




Research Article

High-elevation sheep and goat provisioning on the Tibetan Plateau, 3000–2200 BP

Zhengwei Zhang^{1,2}, Hongliang Lü^{1,*}, Shargan Wangdue³, Xinzhou Chen^{1,2} , Li Tang⁴, Hailun Xu¹, Jixiang Song¹, Petra Vaiglova^{2,5} & Xinyi Liu^{2,*}

¹ Center for Archaeological Science, Sichuan University, Chengdu, P.R. China

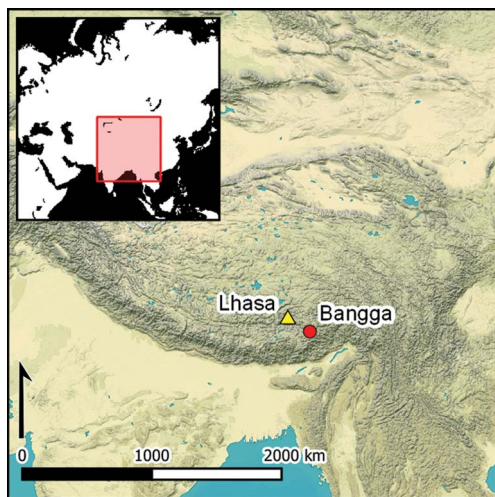
² Department of Anthropology, Washington University in St Louis, USA

³ Tibetan Autonomous Region Cultural Relic and Conservation Institute, Lhasa, P.R. China

⁴ Max Planck Institute for Geoanthropology, Jena, Germany

⁵ School of Archaeology and Anthropology, Australian National University, Canberra, Australia

* Authors for correspondence ✉ liuxinyi@wustl.edu & scottscu@gmail.com



High-elevation environments present harsh challenges for the pursuit of agropastoral subsistence strategies and relatively little is known about the mechanisms early communities employed to adapt to such locations successfully. This article presents the sequential carbon and oxygen analysis of archaeological caprine teeth from Bangga (*c.* 3000–2200 BP), which is approximately 3750masl on the Tibetan Plateau. Made visible through this method, intra-tooth variation in isotopic composition allows insights into herding strategies that possibly included the provisioning of livestock with groundwater and agricultural fodder and summer grazing in saline or marsh environments. Such intensive provisioning differs markedly from lower-elevation agropastoralism.

Keywords: Bangga, agropastoralism, carbon and oxygen isotopes, enamel, sheep and goat, C_4 plants

Introduction

There has been recent momentum in understanding the role of herding practices in the early exploitation of a range of high-elevation environments, including the Pamir Mountains, the Ethiopian Highlands and the Andes (e.g. Capriles 2016; Gifford-Gonzalez 2017; Ananyevskaya *et al.* 2021). The average elevation of the Tibetan Plateau exceeds 4500m above sea level (masl) and much of the area is characterised by alpine tundra environments. The herding of livestock on the plateau has deep historical roots that can be traced back to at least 3500 BP

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(Zhou 1999; Dong *et al.* 2016; Wang *et al.* 2023). How early herders looked after their flocks in such challenging high-elevation environments, however, remains unknown.

Recent archaeological research has revealed a broad spectrum of subsistence systems across the range of environments on the Tibetan Plateau and adjacent territories that included hunting, herding, foraging, farming and hybrid strategies (Hermes *et al.* 2019, 2022; Zhang *et al.* 2019; d'Alpoim Guedes & Aldenderfer 2020; Song *et al.* 2021; Vaiglova *et al.* 2021). During the time between 4000 and 3000 BP, such systems incorporated livestock and cereal crops that originated in east and south-west Asia, forming multiresource agropastoral economies on the plateau (Chen *et al.* 2015; Tang *et al.* 2022, 2023; Wang *et al.* 2023). The site of Bangga, in southern Tibet, is one of only a few prehistoric settlements in this part of the world that have been fully excavated, revealing human and animal lifeways at 3750masl during its occupation *c.* 3000–2200 BP (Figures 1 & 2) (Lü *et al.* 2021). Recent discoveries at Bangga provide us with a glimpse of daily experience at such highland settlements, where the prehistoric community herded sheep, goat, taurine cattle, yak and cattle-yak hybrids and cultivated barley, wheat and likely buckwheat (Lü *et al.* 2021; Tang *et al.* 2021; Zhang *et al.* 2022; Chen *et al.* 2023).

In contrast to lowland communities, early herders at Bangga would have had to overcome altitude-related difficulties in maintaining their flock size; the birth rate of sheep and goats is lower at high altitudes and lamb mortality is increased owing to extreme weather and disease



Figure 1. Locations of Bangga and relevant archaeological sites mentioned in the text: 1) Bangga; 2) Changguogou; 3) Qugong (figure by authors).

