles from all stratigraphical layers and cultural features of the early phase.

3.4 Results

3.4.1 Insights into sheep and other livestock management and mortality from local ethnographical and historic records

Local ethnographical and historic records suggest that more than 90% of people in Tibet rely to some degree on pastoralism (Cheng et al., 1984, pp. 99-101), which is often organized on small scale, i.e., household or village based. Sheep are raised by recent Tibetan pastoralists primary for wool and meat (Huang et al., 1981, p. 28-29). Sheep milk is also used but in a less significant way and is supplementary to cattle/yak milk. In this section, we summarized key information about herders’ culling/crop behavior, reproduction rates of ewes, and natural mortality for understand the wool and meat aimed sheep management of recent Tibetan pastoralists.

Intentional culling
Annual culling rates of livestock among recent Tibetan pastoral communities are low. Recorded crop/culling rates of sheep and goats over the Tibet Autonomous Region as a whole were rarely beyond 20% until late 1990s (Figure 3.3). Goldstein and Beall (1990, p. 97) also recorded that when Tibetan pastoralists at Changtang have to slaughter their livestock for meat, they only slaughter less than 10% of their livestock annually to maintain the size of their livestock. Rather than culling male lamb and kid surplus to reproduction needs for herd growth, herders usually
castrated these animals before they reached one year old. Castrated males served as source of wool and as pack animals for at least three or four years, after which they might be culled for meat (Gele et al., 2002, pp. 76, 406; Thargyal, 2007, p. 84). Wethers are considered the best pack animals by many Tibetan pastoralists and frequently used in long distance trade (Cai et al., 1993; Rizvi, 2001, pp. 101-102). They can move over varied topography, walk 15~20 km a day, carry ~16kg loads, and are easy to control in large groups. Even though skins of lambs and kids are ideal raw materials for making clothes, Goldstein & Beall (1990, p. 102) noted that people never killed their lambs and kids for that purpose intentionally.

![Crop Rate Graph](image)

Figure 3.3 Annual crop rates of sheep and goats of the Tibet Autonomous Region from 1978 to 2020. Data source: (Region, 2000, 2020)

**Reproduction rates**

Reported reproduction rates of adult ewe on the Tibetan Plateau are between 48% and 99% (Table 3.1). Due to effect of the high altitude, ewes on the Tibetan Plateau can usually only bear one lamb per year while ewes at lower altitudinal area more often can bear two per year (Yang et al., 1993).
Table 3. 1 Livestock reproduction data from recent and modern pastoral communities on the Tibetan Plateau

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation (m a.s.l.)</th>
<th>Reproduction rate</th>
<th>Annual natural mortality of newborn herding animal</th>
<th>Average annual natural mortality of adult herding animal</th>
<th>Taxa</th>
<th>Time</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duilong Deqing County, Tibet Autonomous Region</td>
<td>3680</td>
<td>40–70%</td>
<td>48–78%</td>
<td>7–41%</td>
<td>Sheep &amp; Goat</td>
<td>Historical period.</td>
<td>(L. C. C. C. o. D. D. County, 2010, pp. 379, 387, 390-391)</td>
</tr>
<tr>
<td>Gongbu Jiangda County, Tibet Autonomous Region</td>
<td>3600</td>
<td>17%</td>
<td>Sheep &amp; Goat</td>
<td>1981</td>
<td>(County, 2008, pp. 350–351)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jiangzi County, Tibet Autonomous Region</td>
<td>4000</td>
<td>34%</td>
<td>10%</td>
<td>Sheep, goat, cattle and horse</td>
<td>1983</td>
<td>(County, 2004, p. 46)</td>
<td></td>
</tr>
<tr>
<td>Changdu City, Tibet Autonomous Region</td>
<td>~3200</td>
<td>60%</td>
<td>Sheep</td>
<td>2000s</td>
<td></td>
<td></td>
<td>(Local Chronicle Compilation Committee of the Changdu County, 2010, p. 510)</td>
</tr>
<tr>
<td>Naidong County, Shannan City, Tibet Autonomous Region</td>
<td>~3600</td>
<td>&gt;20%</td>
<td>Sheep &amp; Goat</td>
<td>1960s</td>
<td>(Naidong, 2006, p. 357)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chonggye County, Shannan City, Tibet Autonomous Region</td>
<td>~3900</td>
<td>15%</td>
<td>Sheep, goat, yak, cattle and horse</td>
<td>1978</td>
<td>(Local Chronicle Compilation Committee of the Chonggye County, 2010, pp. 334–335)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naq County and Bange County, Tibet Autonomous Region</td>
<td>4500</td>
<td>86%</td>
<td>39%</td>
<td>Sheep</td>
<td>1980s</td>
<td>(Cai et al., 1993b)</td>
<td></td>
</tr>
<tr>
<td>Langkazi County, Tibet Autonomous Region</td>
<td>4500</td>
<td>87%</td>
<td>23%</td>
<td>Sheep</td>
<td>1980s</td>
<td>(Cai et al., 1993)</td>
<td></td>
</tr>
<tr>
<td>Langkazi County, Tibet Autonomous Region</td>
<td>4500</td>
<td>86%</td>
<td>37%</td>
<td>Goat</td>
<td>1980s</td>
<td>(Cai et al., 1993a)</td>
<td></td>
</tr>
<tr>
<td>Yushu prefecture, Qinghai Province</td>
<td>~4000</td>
<td>65%</td>
<td>12–40%</td>
<td>Sheep</td>
<td>1971–1990</td>
<td>(Zhou, 2005, p. 244)</td>
<td></td>
</tr>
<tr>
<td>Delingha City, Qinghai Province</td>
<td>~4000</td>
<td>5–54%</td>
<td>5.20%</td>
<td>Sheep &amp; Goat</td>
<td>1949–1995</td>
<td>(City, 2004, pp. 114–120)</td>
<td></td>
</tr>
<tr>
<td>Gande County, Qinghai Province</td>
<td>4300</td>
<td>81%</td>
<td>All herd animals</td>
<td>1975</td>
<td>(County, 2003, p. 141)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maqin County, Qinghai Province</td>
<td>3700</td>
<td>8–48%</td>
<td>All herd animals</td>
<td>1971–1995</td>
<td>(County, 2005, pp. 264–266)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aha, Sichuan Province</td>
<td>~2600</td>
<td>60–64%</td>
<td>Sheep</td>
<td>1950s</td>
<td>(Prefecture, 1994, p. 1088)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Natural mortality
Natural losses of both young and adult sheep and goat are high. As shown in Table 1 and 2, livestock can be abruptly and completely decimated by highly variable and unpredictable ecological factors, including low temperature, extreme weather, epidemic animal diseases, and wild predators—with snowstorms and consequent serious shortage of food and fuel killing more than 90% of lambs and kids of a pastoral community in some cases (Cheng et al., 1984, pp. 50-51; Guo et al., 2018; Huber, 2005, 2012; Miller, 2000; Xin & Chen, 2013). Regional lamb natural death rates (NDR) were highly variable, between 5% and 81%. Today, the high variation in lamb natural death rates are largely due to fluctuations of local climate conditions. The literature shows, for instance, at Maduo County at the Northeastern Tibetan Plateau, the natural mortality of newborn livestock was only ~11% in 2005 when the County saw prime weather conditions but were as high as 63% in 1996 when Maduo County experienced serious snowstorms (County, 2011, pp. 286-288). This variation is likely lower than during earlier periods, since the improvement of husbandry technology (e.g. stabling, veterinary care) has decreased lamb natural death rates. This can be seen in estimated lamb natural death rates in Duilong Deqing County, Central Tibet, which were 40-70% pre-1950’s but between 7-41% after 1950s (L. C. C. o. D. D. County, 2010, pp. 379, 387, 390-391). Recorded natural loss of adult sheep among recent Tibetan pastoral communities is usually 4.4-15% (Table 3.1). But losses could be as high as 66% in cases of serious snowstorm or diseases (Table 3.2).
Table 3.2 Local records of massive livestock death due to natural reasons on the Tibetan Plateau

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation (m a.s.l.)</th>
<th>Time</th>
<th>Causes of death</th>
<th>Livestock mortality</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>The No. 4 brigade of the Guangming production brigade, Delingha City, Qinghai Province</td>
<td>~ 4000</td>
<td>March, 1980</td>
<td>Snowstorm</td>
<td>93.3% of lamb and kids</td>
<td>(City, 2004, p. 68)</td>
</tr>
<tr>
<td>Delingha City, Qinghai Province</td>
<td>~ 4000</td>
<td>Feb, 1993</td>
<td>Snowstorm</td>
<td>~100% of lamb and kids</td>
<td>(City, 2004, p. 68)</td>
</tr>
<tr>
<td>Guoli commune, Dulan County, Qinghai Province</td>
<td>~ 3500</td>
<td>Feb. ~ April, 1982</td>
<td>Snowstorm</td>
<td>95.6% of neonatal livestock</td>
<td>(County, 2001, p. 122)</td>
</tr>
<tr>
<td>Duilong Deqing County, Tibet Autonomous Region</td>
<td>3680</td>
<td>Early 1930s</td>
<td>Disease (fascioliasis hepatica)</td>
<td>~70%</td>
<td>(L. C. C. o. D. D. County, 2010, p. 405)</td>
</tr>
<tr>
<td>The Huo'er Bang tribe, Burang County, Tibetan Autonomous Region</td>
<td>3800</td>
<td>Late 1920s</td>
<td>Snowstorm</td>
<td>66% of sheep</td>
<td>(L. C. C. o. t. P. County, 2011, p. 58)</td>
</tr>
<tr>
<td>Burang County, Tibet Autonomous Region</td>
<td>3800</td>
<td>Feb, 1993</td>
<td>Snowstorm</td>
<td>66.7% of neonatal livestock</td>
<td>(L. C. C. o. t. P. County, 2011, p. 58)</td>
</tr>
<tr>
<td>Burang County, Tibet Autonomous Region</td>
<td>3800</td>
<td>Sep., 1997</td>
<td>Snowstorm</td>
<td>65% of livestock</td>
<td>(L. C. C. o. t. P. County, 2011, p. 58)</td>
</tr>
<tr>
<td>One pastoral family at Kangding County, Sichuan Province</td>
<td>−2600</td>
<td>Aug 15th, 1951</td>
<td>Disease (Cattle plague)</td>
<td>91% (n=79) cattle</td>
<td>(County, 1995, p. 126)</td>
</tr>
<tr>
<td>One ranch at Rangtang County, Sichuan Province</td>
<td>−3300</td>
<td>1975</td>
<td>Disease (Enterotoxaemia)</td>
<td>33.3% (n=2000) of sheep/goats</td>
<td>(Prefecture, 1994, p. 1115)</td>
</tr>
<tr>
<td>Bairi township, Chamdo City, Tibet Autonomous Region</td>
<td>−3200</td>
<td>April, 1985</td>
<td>Snowstorm</td>
<td>48.05% of lamb (n=1284) and 51.87% of kids (n=291)</td>
<td>(Local Chronicle Compilation Committee of the Changdu County, 2010, p. 107)</td>
</tr>
<tr>
<td>Yushu prefecture, Qinghai Province</td>
<td>−4000</td>
<td>Winter of 1995 ~ Spring of 1996</td>
<td>Snowstorm</td>
<td>33.78% (n=1,290,000) of livestock</td>
<td>(Zhou, 2005, p. 251)</td>
</tr>
<tr>
<td>One pastoral family at Yushu prefecture, Qinghai Province</td>
<td>−4000</td>
<td>1981</td>
<td>Disease (Ecthyma Contagiosa)</td>
<td>39% (n=70) of kids</td>
<td>(City, 2004, p. 127)</td>
</tr>
<tr>
<td>Tibet Autonomous Region</td>
<td>−4000</td>
<td>Before 1990s</td>
<td>Miscarriages likely caused by chlamydia infections</td>
<td>20–95% of goat</td>
<td>(Gao et al., 1993)</td>
</tr>
</tbody>
</table>

3.4.2 Mortality profile for sheep in archaeological samples

Our results (Table 3.3 & Figure 3.4) show that most sheep at Bangga (64.28%, n= 27) died within the first year of their life. Neonatal lambs that did not survive beyond the first two months of their lives made up 30.95% (n= 13) of the sample. Another 21.43% (n= 9) of the sample was
made up of lambs that likely died between two and the six months old. In contrast, mortality among older animals was low, with a pulse between 6-8 years (11.9%, n=5). None of the sheep specimens could be attributed to an age at death older than the eighth year. Lamb mandibles are more friable than the bones of mature animals and especially vulnerable to destruction (Ioannidou, 2003; Lam et al., 2010) and more likely to be underestimated in an assemblage. As a result, the dominance of lamb mandibles in lower levels studied at the site suggests that the general pattern of sheep mortality profile at Bangga was not impacted significantly by taphonomic processes.

