Reconstructing Climate Change and Food Production in the Ancient Peruvian Andes Using Stable Isotope Analysis

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KEY WORDS. Stable oxygen isotope analysis, stable carbon isotope analysis, climate change, enamel hydroxyapatite, Peruvian Andes

BRIEF. Testing the effectiveness of stable isotope analysis in reconstructing climate change and diet in the ancient Peruvian Andes.

ABSTRACT. Analyses of stable oxygen and carbon isotope ratios were used to test the hypothesis that there was a severe drought and related change in human diet in ancient Peru ca. 1100 C.E. Previous studies of ice cores from the Andes and paleobotanical studies of food refuse suggest that the change in climate had a major impact on human food consumption patterns. The ratio of stable oxygen isotopes ($^{18}O/^{16}O$) and carbon isotopes ($^{13}C/^{12}C$) were obtained from the hydroxyapatite in dental enamel from human remains excavated from archaeology sites in the Peruvian Andes. The ^{18}O was used to reconstruct ancient precipitation levels before and after 1100 C.E. and ^{13}C ratios were used to document the amount of C3 vs. C4 plants in human diets in both time periods. Similar ^{18}O values were found, in both time periods, suggesting no change in precipitation, but the ^{13}C values indicate a decrease in C4 plant consumption (*e.g.,* maize) from one era to the next. The isotopic data from this study were compared to other isotopic datasets from the Andes to examine general trends in precipitation and its relationship to food production and consumption.

INTRODUCTION.

Bone collagen and dental enamel (tooth crowns), are some of the best preservers of information in organisms. This process allows archaeologists and anthropologists to record patterns of human behavior from long ago. This study investigates the effectiveness of using stable isotope analysis, a method for testing the anatomical make-up of ancient samples, to address questions arising from the analysis of ancient artifacts and skeletons, and test the idea that climate change (i.e., a severe drought) contributed to significant changes in agricultural production and thus, food consumption and nutritional status among prehispanic peoples in the Andes.

The samples for this study come from human skeletons collected from the central highlands of modern day Peru, dating back to the Middle Horizon (MH, 600 – 1000 C.E.) and the subsequent Late Intermediate Period (LIP, 1000 – 1400 C.E.). To examine whether precipitation levels significantly changed from one era to the next (MH to the LIP), and whether climate change affected food production and consumption, the stable oxygen and carbon isotope ratios were analyzed. If there are significant changes in the oxygen isotope ratio ($^{18}O/^{16}O$) and carbon isotope ratio ($^{13}C/^{12}C$), reported as ^{18}O and ^{13}C values, from one period to the next, then this would suggest changes in precipitation levels and changes in food production and consumption.

Previous stable isotope studies have shown that changes in stable oxygen ratios indicate ancient climate changes, specifically as it relates to rainfall: a less negative ^{18}O value indicates less rainfall and a more negative value indicates more rainfall, with some exceptions that relate to distance from equator, altitude, and contributions from glacial melt water [1]. Because of the locations samples were excavated from high in the Peruvian mountains, most, but not all, of the problems mentioned are eliminated. The value of oxygen isotope ratios is determined based on the presence of a heavier isotope (^{18}O), compared to the lighter (^{16}O). When in the form rain or water vapor, ^{18}O tends to condense and precipitate out more quickly than its counterpart, ^{16}O. Conversely, once collected by runoff in a riverbed or stream, the lighter ^{16}O will evaporate more readily than ^{18}O [1]. The ^{18}O values were retrieved from the hydroxyapatite, crystalline structure of calcium carbonate in the body, of human dental enamel. Thus, making it possible to retrieve a permanent isotope signature based on origin of drinking water of organisms. Enamel hydroxyapatite, the preserved record of water and food used in this study, is more durable than bone collagen enamel. It is also formed mainly during an organism's juvenile period due to the anatomy of tooth development, so only water consumed during the organism's childhood is reflected.

Changes in carbon isotope ratios reveal changes in plant foods consumed. Differences in carbon isotope values stem from the complexity of pathways adapted by plants to obtain oxygen and nutrients from the environment. Two different pathways, the Calvin cycle (C3) and the Hatch-Slack pathway (C4), lead to different ^{13}C values once digested by animals or humans. This is due to the efficiency of carbon absorption for production of glucose; C3 plants do not utilize as much carbon per metabolic cycle as do C4 plants. Certain plants, such as *Zea mays* (corn), utilize the Hatch-Slack (C4) pathway, resulting in a less negative value than C3 plants; this makes C3 and C4 plants easily differentiated in the consumption patterns of mammals. A more negative ^{13}C value indicates less C4 plant consumption and a more positive ^{13}C value indicates more C4 food in the diet [2]. Thus, the plant, the animal, and the human that eats those plants and animals will exhibit similar carbon isotope ratios within dental enamel, and types of food eaten can be determined.

