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Altitude Effect on the Stable Isotope Chemistry of Tooth Enamel from Modern Herbivores in Tibet: Implications for Paleoclimate and Paleoelevation Reconstructions

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ALTITUDE EFFECT ON THE STABLE ISOTOPE CHEMISTRY OF TOOTH ENAMEL FROM MODERN HERBIVORES IN TIBET: IMPLICATIONS FOR PALEOCLIMATE AND PALEOELEVATION RECONSTRUCTIONS

By

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ABSTRACT

A total of 123 bulk and serial enamel samples were obtained from modern goats, horses and yaks from southern Tibet for C and O isotope analysis. The δ^{13}C and δ^{18}O values of tooth enamel were compared with the δ^{13}C values of local vegetation and the δ^{18}O values of local waters to examine the relationship between the isotopic composition of modern herbivores and their environment. The δ^{13}C values of enamel samples from horses range from -11.2‰ to -13.9‰ with an average δ^{13}C value of -12.7 ± 1.0‰ (n=13). The δ^{13}C values of yak tooth enamel range from -7.3‰ to -14.2‰, averaging -10.1±1.4‰ (n=84). The goat teeth have δ^{13}C values ranging from -7.8‰ to -12.1‰, with a mean of -10.2 ± 1.2‰ (n=26). These enamel δ^{13}C values indicate that these modern herbivores were feeding predominantly on C3 plants, consistent with the current dominance of C3 vegetation in the region. Some of the samples have δ^{13}C values between -7.3 and -9‰. Although these higher δ^{13}C values could suggest consumption of some C4 plants by the animals, the lack of significant seasonal δ^{13}C variations within individual teeth indicates that these higher enamel δ^{13}C values are more likely due to consumption of C3 plants experiencing water stress and/or some CAM plants. This suggests that the "cut-off" δ^{13}C value for a pure C3 diet can be as high as -8‰ in water-stressed environments. The δ^{13}C variations within and between species primarily reflect the variations in the δ^{13}C values of the C3 plant foodstuffs consumed by the animals. The δ^{13}C values of tooth enamel do not show a trend with increasing elevation. Oxygen isotopic compositions of tooth enamel varied widely within and between species. In contrast to the small intra-tooth δ^{13}C variations within individual teeth, serial enamel samples display large intra-tooth δ^{18}O variations, reflecting seasonal variations in the oxygen isotopic composition of meteoric water. The mean δ^{18}O values of tooth enamel from goats showed a correlation with water δ^{18}O values, suggesting that the δ^{18}O of tooth enamel can be used as a proxy for the δ^{18}O of meteoric water. Unfortunately, the oxygen isotopic compositions of water and tooth enamel do not show a clear trend with increasing elevation in the study area, suggesting that quantitative reconstruction of paleoelevation in this region using

reconstructed $\delta^{18}O$ values of paleo-meteoric water from fossil tooth enamel or other O-bearing minerals may not be warranted. For a given elevation/environment, horses have the lowest enamel $\delta^{18}O$ values while goats display the highest enamel $\delta^{18}O$ values among the three species studied. The large inter-species $\delta^{18}O$ variations are due to differences in physiology and diet/drinking behavior of the animals. This confirms the importance of species-specific studies when interpreting $\delta^{18}O$ data of fossil mammalian teeth in a stratigraphic sequence as a record of paleoclimate changes.

1. INTRODUCTION

The Tibetan Plateau has an average elevation greater than 4000m. The uplift of the Tibetan plateau has been suggested as a driving force on regional and global climates, particularly on Asian monsoon evolution. The timing history of the Tibetan uplift and its effects on Earth's climate and biosphere remain speculative. Reconstruction of the paleoenvironment and the paleoelevation in areas on and around the high plateau is important for evaluating the effects of high topography on regional and global climate and ecology, and for testing various models for the timing and mechanism of uplift.

In recent years, several studies have utilized the oxygen isotopic composition of terrestrial carbonates to reconstruct the paleoelevation of the Tibetan Plateau (Garzione et al., 2000; Currie et al., 2005). One recent study (Rowley and Currie, 2006), based on oxygen isotopic composition of lake and paleosol carbonates, suggests that the current high elevations were attained at least 35 million years ago, much earlier than previously thought. The underlying principle of this oxygen-isotope-paleo-altimetry approach is that precipitation (rain or snow) generally becomes increasingly depleted in the heavy oxygen (^{18}O) the higher up a mountain range that it falls – the "altitude effect" (Dansgaard, 1964), and therefore systematic changes in the $\delta^{18}O$ of precipitation with elevation could be used to infer the elevation at which the rain or snow fell. This approach also assumes that the $\delta^{18}O$ value of paleometeroric water can be determined from the $\delta^{18}O$ values of O-bearing minerals and that modern precipitation $\delta^{18}O$ vs. elevation relationships can be applied to the distant past. However, studies based on carbon isotopic composition of fossil tooth enamel (Wang et al., 2006) and paleobotanical and sedimentary evidence (e.g., Hsu, 1976; Zheng et al., 2000) suggest that the present high elevation of the plateau was reached much later, in the Plio-Pleistocene, contradicting the interpretations based on carbonate $\delta^{18}O$ data (Garzione et al., 2000; Currie et al., 2005; Rowley and Currie, 2006). Clearly, the timing of the Tibetan uplift is still a contentious issue. The problem cannot be resolved until we understand how the isotopic compositions of modern precipitation and minerals reflect modern climate, vegetation and elevation. In a region with complex tectonic and climatic history, we need to better calibrate the modern systems before applying any modern empirical relations to the distant past for paleoelevation and paleoenvironment reconstruction.

Stable carbon and oxygen isotopic analysis of tooth enamel has been established as a valuable tool for reconstructing paleoenvironment (Koch, 1998; Kohn and Cerling, 2002). Tooth enamel is almost entirely inorganic and has very low porosity (>96% inorganic component by weight and < 1% organic material) (Wang and Cerling, 1994). The inorganic mineral phase of tooth enamel is hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$). Biogenic phosphate (hydroxyapatite) is precipitated in equilibrium with body water, which is mostly comprised of ingested water (Longinelli, 1984; Luz et al., 1984). Mammals larger than 1 kg have a constant body temperature near 37^oC (Cossins and Bowler, 1987). Hydroxyapatite is precipitated in mammals (>1 kg) at a constant temperature which allows for the isotopic signature of the ingested material to be recorded. Tooth enamel is less susceptible to diagenesis than bone or dentine because of its lower organic content, higher density, and larger crystalline size (Ayliffe et al., 1994; Bryant et al., 1994; Fricke et al., 1995). Because of its resistance to diagenetic alteration, the enamel is the most suitable material for paleoenvironmental study using stable isotopes (Wang and Cerling, 1994).

Enamel hydroxyapatite contains a small amount of structural carbonate substituting for phosphate and hydroxyl ions. $\delta^{13}C$ values of structural carbonate in biogenic apatite with low porosity, as in tooth enamel, record carbon isotopic composition of animal's diet. C3 vegetation consists of all trees, most shrubs, and cool season grasses using the Calvin photosynthetic pathway. C3 plants have $\delta^{13}C$ values ranging from -20 to -35‰ with an average of -27‰ (Deines, 1980). C4 vegetation consists of warm season grasses and a few shrubs which are adapted to low atmospheric carbon dioxide concentration, high temperature, and water stressed environments. C4 vegetation uses the Hatch-Slack photosynthetic pathway. C4 plants have a $\delta^{13}C$ range of -9 to -17‰ with an average of -13‰ (Deines, 1980). Carbon incorporated into biogenic hydroxyapatite in herbivorous mammals is consistently enriched in ^{13}C by 13‰ to 14‰ relative to ingested food (Lee-Thorp and Van der Merwe, 1987). This means a C3 signal from tooth enamel would be ~ -13‰, and a C4 signal would be ~ +1‰ (Sullivan and Krueger, 1981; Lee-Thorp and Van der Merwe, 1987). Therefore, based on the isotopic signature found in teeth, the ratio of C3 to C4 vegetation consumed can be deciphered, and the environment present can be interpreted from the plant ratio. Being able to determine the diets of ancient animals can be useful in determining past changes in habitats of the region where the specimens were found.

Oxygen isotopes in tooth enamel contain valuable information about climate. The isotopic composition of oxygen in tooth phosphate from mammals ($\delta^{18}O_{PO4}$) is linked to the isotopic composition of body water ($\delta^{18}O_{W}$). Body water ($\delta^{18}O_{W}$) is controlled by a number of variables including the $\delta^{18}O$ of drinking water and water in food, physiological process, and dietary/drinking behavior (Longinelli, 1984; Luz et al., 1984; Kohn, 1996; Bryant et al., 1994). Studies have shown the oxygen isotopes in teeth carry information about meteoric water because most of an animal's ingested water comes directly from meteoric water (i.e. lakes, ponds, puddles, streams) (Longinelli, 1984; Luz et al., 1984; Fricke et al., 1995; Bryant et al., 1996). Because the $\delta^{18}O$ of meteoric water is sensitive to climatic variables such as mean annual temperature, seasonality of rain, and the amount of rain (Dansgaard, 1964; Rozanski et al, 1992), the $\delta^{18}O$ of tooth enamel can be used as a proxy for paleoclimatic conditions during tooth growth (e.g., Longinelli, 1984; Koch et al., 1989; Fricke et al., 1995; Bryant et al., 1994, 1996; Wang and Deng, 2005). Mammalian tooth enamel forms incrementally from the crown to the base of the tooth during eruption recording a series of $\delta^{13}C$ and $\delta^{18}O$ values over time, usually one to two years in mammals. These values can vary along the growth axis within a single tooth up to several per mil, providing a record of seasonal variations in diet and climate during tooth growth (Cerling and Sharp, 1996; Fricke and O'Neil, 1996, Fricke et al., 1998a, Sharp and Cerling, 1998).

In Tibet, vegetation and climate change with elevation. Because of high altitude (cooler temperatures), Tibetan ecosystems are dominated by C3 vegetation. The $\delta^{18}O$ of surface water, on the other hand, is expected to decrease generally with increasing elevation (Dansgaard, 1964). The altitude effect is caused by the continuous cooling of the air mass to below the dew point in a mountainous precipitation system (Ingraham, 1998). The altitude effect should be visible in herbivore tooth enamel because the majority of the animal's ingested water is from meteoric water.

In this study, carbon and oxygen isotope compositions of modern herbivore teeth (horse, yak, goat) from different elevations were analyzed to examine how they are influenced by altitudinal changes in vegetation and precipitation isotopic ratios. Serial enamel samples were analyzed to look at whether seasonal variations in local vegetation and precipitation $\delta^{18}O$ values are quantitatively recorded in individual teeth. In addition, $\delta^{18}O$ and δD values of water samples collected from various elevations in Tibet were measured. The objective of the study is to examine the effects of altitudinal variations in temperature, precipitation, and flora on the stable isotope chemistry of modern herbivore tooth enamel, and to establish empirical relationships between the $\delta^{13}C$ and $\delta^{18}O$ of tooth enamel and the modern environments in Tibet.

2. STUDY AREA

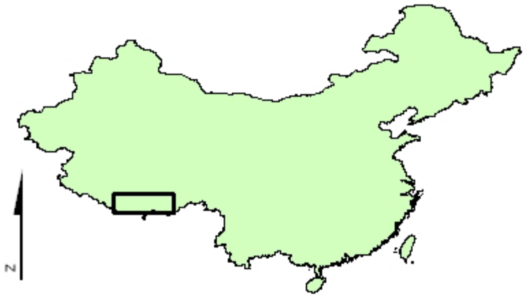

Figure 1. Map showing the study area in southern Tibet.