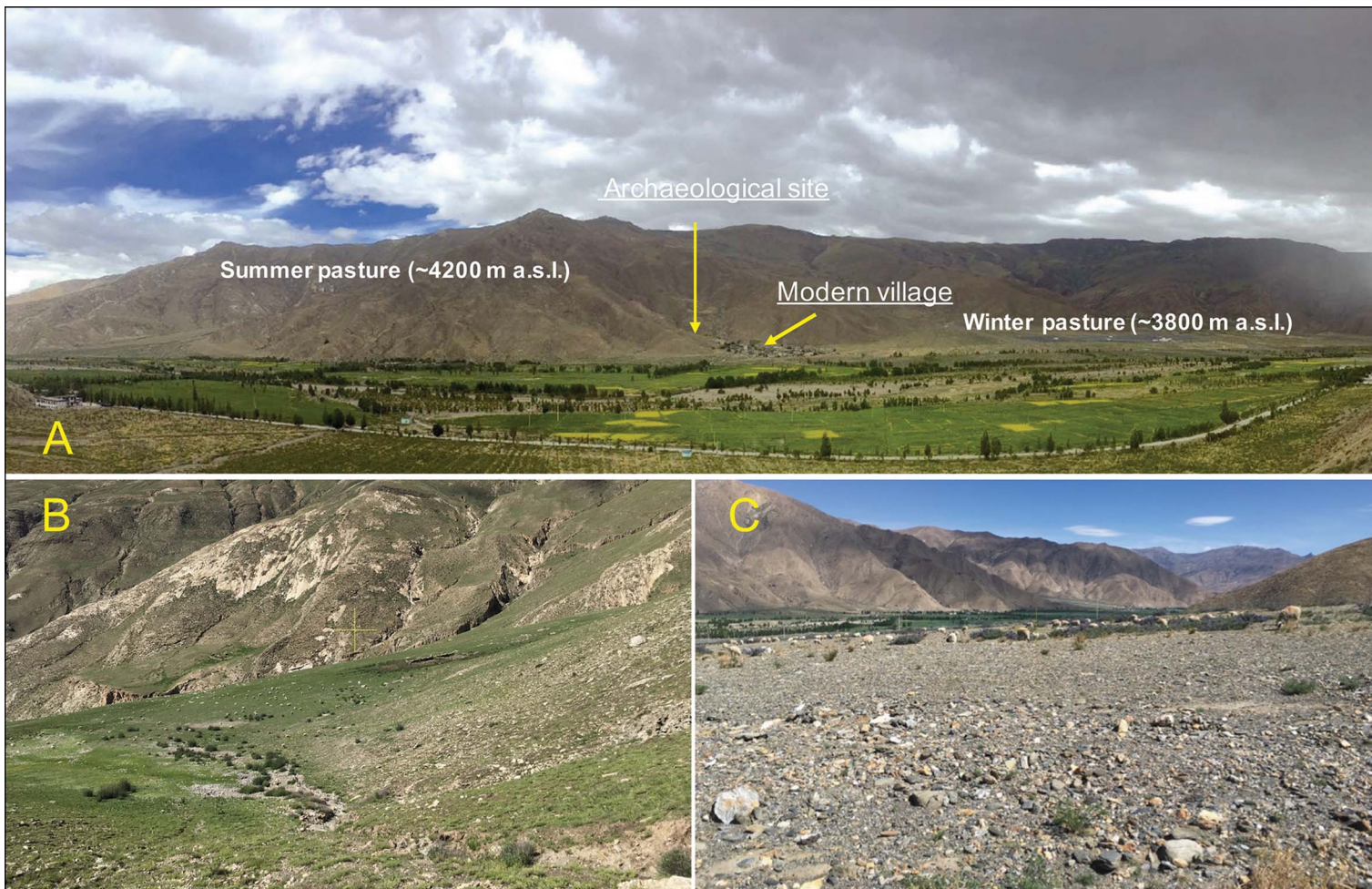


Figure 2. A) Bangga and surrounding environment; B) summer pasture, approximately 4200masl; and C) winter pasture, approximately 3800masl, used by modern day Bangga community (photographs by Z. Zhang).

(Zhang *et al.* 2022). The challenges faced by modern Tibetan pastoralists were likely also faced by early herders, with severe snowstorms, seasonal nutritional deficiency, droughts and epidemics threatening flocks on the plateau (e.g. Miller 2000). A recent zooarchaeological study at Bangga suggests that more than half of sheep did not survive the first year of their life (Zhang *et al.* 2022). In this study, we focus on the ways in which early herders maintained their domestic animals in the face of such challenges at Bangga.

Stable oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) isotope values, serially sampled from dental enamel carbonate, are informative of the dietary and water intake of animals over multiple seasons and have shed light on herding practices in Europe, south-west Asia and, more recently, in central and east Asia (e.g. Balasse *et al.* 2012a; Makarewicz 2017; Hermes *et al.* 2019, 2022; Vaiglova *et al.* 2020; Ventresca Miller *et al.* 2020). We conducted sequential isotope analyses on sheep and goat teeth uncovered at Bangga and on modern teeth collected nearby. The results suggest that some sheep/goats were provisioned with water and cultigens (likely barley and/or millet) all year round.

Research background

Bangga

The site of Bangga is situated on an alluvial deposit on the eastern side of the Qonggyai River—a tributary of the Yarlung Zangbo. The site is adjacent to the modern-day Bangga village in Qonggyai county, at approximately 3750masl (Figure 1). The local precipitation is subject to monsoon rainfall and, at this elevation, events such as droughts, flooding and snowstorms can threaten herd production. Excavations at Bangga in 2000–2002 and 2015–2018 uncovered more than 400m² of the site, revealing archaeological features such as stone-built dwelling structures, hearths, postholes and pits. The 2015–2018 excavation revealed a dwelling complex and adjacent corral area, dating to *c.* 3000–2200 cal BP (Lü *et al.* 2021).

