Re-approaching palaeodiet in the Andes

Use and application of sulphur isotope analysis in reconstructing Peruvian palaeodiet

by Katherine G. Bishop

This research critically examines palaeodietary analyses in ancient Peru. Research is often approached using ceramics, flora, and faunal remains to examine human diet and behaviour prior to written records however these remains may not be indicative of items used exclusively for subsistence. More directed approaches employ stable isotope analyses of human remains as these data can provide direct indication of foods consumed during life. Peruvian isotope studies focus on ^{13}C -enrichment patterns, and follow the premise that *maize* (corn) was the main source of ^{13}C -enrichment recorded in bone collagen. Recent studies in Peru have identified other dietary sources that cause similar enrichment patterns, including *kiwicha* (pseudocereal), marine protein (e.g. shellfish, fish, and seals), and *mococho* (seaweed). As a result, additional methodologies must be employed to more sufficiently identify sources of subsistence in ancient Peru. I propose that stable sulphur isotope methodology may be used to overcome the issues presented. By critically reviewing previous palaeodietary analyses of Peru I examine current limitations and overview the application potential of carbon and nitrogen isotope studies complemented with sulphur isotope analysis of human and faunal remains within a Peruvian context. Ultimately I advocate for a more comprehensive approach to Peruvian palaeodiet.

This research investigates stable sulphur isotope analyses of human and animal remains to better examine human diet and subsistence in ancient Peru. Subsistence practices are an important characteristic of human diet and behaviour, and multiple research avenues have been employed to understand Peruvian palaeodiet. Ethnohistoric data from the Inkan period (~ 1500 CE) serve as comparative means for extrapolating dietary information from the material record however these data cannot definitively describe palaeodiet prior to written history (Bray 2003; Turner, Kingston, and Armelagos 2010). Evidence of ceramics, flora, and fauna from prehistoric assemblages identifies possible foodstuffs, but may not be indicative of items used exclusively for subsistence. Approaches using stable isotope analysis of human remains provide direct

indication of foods consumed during life. Early isotopic studies focused on stable carbon and nitrogen analysis of bone collagen to identify diets with ^{13}C enrichment (DeNiro and Epstein 1981; DeNiro and Schoeninger 1983; Schoeninger, DeNiro, and Tauber 1983). This methodology has been utilized in Peruvian studies for the past 25 years under the premise that *maize* (corn) was the main source of ^{13}C enrichment in bone collagen (Burger and van der Merwe 1990).

Recent studies in Peru have identified other available food sources that cause ^{13}C enrichment in diet, including *kiwicha* (pseudo-cereal) (Cadwallader *et al.* 2012), marine protein (e.g. shellfish, fish, and seals) (Miller, Capriles, and Hastorf 2010), and *mococho* (seaweed) (Finucane, Agurto, and Isbell 2006). Current methodology is no longer sufficient for identifying sources of subsistence, limiting palaeodietary analyses for this region. To

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overcome this issue I will (i) review the biochemical applications of stable sulphur isotope analyses from other studies, (ii) review previous palaeodietary analyses of Peru and examine current limitations, and, (iii) critically examine the application potential of carbon and nitrogen isotope studies complemented with sulphur isotope analysis of human and faunal remains within a Peruvian context.

Quinoa, Cuy, and Yuccas – Examining Peruvian Palaeodiets

The Peruvian landscape contains different ecosystems which correspond to variation in elevation, soil aridity, and access to different water sources (Fernández, Panarello, and Schobinger 1999). The central portion of the country includes the Andes Mountains, which run from north to south, and contain many active volcanoes and shifting tectonic plates (Stewart 2015). The Pacific Ocean forms the western coast of the country, creating many branching marine river valleys and estuaries. The southern lowland region includes Lake Titicaca and the northern lowland region has the southern portion of the Amazon River; both are home to lush ecological environments (Miller, Capriles, and Hastorf 2010).