The study area is between 27^{o} and 29^{o}N and from 85^{o} to 92^{o}E in southern Tibet (Figure 1). In Tibet, the vegetation and climate change with elevation. Rainfall from the southeast and southwest monsoons is a major controlling factor in the distribution of vegetation on the Tibetan Plateau. Precipitation generally decreases from south/southeast to north/northwest and mean annual temperatures decrease with increasing elevation. Changes in precipitation and temperature with elevation result in a distinct zonal vegetation pattern. In southern Tibet where the samples were collected, forests grow in valleys and mountain slopes below ~3500m. The zone between 3500 and 4000m is occupied by subalpine shrub-meadow, and alpine meadow and alpine desert occur above 4000m (Lu et al., 2004). In this region, the forest and meadow communities are dominated by C3 plants whereas the desert is dominated by CAM plants (Lu et al., 2004). There are reports in Chinese literature that C4 grasses could penetrate to high elevations, but they account for negligible amounts of the biomass (Deng and Li, 2005). Unfortunately, there is a lack of direct observations of diet for herbivores in this region in the literature.

3. MATERIALS AND METHODS

Modern tooth, water and grass samples were collected from various elevations in southern Tibet in the summer of 2004. The teeth come from yaks (*Bos mutus*), goats (*Capra hircus*), and horses (*Equus caballus*). The tooth samples were cleaned by scraping off any dirt or other material off the enamel. Bulk samples were taken by drilling down the tooth along the growth axis (Figure 2). Serial samples were taken with a drill at different points along the growth axis, perpendicular to the growth axis (Figure 3). The distance from the cervical margin to the midpoint of each serial sampling line was measured and recorded. All of the samples were then prepared for analysis on a Finnigan MAT Delta Plus XP stable isotope ratio mass spectrometer following the procedure described in Wang and Deng (2005). Samples were treated with 1 M sodium hypochlorite overnight to remove organic material, followed by treatment with 1 M acetic acid for at least 6 hours to get rid of non-structural carbonate. The treated samples are then cleaned with distilled water and freeze-dried. After treatment, the powder contains only hydroxyapatite crystals. The samples were weighed, placed in vials, and then dried in the oven overnight. The vials containing the samples were placed in the Gas Bench and then flushed with Helium gas for 5 minutes per vial. 100% phosphoric acid was then added to react with the sample powders at 25°C to release carbon dioxide, which was then carried in a He stream into the mass spectrometer for isotopic measurements. A GasBench II Auto-carbonate device connected to a stable isotope ratio mass spectrometer was used to analyze the samples. Results are reported in

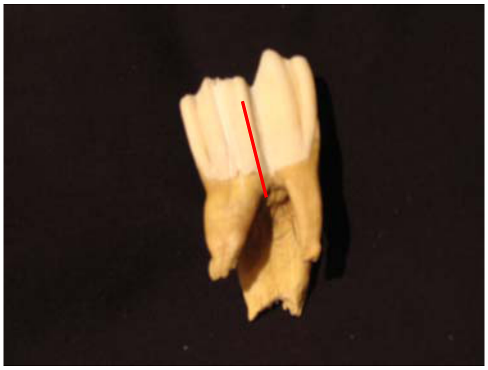

Figure 2. An example of bulk sampling of tooth enamel. (The red line shows the growth axis.)

Figure 3. An example of serial sampling of tooth enamel.

standard delta (δ) notation with units reported in parts per thousand (‰) relative to the PDB standard for $\delta^{13}C$ and SMOW standard for $\delta^{18}O$ as:

$$\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{PDB} - 1] \times 1000$$

$$\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1] \times 1000$$

$$\delta D = [(^{2}H/^{1}H)_{sample}/(^{2}H/^{1}H)_{SMOW} - 1] \times 1000$$

4. RESULTS

4.1. Carbon and Oxygen Isotopic Composition of Modern Herbivore Tooth Enamel

Sixty-four individual teeth from modern goats, horses, and yaks from southern Tibet were collected for this study. A total of 123 bulk and serial enamel samples were obtained from these modern teeth for C and O analysis. The results from the enamel are summarized in Table 1.

Table 1. Modern herbivore tooth enamel samples and their $\delta^{13}C$ and $\delta^{18}O$ results.

Sample Number	Sample Type	Tooth Type	Species	Location	Elevation (m)	Distance from cervical margin (mm)	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)
TB-L-1a	goat	M1	*Capra hircus*	Ladong Village, Tibet	3700		-11.1	-4.8
TB-L-1b	goat	U	*Capra hircus*	Ladong Village, Tibet	3700		-9.8	-8.0
TB-L-1c	goat	P3	*Capra hircus*	Ladong Village, Tibet	3700		-11.1	-1.8
TB-L-1d	goat	M1	*Capra hircus*	Ladong Village, Tibet	3700		-11.0	-5.8
TB-L-1e	goat	m3	*Capra hircus*	Ladong Village, Tibet	3700		-10.1	-10.0
TB-L-1f	goat	P3	*Capra hircus*	Ladong Village, Tibet	3700		-11.0	-2.0
TB-L-1h	goat	L	*Capra hircus*	Ladong Village, Tibet	3700		-10.3	-8.4
TB-L-1i	goat	m1-3	*Capra hircus*	Ladong Village, Tibet	3700		-11.4	-8.5
TB-L-2b	goat	P3-M1	*Capra hircus*	Between Lazi and Jiangzi, Tibet	3900		-11.3	-10.7
GT-18	goat	m1	*Capra hircus*	Woma Village, Gyirong, Tibet	4100		-9.7	-10.1
GT-20a	goat	m1-3	*Capra hircus*	Woma Village, Gyirong, Tibet	4100		-7.7	-8.0
GT-20b	goat	p4-m2	*Capra hircus*	Woma Village, Gyirong, Tibet	4100		-8.5	-8.0
G-1	goat		*Capra hircus*	Gyirong Basin	4100		-9.0	-15.4
G-2	goat		*Capra hircus*	Gyirong Basin	4100		-9.0	-15.4
G-3	goat		*Capra hircus*	Gyirong Basin	4100		-9.0	-14.2
G-4	goat		*Capra hircus*	Gyirong Basin	4100		-10.0	-12.2
G-5	goat		*Capra hircus*	Gyirong Basin	4100		-11.0	-13.2
G-6	goat		*Capra hircus*	Gyirong Basin	4100		-11.1	-15.4
G-7	goat		*Capra hircus*	Gyirong Basin	4100		-11.4	-12.2
G-8	goat		*Capra hircus*	Gyirong Basin	4100		-11.7	-14.6
G-9	goat		*Capra hircus*	Gyirong Basin	4100		-12.1	-12.1
TB-J-5a	goat	p4-m2	*Capra hircus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-7.8	-13.1
TB-J-5b	goat	P3-M3	*Capra hircus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.7	-9.1
TB-J-5c	goat	p2	*Capra hircus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.3	-13.0
TB-J-6	goat	p3-m1	*Capra hircus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.4	-11.1
TB-J-7	goat	p4-m2	*Capra hircus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.6	-14.5
GT-24a	horse	p3	*Equus caballus*	Woma Village, Gyirong, Tibet	4100		-11.1	-14.8
GT-24b	horse	M1	*Equus caballus*	Woma Village, Gyirong, Tibet	4100		-10.8	-15.1

Table 1. – continued.

Sample Number	Sample Type	Tooth Type	Species	Location	Elevation (m)	Distance from cervical margin (mm)	$\delta^{13}C$ (PDB)	$\delta^{18}O$ (PDB)
GT-24d	horse	i3	*Equus caballus*	Woma Village, Gyirong, Tibet	4100		-11.2	-15.2
H-1	horse		*Equus caballus*	Gyirong Basin	4100		-12.8	-19.0
H-2	horse		*Equus caballus*	Gyirong Basin	4100		-12.8	-18.8
H-3	horse		*Equus caballus*	Gyirong Basin	4100		-13.0	-18.5
H-4	horse		*Equus caballus*	Gyirong Basin	4100		-13.1	-19.0
H-5	horse		*Equus caballus*	Gyirong Basin	4100		-13.1	-18.8
H-6	horse		*Equus caballus*	Gyirong Basin	4100		-13.1	-18.6
H-7	horse		*Equus caballus*	Gyirong Basin	4100		-13.3	-18.5
H-8	horse		*Equus caballus*	Gyirong Basin	4100		-13.4	-19.7
H-9	horse		*Equus caballus*	Gyirong Basin	4100		-13.7	-20.0
H-10	horse		*Equus caballus*	Gyirong Basin	4100		-13.9	-20.0
LGT-1	yak	i, I and p	*Bos mutus*	Little Gyirong (near Nepal), Tibet	2700		-12.7	-8.4
TB-B-1	yak	I	*Bos mutus*	Bailang Co., Tibet	3800		-11.0	-16.1
TB-JZ-1b	yak	p4	*Bos mutus*	Jiangzi Co., Tibet	3900		-7.7	-15.9
TB-JZ-1c	yak	M1	*Bos mutus*	Jiangzi Co., Tibet	3900		-7.8	-15.7
TB-JZ-1d	yak	P4	*Bos mutus*	Jiangzi Co., Tibet	3900		-7.9	-16.0
TB-JZ-1e	yak	L	*Bos mutus*	Jiangzi Co., Tibet	3900		-8.4	-16.6
TB-JZ-1f	yak		*Bos mutus*	Jiangzi Co., Tibet	3900		-8.3	-16.5
TB-JZ-1g	yak		*Bos mutus*	Jiangzi Co., Tibet	3900		-8.2	-17.0
TB-JZ-1h	yak	U	*Bos mutus*	Jiangzi Co., Tibet	3900		-8.7	-16.1
TB-JZ-1i	yak		*Bos mutus*	Jiangzi Co., Tibet	3900		-8.3	-16.6
TB-JZ-1j	yak		*Bos mutus*	Jiangzi Co., Tibet	3900		-8.5	-16.3
TB-JZ-1k	yak	p3-4	*Bos mutus*	Jiangzi Co., Tibet	3900		-12.1	-11.9
TB-JZ-1l	yak	L	*Bos mutus*	Jiangzi Co., Tibet	3900		-7.3	-16.9
TB-JZ-2	yak	p and L	*Bos mutus*	Jiangzi Co., Tibet	3900		-10.4	-14.8
TB-JZ-3	yak	i and L	*Bos mutus*	Jiangzi Co., Tibet	3900		-10.8	-11.7
GT-19	yak	m1-3	*Bos mutus*	Woma Village, Gyirong, Tibet	4100		-10.3	-12.6
GT-21a	yak	L	*Bos mutus*	Gyirong, Tibet	4100		-9.6	-15.2
GT-21b	yak	L	*Bos mutus*	Gyirong, Tibet	4100		-9.6	-15.4
GT-23b	yak	P4	*Bos mutus*	Gyirong, Tibet	4100		-10.3	-12.9
GT-23c	yak	M1	*Bos mutus*	Gyirong, Tibet	4100		-10.2	-13.8
Y-1	yak		*Bos mutus*	Gyirong Basin	4100		-10.7	-16.8
Y-2	yak		*Bos mutus*	Gyirong Basin	4100		-11.3	-19.2
Y-3	yak		*Bos mutus*	Gyirong Basin	4100		-11.9	-16.8
Y-4	yak		*Bos mutus*	Gyirong Basin	4100		-12.5	-18.5
Y-5	yak		*Bos mutus*	Gyirong Basin	4100		-13.7	-14.8
Y-6	yak		*Bos mutus*	Gyirong Basin	4100		-14.0	-13.4
Y-7	yak		*Bos mutus*	Gyirong Basin	4100		-14.2	-14.0
GT-22	yak	M1/M1	*Bos mutus*	Gyirong, Tibet	4200		-12.5	-8.6
TB-J-1a	yak	m1	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.6	-13.4
TB-J-1b	yak		*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.4	-13.7
TB-J-1c	yak		*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.0	-12.8
TB-J-1d	yak		*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.2	-12.3
TB-J-1e	yak		*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-8.9	-13.5
TB-J-2a	yak	P4-M2	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.4	-12.7
TB-J-2b	yak	M	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.8	-15.3
TB-J-2c	yak	P3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.4	-13.9
TB-J-2d	yak	P3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.3	-14.3
TB-J-2e	yak		*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.3	-14.4

Table 1. – continued.