More than 12 000 fragments of animal bone were recovered during the 2015–2018 excavation. Zooarchaeological study is ongoing but the initial results suggest that sheep (*Ovis aries*) and goats (*Capra hircus*) dominate the assemblage (Zhang *et al.* 2022). Large-sized Bovinae, Equidae and other smaller-sized mammals, including musk deer, gazelle, hare and rodents, are also present but account for a small proportion of the assemblage. Flotation has collected more than 70 000 charred grains (Tang *et al.* 2021). Barley dominates the crop portion of the macrofossils—over 80 per cent of cereal remains—with a small number of wheat and *Fagopyrum* sp. (cf. buckwheat). A significant number of non-cereal plants was also identified. Notably, *Chenopodium* (goosefoot) and Amaranthaceae are predominant. Millets were not recovered from Bangga despite being commonly encountered at contemporaneous or older sites nearby (Fu 2001; Gao *et al.* 2021).

Stable isotope analysis and local environmental conditions

The oxygen and carbon isotope compositions of tooth enamel are closely related to dietary and water intake (Longinelli 1984; Huertas *et al.* 1995; Sponheimer & Lee-Thorp 1999). Enamel mineralises sequentially along the axis of tooth growth (from the occlusal surface

to the root). For sheep, the second molar (M_2) mineralises during the first 12 months after birth, and the third molar (M_3) mineralises during the first 10–22 months of life (Zazzo *et al.* 2010). Once complete, the bioapatite of the dental crown does not generally remodel. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of incrementally sampled enamel therefore reflect water and dietary input during these periods, enabling insights into seasonal changes and serving as indicators of grazing behaviour and mobility (e.g. Balasse *et al.* 2012b; Tornero *et al.* 2016).

Stable oxygen isotope values of enamel bioapatite are controlled by body water and reflect local meteoric water, which is itself driven by the hydrological cycle and geographic factors (e.g. Gat 1980; Bowen & Wilkinson 2002). On the southern Tibetan Plateau, three processes are critical to the variation of $\delta^{18}\text{O}$ values in surface water: altitude, temperature and the ‘amount effect’. Higher atmospheric temperatures increase rates of evaporation, leading to an enrichment of the heavier ^{18}O isotope in surface water (as the lighter ^{16}O isotope evaporates preferentially), resulting in higher $\delta^{18}\text{O}$ values in the summer and lower values in the winter (Gat 1980). The corollary of this effect is that summer rains brought to the plateau during the Indian Ocean monsoon are ^{18}O depleted, in contrast to the ^{18}O enriched surface water. Additionally, at high elevations, meltwater from surface snow and glacial ice (accumulated over colder seasons/periods with considerably lower $\delta^{18}\text{O}$ values) contributes to further ^{18}O depletion of meteoric water during the warm season (Yao *et al.* 2009). These effects combine to various degrees. Modern data from local meteorological stations on the Tibetan Plateau suggest that the ambient temperature effect is outweighed by the monsoon amount effect and snow melt, resulting in the lowest $\delta^{18}\text{O}$ values for surface water in the summer (approximately -20‰) and the highest values in the spring (approximately -5‰) (Yao *et al.* 2009) (see online supplementary material (OSM) Figure S1). Though ultimately different, this pattern resonates with the bimodal seasonality of ^{18}O depletion during summer (the rainy season) observed in the East Asian monsoon region (Dai *et al.* 2016). It is, however, significantly different from the system in the continental interior where surface temperature is the main driver (Makarewicz & Pederzani 2017). It is also worth noting that the large seasonal variation in water $\delta^{18}\text{O}$ values on the plateau (over 15‰) has the potential to overshadow any interpretation of altitude mobility (precipitation $\delta^{18}\text{O}$ values decrease along the altitude gradient on an order of $1\text{--}3\text{‰}/\text{km}$). In theory, vertical transhumance can be detected using sequential enamel $\delta^{18}\text{O}$ values with well thought-out models (e.g. Hermes *et al.* 2017). On the southern Tibetan Plateau, however, the large seasonal variation in meteoric water $\delta^{18}\text{O}$ values (over 15‰) and its bimodal nature have the potential to offset this altitude effect, making such interpretation challenging.

Stable carbon isotope values in enamel reflect $\delta^{13}\text{C}$ values of food plants (Ambrose & Norr 1993; Lee-Thorp & Sponheimer 2003). Plants utilising C_3 and C_4 photosynthetic pathways differ significantly in $\delta^{13}\text{C}$ values—averaging approximately -26.5‰ and -12.5‰ , respectively—allowing assessment of the relative proportion of C_3 and C_4 plants consumed. Theoretically, C_4 plants are maladapted to high altitudes, where they exhibit low productivity due to frequent chilling injuries and inferior quantum yields (Sage *et al.* 2015). This results in a substantial drop in the C_4 contribution to biomass and local vegetation in high elevation locations like Bangga. On a global scale, environments above 3000masl are considered C_3 -plant dominant, but cold-tolerant C_4 plants—including grasses, sedges and dicots—may occur, particularly in saline environments during warm seasons (Sage

et al. 2015). In addition, C_4 cultivars (broomcorn and foxtail millet) have been reported from several archaeological sites in the southern part of the Tibetan Plateau (Fu 2001; Gao *et al.* 2021; Tang *et al.* 2021) and could have been used for foddering. In modern Tibetan herbivores, the cut-off $\delta^{13}C$ value (bioapatite) for a pure C_3 diet is -7.3 to -8‰ (subjected to a fossil fuel effect of $+1.5\text{‰}$; Wang *et al.* 2008). Above this threshold, the dietary contribution of C_4 plants can be detected.