In this case, corn is considered a target foodstuff, and the possibility for confusion lies with other C4 plants locally consumed, or marine foods, which can make ^{13}C less negative [3]. The ancient human samples in this study have been shown to have no marine foods in the diet [4], and as of yet, no other C4 plants have been identified as food sources in this area of the ancient Andes. By testing the theories concerning the drought that may have befallen the Wari empire, anthropologists gain understanding of the government structure and ways of life of an ancient society that was lost long ago through isotope analysis.

MATERIALS AND METHODS.

^{18}O and ^{13}C isotope ratios were collected from the enamel hydroxyapatite of two camelid teeth and 16 human teeth from the archaeological sites of Conchopata, Huari-Cheqo Wasi, Huari-Vegachayoq Moqo, and Nawinpukio (Figure 2). Each tooth was sampled using a Dremel© hand drill and carbide dental bures, drilling a line perpendicular to the growth axis of the tooth on the buccal or lingual enamel surface. All samples were first dated to their according time periods using radio carbon dating and certain inferences based on their locations and conditions, in order to establish certainty of origin. These tests were completed previous to this study.

Each powdered sample was pretreated with 30% hydrogen peroxide for 24 hours and 0.1 N acetic acid for 18 hours to remove organics and secondary carbonates, respectively [5]. All samples were subsequently analyzed (~1mg) in a Finnigan Delta Plus XP mass spectrometer at the Stable Isotope Facility at the University of Wyoming for both carbon and oxygen isotopes. All data were normalized to normal buffered saline (NBS-19) for carbon (^{13}C) and oxygen (^{18}O) and the standard is VPDB (Vienna Pee Dee Belemnite standard)(6). ^{13}C (parts per mil, ‰) = ((Rsample/Rstandard)-1)*1000 and R = $^{13}C/^{12}C$. ^{18}O (parts per mil, ‰) = ((Rsample/Rstandard)-1)*1000, and R = $^{18}O/^{16}O$; and the standard is VPDB [6].

The data from this investigation were compared to oxygen and carbon isotope ratios from previously published studies from culturally and temporally relevant areas of ancient Peru. The comparative sites includes: the Tiwanaku capital and smaller Tiwanaku sites (MH and LIP), Wari site of Conchopata (MH), Inca site of Machu Picchu (LH), and sites from the Nasca drainage of coastal

Peru (EIP, MH, and LIP). The data was compared to the above other site populations to compare precipitation levels and diet in diverse geographic areas, and during different time periods.

RESULTS.

Among the 19 samples submitted for stable isotope analysis in the Finnigan Delta Plus XP mass spectrometer, 15 yielded human results (Supplemental Table 1). The remaining 2 were camelid samples, and were left out of data analysis for simplicity.

Stable Oxygen Isotope Analysis.

The mean human ^{18}O is -8.47 and the oxygen isotope data show a range from -3.82 to -10.01. The standard deviation of the data is 1.43 (Supplemental Table 2). Human mean and standard deviation was also calculated for each site. The site of Conchopata has a mean of -8.63, and a standard deviation of 0.382. Huari Cheqo Wasi has a mean of -8.81, and a standard deviation of 0.846. Vegachyoq Moqo has a mean of -9.09, and a standard deviation of 0.460. The sites of Nawinpukio and Monqachayoq both only have one data result, so no mean or standard deviation could be calculated for either.

Stable Carbon Isotope Analysis.

The mean ^{13}C values from human samples was found to be -3.71 with a range from -12.57 to -.034. The standard deviation of these values is 3.58 (Supplementary Table 3). The human mean and standard deviations for each site was calculated. The Middle Horizon site of Conchopata has a mean of -3.93, and standard deviation of 0.262, and the Middle Horizon site of Huari-Cheqo Wasi has a mean of -1.87, and a standard deviation of 2.029. The Late Intermediate samples from Huari-Vegachayoq Moqo have a mean of -11.18, and a standard deviation of 1.966 (Supplemental Table 2). The sites of Nawinpukio (MH) and Monqachayoq (LIP) have only one data point, so no mean and standard deviation could be calculated.

Overall, the average ^{18}O value for the second half of the Middle Horizon era (800 – 1000 C.E.) was -8.85667 (s.d. = 0.782924), and it slightly declined to -8.89000 (s.d. = 0.468722) in the first half of the subsequent Late Intermediate Period (1000 – 1200 C.E.) (Supplementary Table 4).