Table 3.3 Mortality data based on sheep and goat mandibles from early phase of Bangga

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Age group</th>
<th>A (0–2 m)</th>
<th>B (2–6 m)</th>
<th>C (6–12 m)</th>
<th>D (1–2 y)</th>
<th>E/F (2–4 y)</th>
<th>G (4–6 y)</th>
<th>H (6–8 y)</th>
<th>I (&gt; 8 y)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capra hircus</td>
<td>Frequency</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Relative frequency</td>
<td>18.18%</td>
<td>0.00%</td>
<td>9.09%</td>
<td>45.45%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>27.27%</td>
<td>0.00%</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Relative frequency density</td>
<td>1.09</td>
<td>0.00</td>
<td>0.18</td>
<td>0.45</td>
<td>0.00</td>
<td>0.00</td>
<td>0.14</td>
<td>0.00</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Survivorship</td>
<td>82.00%</td>
<td>82.00%</td>
<td>73.00%</td>
<td>27.50%</td>
<td>27.50%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>11</td>
</tr>
<tr>
<td>Ovis aries</td>
<td>Frequency</td>
<td>13</td>
<td>9</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Relative frequency</td>
<td>30.95%</td>
<td>21.43%</td>
<td>11.90%</td>
<td>16.67%</td>
<td>4.76%</td>
<td>2.38%</td>
<td>11.90%</td>
<td>0.00%</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Relative frequency density</td>
<td>1.86</td>
<td>0.64</td>
<td>0.29</td>
<td>0.17</td>
<td>0.02</td>
<td>0.01</td>
<td>0.06</td>
<td>0.00</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Survivorship</td>
<td>69.05%</td>
<td>47.62%</td>
<td>35.72%</td>
<td>19.05%</td>
<td>14.29%</td>
<td>11.91%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>42</td>
</tr>
<tr>
<td>Sheep/goat</td>
<td>Frequency</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Relative frequency</td>
<td>18.18%</td>
<td>9.09%</td>
<td>18.18%</td>
<td>18.18%</td>
<td>9.09%</td>
<td>18.18%</td>
<td>9.09%</td>
<td>0.00%</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Relative frequency density</td>
<td>1.09</td>
<td>0.27</td>
<td>0.36</td>
<td>0.18</td>
<td>0.05</td>
<td>0.09</td>
<td>0.05</td>
<td>0.00</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Survivorship</td>
<td>81.72%</td>
<td>72.63%</td>
<td>54.45%</td>
<td>36.27%</td>
<td>27.18%</td>
<td>9.00%</td>
<td>0%</td>
<td>0%</td>
<td>11</td>
</tr>
<tr>
<td>Sheep plus sheep/goat</td>
<td>Frequency</td>
<td>15</td>
<td>10</td>
<td>7</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Relative frequency</td>
<td>28.30%</td>
<td>18.87%</td>
<td>13.21%</td>
<td>16.98%</td>
<td>5.66%</td>
<td>5.66%</td>
<td>11.32%</td>
<td>0.00%</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Relative frequency density</td>
<td>1.70</td>
<td>0.57</td>
<td>0.26</td>
<td>0.17</td>
<td>0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>0.00</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Survivorship</td>
<td>71.70%</td>
<td>52.83%</td>
<td>39.62%</td>
<td>22.64%</td>
<td>16.98%</td>
<td>11.32%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>53</td>
</tr>
</tbody>
</table>
To interrogate our results further and to investigate the question of how the Bangga mortality profile might be altered if the 11 mandibles identified as sheep/goat were all sheep, or all goat we undertook statistical analysis. The result of the Kolmogorov-Smirnov test ($D = 0.25, p = 0.9639$) suggests that age group frequency distributions of all sheep mandibles and that of all sheep mandibles plus 11 mandibles of sheep/goat are indistinguishable from each other. This indicates that even if all 11 Caprine mandibles were from sheep, the current mortality profile based on 42 sheep left mandibles would not be substantially impacted.

Figure 3. 4 Mortality profile of sheep at Bangga
3.4.3 Modelling recent herd management on the Tibetan Plateau: A wool and meat aimed sheep management strategy

Our model aimed to illustrate the outcome of mortality profiles of wool and meat oriented sheep management strategies practiced today on the Tibetan Plateau, under varying natural lamb death rates. Using the medians of recorded data in Table 1, we set adult sheep natural death rates and reproduction rates as fixed parameters: (1) adult sheep natural death rate = 10%; (2) reproduction rate = 75%. To be conservative, we set the crop/culling rate = 15% of each adult cohort.

Recorded regional lamb natural death rates were highly variable, between 5% and 81%. To explore the influence of variation lamb natural death rate (NDR) was a variable parameter in our model. In order to fully illustrate potential outcomes of different lamb natural death rates, we simulated 16 mortality profiles with an interval of 5% for a full range of recorded lamb natural death rates between 5% and 81%. To verify whether our simulated patterns matched survivorship curves in real world, we also constructed three survivorship curves based on actual data from the Maduo County from three years under different climate conditions (Table 3.4) Data from Maduo in northeastern Tibetan Plateau were used because it is currently the only place with comprehensive published livestock reproduction data.
Table 3. 4 Livestock reproduction data from Maduo County. Data source: (County, 2011)

<table>
<thead>
<tr>
<th>Time</th>
<th>Climate condition</th>
<th>Reproduction rate*</th>
<th>Annual natural mortality of newborn herding animal</th>
<th>Annual natural mortality of adult herding animal</th>
<th>Crop rate**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>Bad (serious snowstorms)</td>
<td>N/A</td>
<td>63.10%</td>
<td>22%</td>
<td>18.30%</td>
</tr>
<tr>
<td>1999</td>
<td>Moderate</td>
<td>70.94%</td>
<td>36.19%</td>
<td>6.89%</td>
<td>21.30%</td>
</tr>
<tr>
<td>2005</td>
<td>Prime</td>
<td>70.64%</td>
<td>11.10%</td>
<td>1.50%</td>
<td>42.00%</td>
</tr>
</tbody>
</table>

Notes: * reproduction rate of 1996 is not available, used the mean value of reproduction rates of 1999 and 2005 for 1996 in model.

** A policy was enacted in the Maduo County in late 1990s to encourage herders to crop and sell more livestock every year. Crop rates in Maduo have risen dramatically since then. We use the crop rate of 1996 before the policy was enacted for modeling all three survivorship curves for Maduo.

Figure 3. 5 Simulated survivorship curves of Tibetan sheep herds with different natural death rates (NDR) of lamb.
Figure 3. 6 Numbers of lambs born every year over 100 years with NDRs from 5% to 80%
Figure 3. 7 Comparison of survivorship curves based on data from Maduo and survivorship curves simulated in this study

Figure 3. 8 Comparison of simulated model in this study and Payne (1973)’s model
Figure 3. 9 Comparison of simulated model in this study and Vigne and Helmer (2007)’s model

Figure 3. 10 Comparison of simulated model in this study and Redding Jr (1981)’s model
Simulated models are presented in Figure 5 and Table S2. Because male sheep were preferred when slaughtering, none of male populations in our models survived the sixth year of their life, whilst female sheep could live up to their maximum lifespan (ten years old). With the initial model population of 200 males and 200 females, and current adult sheep natural death rate of 10%, reproduction rate of 75% and the crop rate of 15%, the size of modeled population failed to grow when the NDR was higher than 45% (Figure 3.5). With NDRs higher than 45%, the herd would die out within a few decades unless herders could get supplementary animals from other pastoral communities. Three survivorship curves based on Maduo County’s actual data match those in our simulated model with similar NDR (Figure 3.6). This suggests our model likely represent patterns in the real world.

We also observed similarities between several survivorship curves with NDR higher than 20% simulated in this study and other mortality profiles proposed by Payne (1973), Redding Jr (1981), and Vigne and Helmer (2007) (Figure 3.8–3.10, Table 3.5). Some of those similarities might be because some local historic records on the Tibetan Plateau lumped data for lambs that died in the first year. When higher-resolution information about exact death age of lambs is available in archaeological assemblages, some of these resemblances might be distinguished (e.g. Gifford-Gonzalez, 2018, pp. 138-141).

Table 3.5 List of similar survivorship curves simulated in this study and those in other models

<table>
<thead>
<tr>
<th>Survivorship curves simulated in this study</th>
<th>Survivorship curves in other models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survivorship curve with NDR=20%</td>
<td>Optimization of energy production survivorship curve in Redding Jr (1981)</td>
</tr>
<tr>
<td>Survivorship curve with NDR=25%</td>
<td>Meat aimed survivorship curve in Payne (1973)</td>
</tr>
<tr>
<td>Survivorship curve with NDR=35%</td>
<td>Optimization of herd security survivorship curve in Redding Jr (1981)</td>
</tr>
<tr>
<td>Survivorship curve with NDR=50%</td>
<td>Milk and fleece aimed survivorship curve in Vigne and Helmer (2007)</td>
</tr>
<tr>
<td>Survivorship curve with NDR=65%</td>
<td>Fleece and meat aimed survivorship curve in Vigne and Helmer (2007)</td>
</tr>
<tr>
<td>Survivorship curve with NDR=80%</td>
<td>Meat-tender aimed survivorship curve in Vigne and Helmer (2007)</td>
</tr>
<tr>
<td>Survivorship curve with NDR=80%</td>
<td>Milk aimed survivorship curve in Vigne and Helmer (2007)</td>
</tr>
</tbody>
</table>
3.4.4 Comparison of sheep survivorship curve at Bangga with previous models and model simulated in this study

The high proportion of neonatal sheep death at Bangga clearly differentiates the survivorship curve from this site from most mortality profiles proposed by Payne (1973), Redding Jr (1981), and Vigne and Helmer (2007). The Bangga profile does, however, resemble the following four mortality profiles (Figure 3.11): (1) milk aimed kill-off mortality profiles described by Payne (1973) and (2) by Vigne and Helmer (2007), (3) the Tibetan wool and meat aimed sheep management strategy simulated in this study with lamb natural death rate of 65%, and (4) the sheep survivorship in Maduo County in 1996 when the weather conditions were bad. However, some slight, but probably important, differences are present between survivorship curves at
Bangga and those of milk oriented kill-off mortality profiles in Payne (1973)’s and Vigne and Helmer (2007)’s model. In particular, lamb loss at Bangga was gradual throughout the first year, which contrasts with the Payne (1973)’s and Vigne and Helmer (2007)’s models where it was concentrated in the first two months. Further comparison between the survivorship curve at Bangga and the one simulated from our model, however, is hindered by the relatively low resolution of lamb death time in our model.

3.4.5 Comparison of sheep survivorship curve at Bangga with sheep/goat survivorship curves at other archaeological sites on or near by the Tibetan Plateau

Comparison of sheep/goat mortality profiles at Bangga and contemporary or earlier pastoral/agropastoral settlements on or near by the Tibetan Plateau reveal differences in lamb mortality with altitude, with the lamb death rates at Bangga (~3800 m a.s.l.) and Shidaqiu (>2500 m a.s.l.) considerably higher than lamb death rates from sites at lower altitudes (<2000 m a.s.l.) (Table 3.6, Figure 3.12). The mortality of sheep/goat less than one year old is 64.29% (n=27) at Bangga and 81.25% (n=13) at Shidaqiu. Another relatively high altitude early pastoral settlement, the site of Changning (~2500 m a.s.l., ~2300-1850 Cal BCE) on the northeast Tibetan Plateau had 47.7% mortality for sheep/goat under two years old (Li, 2012), which is high juvenile mortality. However, the report lumps individuals that died between 3 and 24 months old so these data cannot be directly compared with Bangga. At none of the lower altitude sites (Chap I, Zaoshugounao, Maojiaping, Shirenzigou, and Xishan) is neonatal (0~2 month) mortality of sheep/goat higher than 4%. Similarly, the mortality of sheep/goat less than one year old at Chap I, Zaoshugounao, Maojiaping, Shirenzigou, and Xishan is lower than 30% (but not at Shimao).
Table 3. 6 Comparison of sheep/goat mortality data from archaeological settlements on and near by the Tibetan Plateau

