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Local water source variation and experimental *Chicha de Maíz* brewing: Implications for interpreting human hydroxyapatite $\delta^{18}O$ values in the Andes

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ABSTRACT

Oxygen isotope data (expressed as $\delta^{18}O$ values) recovered from human skeletal remains have been the central focus of a number of archeological analyses tracking human migration. However, in the Andes the use of oxygen isotopes to investigate residential mobility is subject to two issues addressed in this study: 1) local variation in water sources and 2) pre-consumption processing of water. To explore these factors we sampled a wide variety of water sources in the Moche watershed of north coastal Peru and experimentally and ethnographically produced *chicha de maíz*, a traditional brewed beverage. Our data indicate an unexpected spatial pattern in Moche valley water source $\delta^{18}O$ values, and identify springs as an important influence on river water. Using *chicha de maíz* as an example of pre-consumption processing of water, we find that brewed beverages may impact human $\delta^{18}O$ values. Together these data indicate that in the Andes the consumption of *chicha de maíz* has the potential to swamp spatial variation in water source $\delta^{18}O$ values. Therefore, we cannot assume that the identification of different $\delta^{18}O$ values in the remains of Andean groups necessarily indicates the presence of migrants.

Oxygen isotope analysis is a well-established approach to assess a number of biological, environmental, and behavioral variables relevant to archeology (e.g., Andrus, 2011; Katzenberg, 2008; Makarewicz and Sealy, 2015; Scherer et al., 2014; Sponheimer and Lee-Thorp, 1999). Oxygen isotope data (expressed as $\delta^{18}O$ values) from humans bones and teeth can be interpreted to determine the isotopic composition of water or other liquids humans drink. Rainfall and continental surface and groundwater $\delta^{18}O$ values vary geographically in a systematic way. This is the result of fractionation during phase transitions and mixing of water from different sources. The lightest oxygen isotope, ^{16}O, evaporates more readily than the heavier isotopes. Conversely, the heaviest isotope, ^{18}O, condenses more readily. Consequently there is a regular and predictable pattern in which precipitation tends to become isotopically lighter with increasing distance from the evaporation point, typically resulting in more negative $\delta^{18}O_{mw}$ (meteoric water) values with increasing latitude and/or altitude (see Kendall and Coplen, 2001 for North American rivers; http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html; http://wateriso.utah.edu/waterisotopes/pages/data_access/ArcGrids.html). When imbibed, $\delta^{18}O_{mw}$ is transferred to $\delta^{18}O_{bw}$ (body water) and the local $\delta^{18}O$ values are reflected in the carbonate and phosphate of hydroxyapatite in human bones and teeth, transferring their signature to human remains (Longinelli, 1984). This has enabled researchers to use $\delta^{18}O_p$ (phosphate) and $\delta^{18}O_c$ (carbonate) values to reconstruct both paleoclimates (e.g., Fricke et al., 1995) and migration (e.g., White et al., 1998).

A variety of factors beyond climate change and residential mobility may affect human $\delta^{18}O_{p\ \&\ c}$ values. Oxygen from inhalation and food consumption is incorporated into the body and so the levels of ^{18}O in air and solid food could affect human $\delta^{18}O_{p\ \&\ c}$ values. Research suggests however, that the effects of these sources is minimal, thus the value of $\delta^{18}O_{bw}$ primarily reflects the $\delta^{18}O$ value of imbibed water (Longinelli, 1984; Longinelli and Peretti Paladino, 1980). Hydroxyapatite drawn from different skeletal elements of the same individual can be characterized by varying $\delta^{18}O$ values. For example, different teeth form at different ages but once formed are not remodeled, thus the $\delta^{18}O$ values of individual teeth reflect the water imbibed during formation. Bones however, are continuously remodeled until death, and so their $\delta^{18}O$ values represent water imbibed during the last ten years of an individual's life (Hedges et al., 2007). Because different elements of a single individual capture $\delta^{18}O$ values of water imbibed at different ages, oxygen isotopes have been used to track residential mobility. Tracking such sources of variation has been central to a number of recent analyses that focus on the $\delta^{18}O$ values of human skeletal remains in the Andes (e.g., Knudson et al., 2009; Buzon et al., 2011; Turner et al., 2009; Toyne et al., 2014). However the use of oxygen isotopes to

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explore residential mobility in the region is subject to two issues addressed in this study: local variation in water sources and pre-consumption processing of water.