These varying ecologies support different flora and fauna and would have caused different subsistence niches for humans in the past (Tomczak 2003). Small-scale agriculture began with crops of manioc (*yucca* spp.), vegetables, and fruits, which thrive in the arid environments to the west and more tropical environments to the northeast (Beresford-Jones *et al.* 2009). More efficient agricultural practices were required to sustain crops in arid environments and continue to support large modern populations (Downey 2015). Archaeological studies of settlement architecture have illustrated large-scale irrigation canals in many growing communities, highlighting the importance of subsistence

agriculture for establishing statecraft (Downey 2015; Millaire and Eastaugh 2014). According to Moseley (1975), Peruvian ecosystems are particularly susceptible to the effects of El Niño. Based on ethnohistoric data, El Niño effects include large-scale temperature changes for aquatic environments, drought conditions, and destructive rainstorms resulting in mudslides (Moseley 1975). Subsistence availability will vary in each environmental niche according to its ecology (Miller, Capriles, and Hastorf 2010), ongoing climate changes (Beresford-Jones *et al.* 2009), and seasonal growing conditions (Williams and Katzenberg 2012).

Floral Analysis

There are many arid environments in Peru that enable the preservation of organic materials like seeds, pits, shells, and fruits. Using measures of speciation, quantity, and quality of the remains, Masur (2012) examined floral remains and identified available food items in specific niches. In her work at the Virú Valley, Masur (2012) recovered fragments of peanut, bean, chili pepper, squash, seaweed (*mococho* spp.), gourd, *yucca*, and corn (*maize* spp.). According to the context and prevalence of peanut remains, Masur (2012) argued that they were an elite food source within hierarchical societies. Other floral analyses (e.g. Beresford-Jones *et al.* 2009) have similarly examined available food and aspects of dietary importance in ancient Peru. Vegetation can be consumed directly or processed in a number of ways. For example *maize* can be processed into a fermented corn beer (*chicha*). According to Inkan ethnohistoric accounts, *chicha* was a focal aspect of subsistence that has been examined in other archaeological contexts (Bray 2003; Goldstein 2003). Botanical remains provide an indication of available crops within a region, however their form or function within diet is more difficult to examine entirely from floral remains.

Ceramic Analysis

Ceramic fragments also indicate aspects of subsistence through analyses of vessel form and function (Goldstein 2003), artwork (Somerville *et al.* 2015), and residues on ceramic fabric (Duncan, Pearsall, and Benfer 2009). Ancient *chicha* production is illustrated on ceramic vessels from sites at Lake Titicaca (Goldstein 2003). Somerville *et al.* (2015:412) have identified specific “*chicha* drinking goblets” in grave good assemblages associated with the Tiwanaku people. Bray (2003:3) examined ceramic assemblages to analyze “food, feasting, and gender” within the Inka empire. In this study the form and functionality of each vessel was studied to determine the role of women in the domestic sphere of large-scale state populations. Food storage vessels and preparation methodology have also been indicated using macroscopic ceramic analyses and ethnohistoric data in conjunction (Duncan, Pearsall, and Benfer 2009). According to Bray (2003:7), “potatoes could be eaten green, roasted, cooked, or in stews,” or “preserved through a process of alternative exposure to sun and frost” as a means of dehydrating them for storage. When used in conjunction, ceramic, ethnohistoric, and botanical evidence indicate a more holistic picture of crops and preparation methods for available foods.

Foods that are cooked in ceramic vessels may leave a residue of food remains on the vessel fabric (Salque *et al.* 2012). Unlike basic floral analysis, residue analysis indicates direct processing or cooking of floral remains. Zarrillo *et al.* (2008) analyzed cooking vessels and food-processing tools (e.g. grinding stones) from a site in Ecuador and identified the presence of charred *maize* starch residues. Despite a lack of macrobotanical remains in their assemblage, Zarrillo *et al.* (2008) were able to identify accessible crops and potential food items that had been directly processed. In preceramic sites, like

Buena Vista, Peru, Duncan, Pearsall, and Benfer (2009) similarly analyzed bottle gourd and squash vessels to identify the presence of food residues. Due to the excellent preservation conditions in Peru, these utilitarian vessels contained ancient residues of *yuccas*, potato, chili pepper, arrowroot, and tree root (*algarrobo* spp.). Unlike the charred residues from Ecuador, Duncan, Pearsall, and Benfer (2009) interpreted the floral residues from drinking vessels as support for the concept of fermented *yuccas* and *algarrobo* into alcoholic beverages. Botanical and ceramic analyses from archaeological contexts can be used to identify foods prepared and stored in antiquity. Alternatively, floral remains can be processed for medicinal and decorative (e.g. dye for fabrics) means, which makes it difficult to interpret ‘food remains’ that were definitively used for dietary purposes.