An altitude effect on C_3 plants may apply due to changes in atmospheric pressure and/or high carboxylation efficiency along the elevation gradient (e.g. Körner *et al.* 1991; Szpak *et al.* 2013). On the Tibetan Plateau, a linear regression may be observed between elevation and plant $\delta^{13}C$ values with a $0.7\text{--}2.6\text{‰}/\text{km}$ decreasing rate (Deng & Li 2005). A relatively moderate seasonal variation ($1\text{--}2\text{‰}$) in $\delta^{13}C$ values may also occur, with the higher values in dry seasons and lower values in wet seasons (Tornerio *et al.* 2016). An increase in $\delta^{13}C$ values would therefore be expected if animals were moving vertically towards higher pastures in the summer. However, the extent to which this pattern would be counterbalanced by the accessibility of C_4 plant food (via foddering or abundance of C_4 in rare locations) depends on the context.

Materials and methods

Fourteen modern mandibular molars, from 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 S1). The archaeological samples consist of 10 Caprinae mandibular molars that likely represent five individuals (Table S2).

We followed approaches established in previous studies (e.g. Balasse *et al.* 2012b, 2013; Tornerio *et al.* 2013), which suggest that localised seasonal movements in both wild and domestic herding strategies of bovids can be identified through sequential analysis of oxygen and carbon stable isotopes from hypsodont crowned herbivore dental enamel (see OSM for detailed explanation of method). We fit a cosine function to the $\delta^{18}O$ values from each analysed tooth to visualise the data and estimate seasonality. Such an approach was initially implemented by Balasse and colleagues (2012b) using Excel and subsequently widely used. We follow the method and R scripts described by Hermes and colleagues (2019, 2022) to generate 95% confidence intervals for the curve fitting. Unfitted plots are in Figures S2 & S3.

Results

The isotopic values of all modern and archaeological samples are presented in Table 1 and Figures 3, 4 and 5, S2 and S4. The intra-tooth $\delta^{18}O$ and $\delta^{13}C$ values of most modern teeth are inversely proportional (Figure 3), with two exceptions (MG2M2 and MS3M3, see Table S3 for statistical tests). For both modern sheep and goats, intra-tooth variations in $\delta^{13}C$ series for M_2 are slightly greater than M_3 . Mean $\delta^{13}C$ values of modern sheep are consistently slightly higher than those of modern goats at Bangga, a trend also observed in other regions of the world (Janzen *et al.* 2020).

Table 1. Stable carbon and oxygen isotope values of tooth enamel carbonate analysed in this study.

ID	Tooth	Enamel length (mm)	n	Min $\delta^{13}\text{C}$	Max $\delta^{13}\text{C}$	Range $\delta^{13}\text{C}$	Mean $\delta^{13}\text{C}$	Intra-tooth $\delta^{13}\text{C}$ SD	Min $\delta^{18}\text{O}$	Max $\delta^{18}\text{O}$	Range $\delta^{18}\text{O}$	Mean $\delta^{18}\text{O}$	Intra-tooth $\delta^{18}\text{O}$ SD
MS1	M ₂	23.02	16	-10.1	-7.3	2.9	-8.7	1.1	-11.1	-6.7	4.4	-8.7	1.5
	M ₃	31.86	20	-10.0	-8.6	1.4	-9.1	0.4	-10.7	-3.6	7.1	-7.7	2.1
MS2	₂ M	24.28	16	-9.4	-6.2	3.2	-7.6	1.2	-11.6	-7.6	4.1	-9.7	1.4
	₃ M	32.77	21	-9.6	-7.9	1.8	-8.8	0.5	-11.9	-3.7	8.2	-8.1	2.3
MS3	M ₂	31.8	26	-8.1	-4.2	3.9	-6.3	1.3	-10.9	-4.9	6.0	-8.2	1.8
	M ₃	31.3	22	-8.2	-5.8	2.4	-7.1	0.9	-12.0	-6.7	5.4	-9.4	1.9
MS4	M ₂	11.5	9	-9.0	-7.0	2.0	-7.5	0.6	-11.5	-6.6	5.0	-9.1	1.9
	M ₃	21.3	16	-9.2	-7.7	1.6	-8.6	0.5	-11.7	-7.0	4.7	-9.4	1.4
MG1	M ₂	29.3	17	-10.3	-8.0	2.4	-9.0	0.7	-11.1	-4.5	6.6	-7.8	2.0
	M ₃	21.3	13	-10.3	-8.2	2.2	-9.0	0.6	-11.6	-7.5	4.1	-9.8	1.4
MG2	M ₂	31.4	18	-9.6	-6.8	2.8	-8.4	0.9	-9.4	-4.1	5.3	-6.9	1.9
	M ₃	29.6	19	-10.0	-7.6	2.4	-8.7	0.9	-11.6	-3.3	8.2	-7.4	2.8
MG3	M ₂	31.6	25	-10.4	-8.0	2.4	-9.0	0.8	-11.9	-4.3	7.5	-8.0	2.3
	M ₃	22	17	-9.9	-8.3	1.6	-9.1	0.5	-12.0	-7.0	5.0	-9.8	1.5
AS1	₂ M	18.35	9	-9.4	-8.8	0.6	-9.0	0.2	-15.4	-13.5	1.8	-14.5	0.5
	₃ M	28.48	15	-7.1	-4.6	2.5	-5.4	0.9	-14.5	-9.4	5.1	-12.4	1.6
AS3	M ₂	24.6	16	-7.9	-3.2	4.6	-4.8	1.5	-14.2	-10.8	3.4	-12.8	1.1
AS4	M ₂	36.6	18	-7.7	-1.4	6.3	-4.0	2.0	-13.4	-7.5	5.9	-11.7	1.7
AS2	M ₂	18.6	13	-9.2	-7.3	1.9	-8.6	0.6	-15.1	-9.9	5.2	-13.6	1.5
	M ₃	29.3	18	-7.7	-4.7	3.0	-5.5	0.9	-13.6	-9.4	4.2	-12.0	1.2
AG1	M ₂	32	21	-9.8	-8.4	1.4	-9.1	0.4	-13.7	-10.0	3.6	-12.2	1.0
	M ₃	40.6	27	-9.1	-8.4	0.7	-8.7	0.2	-14.8	-11.7	3.1	-13.4	1.1
AG2	M ₂	17	12	-5.4	-3.1	2.3	-3.8	0.6	-13.2	-5.3	7.9	-10.0	2.8
	M ₃	25	17	-4.2	-2.5	1.7	-3.3	0.5	-12.2	-6.4	5.8	-9.6	1.8