The average ^{13}C value for the second half of the Middle Horizon era was -2.40667 (s.d. = 1.985407), and it decreased to -8.93333 (s.d. = 4.132146) in the first half of the subsequent Late Intermediate Period (Supplemental Table 4).

Oxygen and carbon isotope ratios in this study were plotted against each other to explore possible relationships between the two variables (Figure 1). However, no relationship was found.

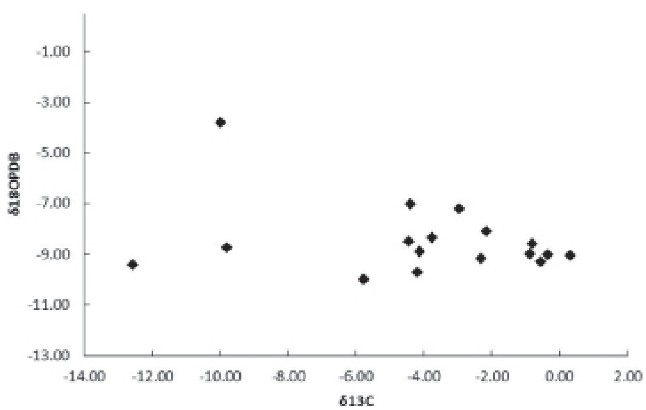

Figure 1. Relationship between oxygen and carbon isotope ratios from hydroxyapitite dental enamel.

DISCUSSION.

Although sample sizes are small, oxygen isotope ratios show little to no change between sites (Supplementary Table 2). This suggests sites analyzed within the same area generally received the same precipitation, and had low variability. On the other hand, carbon isotope ratios varied greatly between sites. The site of Huari-Cheqo Wasi—an elite mortuary area—has carbon isotope values indicative of large amounts of C4 plant (maize) consumption, while the site of Huari-Vegachayoq Moqo—a funerary area with injured and dismembered bodies [7]— exhibits a more C3 plant based diet (Supplemental Table 3).

The changes in oxygen isotope values over time have very little variation, suggesting that climate change was minimal in the central, highland Andes between the MH and LIP; this contradicts previous theories (Supplementary Table 4). Because of this discrepancy, the authors suggest that the limitations of oxygen isotope analysis are related to the numerous variables that can affect the outcomes. The authors suggest that further research is necessary to understand the complex ways that variables such as rainfall, glacial water melt, altitude, and temperature can affect oxygen isotope values.

In contrast, the carbon isotope ratios in this study are highly variable, suggesting that human diets were quite distinct between sites of the same time period, and that they changed dramatically from one era to the next (Supplementary Table 4). Because of these significant differences and agreement with previous studies, the data suggests that carbon isotope analysis is a reliable scientific technique to document ancient dietary practices.

Overall the two variables together, oxygen and carbon isotope ratios, show no correlation (Figure 1). Considering the hypothesis, the data provided by this study suggests that climate change was not the cause of transformations in diet in the central, highland Andes. Based on these findings, further investigation must be done to understand not only the reasons behind such dramatic diet changes.

Comparisons to Other Andean Sites.

Values collected in this study were analyzed and compared with previously published data from the Andes to strengthen the analyses (Supplementary Table 5). Data was compared to human samples from Conchopata [4, 8], Machu Picchu, [9, 10], Nasca sites [1], from the ancient capital city of Tiwanaku [11], and from Chanka sites in the nearby site of Andahuaylas [12].

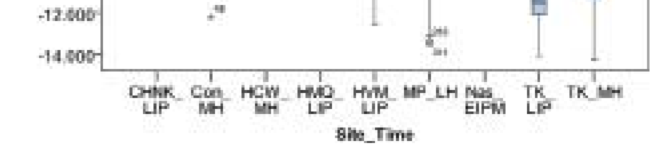

Figure 2. Box plots grouped by site and time; greater ^{13}C values mean more C4 plant consumption.

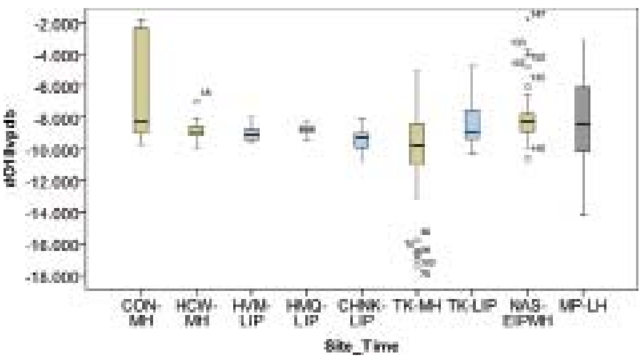

Figure 3. $\delta^{18}O$ box plots grouped by site and time. CHNK=Chanka, Con=Conchopata, HCW=Huari Cheqo Wasi, HMQ=Huari Moqachayoq, HVM=Huari Vegachayoq Moqo, MP=Machu Piccu, Nas=Nasca, TK=Tiwanaku.