Sample Number	Sample Type	Tooth Type	Species	Location	Elevation (m)	Distance from cervical margin (mm)	δ^{13}C (PDB)	δ^{18}O (PDB)
TB-J-2f	yak		*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.1	-14.6
TB-J-2g	yak	P	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.8	-14.7
TB-J-3a	yak	P3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-8.8	-14.0
TB-J-3b	yak	p2	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-7.5	-14.7
TB-J-3c	yak	P3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-7.5	-13.2
TB-J-3d	yak	P4	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-8.9	-13.3
TB-J-3e	yak	P2	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-9.0	-14.5
TB-J-4a	yak	P3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.3	-14.4
TB-J-4b	yak	P4	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.1	-14.8
TB-J-4c	yak	M3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-8.1	-14.9
TB-J-9a	yak	p2	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.4	-16.0
TB-J-9b	yak	m1	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-11.0	-15.1
TB-J-9c	yak	m3	*Bos mutus*	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700		-10.9	-15.3
TBJZ3-01	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	3.0	-10.9	-10.7
TBJZ3-02	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	5.0	-10.9	-11.0
TBJZ3-03	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	7.0	-11.1	-10.4
TBJZ3-04	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	9.0	-11.3	-9.8
TBJZ3-05	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	11.0	-11.3	-9.1
TBJZ3-06	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	13.0	-11.5	-8.3
TBJZ3-07	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	14.5	-11.6	-7.8
TBJZ3-08	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	16.5	-11.6	-7.3
TBJZ3-09	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	18.0	-11.7	-6.7
TBJZ3-10	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	20.0	-11.8	-7.0
TBJZ3-11	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	22.0	-11.9	-6.9
TBJZ3-12	yak	i and L	Bos mutus	Jiangzi Co., Tibet	3900	24.0	-12.1	-6.7
TBJZ2-43	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	2.5	-10.7	-14.5
TBJZ2-44	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	6.0	-10.9	-14.4
TBJZ2-45	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	9.0	-10.7	-14.5
TBJZ2-46	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	12.5	-10.4	-16.0
TBJZ2-47	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	15.0	-10.4	-16.0
TBJZ2-48	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	18.0	-10.4	-16.1
TBJZ2-49	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	20.5	-10.5	-15.5
TBJZ2-50	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	23.0	-10.6	-15.4
TBJZ2-51	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	25.5	-10.6	-14.9
TBJZ2-52	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	28.0	-10.9	-14.0
TBJZ2-53	yak	p and L	Bos mutus	Jiangzi Co., Tibet	3900	30.5	-10.9	-13.8
GT23b-37	yak	P4	Bos mutus	Gyirong, Tibet	4100	3.5	-10.3	-13.3
GT23b-38	yak	P4	Bos mutus	Gyirong, Tibet	4100	6.0	-10.5	-12.2
GT23b-39	yak	P4	Bos mutus	Gyirong, Tibet	4100	8.5	-10.2	-11.3
GT23b-40	yak	P4	Bos mutus	Gyirong, Tibet	4100	11.0	-10.2	-11.5
GT23b-41	yak	P4	Bos mutus	Gyirong, Tibet	4100	13.5	-10.6	-12.6
GT23b-42	yak	P4	Bos mutus	Gyirong, Tibet	4100	15.5	-10.3	-13.5
GT19-54	yak	m1-3	Bos mutus	Woma Village, Gyirong, Tibet	4100	2.5	-9.5	-11.9
GT19-55	yak	m1-3	Bos mutus	Woma Village, Gyirong, Tibet	4100	5.5	-9.4	-12.7
GT19-56	yak	m1-3	Bos mutus	Woma Village, Gyirong, Tibet	4100	8.5	-9.6	-12.6
GT19-57	yak	m1-3	Bos mutus	Woma Village, Gyirong, Tibet	4100	11.0	-10.0	-12.5
GT19-58	yak	m1-3	Bos mutus	Woma Village, Gyirong, Tibet	4100	13.0	-10.3	-12.7
GT19-59	yak	m1-3	Bos mutus	Woma Village, Gyirong, Tibet	4100	15.0	-10.5	-13.0
TBJ1a-13	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	2.0	-8.2	-10.9
TBJ1a-14	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	4.0	-8.1	-12.7
TBJ1a-15	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	6.5	-8.4	-13.4
TBJ1a-16	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	8.5	-8.7	-14.1
TBJ1a-17	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	11.0	-8.7	-14.8

Table 1. – continued.

Sample Number	Sample Type	Tooth Type	Species	Location	Elevation (m)	Distance from cervical margin (mm)	δ^{13}C (PDB)	δ^{18}O (PDB)
TBJ1a-18	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	13.0	-8.8	-15.0
TBJ1a-19	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	16.0	-8.8	-15.0
TBJ1a-20	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	18.0	-8.9	-14.3
TBJ1a-21	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	20.5	-9.0	-14.0
TBJ1a-22	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	23.0	-9.1	-13.8
TBJ1a-23	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	25.0	-9.4	-13.1
TBJ1a-24	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	27.0	-9.8	-12.1
TBJ1a-25	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	29.5	-10.0	-11.1
TBJ1a-26	yak	m1	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	32.0	-10.2	-10.1
TBJ4c-27	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	2.5	-9.7	-15.5
TBJ4c-28	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	5.0	-9.8	-15.3
TBJ4c-29	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	7.0	-10.0	-14.3
TBJ4c-30	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	9.5	-10.0	-13.9
TBJ4c-31	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	12.0	-9.6	-14.1
TBJ4c-33	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	17.0	-9.6	-15.1
TBJ4c-34	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	19.0	-9.7	-15.6
TBJ4c-35	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	21.5	-9.7	-15.8
TBJ4c-36	yak	M3	Bos mutus	Jiajie Port (Yaluzhangbujiang) near Shajia, Tibet	4700	25.0	-9.6	-16.0

4.1.1. δ^{13}C and δ^{18}O values of bulk enamel samples

All 13 horse teeth come from the Gyirong Basin (28° 46.13’ N, 85° 17.84’ E) at an elevation of about 4100 meters above sea level (a.s.l.). The δ^{13}C values of enamel samples from horses range from -11.2‰ to -13.9‰ with an average value of -12.7 ± 1.0‰ and a median value of -13.1‰. The δ^{18}O values of horse tooth enamel are from -14.8‰ to -20.0‰, averaging -18.2 ± 1.9‰ with a median value of -18.8‰.

The goat teeth were collected from an elevation range of 3700m to 4700m a.s.l. and have δ^{13}C values ranging from -7.8‰ to -12.1‰, averaging -10.2 ± 1.2‰ with a median of -10.3‰. The mean δ^{18}O value for all goats is -10.5 ± 3.9‰ with a range of -1.8‰ to -15.4‰ and a median of -10.9‰. There are 8 samples from 3700m a.s.l. with an average δ^{13}C value of -10.7 ± 0.6‰ and a median of -11.0‰ and an average δ^{18}O of -6.2 ± 3.1‰ and a median of -6.9‰. The only sample from 3900m a.s.l. has a δ^{13}C value of -11.3‰ and a δ^{18}O of -10.7‰. There are 12 samples from the Gyirong Basin at

~4100m a.s.l. These samples have an average $\delta^{13}C$ of -10.0 ± 1.4‰ and a median of -9.9‰, about 3‰ higher than the average enamel $\delta^{13}C$ value of horses from the same basin. The average $\delta^{18}O$ of the goat tooth enamel from the Gyirong Basin is -12.6 ± 2.7‰ and a median of -12.7‰, which is also higher (~6‰) than that of the horses from the same elevation. Five samples from 4700 m a.s.l. have an average $\delta^{13}C$ of -9.5 ± 1.1‰ with a median of -9.7‰ and an average $\delta^{18}O$ of -12.2 ± 2.1‰ with a median of -13.0‰.

The yak samples also span a range of elevations from 2700m to 4700m a.s.l., and have yielded an average $\delta^{13}C$ value of -10.1 ± 1.4‰ with a median of -10.1‰ and an average $\delta^{18}O$ value of -13.6 ± 2.6‰ with a median of -14.0‰. The $\delta^{13}C$ values of yak tooth enamel range from -7.3‰ to -14.2‰, and the $\delta^{18}O$ values have a range from -6.7‰ to -19.2‰. The only sample from 2700m a.s.l. has a $\delta^{13}C$ value of -12.7‰ and a $\delta^{18}O$ value of -8.4‰. The sample from 3800m a.s.l. has a $\delta^{13}C$ value of -11.0‰ and a $\delta^{18}O$ value of -16.1‰. The 36 samples from 3900m a.s.l. have an average $\delta^{13}C$ of -10.3 ± 1.4‰ with a median of -10.7‰ and an average $\delta^{18}O$ of -13.0 ± 3.6‰ with a median of -14.5‰. There are 24 samples from 4100m a.s.l. with an average $\delta^{13}C$ of -10.8 ± 1.4‰ with a median of -10.3‰, similar to that of horses from the same elevation, and an average $\delta^{18}O$ of -13.9 ± 2.1‰ with a median of -13.1‰, which is higher compared to the horses from the same elevation. The sample from 4200m a.s.l. has a $\delta^{13}C$ value of -12.5‰ and a $\delta^{18}O$ value of -8.6‰. The 46 samples from 4700m a.s.l. have an average $\delta^{13}C$ of -9.4 ± 0.8‰ with a median of -9.6‰ and an average $\delta^{18}O$ of -14.0 ± 1.3‰ with a median of -14.3‰.

4.1.2. $\delta^{13}C$ and $\delta^{18}O$ values of serial enamel samples

The serial enamel samples come from six yak teeth. All teeth show little intra-tooth $\delta^{13}C$ variations (<2.2‰). In contrast, $\delta^{18}O$ values display large intra-tooth variations. Sample TB-JZ-3 has a $\delta^{13}C$ range of -10.9 to -12.1‰ and $\delta^{18}O$ of -6.7 to -11.0‰. Sample TB-J-1a has a $\delta^{13}C$ range from -8.1 to -10.2‰ and $\delta^{18}O$ from -10.1 to -15‰. For sample TB-J-4c, the intra-tooth variations are from -9.6 to -10.0‰ for $\delta^{13}C$ and from -13.9 to -16.0‰ for $\delta^{18}O$. Unfortunately, only 6 serial samples were obtained from sample GT-23b. The $\delta^{13}C$ and $\delta^{18}O$ values of these samples range from -10.2 to -10.6‰ and from -11.3 to -13.5‰, respectively. Sample TB-JZ-2 has a $\delta^{13}C$ range of -10.4 to -10.9‰ and a $\delta^{18}O$ range of -13.8 to -16.1‰. Sample GT-19 has a $\delta^{13}C$ range of -9.4 to -10.5‰ and a $\delta^{18}O$ range of -11.9 to -13.0‰. The $\delta^{13}C$ and $\delta^{18}O$ variations within individual teeth reflect seasonal variations in diet and water.

4.2. Oxygen Isotopic Composition of Surface Waters in Southern Tibet

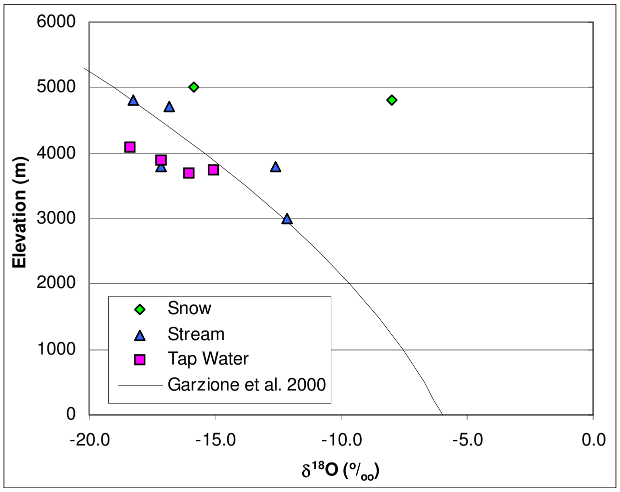

Figure 4. Variations of $\delta^{18}O$ of surface water with elevation in southern Tibet.