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Elevation (m a.s.l.)</th>
<th>Taxa</th>
<th>Age group</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>EF</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zaoshugounao</td>
<td>~1400 - 900</td>
<td>~1000</td>
<td>Caprine</td>
<td>0 - 2 m</td>
<td>2.78%</td>
<td>5.56%</td>
<td>15.28%</td>
<td>22.2%</td>
<td>25.0%</td>
<td>9.72%</td>
<td>9.2%</td>
<td>9.2%</td>
<td>5.56%</td>
</tr>
<tr>
<td>Shimao</td>
<td>~2000 BCE</td>
<td>1100-1300</td>
<td>Ovis</td>
<td>0 - 2 m</td>
<td>0.00%</td>
<td>14.2%</td>
<td>9.9%</td>
<td>35.71%</td>
<td>7%</td>
<td>7.14%</td>
<td>0.00%</td>
<td>7.14%</td>
<td>7.14%</td>
</tr>
<tr>
<td>Xishan</td>
<td>~800 - 300 BCE</td>
<td>~1500</td>
<td>Caprine</td>
<td>0 - 2 m</td>
<td>0%</td>
<td>11%</td>
<td>11%</td>
<td>33%</td>
<td>39%</td>
<td>6%</td>
<td>0%</td>
<td>0%</td>
<td>≤10</td>
</tr>
<tr>
<td>Maojiaping</td>
<td>~800 - 300 BCE</td>
<td>1500</td>
<td>Caprine</td>
<td>0 - 2 m</td>
<td>0.00%</td>
<td>5.88%</td>
<td>23.53%</td>
<td>11.7%</td>
<td>23.5%</td>
<td>0.00%</td>
<td>11.7%</td>
<td>23.5%</td>
<td>3%</td>
</tr>
<tr>
<td>Shirenzigou</td>
<td>~1250 - 950 BCE</td>
<td>~1700-2100</td>
<td>Ovis</td>
<td>0 - 2 m</td>
<td>5.00%</td>
<td>40.0%</td>
<td>0%</td>
<td>20.0%</td>
<td>0%</td>
<td>15.0%</td>
<td>0%</td>
<td>0.00%</td>
<td>20</td>
</tr>
<tr>
<td>Shirenzigou</td>
<td>~950 - 750 BCE</td>
<td></td>
<td>Ovis</td>
<td>0 - 2 m</td>
<td>14.29%</td>
<td>20.0%</td>
<td>0%</td>
<td>25.7%</td>
<td>1%</td>
<td>14.2%</td>
<td>9%</td>
<td>11.4%</td>
<td>14.2%</td>
</tr>
<tr>
<td>Chap I</td>
<td>1065–787 BCE</td>
<td>2000</td>
<td>Caprine</td>
<td>0 - 2 m</td>
<td>10.00%</td>
<td>25.0%</td>
<td>0%</td>
<td>17.0%</td>
<td>0%</td>
<td>16.0%</td>
<td>0%</td>
<td>21.0%</td>
<td>11.0%</td>
</tr>
<tr>
<td>Changning</td>
<td>~2000 BCE</td>
<td>~2500</td>
<td>Caprine</td>
<td>0 - 2 m</td>
<td>3.79%</td>
<td>43.94%</td>
<td>0%</td>
<td>52.27%</td>
<td>0%</td>
<td>132</td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>Shidaqiu</td>
<td>~220 BCE - AD 220</td>
<td>2500</td>
<td>Capra</td>
<td>0 - 2 m</td>
<td>62.5%</td>
<td>0.00%</td>
<td>18.75%</td>
<td>18.7%</td>
<td>18.7%</td>
<td>12.5%</td>
<td>6.25%</td>
<td>0.00%</td>
<td>16</td>
</tr>
<tr>
<td>Bangga</td>
<td>~1000 - 200 BCE</td>
<td>3800</td>
<td>Ovis</td>
<td>0 - 2 m</td>
<td>30.2%</td>
<td>20.9%</td>
<td>13.95%</td>
<td>16.2%</td>
<td>4.65%</td>
<td>2.33%</td>
<td>11.6%</td>
<td>0.00%</td>
<td>42</td>
</tr>
</tbody>
</table>

3.5 Discussion

Taken together metadata from contemporary herd management strategies and risks on the Tibetan Plateau, modeling and archaeological mortality profiles, and comparisons of mortality among sites of varying altitudes emphasize environmental risks faced by early sheep herders on the Tibetan Plateau.

3.5.1 Sheep management strategies of recent Tibetan herders

Data from ethnographical sources and the local gazetteer clarify that recent Tibetan pastoralists practice a *survival subsistence strategy* (Sensu: Sasson & Greenfield, 2014). Due to slow reproduction of sheep at high altitude and high natural lamb mortality caused by extreme weather...
and disease, recent Tibetan herders cull relatively few animals and raise sheep primarily for herd
growth and beyond that for wool, meat, and milk and transport (Goldstein & Beall, 1990; Huang
et al., 1981, p. 28–29). This differs from strategies for specialized pastoral production which
usually involve targeted culling of animals of a certain age/life stage to obtain the maximum
yield of products such as meat, milk, or wool. Archaeologists have also suggested that
specialized management is more commonly practiced by herders in large-scaled complex
economies than by subsistence herders living in high risk environments (Greenfield et al., 1988;
Sherratt, 1983).

3.5.2 Interpreting high lamb mortality at Bangga

Archaeological mortality profiles revealed high lamb death rates at Bangga. Neonates or
animals that did not survive the first two months of their lives made up at least 30% of the
sample, and most of the sheep that died were younger than a year old. This survivorship curve
matched our simulated lamb natural death rates of 65% in Tibetan flocks. In a case of
equifinality, lamb death rates at Bangga also resulted in a survivorship curve almost identical to
the milk aimed mortality discussed in Payne (1973)’s and Vigne and Helmer (2007)’s models.
This suggests that caution should be used in interpretation of archaeological mortality profiles in
the Tibetan Plateau region and that alternate lines of evidence are necessary to discriminate
intentional culling and natural mortality.

Herd mortality in recent herd metadata from Tibetan Plateau (Table 3.1) and our simulations
of varied natural mortality rates both indicate that under high risk conditions specialization is a
less probable interpretation than high natural mortality. Serious snowstorms and droughts that
heavily impact local flocks occur in central Tibet (L. C. C. o. D. D. County, 2010, p. 68; L. C.
Epidemic animal diseases that can kill kids and lambs or cause miscarriage in ewes also affect contemporary Tibetan pastoralists (Table 3.2). Contextual archaeological and isotopic data for corralling and foddering at Bangga indicated specific ancient disease and nutritional risks at the settlement, associated with periodic confinement and lack of access to pasture. That herders and their flocks spent a significant amount of time at the site, is indicated by the investment in stone construction and house-adjacent livestock pens with substantial caprine dung accumulation. Given increased labor costs of protection and provisioning, it is likely that enclosed herd management strategies were prompted by extreme temperatures or weather conditions. Stable carbon and oxygen isotopic data demonstrate that sheep were foddered with domestic cereals and provisioned with water over long period, even all year around in some extreme cases (Zhang et al., in prep.). The crowding, restricted movement, and lack of access to fresh pastures of penned animals is well known to increase the risks of disease and associated juvenile mortality (e.g. Halstead, 1998).

The interpretation of high sheep mortality due to conditions of confinement could be interrogated in the future through new evidence on contexts of mortality, sex ratio of infant livestock, and season of death. Mortality profiles from other sites on the plateau and its vicinities, however, provide some additional insights into the frequency of high lamb/kid mortality and issues of specialization versus environmental risk.

Our comparison suggests that high lamb/kid mortality was not unusual at high altitude sites. (Table 3.6 and Figure 3.12). Like Bangga, sheep mortality profiles from the site of Shidaqiu (~2500 m a.s.l., ~ 220 BCE - AD 220) on the east rim Tibetan Plateau reveal an unusually high lamb death rate (81.25%) (He et al., 2012). A large number of sheep also died less than two years old at the site of Changning (~2500 m a.s.l., ~2300-1850 Cal BCE) on the northeast Tibetan
Plateau (Li, 2012). High altitude sites are rare, but it is striking that more numerous lower altitude (< 2000 m a.s.l.) small scale pastoralist sites including Chap I, Zaoshugounao, Maojiaping, Shirenzigou, and Xishan do not exhibit lamb/kid mortality higher than 30%, unlike the early urban site of Shimao.

Overall, the considerable differences in sheep mortality profiles between high altitudinal sites and low altitudinal sites highlight the contribution of environmental risk to the high lamb mortalities at Bangga. We hypothesize that increases in lamb mortality coincided with the emergence of sheep pastoralism in the higher altitudinal regions of the Tibetan Plateau.

Taking together various lines of evidence (zooarchaeology, isotope and archaeobotany), the ancient community that lived at Bangga represents a novel agro-pastoralist approach to facing an extreme environment, employing less mobile but more labor-intensive strategies such as foddering, coralling and water provisioning selected domestic animals, alongside heavy investments in barley cultivation in facing an extreme environment. This constitutes a departure rather than a continuity from the Bronze Age pastoralism well documented across the Inner Asian Mountains and lower altitude western China, where communities sought diverse resources in a much more mobile, less labor intensive but more environment-extensive manner.

3.5.3 Age profiles and equifinality

Modelling based on high natural mortality and management for growth in extreme Tibetan Plateau conditions contributes to current thinking regarding equifinality and interpretation of mortality profiles in zooarchaeology. Our model shows that when varied lamb natural death rates (NDR) are considered, the same Tibetan wool and meat aimed sheep management can result in
highly divergent mortality profiles (Figure 3.5). Comparing our models with other commonly used sheep/goat mortality models in zooarchaeological analyses confirmed that a relatively high natural lamb death rate (>60%) will result in a survivorship curve almost identical to milk aimed mortality profile (Payne, 1973; Vigne & Helmer, 2007), as other archaeologists have cautioned (e.g. Boschin, 2020; Halstead, 1998). Furthermore, patterns presented in Figures 8–10 and Table 5 suggested high similarities between many other mortality profiles proposed by Payne (1973), Redding Jr (1981), and Vigne and Helmer (2007) and several survivorship curves simulated in this study with lower natural lamb death rates. These similarities illustrate ways that high levels of natural lamb death complicate the interpretation of archaeological livestock mortality data. Our findings support the perspective (see Sasson & Greenfield, 2014) that interpretation of archaeological livestock mortality data consider local ethnographical and ethological information, including data regarding environmentally conditioned natural mortality. Models simulated in this study could be referenced and adjusted to evaluate natural pressures confronted by sheep herding systems in high risk areas of the world.

3.6 Conclusion

Our findings draw attention to high lamb mortality at Bangga, tensions between interpretations of specialized management and natural mortality, and specific environmental pressures on ancient herders and their flocks on the Tibetan Plateau. At Bangga, which is one of the highest early pastoral settlements excavated on the plateau, more than half of the lamb deaths were likely natural, due to extreme weather or other catastrophic factors such as disease that occurred during the first year of life. We observed a similar pattern in comparative data from other archaeological
sites on the Tibetan Plateau, such as Shidaqiu. The archaeological data from Bangga are the first to detail herd-based environmental challenges that early pastoralists confronted in the highest altitude regions of Tibetan Plateau. Other archaeological discoveries at Bangga and Tibetan Plateau sites indicate that even under serious environmental pressures, ancient herders survived and maintained their pastoral/agropastoral lifeways for centuries. This contributes to growing insights on the diversity of agropastoralism in the Bronze Age Eurasia with emphasis on particularities of local conditions. Examination of diverse lines of evidence regarding strategies that ancient herders used to manage their sheep to achieve resilient agropastoral systems in the range of high altitude environments of Tibetan Plateau is a priority for further investigation.
3.7 References


Aldenderfer, M., & Moyes, H. (2004). Excavations at Dindun, a pre-Buddhist village site in far western Tibet. Essays of the International Conference on Tibetan Archaeology and Art, Center for Tibetan Studies, Sichuan Union University, Chengdu, China.


Mutundu, K. (2005). Domestic stock age profiles and herd management practices:


Zeder, M. A. (2006). Reconciling rates of long bone fusion and tooth eruption and wear in sheep (Ovis) and goat (Capra). Recent advances in ageing and sexing animal bones, 9, 87-118.