Faunal Remains

Meat is an important part of Peruvian diet, and processing patterns on faunal bone indicate which animals were likely butchered and/or cooked for consumption in the past. Venet-Rogers (2013) examined evidence of tool cut marks and charring or burning on faunal remains from Gallinazo Group in Peru; both signs indicate that fauna were prepared for subsistence. This near-coastal site included deposits of fish (anchovy, mackerel, and sharks), molluscs (clams, limpets, and urchins), reptiles (iguana and tegus), birds (gulls, pelicans, and ducks), and mammals (camelids, guinea pigs, and deer), all of which exhibited some form of processing or butchery (Venet-Rogers 2013).

Miller and Burger (1995) examined faunal assemblages at Chavín de Huántar and documented a change in the quantity and quality of specific cuts of meat. Their analysis indicated that earlier populations preferred deer meat, whereas more recent populations depended on

camelid meat for subsistence. Miller and Burger (1995) utilized previous studies of animal carcass weight and known meat utility values to examine how different animals were utilized at this site. Their study supported the hypothesis that dried camelid meat was used by travelling herders in the society. Dried meat and fish products (*ch'arki*) are reported to have been efficient year-round food products for direct consumption or as trade goods (Miller and Burger 1995; Venet-Rogers (2013). Meat utility, taxonomic analyses, and butchery patterns indicate which fauna were available for consumption and which elements were 'preferred cuts'. Lipid residue analysis on ceramics has also been used to identify evidence of animal by-product (e.g. milk) processing in other contexts (Salque *et al.* 2012). Lipid residue analysis has not been conducted on Peruvian ceramic assemblages, but studies of this nature could identify camelid by-products or the direct processing of animal flesh, which would add to the subsistence data in this region.

Limitations and a More Direct Approach

Floral and faunal artifacts illustrate available food items however they do not indicate remains that were definitively intended for human consumption. Ceramic residue analysis of cooked materials provides evidence of material preparation, but still may not identify remains that were directly prepared for human diet. According to Cadwallader *et al.* (2012), fruits found in Peru, like the prickly pear, were used for human food and animal fodder, whereas tobacco was grown for recreational and medicinal smoking use. In order to identify foods that were directly consumed by humans, many studies focus on examining human osteological remains.

Similar to ceramic residue analysis, starch grains preserved in human dental calculus illustrate foods that were processed by the human mouth. Piperno and Dillehay (2008) identified

seed, nut, and other fruit starches on human dental remains from early and middle Holocene sites in northern Peru. Their analysis showed that domesticated plant species were consumed much earlier than previous botanical studies suggested. When dental plaque mineralizes it forms dental calculus, and any starch molecules that were stuck in the plaque will preserve as an 'oral fingerprint' (Piperno and Dillehay 2008). Modern studies have shown that certain particles, like more adhesive starches, will preferentially preserve in dental plaque (Leonard *et al.* 2015). Alternatively, animal protein sources and liquids like *chicha* would not be captured by dental calculus analysis. These factors bias research and create an overrepresentation of certain food types (Leonard *et al.* 2015). This method provides more direct evidence of floral items that pass through the oral cavity, but does not definitively illustrate foods that were consumed. In the modern horticultural population studied by Leonard *et al.* (2015), palm leaf remains were found in dental plaque because of palm-leaf basket-making practices. Without ethnographic information detailing basketry practices, dental plaque analysis might have led to the interpretation that palm leaves were a food item (Leonard *et al.* 2015). There are many positive applications of dental calculus analysis, but it still does not identify direct evidence of ancient subsistence.

Alternatively, stable isotope analysis permits an examination of the chemical composition of human bones, highlighting the foods ingested during life (Schwarcz and Schoeninger 2011). The carbon and nitrogen stable isotopes of bone collagen are utilized to examine predator-prey relationships of the regional food chain (Ambrose and Norr 1993; Richards *et al.* 2003). These fundamental principles of stable isotope methodology have been applied to many different research contexts in Peru (e.g., Goldstein 2003, Horn *et al.* 2009, and Tomczak 2003). Chemical

analyses of human bone can be used to directly analyze palaeodiet.