The general arid climate and complex hydrology of the Andes can lead to a wide range of $\delta^{18}O_{mw}$ values in local water sources in some but not all areas. A number of recent local water source studies have begun to examine such local variation in the southern Andes (Buzon et al., 2011; Knudson, 2009; Webb et al., 2013), however the northern Andes remain under-characterized. To begin to characterize north coast water sources, we present $\delta^{18}O_{mw}$ values from several dozen river locations, as well as canal and spring sources in the north coastal region.

The $\delta^{18}O$ value of imbibed water may differ from local $\delta^{18}O_{mw}$ value because imbibed water may be subject to evaporation during food preparation. Such enrichment from processing has been documented through isotopic analysis of commercially available beer (Carter et al., 2015) and experimentally produced, Medieval-style foods and drinks (Brettell et al., 2012). Andean food and drink preparation, while noted by researchers as being a potentially important source of variation in human $\delta^{18}O_{p\ \&\ c}$ values, has not yet been experimentally investigated. Such work is especially important as the consumption of *chicha de maíz*, a traditional, Andean brewed beverage, has been well documented in the archeological record. This study examines this second issue through stable isotopic analysis of both experimentally and ethnographically brewed *chicha de maíz*.

1. Hydrology of the Andes

Precipitation in the Andes is derived primarily from moisture sources to the east (Aravena et al., 1999). The western slope of the Andes is a rain shadow, consequently much of coastal Peru and northern Chile receive almost no precipitation except during El Niño events, which cause spatially and temporally variable rains (Bourrel et al., 2015). As one would expect in high altitude locations, meteoric, surface, and ground waters in the Andes are depleted in the heavy isotopes of oxygen (Aravena et al., 1999; Ohlanders et al., 2013). The rivers that cross the coastal desert are sourced in the western slope of the Andes and fed by high altitude precipitation and glacier melt, resulting in comparatively negative $\delta^{18}O$ values similar to those measured in high altitudes (see Knudson, 2009 for a more complete explanation of the distribution of meteoric $\delta^{18}O$ values across altitude zones). Groundwater aquifers in this coastal desert are fed by contributions from these rivers, high altitude precipitation, and to a lesser extent, from percolation by irrigation waters in agricultural fields (Gilboa, 1971). As a result, groundwater $\delta^{18}O$ values in this region are similar to surface water, but could be variably heavier if the source waters underwent evaporation prior to percolation. Anthropogenic change to Andean surface and groundwater hydrology over the past few millennia is likely widespread considering the extensive irrigation practices used by pre-Hispanic cultures, though the impacts to $\delta^{18}O$ values are not known.

2. Chicha de maíz

Broadly, the term *chicha* refers to any locally produced, fermented beverage (Goldstein et al., 2009). Most commonly, the term *chicha* is used in the Andes as a short hand for *chicha de maíz*, which is primarily made from maize. *Chicha*, was and continues to be socially, politically, and economically important in the Andes and Amazon Basin (Allen, 1988; Jennings, 2005; Jennings and Bowser, 2009; Weismantel, 1988). The use of *chicha de maíz* in the Andes has been well documented ethnohistorically, archeologically and ethnographically with the earliest evidence of consumption being identified in Southern Highlands and dating to as early as 800 B.C. (Logan et al., 2012).