Chapter 4: Feeding sheep and goats in the 2nd–1st millennium BCE central Tibet: insights from stable carbon and oxygen isotopic analysis of tooth enamel

Zhengwei Zhang, Petra Vaiglova, Shargan Wangdue, Xinzhou Chen, Li Tang, Hailun Xu, Jixiang Song, Hongliang Lü, Xinyi Liu

Abstract: Currently, little is known about the development of pastoralism – or the specific herding strategies employed by prehistoric pastoralists – on the Tibetan Plateau. To fill this gap, we analyzed sequential tooth enamel carbonate stable carbon and oxygen isotope values from 10 archaeological sheep and goats from the site of Bangga (3005–2161 cal. BP), which represents one of the earliest pastoralist communities in central Tibet. To help better interpret the archaeological results, teeth from 14 modern sheep and goats sourced from close to the site were analyzed and used as a comparative reference set representing the Indian summer monsoon region. The findings present clear evidence of human control over diet and drinking water of domestic sheep and goats. The data suggests that some sheep and goats were foddered by early central Tibetan pastoralists with C3 plants (likely wheat and barley), while some may have been foddered with significant amounts of C4 plants (either harvested wild C4 plants or C4 crops like millet). Despite the uncertainty of the source of C4 fodder, our results demonstrate that unlike present day central Tibetan pastoralists, who cope with seasonal pasture resource shortage mainly through seasonal movements between pastures, central Tibetan pastoralists three thousand years ago practiced a more elaborated livestock management strategy to assure year-round food of their livestock in order to survive in the extreme environment.
Keywords: Bangga; Tibetan Plateau; Pastoralism; Carbon isotope values; Oxygen isotope values; Sheep; Goat; Tooth enamel carbonate; C4 plants

4.1 Introduction

High-altitude hypoxia, alpine-tundra environment, harsh winter, seasonal rainfall, and aridity make Tibetan Plateau one of the most challenging environments for human survival. Today, the subsistence economy practiced on the Tibetan Plateau is dominated by subsistence agriculture and pastoralism, with a large proportion of the population engaging with agropastoral activities focused on livestock, such as sheep, goats, cattle, and yaks, accompanied by cultivation of crops, such as barley, wheat and buckwheat (e.g. Cheng et al., 1984). This system of multi-resource agropastoralism has its roots in antiquity and can be traced back to at least 3,600 years ago. There has been considerable momentum in recent years towards understanding the prehistoric conditions across the plateau, and the consequent knowledge is having profound implications for our understanding of the Neolithic and Bronze Age societies on a global scale. (e.g. Aldenderfer, 2011; Aldenderfer & Moyes, 2004; d’Alpoim Guedes et al., 2013; Dong et al., 2016; Huo, 2013, 2016; Li, 2007; Lü, 2007, 2016; Meyer et al., 2017; Song et al., 2021; Tong et al., 2015; Zhang et al., 2015; Zhou, 1999). Much of the recent research points to the second half of the second millennium BCE as a period with significant increase in archaeological site numbers across the plateau associated with unambiguous evidence of agropastoral activities (e.g. d’Alpoim Guedes et al., 2015; d’Alpoim Guedes et al., 2013; Dong et al., 2016; Lü, 2007; Lü et al., 2021; Tang et al., 2021; Zhang et al., 2015). This in turn indicates the readiness of those agropastoral groups to adapt to a range of markedly different environments across the areas adjacent Tibet-Qinghai highland. In an even broader geographical scale, the pastoral economy has deeper roots in the
nearby lower altitude environments than on the plateau and can be traced back at least to the
third millennium BC in northwestern China, Inner Asian Mountains and northwest India (e.g.
Chen et al., 2015; Flad, 2007; Frachetti, 2012; Olsen et al., 2006; Outram et al., 2009; Patel &
Meadow, 2017). Much less is known about the nuanced animal herding strategies employed by
people to cope with challenging environments, particularly in central Tibet.

By the middle of the second millennium BC, the subsistence in central Tibet consisted of
cultivation of cereals and husbandry of livestock originating from far-flung locations from either
side of the Asian continent. These include sheep, goat, cattle, wheat, barley, and pea
domesticated in the Fertile Crescent of southwest Asia; broomcorn and foxtail millet and
possibly rice initially cultivated in regions associated with the Yellow and Yangtze River; horse
from northern Kazakhstan; as well as domesticates originating from the border Tibetan Plateau
such as yak and buckwheat (Fu, 2001; Gao et al., 2021; Lü et al., 2020; Tang et al., 2021; Zhou,
1999). The presence of both crops and animals from both the East and West should be
understood in the wider context of the prehistoric food globalization process (Jones et al., 2011;
Liu et al., 2019).

It is well documented that during the three and half millennia between c. 7000 and 3500 BP,
free threshing wheat (Triticum cf. aestivium) and barley (Hordeum vulgare), for instance, spread
from southwest Asia to South and East Asia (including the Tibetan Plateau), while broomcorn
millet (Panicum miliaceum) and foxtail millet (Setaria italica) moved in the other direction: from
China to the West, via Central and South Asia (e.g. Frachetti, 2012; Jones et al., 2011; Liu et al.,
2019; Liu et al., 2017; Spengler et al., 2014). The Tibetan Plateau played a central role in this
narrative, not only for understanding the trans-Eurasian movements of cereal crops and animal
husbandry, but also for enriching the discussion for the context in which subsistence and dietary
innovation occurred in prehistory (e.g. d’Alpoim Guedes et al., 2013; Liu et al., 2019; Spengler et al., 2014). The high-altitude conditions provide a unique setting for assessing how exotic animals and grains were adapted to the novel environments such as central and eastern Tibet (e.g. Liu et al., 2017; Song et al., 2021; Tang et al., 2021).

In this paper, we engage with recent archaeological discoveries in central Tibet and investigate the herding strategies at one of the earliest agropastoral sites in this region. The archaeological site of Bangga (~3000–2200 cal BP) is one of the few prehistoric settlements in central Tibet that has been fully excavated (Liu et al., 2016; Lü, 2016; Lü et al., 2021; Tang et al., 2021). It plays a key role in understanding the prehistoric occupation of southern Tibetan Plateau. To investigate livestock management strategies that enabled prehistoric pastoralists to occupy Bangga, we conducted sequential stable oxygen and carbon isotopic measurements of archaeological and modern teeth from the site. This method has been used in other parts of the world to document how early pastoralists adapted to harsh environments without a year-round supply of available grazing (e.g. Balasse, Boury, et al., 2012; Janzen et al., 2020; Makarewicz, 2017; Vaiglova et al., 2020; Ventresca Miller et al., 2020). This study is the first to document the prehistoric livestock management strategies in this marginal high-altitude environment.
Figure 4. 1 Locations of archaeological sites mentioned in this paper (1. Bangga; 2. Changguogou; 3. Qugong).

4.2 Background

4.2.1 Bangga site

The site of Bangga, located in central Tibet, is situated on a large U-shaped valley on the eastern side of the Qonggyai River, a tributary of the Yarlung Zangbo. The Bangga archaeological site
and the modern village of Bangga are located on an alluvial fan on the western flank of a hill, at an altitude between 3700 and 4800 meters above sea level (m a.s.l). The site was discovered and initially investigated in 1985, and subsequently excavated by archaeologists from various institutions in two archaeological expeditions, 2000–2002 and 2015–2018 (Li, 2001; Lü et al., 2020; Wangdui, 2001). The estimated area of the site is over 3000 m², with more than 400 m² having been excavated to date. The site is composed of irregular stone structures associated with stone-constructed hearths, post holes, and pits dated to around 3005 to 2160 cal. BP (Lü et al., 2020; Tang et al., 2021). At least one stone structure is being identified as a corral, in which a large quantity of sheep and goat dung was retrieved. Over 12,000 archaeological faunal remains have been recovered during the 2015–2018 seasons.

Zooarchaeological analysis of faunal remains suggest sheep (Ovis aries) and goats (Capra hircus) dominate the assemblage (Lü et al., 2021). Specimens that can be attributed to large-sized Bovinae, Equidae, and other smaller-sized wild mammals, including musk deer, gazelle, rodent, and hare, also present but only account for very small proportion of the assemblage. Macro-botanical remains recovered through flotation consist of more than 70,000 charred grains (Tang et al., 2021). Barley dominates the crop portion of the assemblage–over 88% cereal accounts–with a small number of wheat and Fagopyrum sp. (cf. buckwheat). A significant quantity of non-cereal plant remains were identified at Bangga, especially Chenopodium accounts for around 97% of the total identified seeds, likely indicating dung burning contributed to the assemblage formation process. Millet remains were not recovered from Bangga, although they have been documented at nearby archaeological sites that earlier than Bangga (Fu, 2001; Gao et al., 2021).
4.2.2 Local climate and pastures

Under the influence of the Indian Ocean summer monsoon, rainfall is concentrated between June and September, with an average precipitation of 80 mm/month in the summer season. Thunderstorms, hail, torrential rains, and flooding occur frequently in the summer, while the rest of the year is rather arid and windy, with an average precipitation of only 6 mm/month and an average relative humidity of 30 % (Figure 4.2).

Figure 4.2 Annual variation of modern climate and $\delta^{18}$O values of precipitation at Central Tibet. Data from Song et al. (2013) and Yao et al. (2009)

Today people live in Bangga year-round and practice a variety of subsistence activities including farming, herding, gathering, crafting and trade. Cultivated fields are concentrated at the
bottom of the Qonggyai valley and grow various crops, such as barley, wheat, buckwheat, rapeseed, potato, and pea. Animal husbandry is essential, including cattle, sheep, goat, horse, pig, and chicken. More than 75% of the livestock is composed of sheep and goat (Naidong, 2006, pp. 373-374).

Modern sheep and goats at Bangga are born in the winter/early spring, around the time of the Tibetan Spring festival (January or February). Herds are taken to graze on pastures outside the village (Figure 4.3-A), the specific location depending on the seasonal availability of grasses. In the summer/fall (June to October), when temperatures are warmer, sheep and goats are taken to pastures at higher altitudes (~4200 m a.s.l.), situated 2.5 km to the north of the village (see Figure 4.3-B). In the winter/spring (November to May), when the temperatures are colder and higher elevations are susceptible to frost, grazing pastures at altitudes of c.3800 m a.s.l., and within 1 km to the south are targeted (Figure 4.3-C).

Because of differences in altitude and topography, winter and summer pastures are distinct in vegetation composition. In winter, the sheep and goats mainly subsist on mesothermal xeric grasses and shrubs, such as *Sophora moorcroftian*. The summer pasture is covered by alpine and subalpine steppe and is dominated by *Stipa purpurea*, *Carex* sp., and *Artemisia* sp. Both winter and summer pastures are dominated by plants utilizing C₃ photosynthetic pathway. Most C₄ plants are intolerant of high-altitude environments because they originated in warm temperate climates (Sage et al., 2015). Some cold tolerant C₄ species are adapted to this environment but they contribute little to the biomass production (Deng & Li, 2005; Wang et al., 2004). In addition to pasturing, young sheep and goats are occasionally fed on cultivated plants such as barley.
4.3 Principles of tooth enamel carbonate stable isotope analysis

Oxygen and carbon are incorporated into animal tooth enamel through dietary and water intake. Second (M2) and third (M3) molars of sheep and goat mineralize during the first 12 (M2) to 18 (M3) months of the animals lives, and do not remodel thereafter (Zazzo et al., 2010). As the mineralization proceeds from the top of the crown down to the enamel root junction (EDJ), enamel sampled incrementally along the axis of tooth formation records seasonal variation in the isotopic ratios of water and food sources (Kohn et al., 1998; Land et al., 1980; Luyt & Sealy,
Stable isotope analysis of tooth enamel carbonate thus enables reconstruction of the seasonal movements of individuals and animal herds, as well as the season of lambing (e.g. Balasse, Obein, et al., 2012; Blaise & Balasse, 2011; Tornero et al., 2013; Tornero et al., 2016).

Tooth enamel carbonate stable oxygen isotope values (δ¹⁸O) reflect the oxygen isotope composition of body water, which in turn reflects the ratio of ¹⁸O/¹⁶O of local precipitation and ingested plant water (Luz et al., 1984). A range of factors, including elevation, temperature, humidity and amount of precipitation, influence the seasonal δ¹⁸O values of water available for sheep/goat consumption, and in general result in ¹⁸O-depleted signatures at higher elevations (Bar-Matthews et al., 1999; Britton et al., 2009; Dansgaard, 1964; Gat, 1980; Kohn & Welker, 2005; McCrea, 1950; Tornero et al., 2016).

Precipitation in central Tibet is fed by the Indian Ocean (Liu et al., 2007) and is concentrated in summer (Song et al., 2013). The region around Bangga does not have any nearby lakes, glaciers or snowlines (Tang et al., 2000). Measurements of local modern-day precipitation have recorded high δ¹⁸O values in the winter (the drier season; c. –5 ‰) and low values in the summer (the wet season, c. –20 ‰) (Yao et al., 2009) (Figure 4.2). Tooth enamel carbonate of animals feeding on fresh local vegetation all year round should thus record similar sinusoidal patterns.

Sequential tooth enamel carbonate stable carbon isotope values (δ¹³C) reflect the seasonal changes in composition of ingested food sources. A range of factors, including temperature, altitude and water availability, can influence the δ¹³C values of plants, with C₃ plants recording less negative δ¹³C values when grown under water stress and at higher elevations (e.g. Hartman & Danin, 2010; Körner et al., 1991; P. Smedley et al., 1991; Tieszen, 1991). In a survey of plants across the Tibetan Plateau, Deng and Li (2005) observed altitudinal increases of 0.7–2.6 ‰ / km.
Seasonal diets of herbivores can thus vary as a result of grazing in locations at varying altitudes with varying compositions of plant communities (Cerling et al., 1993; Thorp & Van Der Merwe, 1987).

Both summer and winter pastures at Bangga are dominated by $C_3$ plants with $\delta^{13}C$ values ranging between $-21.8\%$ and $-29.1\%$ (Deng & Li, 2005; Wang et al., 2008). If sheep and goats raised at Bangga consumed on $C_3$ plants and did not migrate between higher-altitude summer pastures and lower-altitude winter pasture, their tooth enamel carbonate $\delta^{13}C$ values should record sinusoidal patterns reflecting seasonal fluctuation in local plant water and rain water $\delta^{13}C$ values. If, on the other hand, they moved altitudinally, or were fed on stored fodder (reflecting $\delta^{13}C$ values of plants from a different season), their tooth enamel carbonate sequences would not follow the sinusoidal pattern.