Stable Isotope Methodology

Bodies incorporate elements from the surrounding environment through diet, which are reflected in the isotopic composition of proteins used for structural elements such as hair, bone, and keratin (Schwarcz 2000). Structurally, bone is composed of ~70% mineral (bioapatite) and ~30% protein (collagen) (Schwarcz and Schoeninger 2011). Carbon atoms from proteins are preferentially routed to collagen, so the stable isotope values from collagen mostly reflect the protein component of diet (Krueger and Sullivan 1984). Total diet is analyzed using carbon isotope differences recorded in the carbonate fraction of tooth enamel (Ambrose and Norr 1993; Lee-Thorp and van der Merwe 1987).

Carbon

Many elements exist on earth in numerous radioactive and non-radioactive (stable) forms. Carbon isotopes occur naturally in two different stable forms that vary in weight. Carbon atoms maintain the same number of protons (six) and electrons (six) with varying numbers of neutrons between stable isotopes. A carbon isotope with six neutrons (^{12}C) weighs less than a carbon isotope with seven neutrons (^{13}C), causing them to react differently (Hoefs 2009). Both forms of carbon are naturally occurring in flora, fauna, and mineral, but in varying quantities. Stable isotopes are expressed as a ratio between the heavier and lighter isotope. The ratio of $^{13}\text{C}/^{12}\text{C}$ is measured in parts per mille (‰) within the sample, and is recorded as a delta value ($\delta^{13}\text{C}$) in relation to an international standard (Hoefs 2009:28). Carbon's standard (Vienna Pee Dee Belemnite, or VPDB) is naturally ^{13}C -enriched and causes most sample $\delta^{13}\text{C}$ values to be expressed as negative values (Hoefs 2009).

Bioavailable carbon can come from atmospheric CO_2 and dissolved inorganic carbon, and the analysis of $\delta^{13}\text{C}$ in bone collagen is used to differentiate dietary aspects of plant and animal-protein as they relate to available carbon sources (Schwarcz 2000). Carbon isotope ratios of plant tissues are impacted by the photosynthetic pathway each plant uses to fix carbon. Most cultivars (e.g. *yuccas*, fruits, and vegetables) use the C_3 photosynthetic pathway and are referred to as C_3 plants. The C_3 photosynthetic pathway discriminates against ^{13}C , giving C_3 plants a ^{13}C -depleted carbon isotope ratio ($\delta^{13}\text{C}$ between -30‰ and -25‰) (DeNiro and Schoeninger 1983) (fig. 1). Wild grasses and a few cultivars (e.g. *maize*) use the C_4 photosynthetic pathway and are referred to as C_4 plants. The C_4 photosynthetic pathway does not heavily discriminate against ^{13}C compared to C_3 plants, giving C_4 plants a comparably ^{13}C -enriched carbon isotope ratio ($\delta^{13}\text{C}$ between -20‰ and -15‰) (Schwarcz 2000) (fig. 1). Table 1 also summarizes other influences on the carbon isotope composition of diet that are visually illustrated by Figure 1.

Nitrogen

Nitrogen is available in atmospheric N_2 , nitrogen-containing compounds (e.g., nitrite and ammonia) and in nitrogen-fixing organisms (e.g., algae and bacteria) (Schoeninger, DeNiro, and Tauber 1983). The two most commonly occurring nitrogen isotopes are ^{15}N and ^{14}N , and the ratio ($^{15}\text{N}/^{14}\text{N}$) is most frequently used to illustrate differences in predator-prey relations as they relate to available nitrogen resources (DeNiro and Epstein 1981). Predators are ^{15}N -enriched when they consume prey ($\delta^{15}\text{N}$ values are +3‰ with each subsequent step up the food chain), a process known as the 'trophic level effect' (Schwarcz and Schoeninger 2011) (fig. 1). Aquatic environments contain more levels in their

Figure 1. Trophic level representation illustrating relative $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ for different plants and animals (from Schwarcz and Schoeninger 2011:732)

food chain, so consumers of aquatic resources will illustrate subsequently higher $\delta^{15}\text{N}$ values (Schoeninger, DeNiro, and Tauber 1983). Table 1 outlines other sources of nitrogen that influence stable isotope signatures.