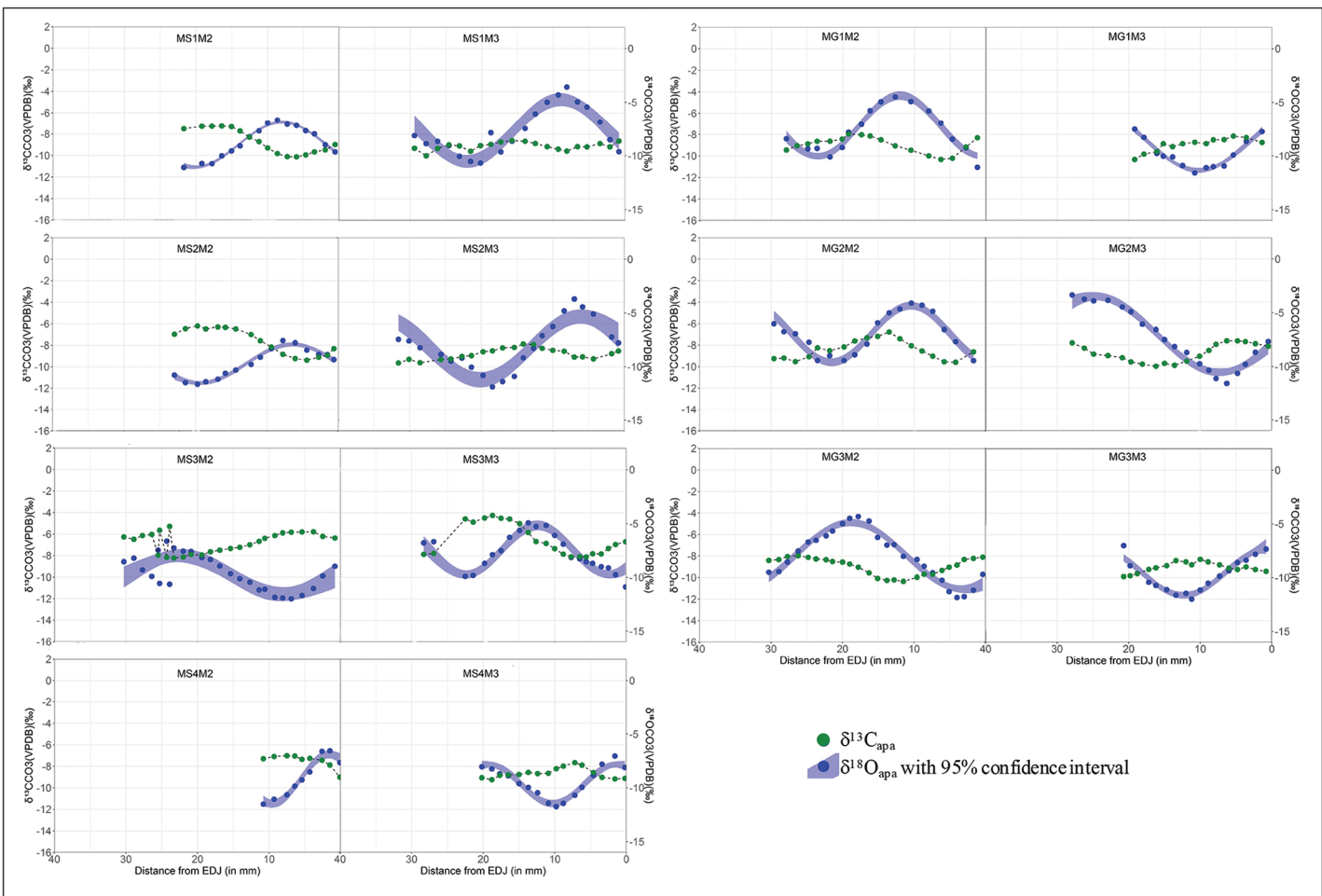


Figure 3. Sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of modern sheep and goat enamel bioapatite (CO3) from Bangga. First M stands for modern sample; S or G indicate sheep or goat; M_2 : second molar; M_3 : third molar; EDJ: enamel-dentine junction (figure by authors).