In addition, high $\delta^{13}C$ values could have been caused by consumption of $C_4$ plants. In high altitude cool environments, $C_4$ photosynthesis is considered to be maladapted, due to frequent chilling injury, low productivity, and inferior quantum yields compared with $C_3$ (Sage 2015). However, it is also recognized that $C_4$ photosynthesis per se does not exclude plants from cold climates. Although there is a substantial drop in the $C_4$ contribution to biomass production and regional floras at high altitudes, $C_4$ species do exist in such environments. In Tibet, numerous cold-and/or cold-tolerant $C_4$ plants—including grasses, sedges, and dicots—has been documented growing in locations over 4000 m a.s.l. (Sage et al., 2015; Wang et al., 2004; Wang, 2003) with $\delta^{13}C$ values ranging from $-11.10\%$ to $-13.69\%$ (Deng & Li, 2005; Wang et al., 2004). In addition, although no archaeological remains of $C_4$ crops were reported at the site of Bangga, millet remains have been previously reported from the several nearby contemporary sites including Changguogou, Qugong, and Bangtangbu (Fu, 2001; Gao et al., 2021; Tang et al., 2021).
2021). An assessment of the plants consumed by caprine from Bangga will shed light on the
dietary and mobility patterns of the animals and aid in determining whether C₄ plants grew
locally around Bangga in prehistory.

4.4 Materials and methods

Fourteen modern mandibular second (M2) and third molars (M3), representing four sheep and
three goats were sampled to help interpret the archaeological measurements. They were collected
at the village of Bangga in the summer of 2017 (Table 4.1). The archaeological samples consist
of 10 Caprinae mandibular M2 and M3s (Table 4.2). Four of these mandibles are likely
attributed to sheep and two are attributed to goats based on morphological characteristics
following (Gillis et al., 2011; Zeder & Pilaar, 2010). These mandibles likely represent six
individuals. Specimens AS1 and AS2 were collected from the same context and due to their
similar size likely represent one individual.

Table 4. 1 Modern sheep and goat samples analyzed in this study

<table>
<thead>
<tr>
<th>ID</th>
<th>Tooth</th>
<th>Species</th>
<th>Tooth wear stage</th>
<th>Age (yr.)**</th>
<th>Sex</th>
<th>Birth season</th>
<th>Death season</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS1</td>
<td>M2</td>
<td>Sheep</td>
<td>g</td>
<td>3–4</td>
<td>Female</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>g</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS2</td>
<td>M2</td>
<td>Sheep</td>
<td>g</td>
<td>N/A</td>
<td>N/A</td>
<td>Winter</td>
<td>Unknown</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>g</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS3</td>
<td>M2</td>
<td>Sheep</td>
<td>g</td>
<td>3–4</td>
<td>Female</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>b</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MS4</td>
<td>M2</td>
<td>Sheep</td>
<td>j</td>
<td>3–4</td>
<td>Male</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>g</td>
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<td></td>
</tr>
<tr>
<td>MG1</td>
<td>M2</td>
<td>Goat</td>
<td>e</td>
<td>3–4</td>
<td>Male</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td>M3</td>
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<td>b</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MG2</td>
<td>M2</td>
<td>Goat</td>
<td>e</td>
<td>3–4</td>
<td>Male</td>
<td>Winter</td>
<td>Summer</td>
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<tr>
<td></td>
<td>M3</td>
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</tr>
<tr>
<td>MG3</td>
<td>M2</td>
<td>Goat</td>
<td>e</td>
<td>3–4</td>
<td>Male</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>a</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* Recorded following Grant (1982).
** Informed by local herder
Table 4. 2 Archaeological sheep and goat samples analyzed in this study

<table>
<thead>
<tr>
<th>ID</th>
<th>Teeth</th>
<th>Archaeological Context</th>
<th>Radiocarbon Dates*</th>
<th>Species</th>
<th>Tooth wear stage**</th>
<th>Estimated age (yr.)***</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Conventional age</td>
<td>Calibration (95.4% credible interval)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS1</td>
<td>2M</td>
<td>Layer 11</td>
<td>\</td>
<td>Sheep (?)</td>
<td>g</td>
<td>5–6</td>
</tr>
<tr>
<td></td>
<td>3M</td>
<td></td>
<td>\</td>
<td>g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS2</td>
<td>M2</td>
<td>Layer 11</td>
<td>2280 ± 30 BP</td>
<td>ca. 403–211 BC</td>
<td>Sheep</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>\</td>
<td>g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS3</td>
<td>M2</td>
<td>Layer 13</td>
<td>2590 ± 30 BP</td>
<td>ca. 820–595 BC</td>
<td>Sheep</td>
<td>f</td>
</tr>
<tr>
<td>AS4</td>
<td>M2</td>
<td>2017F2-Layer 1</td>
<td>1790 ± 30 BP</td>
<td>ca. AD 133–330</td>
<td>Goat</td>
<td>g</td>
</tr>
<tr>
<td>AG1</td>
<td>M2</td>
<td>Layer 12</td>
<td>\</td>
<td>Goat</td>
<td>g</td>
<td>3–5</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>\</td>
<td>g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AG2</td>
<td>M2</td>
<td>Layer 10</td>
<td>1790 ± 30 BP</td>
<td>ca. AD 133–330</td>
<td>Goat</td>
<td>g</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td></td>
<td>\</td>
<td>g</td>
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<td></td>
</tr>
</tbody>
</table>

* Data from (Tang et al., 2021)

** Recorded following Grant (1982).

*** Estimated following Zeder (2006).

We followed approaches established in previous studies, which demonstrated that seasonal movements in both wild and domestic bovids can be identified through sequential oxygen and carbon stable isotopic analyses of hypsodont crowned herbivore dental enamel (Balasse et al., 2013; Balasse, Obein, et al., 2012; Tornero et al., 2018; Tornero et al., 2013; Tornero et al., 2016). All tooth surfaces were cleaned using a tungsten abrasive drill bit and between 9-27 samples were taken from each tooth using a diamond drill bit following Balasse (2003); Miller et al. (2018). Samples were taken sequentially and perpendicularly to the crown growth axis of buccal side of distal lobe of M2 and middle lobe of M3. Samples of enamel powder weighing between 1.7 and 14.7 mg were treated in 30% hydrogen peroxide for 24 h and subsequently in 1M buffered acetic acid for 24 hours following Crowley and Wheatley (2014). Mass loss during pre-treatment was between 5 % and 52 % (0.36–5.36 mg) for all samples.

Bulk δ¹³C and δ¹⁸O values were measured using a Gas Bench II coupled to a Delta V advantage isotope ratio mass spectrometer at the Fike Laboratory for Biogeochemistry at Washington University in St Louis. δ¹³C and δ¹⁸O values were both calibrated relative to VPDB using international standards NBS-18 (δ¹³C = −5.01 ‰, δ¹⁸O = −23.20 ‰), NBS-19 (δ¹³C = 110...
1.95 ‰, $\delta^{18}O = -2.20 ‰$), and CO-8 ($\delta^{13}C = -5.76 ‰, \delta^{18}O = -22.70 ‰$). Measurement uncertainty was monitored using the enamel standard 2 ($\delta^{13}C = -13.2 \pm 0.26 ‰, \delta^{18}O = -4.6 \pm 0.21 ‰$) and the enamel standard 3 ($\delta^{13}C = -10.0 \pm 0.19 ‰, \delta^{18}O = -0.8 \pm 0.2 ‰$), and calculated following the standardized procedure outlined in Szpak et al. (2017). Precision ($u(Rw)$) was determined to be ± 0.133 ‰ for $\delta^{13}C$ and ± 0.267 ‰ for $\delta^{18}O$ on the basis of repeated measurements of nine enamel standard 2 and nine enamel standard 3 placed in every analytical run and on the triplicate measurements of the samples. Accuracy (systematic error, $u(bias)$) was determined to be ± 0.382 ‰ for $\delta^{13}C$ and ± 0.416 ‰ for $\delta^{18}O$ on the basis of the difference between the observed and known $\delta$ values of the internal standards. Using the equations in Appendix F from Szpak et al. (2017), the total analytical uncertainty was estimated to be ± 0.405 ‰ for $\delta^{13}C$ and ± 0.494 ‰ for $\delta^{18}O$.

The modern sequences were used as a proof of concept for the cosine-function method outlined in Balasse, Boury, et al. (2012); Balasse, Obein, et al. (2012). The method, built using reference samples from France and Scotland, has been successfully used to determine the timing of birth of herbivores by comparing the positions at which the maximum $\delta^{18}O$ values occur on the tooth axis. Due to the fact that teeth of different individuals grow to different lengths, the positions are normalized to the tooth length. These samples will provide a new set of reference materials for applying this method to assess whether the animals were born in the same month or several months apart.
4.5 Results

The results of all modern and archaeological samples are presented in Table 4.3 and Figures 4.4 to 4.7.

Table 4.3 Summary of stable carbon and oxygen isotopic values of tooth enamel carbonate analyzed in this study

<table>
<thead>
<tr>
<th>ID</th>
<th>Tooth</th>
<th>Enamel length (mm)</th>
<th>n=</th>
<th>Min δ¹³C</th>
<th>Max δ¹³C</th>
<th>Range δ¹³C</th>
<th>Mean δ¹³C</th>
<th>Intra-tooth δ¹³C SD</th>
<th>Min δ¹⁸O</th>
<th>Max δ¹⁸O</th>
<th>Range δ¹⁸O</th>
<th>Mean δ¹⁸O</th>
<th>Intra-tooth δ¹⁸O SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS1</td>
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4.5.1 Modern samples

Intra-tooth variation in the δ¹⁸O and δ¹³C values of most modern teeth is reversed (Figure 4.4), in other words maximum δ¹³C values occur together with minimum δ¹⁸O values and vice versa.

The mean δ¹⁸O value of modern sheep is −8.9 ‰ for M2 (with intra-tooth variation from 4.1 ‰ to 6 ‰) and −8.6 ‰ for M3 (with intra-tooth variation from 4.7 ‰ to 8.2 ‰). The mean δ¹⁸O values of modern goats are −7.6 ‰ for M2 (with intra-tooth variation from 5.3 ‰ to 7.5 ‰) and −9 ‰ for M3 (with intra-tooth variation from 4.1 ‰ to 8.2 ‰). In contrast, the mean δ¹³C values of modern sheep are −7.5 ‰ for M2 (with intra-tooth variation from 2 ‰ to 3.9 ‰) and −8.4 ‰
for M3 (with intra-tooth variation from 1.4 ‰ to 2.4 ‰). The mean δ¹³C values of modern goat are −8.8 ‰ for M2 (with intra-tooth variation from 2.4 ‰ to 2.8 ‰) and −8.9 ‰ for M3 (with intra-tooth variation from 1.6 ‰ to 2.4 ‰). Samples from both modern sheep and goat present much wider ranges of δ¹⁸O than δ¹³C values. For both modern sheep and goat, the intra-tooth variation in δ¹³C values are slightly larger for M2 than for M3. Similarly, to what has been observed in other regions of the world (Janzen et al., 2020), the mean δ¹³C values of modern sheep are consistently slightly higher than those of modern goats at Bangga.

Figure 4. 4 Sequential δ¹³C and δ¹⁸O values of modern samples.
Figure 4. 5 Sequential δ^{13}C and δ^{18}O values of archaeological samples.

Figure 4. 6 The δ^{13}C values of modern (left) and archaeological (right) samples analyzed in this study. Unshaded areas indicate ranges of δ^{13}C values for pure C_{3} diets (> −8 ‰ for modern samples, > −6.5 ‰ for archaeological samples).
Figure 4. The δ¹⁸O values of modern (left) and archaeological (right) samples analyzed in this study.

Table 4. Results of the calculation of a line of best fit (using the method of least squares) for variation in period (X), amplitude (A), position of the δ¹⁸O max value (x₀), and mean δ¹⁸O (M) of modern tooth enamel carbonate sequences from this study. Pearson’s R expresses the correlation between the measured and the modelled values. x₀/X represents the delay of δ¹⁸O max values with respect to the period, used in this study to assess the timing of the animals’ births.

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<th>MS2 (M2)</th>
<th>MS3 (M2)</th>
<th>MG1 (M2)</th>
<th>MG2 (M2)</th>
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Figure 4. 8 Uni-variate scatter plot of x0/X values (distance at which $\delta^{18}O_{\text{max}}$ values occur in a tooth, $x_0$, with respect to the period recording the annual cycle, $X$) of sheep and goats from Bangga. The y–axis is divided into 12 units, each corresponding to one month of the year.