Isotopes in Conjunction

Studies that integrate multiple isotopes can lead to a more accurate understanding of local subsistence practices. For example, marine fauna exhibit $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values that are different from terrestrial fauna (fig. 1). Large mackerels are more ^{13}C -enriched than llamas that feed on C_3 plants because of the carbon-content of dissolved inorganic carbon in water (DeNiro and Epstein 1981). Mackerel will also have a more positive $\delta^{15}\text{N}$ ratio than llamas because carnivores occupy apex positions in aquatic food chains, and aquatic systems have more food chains (DeNiro and Epstein 1981). If the llama has consumed a *maize*-heavy diet, it will be more ^{13}C -enriched

than the mackerel because of the C_4 plant photosynthetic pathway (Krueger and Sullivan 1984). If the diet has a mix of C_3 and C_4 plants, the $\delta^{13}\text{C}$ values will be much more variable (Schwarcz and Schoeninger 2011).

Stable isotope analyses have also been used to indicate animals that have been specifically fed for consumption (Finucane, Agurto, and Isbell 2006). In particular, *cuy* (guinea pig) is a common dish in modern highland Peruvian diet. *Cuy* that are intended for consumption are fed an omnivorous diet of mixed vegetation and protein sources, which would be reflected by mid-range $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values consistent with other omnivores (e.g. pigs, dogs). Wild *Cuy* likely reflect a ^{15}N -depleted diet compared to their domesticated counterparts because they are not feeding on ^{15}N -enriched sources in the wild. Finucane, Agurto, and Isbell (2006) documented archaeological *cuy* remains that had ^{15}N -elevated bone collagen and indicated guinea pigs that were specifically fed for human subsistence.

TABLE 1. The relative influence of specific factors on isotope signatures (recorded in bone collagen), when compared to the norm^{1,5}

Category	Influence on Isotope Signature			References
	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	$\delta^{34}\text{S}$	
Marine Protein	Increase ²	Increase	Variable ³	Craig <i>et al.</i> 2006; Nehlich <i>et al.</i> 2011; Privat, O'Connell, and Hedges 2007; Richards, Fuller, and Hedges 2001, 2003
Mococho (Seaweed)	Increase	Increase	Variable	Finucane, Agurto, and Isbell 2006; Froehle, Kellner, and Schoeninger 2010; Horn <i>et al.</i> (2009); Richards, Fuller, and Molleson 2006
Fungi	Increase	Decrease	N/T	Millard <i>et al.</i> 2011
Maize, Kiwicha	Increase	-	N/T	Cadwallader <i>et al.</i> 2012; Krueger and Sullivan 1984; Schwarcz and Schoeninger 2011
Shallow Water Organisms	Decrease	Increase	Decrease	Craig <i>et al.</i> 2006; Miller, Capriles, and Hastorf 2010; Nehlich <i>et al.</i> 2011
Salt Marsh Grazing	-	Increase	Increase	Britton <i>et al.</i> 2008; Madgwick <i>et al.</i> 2013; Weinstein <i>et al.</i> 2000
Freshwater Protein	-	Increase	Variable	Craig <i>et al.</i> 2006; Katzenberg 1989; Linderholm and Kjellström 2011; Nehlich <i>et al.</i> 2011
Terrestrial Protein	-	Increase	-	Katzenberg 1989; Nehlich <i>et al.</i> 2011; Richards <i>et al.</i> 2003; Schwarcz 2000
Manured Cultigens	-	Increase	Variable	Bogaard <i>et al.</i> 2007; Mizota and Sasaki (1996)
Legumes⁴	-	Decrease	N/T	DeNiro and Epstein 1981
Sea-Sprayed Cultigens	-	-	Increase	Horn <i>et al.</i> 2009; Richards, Fuller, and Hedges 2001; Richards <i>et al.</i> 2003
Geographic Change	-	-	Variable	Craig <i>et al.</i> 2006; Nehlich <i>et al.</i> 2011; Richards, Fuller, and Hedges 2001, 2003; Wilson <i>et al.</i> 2007

1 Isotopically 'normal' here refers to a small-bodied herbivore that consumes C₃ plants, no meat, and has no other influences acting on ingested dietary protein.