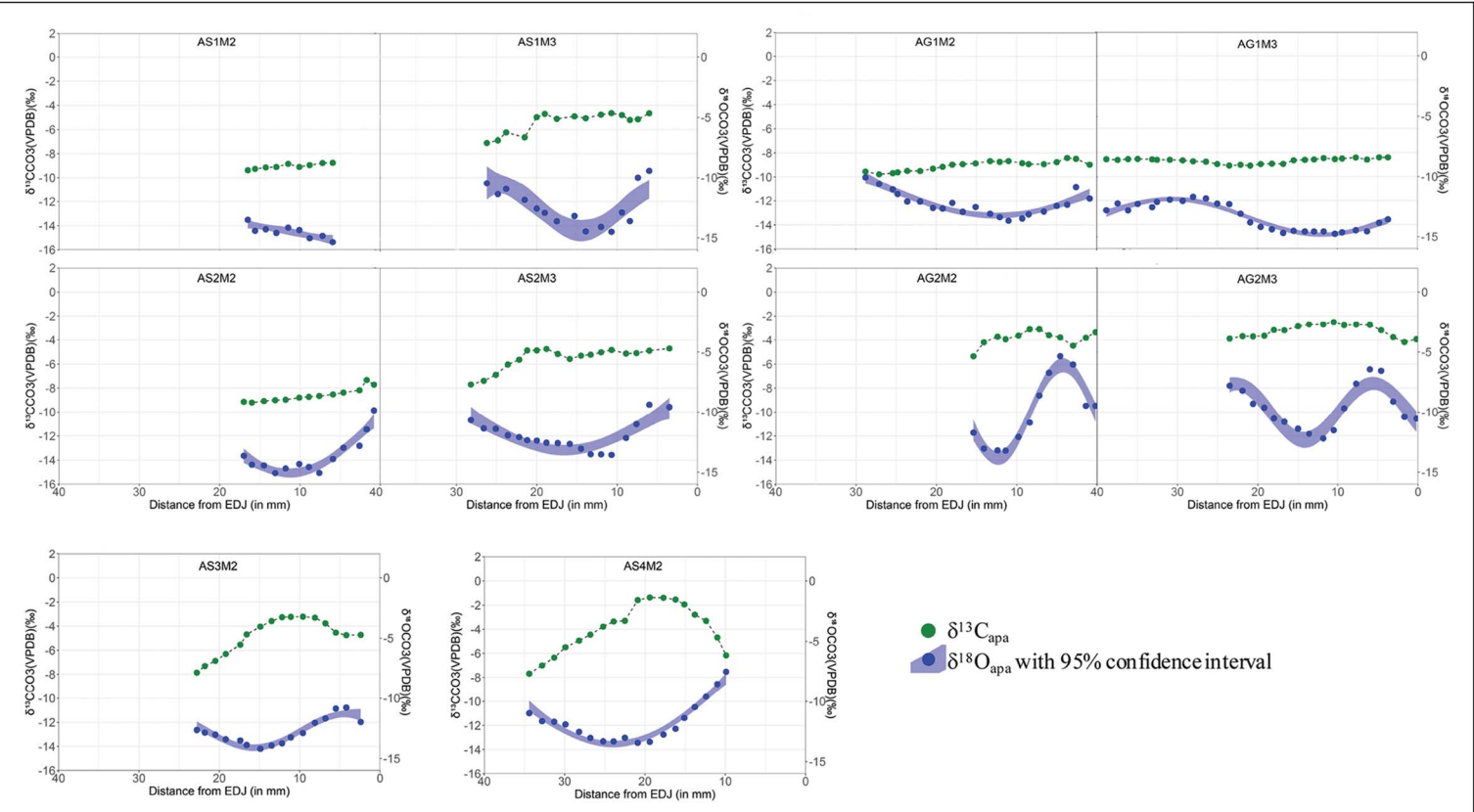


Figure 4. Sequential $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of archaeological samples from Bangga. A stands for archaeological sample; S or G indicate sheep or goat; M₂: second molar; M₃: third molar; EDJ: enamel-dentine junction (figure by authors).