The $\delta^{18}O$ sequences of 6 modern individuals (three sheep and three goats) showed full annual sequences, which made them amenable to use for estimating the timing of birth following Balasse, Obein, et al. (2012) (see Table 4.4 and Figure 4.8). The fit between the measured $\delta^{18}O$ values and the modelled values are significant ($R \geq 0.968$ for all teeth). The normalized delay, $x_0/X$, is between 0.25 and 0.60, suggesting that these individuals were born in a narrow range of time that within 3 months of the year. This corresponds well with the known information from modern specimens from individuals that were born in the winter and early spring. The accordance between the modeled and the actual lambing season of modern samples in this study suggests that Balasse, Obein, et al. (2012)’s cosine-function method is applicable for assessing birth seasonality of caprine from the Tibetan Plateau. This method can therefore be applied in the
future to investigate prehistoric pastoralists’ preference of lambing season when suitable archaeological samples are available from the Tibetan Plateau.

4.5.2 Archaeological samples

The δ¹³C and δ¹⁸O values of archaeological tooth enamel carbonate of both sheep and goats show varied patterns. Only AS3 (M2), AG2 (M2), and AG2 (M3) display patterns close to the sinusoidal variation in δ¹³C and δ¹⁸O values (Figure 4.5). The δ¹⁸O and δ¹³C values of the remaining teeth show either flat curves or curves that are too short to record an entire annual cycle. The δ¹³C and δ¹⁸O value sequences of AS2M3, AS3M2, AS4M2, AG2M2, and AG2M3 are reversed. The mean δ¹⁸O values from archaeological samples are significantly lower than those of modern samples. The mean δ¹³C values of archaeological sheep and goat teeth (mean = −6.31 ± 2.44 ‰, n=166) are higher than those of modern samples (mean = −8.3 ± 1.23 ‰, n=255). The mean δ¹⁸O values archaeological sheep are −13.2‰ for M2 (with intra-tooth variation from 1.8 ‰ to 5.9 ‰) and −12.2 ‰ for M3 (with intra-tooth variation from 4.2 ‰ to 5.1 ‰). The mean δ¹⁸O values of archaeological goat are −11.1 ‰ for M2 (with intra-tooth variation from 3.6 ‰ to 7.9 ‰) and −11.5 ‰ for M3 (with intra-tooth variation from 3.1 ‰ to 5.8 ‰). The mean δ¹³C values of archaeological sheep are −6.6 ‰ for M2 (with intra-tooth variation from 0.6 ‰ to 6.3 ‰) and −5.5 ‰ for M3 (with intra-tooth variation from 2.5 ‰ to 3 ‰). The mean δ¹³C values of archaeological goat are −6.5‰ for M2 (with intra-tooth variation from 1.4 ‰ to 2.3 ‰) and −6 ‰ for M3 (with intra-tooth variation from 0.7 ‰ to 1.7 ‰).
4.6 Discussion

4.6.1 Modern sheep and goats: drinking water and diets

Stable oxygen and carbon isotope values of modern sheep and goat dental enamel provide a reference set for interpreting human and sheep/goat behaviors and their likely consequences in archaeological sheep and goat enamel stable oxygen and carbon isotopic values. Modern sheep and goat enamel specimens present intra-tooth variation in δ¹⁸O sequence reverse to that in δ¹³C sequences – i.e., lower δ¹⁸O values correspond to higher δ¹³C, and *vice versa*. This is consistent with what would be expected for seasonal movements between pastures and confirms the intra-tooth δ¹⁸O value variations can be used as seasonality indicator. The lower δ¹⁸O values reflect the summer season as the water bodies in the domain of Indian Ocean summer monsoon are more depleted in ¹⁸O compared to those in the westerly domain dominating this area in the winter (Yao et al. 2009). Furthermore, rain water in central Tibet that derived from the Indian Ocean summer monsoon becomes further ¹⁸O-depleted as a result of gradual rainout of southwesterly borne marine moisture in the course of long-distance transportation and lifting over the Himalayas during the rainy season. This results in the summer-winter lapse rate of δ¹⁸O values in groundwater in central Tibet is as large as 15 ‰ (cf. Yao et al., 2009). Our results also show a relatively small amplitude of intra-tooth variation in δ¹⁸O values (ranging between 4 and 8 ‰), which is lower than that reported in other parts of mid-latitude Eurasia (e.g. Hermes et al., 2019; Tornero et al., 2016). This is likely due to the opposing effects of the monsoon borne moisture with very low δ¹⁸O values (c. –20 ‰), and the ambient temperature leads to higher δ¹⁸O values in the warm season.
Our modern samples also confirm that $\delta^{13}$C values in sheep and goat dental enamel from the study area can be used as the indicator for investigating mobility of sheep/goat and likely for detecting other factors that might impact dietary of sheep/goat, such as human foddering. Lower $\delta^{18}$O values in our modern samples reflect summer conditions and correspond to higher $\delta^{13}$C values. Variation in the carbon stable isotope compositions of enamel bioapatite reflect either seasonal changes in dietary plant $\delta^{13}$C values or/and the changes in relative proportions of C$_3$/C$_4$ plants. This could be biased by grazing preferences. However, the contribution of C$_4$ species to local floras and vegetation stands shows a sharp decline with increasing altitude (see Sage & Monson, 1998 for a summary). On a global scale, such a shift towards C$_3$ plant domination occurs between 1500 and 3000 m a.s.l. Given the elevation range of the pastures near Bangga is 3700–4200 m a.s.l., C$_3$ plants are expected to dominate the local floras. Our results show the mean $\delta^{13}$C values for both M2 and M3 in modern sheep and goats are below (notwithstanding an outlier MS3) the cut-off value for a pure C$_3$ diet of $-7.3$ to $-8\%$ for modern Tibetan herbivores suggested by Wang et al. (2008). If the intra-tooth $\delta^{13}$C variations are driven by changes in stable carbon isotope values in C$_3$ plants, the inverted cyclicity in the $\delta^{13}$C and $\delta^{18}$O sequences implies the animals were at drier and/or higher locations during summer. This is supported by our observation of modern herders’ seasonal movements between winter and summer pastures near Bangga. The higher $\delta^{13}$C values in modern samples corresponding to summer could be explained by the altitude effect, due to changes in aridity and atmospheric pressure along altitude gradient (e.g. Körner et al., 1991; Szpak et al., 2013). High carboxylation rates relative to stomatal conductance and/or high carboxylation efficiency for plants growing at high altitudes could also result in an increase in $\delta^{13}$C values (Korner & Diemer, 1987; Körner et al., 1991).
Although the majority of modern sequential data show that modern sheep were predominantly grazing on C₃ plants, there are a few exceptions, which suggest a dietary contribution from C₄ or CAM plants (Figure 4.6). This potential of C₄ (or CAM) contribution is particularly visible in individual MS3, a sheep with maximum δ¹³C values of −4.2 ‰ in M2 and −5.8 ‰ in M3, significantly higher than the −7 ~ −8 ‰ cut-off between mixed C₃/C₄ consumption, although mean intra-tooth δ¹³C values are much lower (Table 4.3). This suggests some animals, particularly individual MS3 have grazed small amounts of C₄ (or CAM) plants in summer. This can best be explained as there are wild-standing C₄ plants growing around Bangga. The most common fodder that modern Bangga herders feed to sheep and goats are wheat and barley (C₃ plants) seeds and by-products of their processing, such as straw and chaff. No C₄ crops (e.g., maize, millet, sorghum) being cultivated in modern day Bangga. In a study of animal forage in modern-day Tibet, Jiang (2008, pp. 15–18) listed 57 taxa that are commonly used to feed domestic animals, none of which is C₄ (or CAM) plant. The likelihood of C₄ plants is incorporated into animals’ diets via husbandry activities is low.

4.6.2 Archaeological sheep and goats: Drinking water resources

Patterns observed in archaeological intra-tooth δ¹⁸O sequences show significant differences from those found in modern sheep and goats, indicating that they were drinking from different water sources. Furthermore, most archaeological animals display some degree of intra-tooth δ¹⁸O variation, which could be interpreted as representing a seasonal change in the δ¹⁸O of drinking water. However, the amplitude of this intra-tooth variation in archaeological specimens is much narrower than that in contemporary animals. At least two individuals (AS2 and AG1) display
considerably lower intra-tooth changes than recorded in modern animals (Figure 4.5). This could be because the primary drinking water source was derived from groundwater as small intra-tooth variation of this kind have been documented due to ground water sources in other studies (e.g. Reade et al., 2016). Unlike surface water, however, the δ¹⁸O value of groundwater reflects mean oxygen isotope compositions in long-term precipitation and the δ¹⁸O of groundwater does not typically vary seasonally (Darling, 2004; Fricke et al., 1998).

4.6.3 C₃ fodders and Contribution of C₄ plants to archaeological sheep/goat diets

It is interesting to note the archaeological specimens fall into two distinct groups: teeth that display extremely low variations in intra-tooth δ¹³C values and lower δ¹³C values (AG1M2, AG1M3, AS1M2, and AS2M2), and teeth that display high variations in intra-tooth δ¹³C values and higher δ¹³C values (AS1M3, AG2M2, AG2M3, AS3M2, AS4M2, and AS2M3) (Figure 4.4–4.6). These two groups suggest that early Bangga herders may have applied different strategies to managing their herds. Noteworthily, different teeth from the same individual can display distinct δ¹³C values. For example, M₂ of the archaeological sheep AS1 falls into the first group signifying C₃ plant based diet, while the M₃ of the same individual fall into the second group that is consistent with C₄ plant diet (same patterning for another sheep from Bangga AS2). This indicates diet of the same animal changed significantly from the first and second year perhaps reflecting different foddering strategies employed by herders according to animals’ age span.

The first group is best explained as year-round dietary homogeneity resulting from human provisioning with C₃ plants. If the animals were taken to graze on extensive pastures, we would
expect more pronounced intra-tooth variation as a result of variability in stable carbon isotope compositions in wild-standing vegetation, and more dietary heterogeneity resulting from individualized grazing/browsing behaviors. Since barley is the dominating grain in the archaeobotanical assemblage at Bangga and was locally processed (Tang et al. 2021), this suggests barley may have been used for provisioning sheep and goats.

The second group displays more intra-individual δ¹³C variation also displays higher δ¹³C value than the first group. Taking the fossil fuel effect (+1.5 ‰; Friedli et al., 1986) into account, it has been suggested, the absolute cut-off value for a pure C₃ diet in pre-industrial times is between −7 and −8 ‰ on a global scale (Cerling et al., 1997). Wang et al. (2008) suggest it is closer to −6.5 ~ −7 ‰ in Tibet due to the altitude effect. As such, most of archaeological samples in this second group show clear dietary contribution from C₄ plants. These cut-off values are, however, calculated using an enamel-diet δ¹³C enrichment factor of +14 ‰ (Cerling & Harris, 1999). It has been suggested the enamel-diet offset for ruminants like sheep and goat is closer to +11 ~ 12 ‰ (Cerling & Harris, 1999), which makes the C₄ signals more pronounced for archaeological sheep/goats at Bangga. We conclude that individuals in group two grazed on a significant amount of C₄ plants. Our modern samples have revealed, though there are wild-standing C₄ plants, the landscape near Bangga dominated by C₃ vegetation. Archaeobotanical remains at Bangga also lack clear evidence of C₄ plant (Tang et al., 2021). This suggests that if those C₄ plants in diets of sheep at Bangga are derived wild-standing C₄ plants, these sheep might have been taken away from the immediate eco-zone. If this the case, we should have also observed more dramatic variation in δ¹⁸O values of archaeological samples. Furthermore, three individuals, AS1M3, AS2M3, and AG2 that show clear C₄ signals also display very low intra-tooth δ¹³C variations (Figure 4.5). AG2, in particular, shows almost no seasonal dietary variation
during the period of M2 and M3 mineralization. In other words, this animal consumed a significant amount of C₄ plants in the winter. If this animal grazed on pastures (assuming dominated by C₄ plants), we should still expect seasonal variations due to the cold intolerance nature of C₄ taxa and incompatibility with high altitude winter. It is most likely that this animal was provisioned by humans with a diet that included significant amounts of C₄ plants. One possibility is that ancient Bangga inhabitants harvested some wild C₄ plants (e.g. *Salsola*) and provided them to their livestock intentionally. On the other hand, though no C₄ crop has been reported from archaeobotanical assemblage at Bangga (Tang et al., 2021), broomcorn and foxtail millet (both C₄ taxa) are recovered at nearby archaeological sites, such as Changguogou (~60 km to the northwest of Bangga, dated to between 3500 and 2800 Cal BP) and Qugong (~90 km to the northwest of Bangga, dated to between 3500 and 3000 Cal BP) (Fu, 2001; Gao et al., 2021). C₄ crops is thus known to the communities in central Tibet since the second millennium BC. Another plausible scenario is that millet was cultivated near Bangga and used exclusively as animal fodder rather than human food, leaving no trace in the macrofossil assemblage (as it is formed primarily through domestic food preparing activities), but raveled by the isotopic evidence. This scenario resonates with the earliest use of millet crop in Inner Asian Mountain Corridor with isotopic evidence suggesting provisioning sheep and goats with C₄ in the third millennium BC (Hermes et al., 2019).