Rainout by a Rayleigh fractionation process predicts that $\delta^{18}O_{MW}$ will become increasingly more negative with each rainout event. The "altitude effect" predicts that with increasing altitude the $\delta^{18}O_{MW}$ becomes more negative. The $\delta^{18}O$ values of water samples are shown in Table 2. The $\delta^{18}O$ values of water samples do not show a significant trend with elevation ($R^2 = 0.006$ and $t = -0.230$ for linear fit to the data, where t is a test of significance of the difference of the slope from zero, Degrees of freedom DF = 10) in Figure 4. The curve in Figure 4 from Garzione et al. 2000 follows the equation:

$$\delta^{18}O = (2.61 \times 10^{-7})h^2 - (0.0013)h - 6.00$$

This equation is based on samples taken from tributaries in the Himalayas (Garzione et al., 2000). A linear relationship exists between the oxygen and hydrogen isotopic compositions of precipitation and fresh waters on a global scale, and the relationship follows this equation:

$$\delta D = 8.0(\delta^{18}O) + 10$$

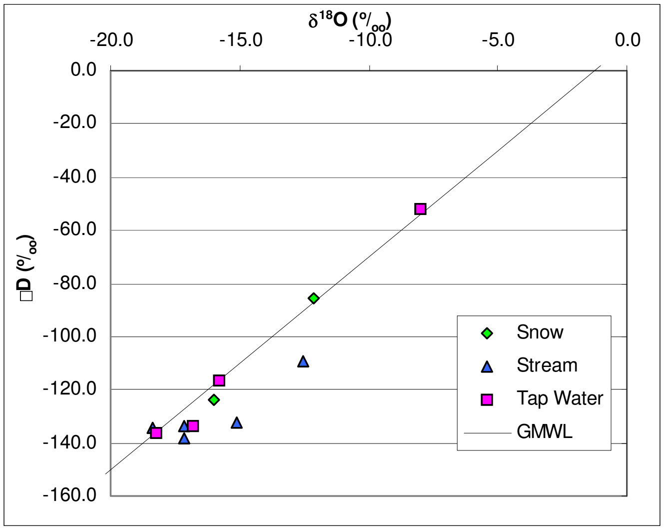

Figure 5. δD versus $\delta^{18}O$ of water samples from southern Tibet plotted with the Global Meteoric Water Line (GMWL).

This linear relationship is known as the Global Meteoric Water Line. Any points falling below this line has been affected by evaporation (Dansgaard, 1964). Some of the water samples may have been affected by evaporation as they plot below the global meteoric water line (GMWL) in Figure 5.

Table 2. Water samples from southern Tibet.

Sample	$\delta^{18}O_{VSMOW}$ (‰)	δD_{VSMOW} (‰)	Location	Elevation (m)	Sample Type	Note
JZ-TP	-17.2	-138.3	Jiangzi Co., Tibet	3900	Tap	Tap, Jiangzi Co., Tibet
YW-10	-17.2	-133.5	Dong-Gu-La-Shan, Tibet	3800	Stream	stream water, Dong-Gu-La-Shan, ~3800m, 6/25/04
YW-11	-16.8	-133.8	Dong-Gu-La-Shan, Tibet	4700	Stream	stream water, Dong-Gu-La-Shan, ~4700m, 6/25/04
YW-12	-15.1	-132.2	Re-Ke-Shi,Tibet	3750	Tap	Tap water, Re-Ke-Shi (2nd largest city in Tibet), ~3750 m, 6/25/04
YW-13	-12.6	-109.2	Gyirong, river, Tibet	3800	River	Gyirong river, ~3800m, 6/28/04
YW-14	-8.0	-52.1	Xue-Gu-La-Shan, Tibet	4800	Snow	snow on the ground, Xue-Gu-La-Shan (Tibet), ~4800m, 6/25/04
YW-16	-16.0	-123.9	Lhasa, Tibet	3700	Tap	Tap water, Lhasa, 6/23/04
YW-2	-18.4	-134.6	Gyirong,, Tibet	4100	Tap	Gyirong Tap Water, Tibet, ~4100m, 6/27/04
YW-4	-12.1	-85.6	Little Gyirong,, Tibet	3000	River	River Water, Little Gyirong, Tibet, ~3000m, 6/28/04
YW-5	-15.8	-116.7	Xue-Gu-La-Shan, Tibet	5000	Snow melt (Small pond)	Xue-Gu-La-Shan (Tibet),, small pond(snow melt), ~5000m, 6/25/04
YW-9	-18.3	-136.2	Xue-Gu-La-Shan, Tibet	4800	Stream	small stream, Xue-Gu-La-Shan, ~4800m, 6/25/04

5. DISCUSSIONS

5.1. Vegetation δ^{13}C Variability and Diets of Modern Herbivores

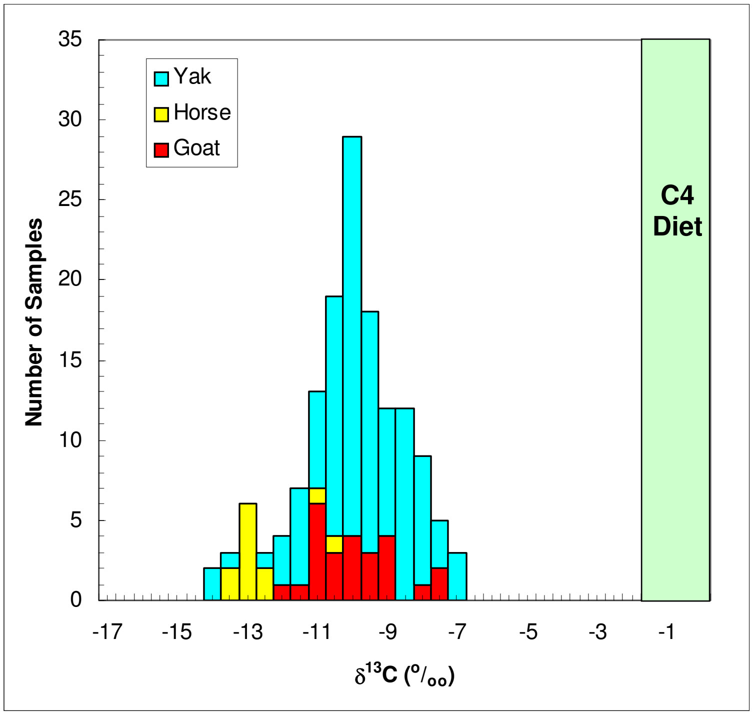

Figure 6. Stable carbon isotope composition of tooth enamel from modern herbivores. The green box represents the values of a C4 diet as would be expressed in tooth enamel.

Tibetan ecosystems consist primarily of C3 vegetation except for the alpine desert where CAM plants dominate (Lu et al., 2004). Studies (Li et al., 1999; Wang et al., 2003) have shown that the δ^{13}C values of C3 plants in the region increase with increasing altitude, with a lapse rate of 1.14±0.76‰ per 1000m increase in altitude, primarily in response to changes in precipitation or moisture. When plants are dealing with a water-stressed environment, they will close their stomatal apertures (openings of the leaf surface) to conserve water. The side effect of the stomatal aperture closing is a decrease in CO_2 diffusion into the plant, and this decrease in diffusion gives the plant a higher (or less negative) δ^{13}C value (Farquhar et al., 1989; Boutton, 1996). Recently, C4 grasses were discovered on the Tibetan Plateau, but they account for negligible amounts of the biomass (Deng and Li, 2005). The δ^{13}C values of tooth enamel from modern herbivores in southern Tibet (Figure 6) range from -7.3 to -14.2‰ with a mean of -10.3±1.5‰ (n=123). Tooth enamel δ^{13}C values of -9‰ or lower are typically taken as indication of a pure C3 diet (Cerling et al., 1997). Some of the samples have δ^{13}C values between -7.3 and -9‰. Although the slightly higher δ^{13}C values could suggest consumption of some C4 plants by the animals, the lack of significant seasonal variations within individual teeth (Figure 7) indicates that these higher enamel δ^{13}C values are more likely due to consumption of

C3 plants experiencing water stress and/or some CAM plants. There is a lack of documented observations of the diets of the herbivores analyzed in this study. Because tooth enamel is enriched in ^{13}C by ~14‰ relative to the diet (Lee-Thorp and Van der Merwe, 1987; Cerling et al., 1997), the $\delta^{13}C$ values of tooth enamel from southern Tibet correspond to a dietary intake of -21.3 to -28.2‰, with a mean value of -24.4±1.5‰. These estimated diet $\delta^{13}C$ values are well within the $\delta^{13}C$ range for modern C3 plants and indicate that the primary diets of the individual samples are composed of C3 plants (Figure 6), which is consistent with the current C3 dominance in the region. The data in this study also suggest that the "cut-off" enamel $\delta^{13}C$ value for a pure C3 diet could be -8‰ or higher in environments with water-stress.

On the Tibetan Plateau, the cooler temperatures inhibit the growth of C4 grasses. About 50 grass samples were collected spanning an elevation range of 2700m to 4800m a.s.l. on the Tibetan Plateau in the summers of 2004 and 2005. Carbon isotope analyses of these plant samples show that only four are C4 grasses (unpublished data from Dana Biasatti and Chunfu Zhang). Two of the C4 grasses were found in the town of Little Gyirong near the Nepal-China border at 2700m a.s.l., and the other two samples were found along side of the main highway in southern Tibet, near villages at 4000m and 4100m a.s.l. respectively. Although many of the grass samples have not yet been identified into species, three of the four C4 grasses clearly belong to the same species except that the samples found at higher elevations were smaller compared to the one collected at 2700m a.s.l. Therefore, reports in Chinese literature as well as our own work show that although C4 grasses could be found in the warmest months on the Tibetan Plateau, they account for negligible amounts of the biomass (Deng and Li, 2005) and are clearly not a significant dietary component for herbivores in the region.