In Gillin's (1947:46) mid-twentieth century ethnographic study of the Moche valley of Peru, he estimated adult *chicha de maíz* consumption of approximately two liters daily, with substantially more consumption occurring during feasting events. Incan chroniclers de Betanzos (1996:56) and Cobo (1979:28) both note that people drank prodigious amounts of *chicha* at social events with Cobo (1979:27) suggesting that "there is no worse torment for them than being compelled to drink water (a punishment which the Spaniards sometimes give them)." In more recent ethnographic investigations Peruvian work-party and fiesta consumption has been estimated between nine and fifteen liters per person (Jennings, 2005).

Ethnohistoric and archeological research has found that *chicha de maíz* played an important role in Inca state politics. It was consumed in large quantities at political feasting events and its consumption was central to the idea of reciprocity that supported the social structure of the state (Bray, 2009; Dillehay, 2003; Morris, 1979). *Chicha* was used, not just in the heartland of the southern Andes, but throughout the state to "pay" men for their work on large-scale, state-sponsored projects and the production of *chicha* was a site of power negotiations at the local level (Costin and Earle, 1989; Hastorf, 1990, Hastorf and Johannessen, 1993; Morris, 1979; Murra, 1960). Bray (2003) identified three ceramic forms associated with three different elite foods: *chicha*, meat, and maize stew. Of these, the vessels used to store and transport *chicha* were the most common forms found outside the state heartland, indicating that *chicha* was an important tool of state expansion.

The importance of *chicha de maíz* in the Andean highlands pre-dates the Inca. Goldstein (2003) discusses the role *chicha* played in earlier Tiwanaku state politics in the Southern Highlands. Unlike among the later Inca, it appears that *chicha de maíz* was primarily consumed at the household and corporate group level, rather than as part of temple rituals. However, Goldstein (2003) notes that corporate competitive feasting with *chicha de maíz* may have played an important role in the Tiwanaku expansion, particularly into lower elevation, maize producing regions. Among the contemporaneous Wari state of the central highlands, archeological evidence also argues for the importance of maize and *chicha* production (Valdez, 2006; Valdez et al., 2010), but Goldstein et al. (2009) and Sayre et al. (2012) suggest that *chicha de molle* (made with fruit of the Peruvian pepper tree) was the Wari drink of choice. Goldstein et al. (2009) identified several scales of *chicha de molle* production at one Wari administrative center, but Laffe (2015) suggests that the Wari may not have centralized *chicha de molle* production everywhere, allowing for substantial amounts at the household level.

On the north coast of Peru, ethnohistoric research suggests the uses of *chicha de maíz* mirror those found in the Southern Highlands (Netherly, 1977; Rostworowski de Diez Canseco, 1977). Production has been identified archeologically based on the presence of fermentation vessels or preserved *jora* (sprouted maize) at Huacas de Moche, the capital of the first regional polity in the Moche valley (Ucede Castillo, 2010), in the Lambayeque valley at Pampa Grande (Shimada, 1994), at Chan Chan, the Chimu capital (Topic, 1990) and at Manchan, a Chimu region center in the Casma valley (Morre, 1989).

Stable isotopic analysis of human skeletal remains has been used to identify the prehistoric use of *chicha de maíz*. In her analysis of pre-Inca and Inca period elites and non-elites from the Southern Highlands of Peru, Hastorf (1990, 1991) identified increasing production of maize and changing patterns of $\delta^{13}C$ values as a result of Inca imperialism. She suggested these changes resulted from Inca elites re-orienting agricultural production toward maize for *chicha*, which they then supplied to men involved in *mit'a* labor. In their analysis of elite and non-elite prehistoric period individuals from highland Ecuador, Ubelaker and Katzenberg (1995) identified status differences in $\delta^{13}C$ values. Because $\delta^{13}C_{collagen}$ and $\delta^{13}C_{carbonate}$ are tightly correlated, they argue that less negative $\delta^{13}C$ values among elites result from the consumption of maize, the only C_4 plant in the area, not from variations in protein sources. This assessment was further supported by a lack in significant difference between elites and non-elites in $\delta^{15}N$ values. These researchers have interpreted changes in $\delta^{13}C$ values as indicative of *chicha de maíz* consumption based on ethnohistoric models. However, it is