4.7 Conclusion

This article presents the first high-resolution sequential stable oxygen and carbon isotopic analysis of archaeological animal tooth in the Tibetan Plateau region, documenting livestock
management strategies in central Tibet during the second and first millennium BC. Results presented in the paper allows several primary implications concerning both the modern and archaeological animals.

Intra-tooth $\delta^{18}$O and $\delta^{13}$C sequences of the modern animals fit a pattern of movement between pastures consistent with the observation that present day central Tibet herdsmen move their sheep and goats in order to cope with seasonal shortage of grazing resource. Pastures used by modern herds are dominated by C$_3$ plants, although a small amount of C$_4$ plants could be grazed by some animals (e.g. specimen AS4). Surface water is the main source of drinking water.

In contrast to modern animals, archaeological specimens indicate different sheep and goat pasturing systems. First, some ancient sheep and goats at Bangga could have obtained a considerable proportion of their drinking water from springs or wells fed by local groundwater. Second, it is likely that herdsmen provisioned some animals with fodder that included byproducts of cultivation of both C$_3$ (likely barley) and C$_4$ (e.g. millet) cereals. Our findings also suggest that some animals spent the summer in environments with high salinity e.g. salt marsh near brackish water lakes and fed on salt-tolerant C$_4$ plants. This possibility fits archaeobotanical observations of the endozoochoric origin of Salsola and Cheopodium, as well as ethnographic records of herdsmen using sheep/goats as draft animals for salt pan transportation.
4.8 References


Aldenderfer, M., & Moyes, H. (2004). Excavations at Dindun, a pre-Buddhist village site in far western Tibet. Essays of the International Conference on Tibetan Archaeology and Art, Center for Tibetan Studies, Sichuan Union University, Chengdu, China,


Luyt, J., & Sealy, J. (2018). Inter-tooth comparison of δ13C and δ18O in ungulate tooth enamel


(Ovis) and goat (Capra). Recent advances in ageing and sexing animal bones, 9, 87-118.


Serving as pack animals and for dairy, meat, fiber, and fuel, herd animals that include yak (Bos grunniens), cattle (Bos taurus), horse (Equus caballus), sheep (Ovis aries), and goat (Capra hircus) are indispensable to the everyday lives of contemporary people on the Tibetan Plateau (Huang et al., 1981). Recent archaeological studies accentuated the role played by pastoralism and reliance on herd animals in the process of large-scale human occupation of high altitudinal areas of the Tibetan Plateau since at least the second millennium BC. Ethnographical records regarding recent Tibetan herders, however, highlight the difficulties of maintaining pastoral lifeways on Tibetan Plateau. Due to effect of the high altitude, reproduction rates of livestock on the Tibetan Plateau are relatively low which slows the growth of herds (Yang et al., 1993). Meanwhile, natural loss of livestock on the Tibetan Plateau is rather high and makes the maintenance of herd size difficult. Livestock can be abruptly and completely decimated by highly variable and unpredictable ecological factors, including low temperature, extreme weather, epidemic animal diseases, and wild predators (Cheng et al., 1984, pp. 50-51; Guo et al., 2018; Huber, 2005, 2012; Miller, 2000; Xin & Chen, 2013). Surviving and maintaining pastoral lifeway on the plateau thus requires resilience to a range of environmental challenges.

Among herd animals central to pastoralism and pastoral survival on the Tibetan Plateau today, yak are the only animals indigenous to the high altitudinal Tibetan Plateau (Qiu et al., 2015). All the remaining taxa were domesticated elsewhere and introduced to the plateau from much lower environments together with non-native cultigens such as barley and millet in the second millennium BC. How novel forms of pastoralism developed in the environments of the
Tibetan Plateau in the past is poorly understood. This has been obscured, in part, by a lack of systematic zooarchaeological studies of faunal remains from early pastoral settlements on high elevation (>3500 m a.s.l.) regions of the Tibetan Plateau. In this project, I addressed this question in two ways.

To address the challenge of identifying and discriminating among Tibetan wild bovids and domestic animals, I developed new method for identifying and discriminating takin (*Budorcas taxicolor*) from yak, cattle, gaur (*Bos gaurus*), and water buffalo (*Bubalus bubalis*) in archaeofaunal assemblages. This research provided a reproducible method for distinguishing takin from other large bovids in this region. The osteomorphological criteria established in this study are important to archaeological investigations on early usage of wild bovids and the emergence and development of pastoralism on the Tibetan Plateau.

To examine ways that environmental challenges might have threatened the survival of early pastoralists at the high altitudinal regions of the Tibetan Plateau and how early central Tibetan pastoralists managed their livestock to cope with environmental pressures I studied faunal materials from the site of Bangga in Central Tibet. With an elevation of near 4000 m a.s.l. and dated to the first millennium BC, the archaeological settlement of Bangga represents one of the early agro-pastoral communities at high altitudinal area of the Tibetan Plateau (Li, 2001; Lü et al., 2020; Lü et al., 2021; Region, 1986; Tang et al., 2021; Wangdui, 2001).

The question about how environmental challenges might threaten the survival of early pastoralists at the high altitudinal regions of the Tibetan Plateau is addressed through reconstruction of the mortality profile for sheep at Bangga. A relatively large sample, with a total of 42 sheep left mandibles excavated from Bangga were used for this analysis. Result reported in the Chapter 3 revealed that most sheep at Bangga (64.28%, n= 27) died within the first year of
their life. Neonatal lambs, which did not survive the first two months of their lives, made up 30.23% (n=13) of the assemblage. This resembles a specialized milk oriented kill-off pattern as described by Payne (1973); Vigne and Helmer (2007) in other regions of Eurasia. However, a model for sheep mortality simulated based on local Tibetan livestock management data today and regional ethnographical records provides alternate perspectives on interpretation, augmented by archaeological evidence from the broader area. Herd mortality metadata from Tibet and simulation suggest that under high risk conditions specialization is a less probable interpretation than high natural mortality. Contextual archaeological and isotopic data for corraling and foddering at Bangga indicate specific ancient disease and nutritional risks associated with periodic confinement and lack of access to pasture. Comparison with sites from other regions of the plateau and its vicinities document similar high mortality at Shidaqiu (~2500 m a.s.l.) (He et al., 2012), but not at lower elevations (<2000 m a.s.l.), drawing attention to high altitude risk. Together, these findings indicate that high juvenile mortality presented a threat for ancient herders who suffered from serious environmental pressures on the Tibetan Plateau.

Record on the reproduction of modern Tibetan sheep shows that due to effect of the high altitude, ewes on the Tibetan Plateau can usually only bear one lamb per year while ewes at lower elevations more often can bear two per year (Yang et al., 1993). This results in a relatively low reproduction rate (48% ~ 87%) of Tibetan sheep herds and makes the growth of herd size rather slow. If reproduction rates of ancient Bangga sheep were not higher than the modern records, given high lamb mortality, the maintenance of sheep herd size would have been challenging. Nevertheless, the radiocarbon dates of Bangga suggests that the settlement was occupied by agropastoralists for at least six centuries (Lü et al., 2021). Throughout this period, the Bangga faunal assemblage indicates consistent reliance on sheep and other domestic animals.
and cultigens. It is, therefore, particularly interesting to explore additional ways that these early central Tibetan pastoralists maintained their pastoral life.

To address the question of how early central Tibetan communities manage their sheep and goats to cope with environmental pressures, I analyzed sequential stable carbon and oxygen isotope compositions in tooth enamel carbonate of 10 archaeological sheep and goats from Bangga. In order to provide a better isotopic baseline, I collected teeth specimens of 14 modern sheep and goats from the research area and conducted sequential isotopic analysis. The findings detailed in Chapter 4 show clear evidence of human control over diet and drinking water of domestic sheep and goats. First, some animals obtained a considerable proportion of their drinking water from sources fed by groundwater, indicating human influences. Second, the data suggests that some sheep and goat were provisioned with cereals such as barley and foxtail millet. Both these cultigens were new components of the central Tibetan economy, as they were domesticated in low altitude environments elsewhere and introduced to the area during the second millennium BC. Thirdly, some animals show unambiguous C₄ plant base diet during summer seasons in a place where these plants contributed little to the natural vegetation. This infers either seasonal provisioning with C₄ crops such as millet, or the animals were taken to nearby saline marsh environments during the summer seasons.

These results demonstrate that central Tibetan agropastoralists three thousand years ago practiced a specialized livestock management strategy focusing on sheep and goat herds (although data relates bovid taxa is current limited) alongside intensive cultivation systems to assure year-round food supplies for both humans and livestock in this extreme environment.

This suggests that early herders strengthened ecological/economic resilience through assets such as high labour inputs relating to sheep/goats foddering and water sustaining. This is a
surprise as the Tibetan pastoralist economy is generally viewed as a system that relies less on heavy labor input per area unit but as a productive system driven by the expansiveness of food production and land ecological opportunism linked to pastoral activities (low labor input per area maybe but highly mobile). However, the evidence presented in this dissertation elucidated an agropastoral community in central Tibet three thousand years ago invested labor-intensive strategies— in both the agricultural and pastoral spheres of the economy—to buffer an otherwise challenging environment.

Archaeobotanical studies at Bangga have revealed that the Bangga community also practiced farming with six-row hulled barley—a frost tolerant hardy crop—being the primary focus of the cultivation activities. Wheat and buckwheat were also present at the site but in low ubiquity (Tang et al., 2021). No millet was found at Bangga. Although C₄ plants are non-adaptive to high altitude environments, both broomcorn and foxtail millet remains have been reported from contemporary or slight earlier sites at central Tibet, such as Qugong, Changguogou, and Bangtangbu (Fu, 2001; Gao et al., 2021; Tang et al., 2021). Millet cultivation was likely known to the Bangga community.

The picture that emerged from the results presented in this research is that the agropastoralists in central Tibet employed a labor-intensive mode of subsistence incorporating both cultivation and herding practices. Unlike the contemporary Bronze/Iron Age communities in the Inner Asian Mountains who relied on diverse domestic and wild animal resources and equally diversified cereal products, the Bangga community focused on two resources: cultivation of hulled barley and management of ruminant animals. A recent study (Ritchey et al., 2022) and available archaeobotanical information, suggests a labor-intensive cultivation system with high water and manuring inputs per unit area. This resonates with my observation of the high labor
costs of animal management at Bangga given isotopic evidence for year-round fodder and drinking water provisioning. I infer that this strategy was a response to the challenges of maintenance of sheep/goat herd size and high lamb mortality. The new evidence presented in this dissertation constitutes a conceptual departure from the extensive mode of subsistence employed by Bronze Age pastoral groups across central Eurasia, where productivity was driven by extensive pasturing activities. At high-altitude Bangga, the productivity is primarily driven by the intensiveness of labor inputs in herding and cultivation practices.

5.1 Significance

The question of how early pastoralists managed to settle on the Tibetan Plateau remain largely unanswered and has been obscured by the scarcity of archaeological studies conducted to date, although recent momentum has been gained by investigations led by various institutions and international collaborations. This dissertation research explores the ways in which early pastoralists of central Tibet increased resilience to periodic stresses and survived despite the inhospitable and unpredictable environment. Taking the rare opportunity to study a high-altitude settlement site with excellent faunal preservation at Bangga and combining systematic zooarchaeological analyses, sequential stable oxygen and carbon isotope analyses, and incorporating documented ethnographical records, this research is the first to reveal animal-based subsistence strategies of some of the earliest central Tibetan pastoral groups at great detail. This research also provides complementary data to better interpret other archaeological materials from this region. It will ultimately expand our knowledge of the process of peopling the Tibetan
Plateau and shed light on the diversity of strategies that contributed to the resilience of human communities’ in extreme environments worldwide.

This project also contributes to fundamental methods for regional faunal analysis in three ways, which I will discuss subsequently.

I present a set of comprehensive comparative osteomorphological criteria for distinguishing takin (*Budorcas taxicolor*) mandibular teeth and post-cranial skeletons from four taxa, that are commonly available on the Tibetan Plateau, including yak, taurine cattle, gaur (*Bos gaurus*), and water buffalo (*Bubalus bubalis*). These criteria will be useful for future studies to facilitate taxonomic identification of faunal remains from the Tibetan Plateau and its vicinities.

My analysis of caprine age profiles demonstrates that conventional livestock mortality models (e.g. Payne, 1973; Vigne & Helmer, 2007) are not always capable in explaining data sets from extreme environments such as Tibetan Plateau due to the slow herd growth and high natural mortality of livestock. Environment-specific mortality models are needed, and I wanted to draw scholarly attention to the risk of applying universal mortality models to variable cultural and environmental conditions. To better interpret archaeological livestock mortality profile from the Tibetan Plateau taking in account of localized natural mortality rate, I propose a new sheep mortality model based on ethnographic livestock management data from the plateau.