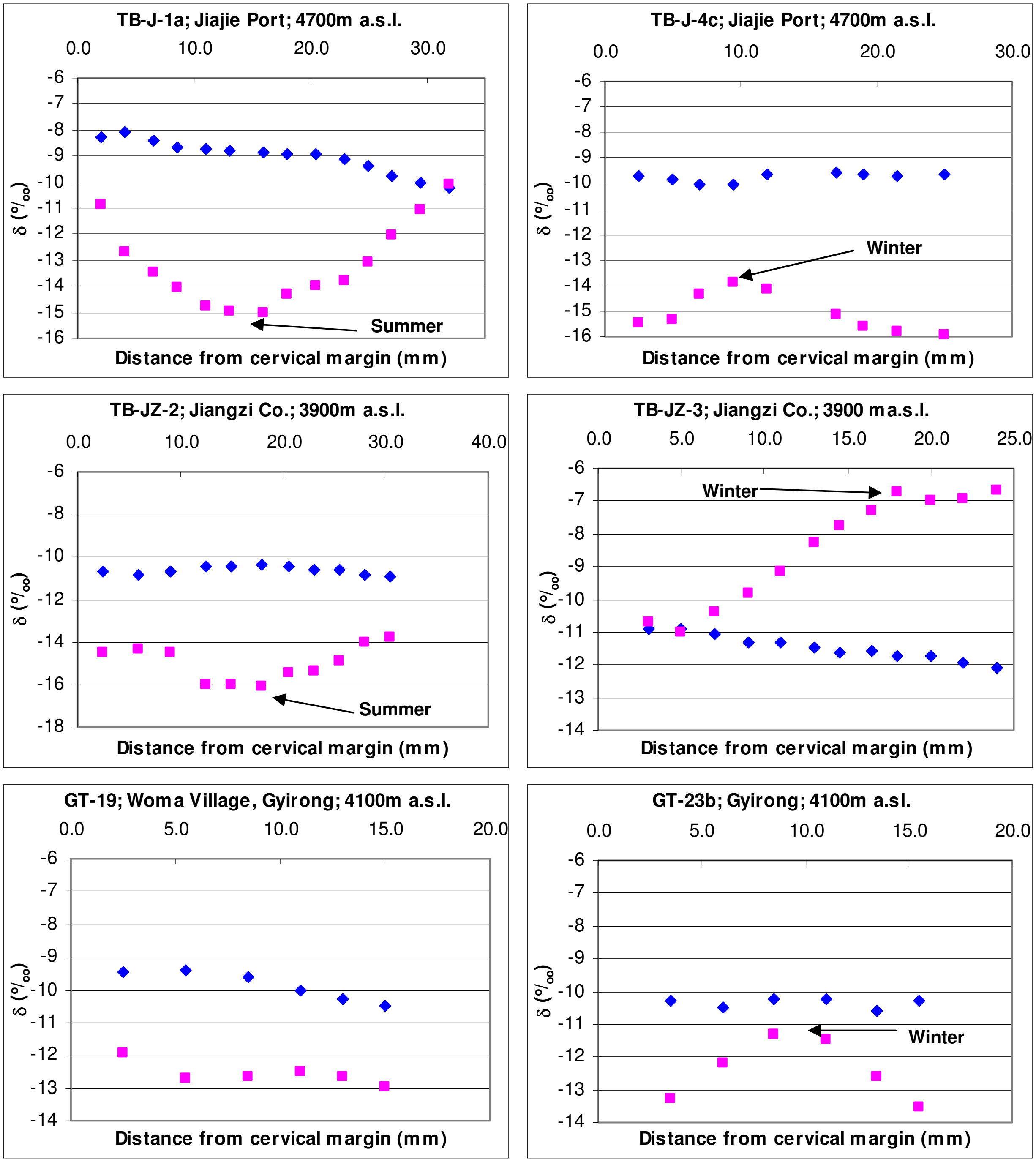

Figure 7. δ^{13}C and δ^{18}O values from enamel from 6 yak teeth. The distance from the cervical margin (the margin between the crown and the root of the tooth) is measured to the center of each sampling line. The blue diamonds represent δ^{13}C, and the pink squares represent δ^{18}O.

5.2. Variations of Enamel $\delta^{13}C$ and $\delta^{18}O$ Values Within and Between Species

Inter-tooth variations in $\delta^{13}C$ within an individual are small (Figure 10). The largest variation seen is 2.2‰ between a P3 and M3 from TB-J-4, a yak from Jiajie Port at 4700m a.s.l. This amount of variation falls within the standard deviation for the samples. The inter-tooth $\delta^{13}C$ variation reflects the variations in the $\delta^{13}C$ values of the plants consumed by the individual during the time these teeth were mineralizing.

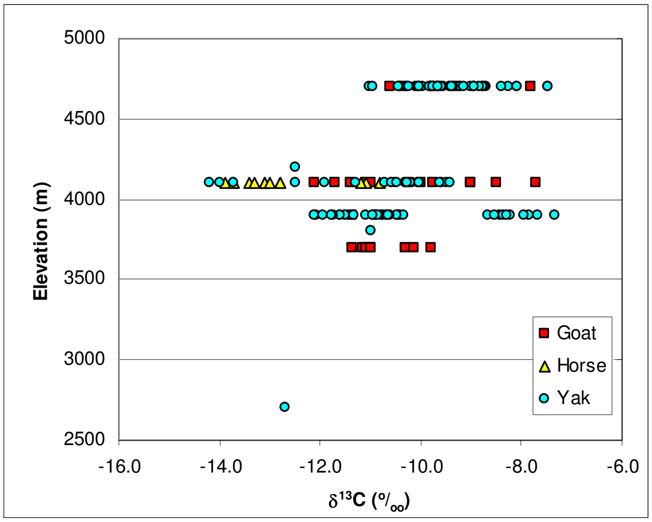

Figure 8. Variations of $\delta^{13}C$ values of modern herbivore tooth enamel with elevation.

In contrast to $\delta^{13}C$ values, inter-tooth variations in $\delta^{18}O$ within an individual are generally larger than the variations in $\delta^{13}C$ with some variations up to 8.2‰ (Figure 10). The inter-tooth $\delta^{18}O$ variation within an individual reflects variations in the $\delta^{18}O$ of water at the times of mineralization of different teeth. The "milk effect" could also contribute to the large inter-tooth $\delta^{18}O$ variation. Foals rarely drink water before they are weaned (Bryant et al., 1996). The milk produced by a mare has undergone biogenic fractionation processes that offset the milk from the water ingested by the mare (Bryant et al., 1996). These biogenic fractionation processes result in $\delta^{18}O$ values that are higher (more positive) than the values of local meteoric water (Fricke and O'Neil, 1996; D'Angela and Longinelli, 1990; Longinelli, 1984; Luz et al., 1984; Bryant and Froelich, 1995). Because the milk is enriched

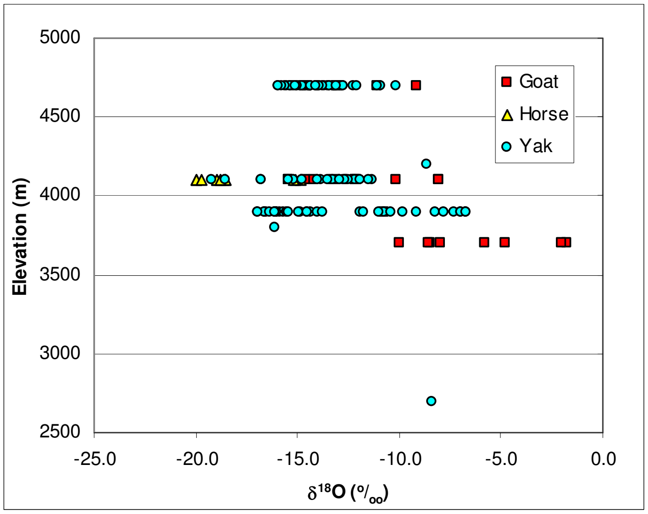

Figure 9. Variations of $\delta^{18}O$ values of modern herbivore tooth enamel with elevation.

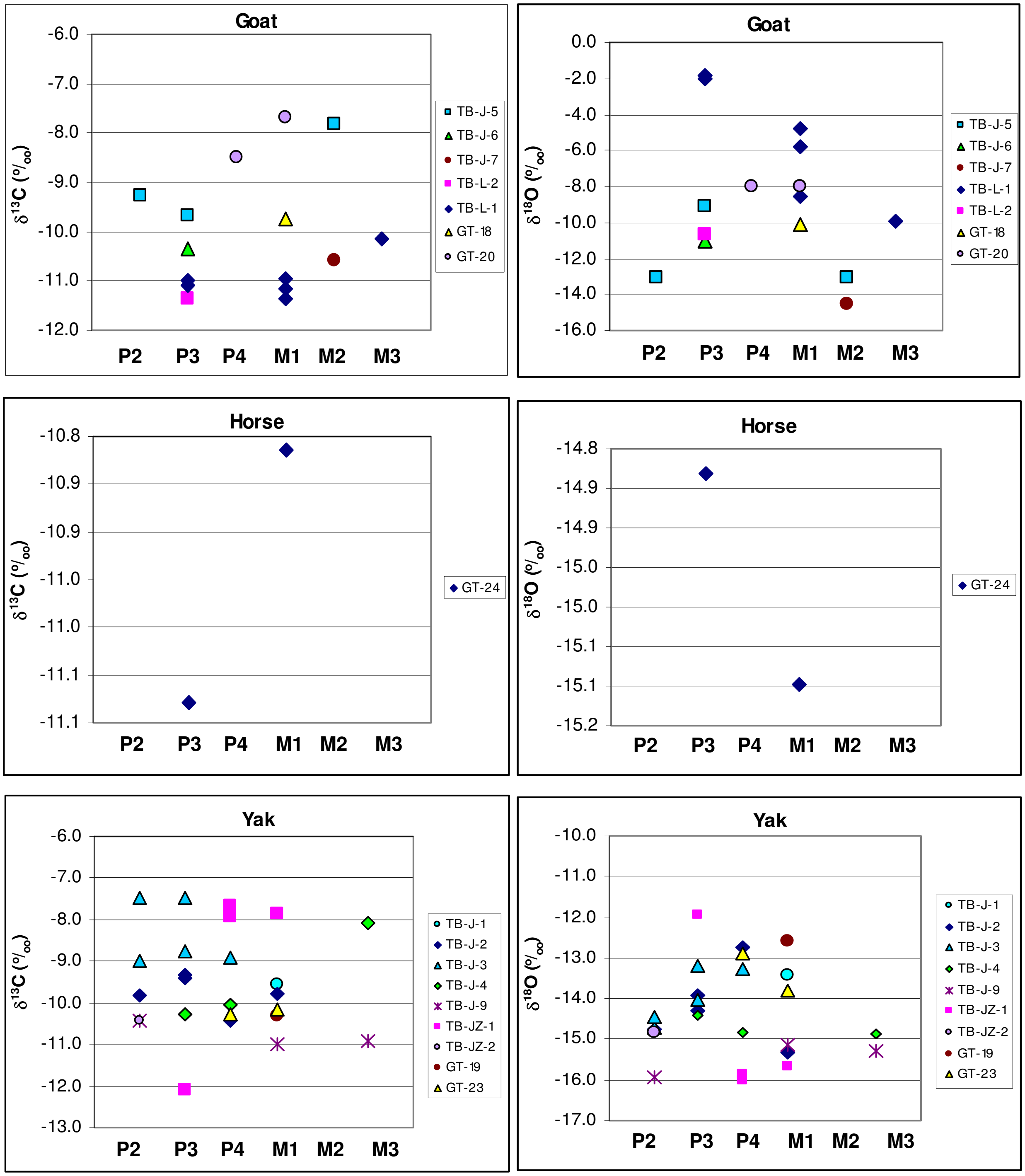

Figure 10. δ^{13}C and δ^{18}O versus tooth type (P = premolar, M = molar).

relative to meteoric water, the tooth enamel from a tooth formed before or during weaning should show a larger δ^{18}O enrichment relative to local meteoric water. Mammalian teeth erupt from 8 to 48 months of age, but all teeth are mineralized by ~ 36 months of age. M1 and M2 molars are formed partly during nursing, erupt between 8 and 12 months, and finish mineralizing by 24 and 36 months on average, respectively. P2 and P3 premolars finish mineralizing at around 24 months and erupt between 30 and 36 months. The M3 molar and P4 premolar finish mineralizing between 51 and 55 months and erupt between 42 and 48 months. Tooth mineralization finishes, for some teeth, after the tooth has erupted. The tooth mineralizes as the enamel is formed, so a sample taken perpendicular to the growth axis only shows a fraction of time during formation and mineralization (Hoppe et al., 2004). The tooth enamel formed before or during weaning, which occurs between 6 months and a year, are from the M1, M2, and deciduous ("baby") P2-P4 teeth, and the remaining teeth (P2, P3, P4, and M3) should not show any milk effect because they are formed after weaning (Bryant et al., 1996). This effect can be seen in the samples from the individual TB-L-1 and GT-19 (Figure 11). However, our data do not show a consistent enrichment pattern in milk teeth (i.e., M1 and M2) compared to other permanent teeth. This may be caused by the large seasonal variations in the δ^{18}O values of water that overwhelmed the relatively small "milk effect".