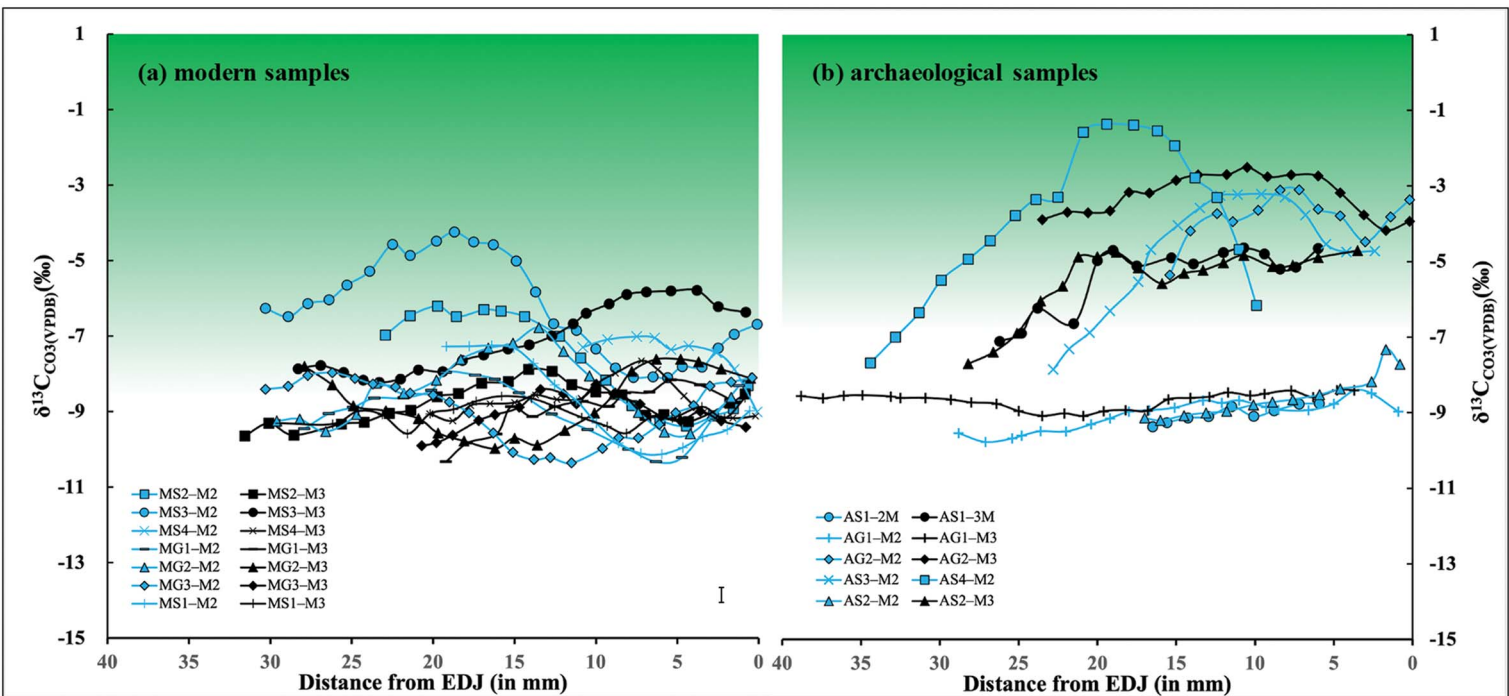


Figure 5. The $\delta^{13}\text{C}$ values of modern (a) and archaeological (b) samples analysed in this study. The shaded areas indicate ranges of bioapatite $\delta^{13}\text{C}$ values for herbivores not purely fed on C_3 plants ($> -8\text{‰}$ for modern high-elevation animals, $> -6.5\text{‰}$ for archaeological specimens due to the Suess effect). Measurement error is shown in the bottom-right of (a); EDJ: enamel-dentine junction (figure by authors).

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of enamel carbonate from archaeological sheep and goats also show inverse cyclicity (except for samples AS2M2 and AS3M2, see Table S3). Only AS3M₂, AG2M₂ and AG2M₃ display patterns close to the sinusoidal variation in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (Figure 5). The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of the remaining teeth show either shallow curves or curves that are too short to record an entire annual cycle. The mean $\delta^{18}\text{O}$ values from archaeological samples are significantly lower than those of modern samples.

Discussion

Crop and water provisioning at Bangga

The majority of modern sheep and goats show inverse cyclicity in intra-tooth isotopic sequences (i.e. lower $\delta^{18}\text{O}$ values correspond to higher $\delta^{13}\text{C}$ values and *vice versa*). This is consistent with what would be expected for seasonal mobility to higher pastures in the summer, reflecting modern herding practice (e.g. Yao *et al.* 2009; Balasse *et al.* 2012b; Tornero *et al.* 2016). The lower $\delta^{18}\text{O}$ values reflect summer conditions when meteoric water is most ^{18}O depleted, while higher $\delta^{13}\text{C}$ values are due to the altitude effect on C₃ plants. As expected for an elevation above 3750masl, most modern animals display enamel $\delta^{13}\text{C}$ values consistent with pure C₃-plant diets (below the current -8‰ threshold). But there are exceptions. Sheep MS3, for example, shows clear C₄ (or CAM) plant dietary input during summer. No C₄ crops (e.g. maize, millet, sorghum) are cultivated at Bangga today, and there is no ethnographic record for the use of free-standing C₄ plants as fodder (Jiang 2011). Maize is, however, cultivated in the broader region today and may sometimes be used for provisioning livestock. The C₄ signals observed in MS3 may therefore result either from grazing on free-living C₄ plants in the summer or from being provisioned with maize fodder. Our results also show a relatively small amplitude in intra-tooth $\delta^{18}\text{O}$ variation (ranging between 4 and 8‰), which is much lower than reported in other mid-latitude environments (e.g. Tornero *et al.* 2016; Hermes *et al.* 2019). This is likely due to the counterbalance between temperature and amount effects in surface water $\delta^{18}\text{O}$ values.

Most archaeological animals display some degree of sinusoidal variation in $\delta^{18}\text{O}$ values, although the amplitudes of such variations are much lower than in modern samples. At least two individuals (AS2 and AG1) display extremely low intra-tooth variation (Figure 4); year-round access to groundwater, in which the $\delta^{18}\text{O}$ value does not typically vary seasonally (Fricke *et al.* 1998; Darling 2004), could explain this observation. In general, unlike surface water, the $\delta^{18}\text{O}$ value of groundwater reflects mean oxygen isotope composition in long-term precipitation accounting for a recharge rate according to the local hydrological system (e.g. Ge *et al.* 2008; Kong *et al.* 2019). In other words, some animals have been provided with groundwater all year round.

Foddering with crops and the source of C₄ dietary input

Archaeological specimens fall into two groups for carbon isotope values: 1) teeth that display shallow curves and low $\delta^{13}\text{C}$ values (AG1M2, AG1M3, AS1M2 and AS2M2), and 2) teeth that show sinusoidal variations and high $\delta^{13}\text{C}$ values (AS1M3, AG2M2, AG2M3, AS3M2, AS4M2 and AS2M3) (Figures 3, 4 & 5). The second and third molars for some individuals

(e.g. AS1 and AS2) fall into the different groups, indicating shifting dietary conditions during the first two years of life. The group 1 teeth probably reflect human provisioning with C₃ plants; grazing on pasture is unlikely to produce such shallow curves but show more varied intra-tooth $\delta^{13}\text{C}$ values. Considering the archaeobotanical evidence at Bangga, it is possible that livestock were provisioned with barley by-products (Tang *et al.* 2021).