I also present the first high-resolution sequential stable oxygen and carbon isotope analysis of archaeological animal teeth in the Tibetan Plateau. Results of this study show unambiguous evidence of foddering and water provisioning of sheep/goats, seasonally or year-round in some extreme cases. The source of the fodders was likely local cultigens such as barley and millet. The latter is absent in archaeobotanical records but revealed by the isotopic results as an important fodder recourse. Together with modern sheep and goat teeth collected from the research area,
archaeological results presented in Chapter 4 will serve as a useful reference enabling future research on similar scales in the Tibetan Plateau and contribute to geographically broader research in the region under the influence of the Indian Ocean Summer Monsoon, which has been previously undocumented isotopically.

5.2 Future research

This study has shown the efficacy of combining systematic zooarchaeological and stable isotopic analyses in investigating livestock management strategies at Bangga, a key site in central Tibet. Due to interruptions of the COVID-19 pandemic, I have focused on sheep and goat remains from the Bangga faunal assemblage in this dissertation. Cattle, yak, and horse are also present and a small number of wild taxa. Local hunting has been recorded as another significant subsistence strategy practiced by recent Tibetan pastoralists to cope with environmental pressure, especially seasonal food shortage (Fox & Dorji, 2009; Goldstein & Beall, 1990; Huber, 2005; Næss & Bårdsen, 2016). Although the proportion of the assemblage is small, further analyses of relative taxonomic frequency and taxonomic diversity of the whole Bangga faunal assemblage will enable me to examine the role of wild animals at the site. Systematic zooarchaeological and stable isotopic analyses of cattle, yak, and horse remains from Bangga will undoubtedly reveal a fuller picture of how early herders managed their livestock. Analyses of body part representation, sexing data and pathologies will address remaining issues regarding roles of culling and disease. The question of whether people at Bangga ever used their cattle and horses as draft animal, or their sheep, goat, horse, and yak as pack animals could also be addressed via inspecting
pathological traces related to working animals on livestock remains from Bangga, integrated with stable oxygen and strontium isotope analyses.

At the broader scale of archaeology of the Tibetan Plateau, investigations of the following five topics will be helpful for understanding human-animal relationships in the past Tibetan Plateau more comprehensively:

a. Subsistence strategies of early hunter-gatherers in different regions of the Tibetan Plateau from the late Pleistocene to the mid-Holocene.

Published zooarchaeological data from the Tibetan Plateau are mostly derived from middle/late Holocene sites. Although there is faunal data published on the early hunter-gatherers’ sites on the Tibetan Plateau, most of these studies are limited to species information and lack detailed zooarchaeological analyses. As a result, data that could illuminate animal-based subsistence is lacking and broad survival strategies of hunter-gatherers on the Tibetan Plateau from the late Pleistocene to the early Holocene are barely known. Furthermore, currently published materials are regionally concentrated in the northeast and east of the Tibetan Plateau. However, the available archaeological data indicates that human activities occurred in the western, northern, central and southern plateaus of the late Pleistocene-Middle Holocene (Lü, 2014; Meyer et al., 2017; Zhang et al., 2018) but zooarchaeological research from these areas is lacking. Currently, archaeologists at Sichuan University are excavating the early hunter-gatherer’s site of Xiadacuo which dated to early and middle Holocene in west Tibet. Faunal remains from Xiadacuo are abundant, which provides a valuable opportunity to investigate these questions in the future.

b. Mechanism of the transformation of animal subsistence on the Tibetan Plateau around the middle Second millennium BC.
Available zooarchaeological evidence from the Tibetan Plateau suggests a shift in animal subsistence strategies among early people on the Tibetan Plateau around the middle Second millennium BC. Prior to this period, hunting was relied on to obtain diverse animal resources. Around 4000 years BP, people in various regions of the Tibetan Plateau began to engage in pastoralism, and at the same time, the species of animals used at sites such as Bangga, Ashaonao (Zhang et al., 2017), Shidaqiu, and Tawendaliha (Dong et al., 2016) were greatly reduced, indicating a trend towards narrowing the animal resource and more specialized reliance on herding after the initial phase that is represented by the sites of Changning (Li, 2012) and Jinchankou (Ren, 2017). In-depth investigation of specific mechanism of this trend towards narrowing the animal resource is needed in the future. Among known sites on the Tibetan Plateau, the Changning, Jinchankou, and Zongri on the northeastern Tibetan Plateau likely present evidence of the initial stage of development of pastoralism in the region. The Qinghai Provincial Institute of Cultural Relics and Archaeology has commissioned me to analyze faunal remains excavated from 2020-2021 field seasons at the site of Zongri, which provides me the opportunity to conduct further zooarchaeological and stable isotopic analyses on the transformation of the animal subsistence strategies on the Tibetan Plateau during the Second millennium BC.

c. Yak domestication

Domesticated yak are indispensable partners in daily life as pack animals and important sources of dairy products, meat, fur and fuel for many pastoralists on the Tibetan Plateau. When and how people on the Tibetan Plateau started using domesticated yak is little known. This is partially due to the fact that yak remains have been recovered from only a few systematically excavated early sites on the Tibetan Plateau. In addition, there has been no systematic study of
methods and criteria for distinguishing domesticated yak remains from wild yak. Although biomolecular methods (such as ZooMS and ancient DNA analysis) are undoubtedly useful to identify fully domesticated yak remains that show genetic differences from their wild progenitors, zooarchaeological analyses of age and sex constructs and body size of yak remains are irreplaceable for tracing the early stage of the domestication. Baseline zooarchaeological research is also need in order to facilitate sampling for further biomolecular analysis when faced with tens of thousands of archaeofaunal remains. To contribute to zooarchaeological investigation of domestication of yak, I plan to conduct research on criteria for ageing and sexing archaeological yak remains through studies of modern specimens from varied regions and varied domesticated yak varieties.

d. Development of local varieties of livestock on the Tibetan Plateau.
   Cattle, horses, goats, sheep, and dogs were originally domesticated by people at much lower regions outside the plateau. Currently, there are local varieties, ecotypes or breeds of these domesticated animals that are well-adapted to the high elevation plateau environment and used by pastoralists in different regions of the Tibetan Plateau. When and how those livestock local varieties developed are unknown. The formation of local ecotypes or varieties is undoubtedly a complicated process, involving natural and artificial selection. Studying this process can provide an in-depth understanding of the strategies and wisdom of ancient herders and development of indigenous knowledge relating to herding and survival on the Tibetan Plateau. In view of the complexity of the definition of livestock breeds, future research on this issue may mainly rely on biomolecular methods, especially ancient DNA analysis. However, morphometric data on modern individuals from local plateau livestock breeds show that their body size is quite different from that of breeds in other regions outside the plateau. The body heights of local sheep
breeds in modern Tibet, such as the Yarlung Zangbo sheep, the high-type Tibetan sheep, and the Sanjiang-type Tibetan sheep, are significantly smaller than those of the local sheep breeds in Xinjiang and other regions adjacent to the plateau. Such differences will also be reflected in the measurements of archaeological animal bones. In future research, systematically recording and comparing the morphometric data of archaeological livestock bones in various regions and periods of the Tibetan Plateau will also be an important mean to track the likely process of formation of livestock varieties on the Tibetan Plateau.

e. Ritual use of animals among early pastoralists on the Tibetan Plateau.

Archaeological evidence from the Tibetan Plateau indicates that the emergence of pastoralism coincides with new cultural and ritual practices on the Tibetan Plateau. Animal remains are commonly present in the tombs of early herders, indicating that animals played an important role in their funeral rituals. This point has already attracted the attention of many researchers (e.g. Huo, 1994; Lü, 2015, pp. 58-86). Due to the lack of systematic zooarchaeological analysis of faunal remains from those ritual contexts, however, most of the previous discussions of this issue have been based on comparisons of scattered archaeological records with historic documents written in much later periods. In recent years, hundreds of early pastoralists’ tombs with numerous animal remains have been excavated over the Tibetan Plateau. I am currently cooperating with archaeologists at Sichuan University and the Tibetan Autonomous Region Cultural Relic and Conservation Institute to analysis animal remains from more than one hundred early pastoralists’ tombs in western Tibet. This project will be the most comprehensive investigation to date regarding the early ritual use of animals on the Tibetan Plateau.
Taken together, it is clear that there are many opportunities for future faunal research on the Tibetan Plateau, at where zooarchaeological and stable isotopic studies are in their primary stage. Research reported in this dissertation has contributed to fundamental methods for regional faunal analysis and will provide basis for future studies.
5.3 References


Li, L. (2012). A Study on Animal Exploitation of Changning Site, Qinghai Province, Northwestern


Ren, L. (2017). *A study on animal exploitation strategies from the late Neolithic to Bronze Age in northeastern Tibetan Plateau and its surrounding areas, China Lanzhou University*.


Appendix 1 Information of modern takin, domesticated yak, gaur, cattle, and water buffalo specimens examined in this study

<table>
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<tr>
<th>Taxon</th>
<th>Specimen No.</th>
<th>Sex</th>
<th>Institute</th>
<th>Taxon</th>
<th>Specimen No.</th>
<th>Sex</th>
<th>Institute</th>
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Appendix 2. STELLA Script for modelling recent herd management on the Tibetan Plateau

A system dynamics model – STELLA, was chosen for describing the interrelated system with its powerful yet simple causal-loop and stock-flow diagrams. (See: Isee Systems, 2006. Technical Document for the iThink and STELLA Software. http://www.iseesystems.com.)

The main dynamical equations automatically generated are as follows:

UNITS: pieces; pieces/years
birth_rate=0.75
Nd = {0.05,0.10,0.15,...,0.75, 0.80}
sr_rate = 0.15
ad_rate = 0.1
INIT ewe_lamb = 200; ram_lamb=200 ; ewe/ram_ag{1,2,...,9,10}=0
birth = (ewe_ag2+ewe_ag3+ewe_ag4+ewe_ag5+ewe_ag6+ewe_ag7+ewe_ag8)*0.75
new_birth = birth*0.5
ewe_lamb_death = Nd*ewe_lamb

ewe_lamb(t) = ewe_lamb(t - dt) + (new_birth - fg1 - ewe_lamb_death) * dt
new_birth = birth*0.5
fg1 = ewe_lamb*(1-Nd)
ewe_lamb_death = Nd*ewe_lamb

i={2,3,4}
ewe_agi(t) = ewe_ag i (t - dt) + (fg(i-1) - ewe_death i - fg i ) * dt
fg (i-1) = ewe_lamb*(1-Nd)
fg i = ewe_ag i -ewe_death i
ewe_death i = ewe_ag i *ad_rtae

j={5,6,7,8,9}
ewe_ag j (t) = ewe_ag j (t - dt) + (fg(j-1) - ewe_death j - fg j ) * dt
fg(j-1) = ewe_ag(j-1) -ewe_death(j-1)
ewe_death j = 
IF
   g_j =0
THEN
   ewe_ag j *ad_rtae+((ewe_ag j +ram_ag j )*(1-ad_rtae))*0.15-ram_ag j *(1-ad_rtae)
ELSE
   ewe_ag j *ad_rtae
   fg j = ewe_ag j -ewe_death j
ewe_ag10(t) = ewe_ag10(t - dt) + (fg9 - ewe_death10 - fg10) * dt
fg9 = ewe_ag9-ewe_death9
ewe_death10 =
   IF
g10=0
   THEN
      ewe_ag10*ad_rtae+((ewe_ag10+ram_ag10)*(1-ad_rtae))*0.15-
      ram_ag10*(1-ad_rtae)
   ELSE
      ewe_ag10*ad_rtae
   fi
   fg10 = (ewe_ag10-ewe_death10)*0

ram_lamb(t) = ram_lamb(t - dt) + (new_birth - ram_lamb_death - g1) * dt
new_birth = new_birth
ram_lamb_death = Nd*ram_lamb
g1 = ram_lamb*(1-Nd)
ram_ag2(t) = ram_ag2(t - dt) + (g1 - g2 - ram_death2) * dt
   g1 = ram_lamb*(1-Nd)
g2 = ram_ag2-ram_death2
   ram_death2 = ram_ag2*2*(1-ad_rate)*sr_rate+ram_ag2*ad_rate

n={3,4,...,9,10}
ram_ag n (t) = ram_ag n (t - dt) + (g (n -1)- g n - ram_death n) * dt
   g (n -1) = ram_ag (n -1)-ram_death (n -1)
g n = ram_ag n -ram_death n
   ram_death n = ((ewe_ag n +ram_ag n)*(1-ad_rate))*sr_rate+ram_ag n *ad_rate

In the formula, ewe_/ram_ag x (t) is the number of rams or ewes at time (t) in a given year.
Appendix 3. Information of goat and sheep mandibles that are used for reconstructing mortality profiles from early phase of Bangga

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* Context names with “P–” were features/layers excavated in 2000–2002, without “P –” were features/layers excavated in 2015–2018 (F–house, H–pit, SQ–Stone wall). For features excavated in 2015–2018 excavations, F2 and F5 were the corral, F1, F3, and F4 were the residential area.