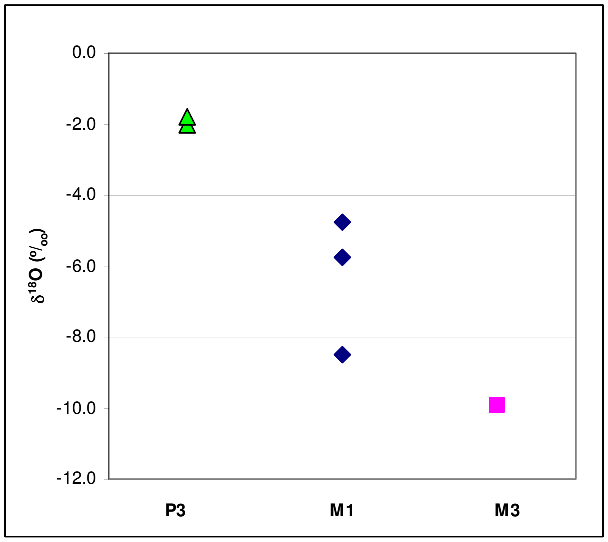

Figure 11. δ^{18}O values for individual teeth from TB-L-1, a goat from Ladong Village at 3700m a.s.l.

There are large δ^{18}O variations within and between species. The goat samples showed the largest variation (-1.8 to -10.0‰). At a given elevation, the horse samples have the lowest δ^{18}O values, while the goat samples are the most δ^{18}O-enriched. The inter-species δ^{18}O variations are caused by differences in physiology, and diet and drinking behavior of different animals (Bryant and Froelich, 1995; Kohn et al., 1996; Kohn, 1996). Both theoretical and empirical studies suggest that the δ^{18}O of enamel is directly related to the δ^{18}O of body water, which for large mammals (>1 kg) is mostly derived from two sources: meteoric water and food (Luz et al., 1984; Longinelli, 1984; Koch et al., 1989; Fricke et al., 1995; Bryant et al., 1996; Kohn, 1996; Fricke et al., 1998; Sponheimer and Lee-Thorp, 1999). Leaf water is generally enriched in ^{18}O relative to local meteoric water due to preferential loss of the isotopically lighter water molecule $H_2{}^{16}O$ during evapotranspiration, and this ^{18}O-enrichment is substantial in arid regions but decreases with increasing relative humidity (Dongmann et al., 1974; Epstein et al., 1977; Yakir, 1992). Thus, obligate drinkers such as horses would have lower δ^{18}O values than animals like goats that obtain a larger proportion of their body water from plant sources (e.g., leaves, fruits) in a given ecosystem. The larger inter-species δ^{18}O variations seen in goats primarily reflect large variations in leaf water δ^{18}O in arid and semi-arid regions (Dongmann et al., 1974; Epstein et al., 1977; Yakir, 1992).

5.3. Climatic Controls on Enamel δ^{13}C and δ^{18}O Variability

Carbon isotope study of soil organic matter in Tibetan soils has shown that the average δ^{13}C value of plant community (that determines the δ^{13}C of soil organic matter) decreases from forest (-25.9±1.2‰) to shrub (-24.7±1.4‰), steppe (-23.1±1.3‰), alpine meadow (-23.6±0.7‰), alpine desert steppe (-21.3±1.6‰), and alpine desert (-18.9±2.5‰), reflecting changes in climatic conditions (i.e., mean annual precipitation and temperature) and species composition (Lu et al., 2004). C3 plants in arid or semi-arid regions, such as this study area, have higher δ^{13}C values than C3 plants in humid or sub-humid regions (Deng and Li, 2005) because C3 plants tend to be enriched in ^{13}C under water stressed conditions (Farquhar et al., 1989).

The δ^{13}C values of tooth enamel do not show a strong trend with increasing elevation ($R^2 < 0.2$, $t < 1.9$, DF = 25, 25, 108 for A, B, and C respectively) (Figure 12(A,B,C)). Also, the δ^{18}O values of tooth enamel do not show a clear trend with increasing elevation in the study area (Figure 12 (D,E,F)). A trend for δ^{13}C or δ^{18}O cannot be see in the horse data because all of the horse samples are from the same elevation (4100 m a.s.l.).

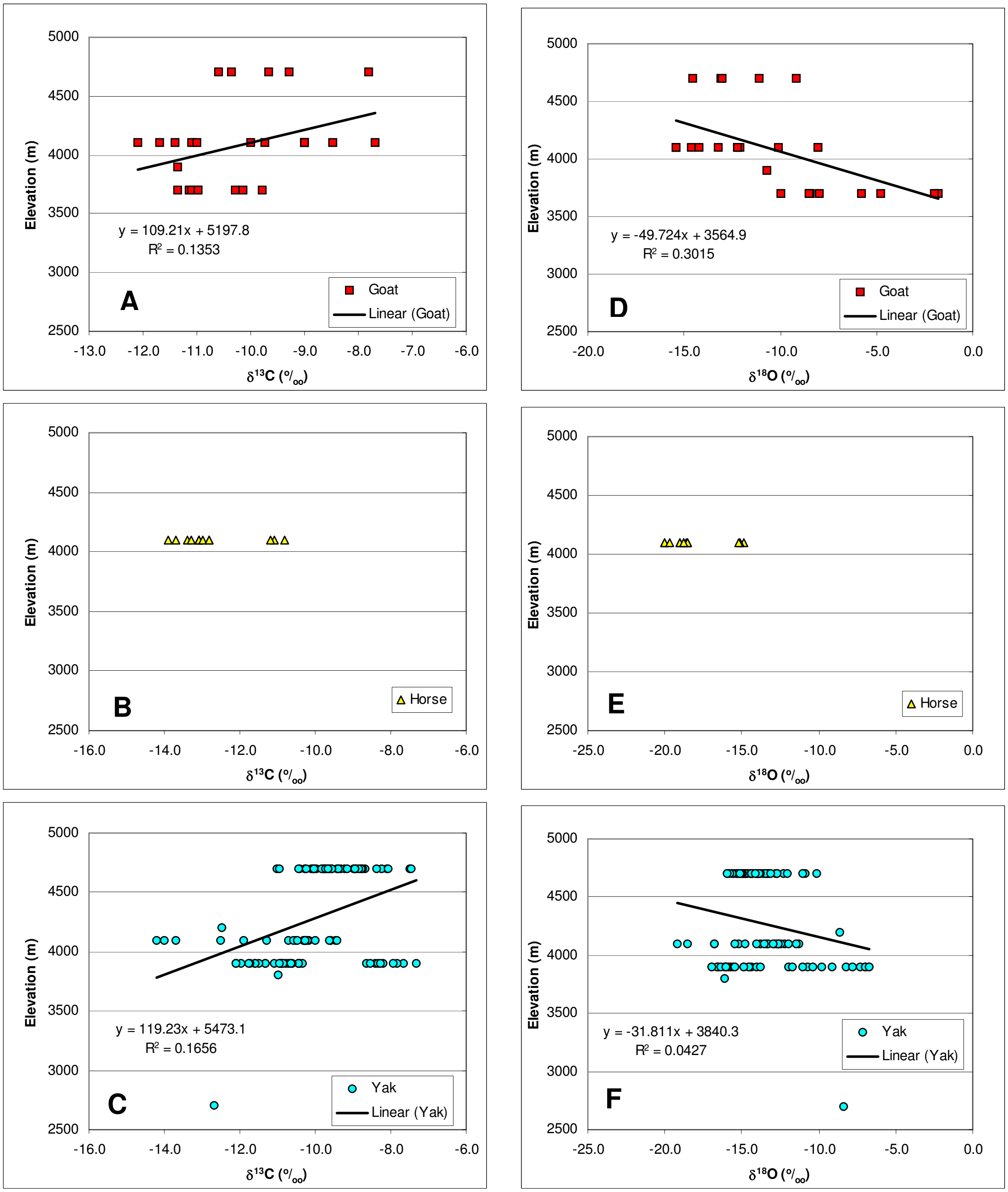

Figure 12. The δ^{13}C (A,B,C) and δ^{18}O (D,E,F) values for each species with elevation.

The mean δ^{18}O values of tooth enamel from goats show a positive correlation with the δ^{18}O values of water (Figure 13). This relationship yields the equation: y = 2.1514x + 26.435 with R^2 = 0.4677, t = 4.592, and DF = 25 (Figure 14). Unfortunately, there are not enough samples from the horses and yaks from different elevations for any meaningful statistical analysis.

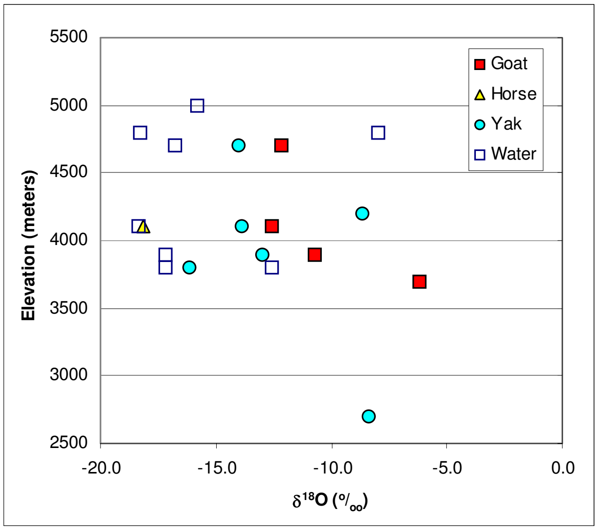

Figure 13. The mean δ^{18}O values for each species and the δ^{18}O values of the water samples collected plotted with elevation.

Serial samples show small δ^{13}C variations (~2‰ or less) within each tooth, but large intra-tooth δ^{18}O variations (Figure 7). The observed small intra-tooth δ^{13}C variations most likely reflect variations in the δ^{13}C of C3 plants consumed by the animals rather than the intake of C4 grasses whose availability would be highly seasonal. In the monsoon region such as Tibet, summer precipitation has lower δ^{18}O values than winter precipitation due to the “amount effect” (Blisniuk and Stern, 2005). Most of the annual precipitation in the region falls during the summer monsoons. During the summer monsoons, moisture bearing winds move over the continent, and the Tibetan Plateau intensifies the uplift and cooling of the air masses over the continent. Due to the preferential removal of heavy isotopes from vapor during condensation, the remaining air mass becomes more depleted in heavy isotopes (^{18}O) as it moves away from the source. The “amount effect” dramatically reduces the δ^{18}O of precipitation. Analysis of data from IAEA-GNIP stations shows large seasonal variations and negative correlations with the amount of precipitation which suggests that δ^{18}O values of precipitation in the monsoon region are more

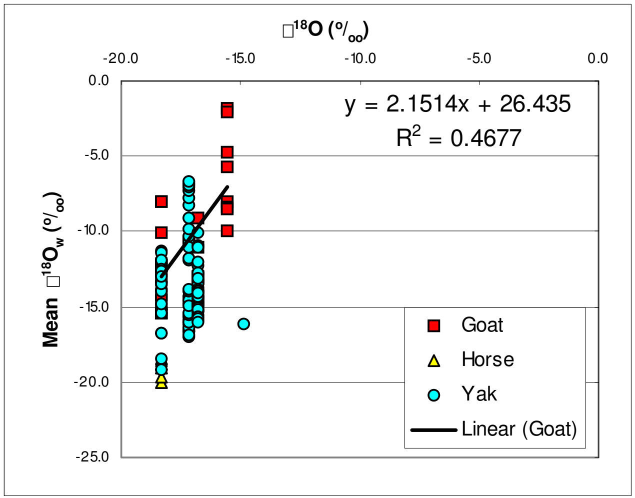

Figure 14. Mean δ^{18}O values of water versus the δ^{18}O values for each species.

dependent on the amount of precipitation than on temperature (Johnson and Ingram, 2004). The summer months show a more negative $\delta^{18}O$ value than the winter months due to the "amount effect" (Dansgaard, 1964). If the intra-tooth $\delta^{13}C$ variations were due to consumption of C4 plants, one would expect that high $\delta^{13}C$ values correspond to low $\delta^{18}O$ values (representing enamel formed in summer months) within each tooth. The samples analyzed here do not show this pattern (Figure 7). The lack of significant seasonal $\delta^{13}C$ variations within individual teeth confirms the C4 grasses were not a significant component of these modern herbivores' diets. The large intra-tooth $\delta^{18}O$ variations reflect seasonal variations in the oxygen isotopic composition of precipitation that provides drinking water for animals and water for plants consumed by animals.