In the study area examined here, the ^{13}C values change significantly from the MH to the LIP (Figure 2, Supplemental Table 4), indicating a major change in diet. Compared to the MH and LIP samples from Tiwanaku in the southern Andes (Bolivian highlands), there is a similar change from one time period to the next. The Tiwanaku samples also exhibit less negative ^{13}C values in the MH, meaning more maize in the diet, and exhibit more negative ^{13}C values in the LIP (less maize) (Figure 2). In that region, the change in diet may be correlated with a decline in precipitation, as evidenced by the decline in the oxygen isotope ratio. Together, those two datasets suggest a correlation between rainfall and the productivity of certain crops. This does not appear to be the case in the central, highland Andes, where this study was carried out.

The ^{18}O values from this study suggest that rainfall in the central, highland Andes (our study area) did not dramatically decline in the second era under study. In contrast, other geographical zones in southern Peru experienced more rainfall during the MH than during the LIP (Figure 3). Notably, populations that experienced a drought also saw a shift in plant production and consumption, as revealed by carbon isotope ratios (Figure 2). This suggests that a drought in the LIP adversely affected some population's ability to produce the much desired plant food, maize. In the study presented here, the oxygen isotope values show no change, yet there is a dramatic decline in the consumption of maize.

CONCLUSION.

By evaluating the oxygen isotope ratios from human dental enamel as a proxy for rainfall, some questions about paleoclimatic change can be addressed. This geographic area in particular was thought to have been disturbed by a severe drought, which then altered plant production and consumption patterns, perhaps negatively affecting the nutritional status of populations living there. While the data presented here do show a change in plant food consumption by ancient humans in the central, highland Andes, there is no evidence to suggest that rainfall levels also significantly changed. This suggests that other non-climatic events contributed to the shift in food production and consumption at the beginning of the Late Intermediate Period. Most notably, this was the era when the powerful Wari Empire collapsed, so perhaps the absence of state governance contributed to the decline in agricultural production, particularly that of maize, a socially valued food in the ancient (and modern) Andes, leading to a sudden shift from a C4 diet to a simpler C3 diet.

Stable isotope data from other Andean areas, especially the Tiwanaku zone, show that there was both a decline in rainfall and maize consumption [11]. By coupling the oxygen and carbon isotope data, researchers can examine both the estimated precipitation levels and the amount of specific food sources. When both data sets are combined, scholars can infer when climate change may have occurred, how severely, and whether those environmental changes affected food production capacity.

In the future, more samples will be isotopically analyzed to confirm the findings of this study. This will facilitate a better reconstruction of the paleoclimate in central Peru. This will add more data points, and add more stability in general to the project as a whole. This study might want to also take a closer look at the differences in oxygen isotope values in order to more clearly define whether our results were due to precipitation, altitude, temperature, etc., and allow us to more accurately reconstruct the paleoclimate in central Peru using stable isotope analysis.

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SUPPORTING INFORMATION.

Table S1. Oxygen and carbon isotope ratios
Table S2. Mean and standard deviation of oxygen isotope ratios
Table S3. Mean and standard deviation of carbon isotope ratios
Table S4. Mean values for carbon and oxygen isotope ratios
Table S5. Reference to published data used in this study

REFERENCES.

1. K. J. Knudson. *Int. Jour. Osteoarch.* 19,171 (2009).
2. M. J. Schoeninger. *Cam. Univ. Press*. 38 (1989).
3. U. Gowik, P. Westhoff. *Plant Phy*. 155, 56 (2011).
4. B. Finucane, *et al., Jou. Arch. Sci.* 33, 1 (2006).
5. P. L. Koch, *et al. Jou. Arch. Sci.* 24, 417 (1997).
6. T. B. Coplen. *Pure. App. Chem.* 66,273 (1994).
7. T. A. Tung. Nawpa Pacha. 29, 101-118 (2008).
8. T. A. Tung, E. Chambers. *Report. Nat. Inst. Culture, Peru.* (2011).
9. B. L. Turner. *et. al. Jou. Arch. Sci.* 36, 317-332 (2009).
10. B. L. Turner, J. D. Kingston, G. J. Armelagos. *Revista de Anth. Chilena.* 42, 515-534 (2010).
11. C. A. Berryman. *Ph. D. Dissertation. Dept. of Anth. Vanderbilt University.* (2010).
12. E. Lefaro, D. Kurin. In prep. (2011).

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