Group 2 teeth, with sinusoidal curves, show clear dietary input of C₄ plants (Figure 5b). Most data points in this group are above the -6.5‰ pure-C₃ diet threshold (Friedli *et al.* 1986; Wang *et al.* 2008). Considering that the enamel-diet offset for ruminant sheep and goats ($+11\text{‰}$) is likely lower than the average enamel-diet $\delta^{13}\text{C}$ enrichment factor ($+14\text{‰}$), the actual pure C₃ diet threshold could be lower than the current -6.5‰ model (Cerling *et al.* 1997). Therefore, our data unambiguously show that the group 2 teeth come from animals that consumed a considerable amount of C₄ plants.

Given that C₄ plants are generally maladapted to high elevations, the elevated $\delta^{13}\text{C}$ values in archaeological caprine teeth at Bangga are striking. There are two possible explanations. Some animals could have been taken to saline-alkali or marsh environments in the summer (most lakes are brackish water in the region), where C₄ plants tolerate such conditions more than C₃ plants (Drake 1989). Support for this explanation is found in the ubiquity of salt-tolerating taxa, such as *Chenopodium* sp. and *Salsola collina*—the latter a C₄ plant—in the flotation assemblage at Bangga, possibly incorporated through dung burning (Mao Zhou, *pers. comm.*). Yet the seasonal use of saline environments cannot explain those teeth (AS1M₃, AS2M₃, AG2M₂ and AG2M₃) that show C₄ dietary input and at the same time have very low intra-tooth $\delta^{13}\text{C}$ variations. AG2, for example, displays almost flat curves in both M₂ and M₃. This indicates that those animals grazed on C₄ plants across seasons, even in the winter when C₄ plants are extremely scarce at high elevations and pasturing is highly risky. This hints at human provisioning as an alternate explanation. C₄ crops such as broomcorn and foxtail millet were not recovered from Bangga but are documented at nearby sites, such as Changguogou, Bangtangbu and Qugong and were thus known to these communities during the period in which Bangga was first occupied (Fu 2001; Gao *et al.* 2021).

This observation enables complementary insights into earlier suggestions of a transition towards a barley-dominant economy during the second millennium BC (Tang *et al.* 2021), grounded in the establishment of a mono-cropping (i.e. barley) system that was possibly associated with the diminished roles of other cereals (e.g. millet) in human diets. Millet could have been used for animal provisioning in some context, a scenario that resonates with the Dzhungar Mountains in the third millennium BC, where isotopic analysis reveals that sheep and goats were foddered with millet without any corresponding archaeobotanical evidence (Hermes *et al.* 2019). Currently, available data do not allow us to distinguish between scenarios where livestock consumed C₄ plants from marsh environments and where they were provisioned with millet, although the latter possibility is, in our view, more likely, given the evidence of C₄ consumption in winter. Nonetheless, millet cultivation at Bangga remains an open inquiry. Isotopic analyses of human skeletal remains or sequentially sampled tooth enamel of other domestic taxa will, in future, enable us to clarify the role of millet in human and animal diets.

Overall, our results show that provisioning was a key strategy for ensuring the success of herding at 3750masl, *c.* 3000–2200 BP. Faced with extreme seasonal and hypoxic conditions and high lamb mortality rates (Zhang *et al.* 2022), Bangga herders provisioned their flocks with water and fodder from agricultural products, in some cases all year round. Such a labour-intensive strategy constitutes a departure from—rather than a continuity of—the Bronze Age pastoral systems that have been well documented across the Asian interior at lower elevations. These lower elevation communities relied on extensive approaches in which productivity was driven by the size of herds, by the quality and expansiveness of the pastures, and by mobility (e.g. Makarewicz 2017; Lazzerini *et al.* 2021). This differs substantially from the less mobile and more labour-intensive provisioning strategies inferred at Bangga, which probably included foddering, corralling and water provisioning alongside heavy investment in barley cultivation to survive in a high elevation environment.

Conclusion

This article presents one of the first applications of sequential isotope analysis of archaeological animal teeth from the Tibetan Plateau, adding to pioneering work in similar environments (cf. Hermes *et al.* 2022). Our results enable three principal inferences. First, some sheep and goats at Bangga were provisioned with groundwater all year round. Second, herders likely foddered their animals with agricultural products, seasonally or year round. And third, some animals show considerable dietary input from C₄ plants. The isotopic evidence presented here is unambiguous regarding water and fodder provisioning but it is unable to identify the source of the C₄ dietary component documented in the enamel $\delta^{13}\text{C}$ values. Either millet foddering or pasturing in saline environments are possible scenarios. Future research can clarify the situation. Together with zooarchaeological and archaeobotanical evidence (Tang *et al.* 2021; Zhang *et al.* 2022), our results indicate that the ancient Bangga community engaged in a labour-intensive agropastoralism on the Tibetan Plateau that has not previously been documented.

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Online supplementary materials (OSM)

To view supplementary material for this article, please visit <https://doi.org/10.15184/aqy.2024.137> and select the supplementary materials tab.

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