The Asian monsoons are a significant factor influencing the $\delta^{18}O$ of meteoric water in China (Hoffman and Heimann, 1997 as in Johnson and Ingram, 2004). The Indian and East Asian summer monsoons are the predominant sources of moisture for the Tibetan region (Araguas-Araguas and Froehlich, 1998). During the summer monsoons, moisture bearing winds move from the Indian Ocean and the Pacific Ocean over the continent, and the Tibetan Plateau intensifies the uplift and cooling of the air masses which leads to increased precipitation over the continent. Because condensation preferentially removes heavy isotopes from vapor, the remaining vapor in an air mass and the precipitation formed subsequently becomes more ^{18}O-depleted as the air mass moves away from its source area. Areas with heavy rainfall can undergo considerable removal of ^{18}O from the vapor. As a result, $\delta^{18}O$ of precipitation becomes progressively more negative as an air mass moves inland or up a mountain range, particularly during the heavy rains of the wet season. This "amount effect" (Dansgaard, 1964) or "rain-out effect" dramatically reduces the $\delta^{18}O$ of precipitation. Although there is a strong positive correlation (~0.55‰/^{o}C) between precipitation $\delta^{18}O$ and surface temperature at mid- to high- latitude sites, this correlation is weaker or non-existent in low latitudes and in monsoon regions (Rozanski et al., 1993; Johnson and Ingram, 2004). Multi-variable regression analysis of data from GNIP areas (Global Network for Isotopes in Precipitation) suggests that $\delta^{18}O$ values of precipitation in the monsoon region in China are more dependent on the amount of precipitation than on temperature. For example, the weighted average δ^{18}O values of summer precipitation (June-September) in Lhasa are ~6‰ lower than those of winter precipitation (November-April) despite higher temperatures in the summer (Araguas-Araguas et al., 1998). That is, in the monsoon region, summer precipitation has lower δ^{18}O values (despite high temperature) than winter precipitation (Johnson and Ingram, 2004). Therefore, the lower enamel-δ^{18}O values within a tooth would correspond to summer months and higher δ^{18}O values would represent colder months (Figure 7). Unfortunately, only yak teeth were sampled for serial analyses, and none of the teeth sampled yielded a complete seasonal cycle (Figure 7). The largest amplitude of δ^{18}O variations recorded in these yak teeth is ~5.5‰, which is comparable to the seasonal δ^{18}O variations of precipitation in Lhasa. Clearly, the seasonal variations in precipitation δ^{18}O are recorded in the modern yak teeth analyzed here. However, the limited serial data presented here do not permit us to assess if (and to what extent) the amplitude of seasonal variations in the δ^{18}O of meteoric water might be amplified or reduced in tooth enamel δ^{18}O record due to dietary/drinking and/or migration behavior of an animal.

5.4. Implications for Paleoclimate and Paleoelevation Reconstruction

The results from this study have important implications for paleoclimate and paleoelevation reconstructions using C and O isotopic compositions of tooth enamel and other C- and O-bearing substrates. The observed δ^{13}C variations within and between species reflect variations in the δ^{13}C of C3 plant foodstuffs in the high elevation habitats. The modern environment in southern Tibet is water-stressed. As a result, C3 plants in this region typically have δ^{13}C values higher than the average value of -27‰ for C3 plants (Deines, 1980). This water-stress-induced ^{13}C-enrichment is recorded in the tooth enamel of modern herbivores, and therefore need to be taken into account when interpreting fossil enamel δ^{13}C values in arid and semi-arid environments. The data presented in this study show that the δ^{13}C values of tooth enamel as high as -8‰ could indicate a pure C3 diet. Serial analysis of individual teeth can help determine if a high δ^{13}C value is caused by ingestion of a small amount of C4 plants or consumption of C3 plants experiencing water stress. Dietary preferences and eating behavior (browsers vs. grazers) can also affect the δ^{13}C values of enamel.

Oxygen isotope composition of tooth enamel is determined predominantly by the $\delta^{18}O$ of body water which comes from drinking water and the water in food ingested by the organism. The $\delta^{18}O$ values of tooth enamel from goats show a positive correlation between the $\delta^{18}O$ of tooth enamel with the $\delta^{18}O$ values of local water (Figures 13 and 14). This is important because it shows that the $\delta^{18}O$ of the meteoric water is the dominant control on the $\delta^{18}O$ of enamel from goats. Therefore, oxygen isotope analysis of tooth enamel is a viable tool in paleoclimate study and can be used as a proxy for the $\delta^{18}O$ of precipitation. However, more data are needed in order to establish a quantitative relationship between water $\delta^{18}O$ and enamel $\delta^{18}O$ for horses and yaks. The milk effect may cause additional O isotope fractionation in tooth enamel because of fractionation during lactation. Therefore, the best way to avoid this effect is to only sample teeth that have formed after weaning. Our data do not show a clear relationship between the $\delta^{18}O$ of water and enamel and the elevation (Figure 4 and Figure 13). This may be due to natural variations in the source and/or the rain-out history and/or source of moisture in this region. The lack of a clear relationship between the $\delta^{18}O$ of water and enamel and the elevation in the study area (with elevations range from 2700 to 5000m a.s.l.) suggests that quantitative reconstruction of paleo-elevation in the area using $\delta^{18}O$ values of paleo-meteoric water estimated from fossil enamel and other O-bearing minerals may not be warranted. However, more data are needed to verify this preliminary conclusion.

6. CONCLUSIONS

In this study, the stable isotopic compositions of modern herbivore tooth enamel, vegetation, and water were used to examine the relationship between the isotopic chemistry of tooth enamel and modern environment. The $\delta^{13}C$ values of tooth enamel from modern herbivores in southern Tibet reflect diets based primarily on C3 plants, consistent with the current dominance of C3 vegetation in the region. The lack of large seasonal variations in $\delta^{13}C$ values within individual teeth indicates that the more enriched enamel $\delta^{13}C$ values are due to consumption of C3 plants under water stressed conditions rather than the consumption of C4 plants. The positive trend of $\delta^{13}C$ values with increasing elevation is in general agreement with altitudinal variations in the $\delta^{13}C$ of plant communities. Carbon isotopic compositions observed within and between species reflect the C isotopic variations of C3 plants available for consumption in local habitats. Oxygen isotopic compositions varied widely within and between species. The mean $\delta^{18}O$ values of tooth enamel from goats showed a correlation with water $\delta^{18}O$ values, suggesting that the $\delta^{18}O$ of tooth enamel can be used as a proxy for the $\delta^{18}O$ of meteoric water. Unfortunately, the oxygen isotopic compositions of water and tooth enamel do not show a clear trend with increasing elevation in the study area. Serial isotopic analysis of several yak teeth shows that seasonal variation in oxygen isotopic composition within a tooth primarily reflects seasonal variation in the $\delta^{18}O$ of meteoric water. However, more data are needed to evaluate if the amplitude of seasonal variations in the $\delta^{18}O$ of meteoric water might be amplified or reduced in the tooth enamel $\delta^{18}O$ record due to dietary/drinking and/or migration behavior of an animal. Climate controls the isotopic composition of tooth enamel through its effects on vegetation and precipitation. These climate effects (e.g., water stress, source and history of air mass) need to be considered when attempting to reconstruct paleoclimate or paleoelevation in this region because the results without considering these effects will likely give a skewed version of the past.

REFERENCES

Araguas-Araguas, L., Froehlich, K., and Rozanski, K., 1998, Stable isotope composition of precipitation over southeast Asia: Journal of Geophysical Research, v. 103, no. D22, pp. 28721-28742.

Ayliffe, L.K., Chivas, A.R., and Leakey, M.G., 1994, The retention of primary oxygen isotope compositions of fossil elephant skeletal phosphate, Geochimica et Cosmochimica Acta, v. 58, pp. 5291-5298.

Behrensmeyer, Anna K., 2006, Climate change and human evolution: Science, v.311, pp. 476-478.

Blisnuik, Peter M., and Stern Libby A., 2005, Stable isotope paleoaltimetry: A critical review: American Journal of Science, v. 305, pp. 1033- 1074.

Bocherens, Hervé, Koch, Paul L., Mariooti, André, Geraads, Denis, and Jaeger, Jean-Jacques, 1996, Isotopic biogeochemistry (^{13}C, ^{18}O) of mammalian enamel from African Pleistocene hominid sites: PALAIOS, v. 11, pp. 306-318.

Boutton, Thomas W., 1996, Stable carbon isotope ratios of soil organic matter and their use as indicators of vegetation and climate change. In: Thomas W. Boutton and Shin-ichi Yamaski (Editors), *Mass spectrometry of soils*, M. Dekker, pp. 47-82.

Bryant, J. Daniel, and Froelich, Philip N., 1995, A model of oxygen isotope fractionation in body water of large mammals: Geochimica et Cosmochimica Acta, v. 59, pp. 4523-4537.

Bryant, J. Daniel, Luz, Boaz, and Froelich, Philip N., 1994, Oxygen isotopic composition of fossil horse tooth phosphate as a record of continental paleoclimate, Palaeogeography, Palaeoclimatology, Palaeoecology, v. 107, pp. 303-316.

Bryant, J.D., Froelich, P.N., Showers, W.J., and Genna, B.J., 1996, Biologic and climatic signals in the oxygen isotopic composition of Eocene-Oligocene equid enamel phosphate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 126, pp. 75-89.

Bryant, J. Daniel, Koch, Paul L., Froelich, Philip N., Showers, William J., and Genna, Bernard J., 1996, Oxygen isotope partitioning between phosphate and carbonate in mammalian apatite: Geochimica et Cosmochimica Acta, v. 60, no. 24, pp. 5145-5148.

Cerling, Thure E., and Sharp, Zachary D., 1996, Stable carbon and oxygen isotope of fossil tooth enamel using laser ablation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 126, pp. 173-186.

Cerling, Thure E., Harris, John M., Ambrose, Stanley H., Leakey, Meave G., and Solounias, Nikos, 1997, Dietary and environmental reconstruction with stable isotope analyses of herbivore tooth enamel from the Miocene locality of Fort Ternan, Kenya: Journal of Human Evolution, v. 33, pp. 635-650.

Cerling, Thure E., Harris, John M., MacFadden, Bruce J., Leakey, Meave G., Quade, Jay, Eisenmann, Vera, and Ehleringer, James R., 1997, Global vegetation change through the Miocene/Pliocene boundary: Nature, v. 389, pp. 153-158.

Chamberlain, C. Page, and Poage, M.A., 2000, Reconstructing the paleotopography of mountain belts from the isotopic composition of authigenic minerals: Geology, v. 28, no. 2, pp. 115-118.

Cossins, A.R. and Bowler, K., 1987, *Temperature Biology of Animals*. Chapman and Hall.

Currie, B, Rowley, D., and Tabor, N., 2005. Middle Miocene paleoaltimetry of southern Tibet: Implications for the role of mantle thickening and delamination in the Himalayan orogen, Geology, v. 33, pp. 181-184.

Dansgaard, W., 1964, Stable isotopes in precipitation, Tellus, v. 16, pp. 436-468.

D'Angela, D., and Longinelli, A., 1990, Oxygen isotopes in living mammal's bone phosphate: Further results: Chemical Geology, v. 86, pp. 75-82.

D'Angela, D., and Longinelli, A., 1993, Oxygen isotopic composition of fossil mammal bones of Holocene age: Palaeoclimatological considerations: Chemical Geology, v. 103, pp. 171-179.

Deines, P., 1980, The isotopic composition of reduced organic carbon. In: P. Fritzand J.C. Fontes (Editors), *Handbook of Environmental Isotope Geochemistry*. 1. Terrestrial Environment. Elsevier, Amsterdam, pp. 329-406.

Deng, Tao and Li, Yumei, 2005, Vegetational ecotype of the Gyirong Basin in Tibet, China and its response in stable carbon isotopes of mammal tooth enamel: Chinese Science Bulletin, v. 50, no. 12, pp. 1225-1229.

Dettman, David L., Kohn, Matthew J., Quade, Jay, Ryerson, F.J., Ojha, Tank P., and Hamidullah, Seyd, 2001, Seasonal stable isotope evidence for a strong Asian monsoon throughout the past 10.7 m.y.: Geology, v. 29, no. 1, pp. 31-34.

Ding, Z.L., and Yang, S.L., 2000, C_3/C_4 vegetation evolution over the last 7.0 Myr in the Chinese Loess Plateau: evidence from pedogenic carbonate $\delta 13C$: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 160, pp. 291-299.

Dongmann, G., Nurnberg, H., Forstel, H., and Wagener, K., 1974, On the enrichment of $H_2{}^{18}O$ in the leaves of transpiring plants: Radiation and Environmental Biophysics, v. 11, pp. 41-52.

Epstein, S., Thomas, P., and Yapp, C., 1977, Oxygen and hydrogen isotopic ratios in plant cellulose: Science, v. 198, no, 4323, pp. 1209-1215.

Farquhar, G., Ehleringer, K., Hubick, K., 1989, Carbon isotope discrimination and photosynthesis: Annual Review of Plant Physiology and Plant Molecular Biology, v. 40, pp. 503-537.

Fricke, Henry C., and O'Neil, James R., 1996, Inter- and intra-tooth variation in the oxygen isotope composition of mammalian tooth enamel phosphate: implications for palaeoclimatological and palaeobiological research: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 126, pp. 91-99.

Fricke, H.C., O'Neil, J.R., and Lynnerup, N., 1995, Oxygen isotope composition of human tooth enamel from medieval Greenland: Linking climate and society, Geology, v. 23, no. 10, pp. 869-872.

Fricke, Henry C., Clyde, William C., and O'Neil, James R., 1998a, Intra-tooth variations in $\delta^{18}O$ (PO_4) of mammalian tooth enamel as a record of seasonal variations in continental climate variables: Geochimica et Cosmochimica Acta, v. 62, no. 11, pp. 1839-1850.

Fricke, Henry C., Clyde, William C., O'Neil, James R., and Gingerich, Philip D., 1998b, Evidence for rapid climate change in North America during the latest Paleocene thermal maximum: oxygen isotope compositions of biogenic phosphate from the Bighorn Basin (Wyoming): Earth and Planetary Science Letters, v. 160, pp. 193-208.

Gadbury, C., Todd, L., Jahren, A.H., and Amundson, R., 2000, Spatial and temporal variations in the isotopic composition of bison tooth enamel from the early Holocene Hudson-Meng Bone Bed, Nebraska: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 157, pp. 79-93.

Garzione, C., Quade, J., DeCelles, P., English, N., 2000. Predicting paleoelevation of Tibet and the Himalaya from $\delta^{18}O$ vs. altitude gradients in meteoric water across the Nepal Himalaya. Earth and Planetary Science Letters, v.183, pp. 215-229.

Ghosh, Prosenjit, Garzione, Carmela N., and Eiler, John M., 2006, Uplift of the Altiplano revealed through 13C-18O bonds in paleosol carbonates: Science, v. 311, pp. 511-515.

Guo, Gguangmeng, and Xie, Gaodi, 2006, The relationship between plant stable carbon isotope composition, precipitation, and satellite data, Tibet Plateau, China: Quaternary International, v. 144, pp. 68-71.

Hoppe, Kathryn A., 2006, Correlation between the oxygen isotope ratio of North American bison teeth and local waters: Implications for paleoclimatic reconstructions: Earth and Planetary Science Letters, v. 244, pp. 408-417.

Hoppe, Kathryn A., Stover, Susan M., Pascoe, John R., and Amundson, Ronald, 2004, Tooth enamel mineralization in extant horses: implications for isotopic microsampling: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 206, no. 3-4, pp. 355-365.

Hsü, J., 1976, On the palaeobotanical evidence for continental drift and Himalayan uplift. Paleobotanist, v.25, pp. 131-142.

Ingraham, N.L., 1998, Isotopic variations in precipitation (Chapter 3). In: Carol Kendall and Jeffrey J. McDonnell (Editors), *Isotope Tracers in Catchment Hydrology*, Elsevier, pp. 87-118.

Johnson, Kathleen R. and Ingram, B. Lynn, 2004, Spatial and temporal variability in the stable isotope systematics of modern precipitation in China: implications for paleoclimate reconstructions: Earth and Planetary Science Letters, v. 220, pp. 365-377.

Koch, P., 1998, Isotopic reconstruction of past continental environments: Annual Review of Earth and Planetary Science, v. 26, pp. 573-613.

Kohn, M. J., 1996, Predicting animal δ^{18}O: Accounting for diet and physiological adaption. Geochim. Cosmochim. Acta, v. 60, pp. 4811-4829.

Kohn, M., Schoeninger, M., and Valley, J., 1996, Herbivore tooth oxygen isotope compositions: effects on diet and physiology: Geochimica et Cosmochimica Acta, v. 60, pp. 3889-3896.

Kohn, Matthew J., Schoeninger, Margaret J., and Valley, John W., 1998, Variability in oxygen isotope compositions of herbivore teeth: reflections of seasonality or developmental physiology?, Chemical Geology, V. 152, pp. 97-112.

Kohn, M., Cerling, T. E., 2002. Stable isotope compositions of biological apatite, In: M. Kohn, J. Rakovan, J. Hughes (eds), Phosphates – Geochemical, Geobiological, and Materials Importance, Reviews in Mineralogy & Geochemistry, v. 48, Mineralogical Society of America, Washington D.C., pp. 455-488.

Lee-Thorp, J. and Van der Merwe, N.J., 1987, Carbon isotope analysis of fossil bone apatite, South African Journal of Science, v. 83, pp. 712-715.

Li, X.B., Chen, J.F., Zhang, P.Z., and Liu, G.X., 1999, The characteristics of carbon isotope composition of modern plants over Qinghai-Tibetan Plateau (NE): Acta Sedimentologica Sinica, v. 17, no. 2, pp. 325-329.

Longinelli, Antonio, 1984, Oxygen isotopes in mammal bone phosphate: A new tool for paleohydrological and paleoclimatological research?, Geochimica et Cosmochimica Acta, v. 48, pp. 385-390.

Lu, Houyvan, Wu, Naiqin, Gu, Zhaoyan, Guo, Zhengtang, Wang, Luo, Wu, Haibing, Wang, Guoan, Zhou, Liping, Han, Jiamao, and Liu, Tungsheng, 2004, Distribution of carbon isotope composition of modern soils in the Qinghai-Tibetan Plateau: Biogeochemistry, v. 70, pp. 273-297.

Luz, Boaz, Kolodny, Yehoshua, and Horowitz, Michal, 1984, Fractionation of oxygen isotopes between mammalian bone-phosphate and environmental drinking water, Geochimica et Cosmochimca Acta, v. 48, pp. 1689-1693.

MacFadden, Bruce J., and Cerling, Thure E., 1994, Fossil horses, carbon isotopes, and global change: Trends in Ecology and Evolution, v. 9, no. 12, pp. 481-485.

Mulch, Andreas, and Chamberlain, C. Page, 2006, The rise and growth of Tibet: Nature, v. 439, pp. 670-671.

Poage, Michael A., and Chamberlain, C. Page, 2001, Empirical relationships between elevation and the stable isotope composition of precipitation and surface waters: Considerations for studies of paleoelevation change: American Journal of Science, v. 301, pp. 1-15.

Poage, Michael A., and Chamberlain, C. Page, 2006, Rising mountain ranges: Science, v. 311, pp. 478-479.

Quade, Jay, Cerling, Thure E., and Bowman, John R., 1989, Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan: Nature, v. 342, pp. 163-166.

Rogers, Karel L., and Wang, Yang, 2002, Stable isotopes in pocket gopher teeth as evidence of a late Matuyama climate shift in the southern Rocky Mountains: Quaternary Research, v. 57, pp. 200-207.

Rowley, D., and Currie, B., 2006. Palaeo-altimetry of the late Eocene to Miocene Lunpola Basin, central Tibet. Nature, v. 439, pp. 677-681.

Rowley, David B., Pierrehumbert, Raymond T., and Currie, Brian S., 2001, A new approach to stable isotope-based paleoaltimetry: implications for paleoaltimetry and paleohypsometry of the High Himalaya since the late Miocene: Earth and Planetary Science Letters, v. 188, pp. 253-268.

Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R., 1992, Relation between long term trends of oxygen-18 isotope composition of precipitation and climate: Science, v. 258, no. 5084, pp. 981-985.

Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R., 1993, Isotopic patterns in modern global precipitation: Geophysical Monograph, v. 78, pp. 1-36.

Sharp, Z.D., and, Cerling, T.E., 1998, Fossil isotope records of seasonal climate and ecology: Straight from the horse's mouth: Geology, v. 26, no. 3, pp. 219-222.

Shugui, Hou, Masson-Delmotte, Valérie, Dahe, Qin, and Jouzel, Jean, 2003, Modern precipitation stable isotope vs. elevation gradients in the High Himalaya. Comment on "A new approach to stable isotope-based paleoaltimetry: implications for paleoaltimetry and paleohypsometry of the High Himalaya since the late Miocene" by David B. Rowley et al. [EPSL 188 (2001) 253-268]: Earth and Planetary Science Letters, v. 209, pp. 395-399.

Sponheimer, Matt, and Lee-Thorp, Julia A., 1999, Oxygen isotopes in enamel carbonate and their ecological significance: Journal of Archaeological Science, v. 26, pp. 723-728.

Sullivan, C.H. and Krueger, H.W., 1981, Carbon isotope analysis of separate chemical phases in modern and fossil bone, Nature, v. 292, pp. 333-335.

Wang, K., Chatterton, B.D.E., and Wang, Y., 1997, An organic carbon isotope record of Late Ordovician to Early Silurian marine sedimentary rocks, Yangtze Sea, South China: Implications for CO_2 changes during the Hirnantian glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 132, pp. 147-158.

Wang, L., Lu, H.Y., Wu, N.Q., and Liu, T.S., 2003, Altitude trends of stable carbon isotope composition of *Poaceae* in Tibetan Plateau: Quaternary Sciences, v. 23, no. 5, pp. 573-580.

Wang, Luo, Lü, Houyan, Wu, Naiqin, Chu, Duo, Han, Jiamao, Wu, Yuhu, Wu, Haibin, and Gu, Zhaoyan, 2004, Discovery of C_4 species at high altitude in Qinghai Tibetan Plateau: Chinese Science Bulletin, v. 49, no. 14, pp. 1392-1396.

Wang, Yang, and Cerling, Thure E., 1994, A model of fossil tooth and bone diagenesis: implications for paleodiet reconstruction from stable isotopes, Palaeogeography, Palaeoclimatology, Palaeoecology, v. 107, pp. 281-289.

Wang, Y. and Deng, T., 2005. A 25 m.y. isotopic record of paleodiet and environmental change from fossil mammals and paleosols from the NE margin of the Tibetan Plateau. Earth and Planetary Science Letters, v. 236, pp. 322-338.

Wang, Yang, Cerling, Thure E., and MacFadden, Bruce J., 1994, Fossil horses and carbon isotopes: new evidence for Cenozoic dietary, habitat, and ecosystem changes in North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 107, pp. 269-279.

Wang, Y., Deng, T., and Biasatti, D., 2006. Ancient diets indicate significant uplift of southern Tibet after ca. 7 Ma. *Geology*, v. 34, pp. 309-312.

Yakir, D., 1992, Variations in the natural abundance of oxygen-18 and deuterium in plant carbohydrates: Plant, Cell and Environment, v. 15, pp. 1005-1020.

Zheng, H., Powell, C., An, Z., Zhou, J., and Dong, G., 2000, Pliocene uplift of the northern Tibetan Plateau, Geology, v. 28, pp. 715-718.

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