2 Increase is contested (see: Reitsema *et al.* 2013)

3 Average range of +17‰ to +20‰ contested (see: Craig *et al.* 2006; Nehlich *et al.* 2011)

4 Legumes grown with or without manure

5 Adapted from Bishop (2013)

(-) No change; (N/T) Information has not yet been tested

Figure 2. Visual overview of sulphur cycling, including expected sulphur isotope values within the environment (from Nehlich 2015:3).

Many Peruvian palaeodietary studies examine stable carbon and nitrogen isotope values from human bone collagen. Studies illustrate different subsistence practices according to significant variation in individual age (Turner, Kingston, and Armelagos 2010), sex (Somerville *et al.* 2015), political regimes (Lambert *et al.* 2012), and in areas where there were different animal husbandry practices (Finucane, Agurto, and Isbell 2006). Alternatively, some studies have been unable to identify specific parameters of subsistence practices (Burger and van der Merwe 1990; Kellner and Schoeninger 2008). All of these analyses worked under the premise that *maize* was the main source of $\delta^{13}\text{C}$ enrichment in Peru. According to Cadwallader *et al.* (2013), multiple plant sources can elevate $\delta^{13}\text{C}$ values, including *kiwicha* and the prickly pear (*Opuntia* spp.). Finucane, Agurto, and Isbell (2006) identified ^{13}C - and ^{15}N -enriched bone collagen in rodent samples, which was attributed to the

consumption of *mococho* in a non-coastal area. Carbon isotope analysis can no longer be used to examine the direct consumption of *maize* in Peruvian diets. This illustrates a major limitation of carbon and nitrogen stable isotope analyses, and to some extent, all analyses that examine isotopic composition of bone: the specific isotope analyzed limits the aspects of palaeodiet that can be analyzed through isotope studies.

Same Materials, New Method

Sulphur isotopes are a recent addition to palaeodietary studies (Craig *et al.* 2006; Sayle *et al.* 2013; Vika 2009). The main sources of sulphur originate from the earth's core, atmospheric SO_2 , oceanic sulphur and bacterial environments in the sediment of freshwater (Trust and Fry 1992; Richards *et al.* 2003). Figure 2 visually illustrates sulphur variation across a typical landscape. The two most commonly

Figure 3. Environmental reservoirs influencing the amount of sulphur taken up by growing plants (created according to the information presented in Nehlich 2015).

occurring sulphur isotopes are ^{34}S and ^{32}S , and the ratio ($^{34}\text{S}/^{32}\text{S}$) is used to illustrate differences in nutrient source (Krouse and Coplen 1997). All of the sources of sulphur impact the $\delta^{34}\text{S}$ composition of each environmental niche (fig. 3), which is then reflected in the stable isotope signatures of the organisms consuming food from these regions (fig. 4) (Nehlich 2015). Insignificant fractionation occurs between landscape, flora, and fauna, enabling a direct indication of dietary niche source (Nehlich and Richards 2009).

Most studies have focused on the use of sulphur isotopes as a tool for differentiating fauna found in various aquatic environments (e.g., Craig *et al.* 2006; Leach *et al.* 2001; Nehlich *et al.* 2011). According to Privat, O'Connell, and Hedges (2007), sulphur isotope data coupled with nitrogen isotope values from their Russian study samples reflected a terrestrial-based diet in one group, but a freshwater source in another. Richards, Fuller, and Hedges (2001) additionally

examined the influence of regional bedrock signatures on two terrestrial assemblages in order to examine the potential use of sulphur isotopes in terrestrial migration analyses. An inland Medieval England site at Bordesley Abbey (ca. 1300 CE), and an inland Mesolithic Ukraine site at Oleneostrovski (ca. 6500 BCE) contained human and faunal remains with $\delta^{34}\text{S}$ values ($\sim 12\text{‰}$ and $\sim 6\text{‰}$, respectively) that were consistent within each population, and were distinct from other populations within their study (Richards, Fuller, and Hedges 2001). Their analysis also demonstrated that oceanic sulphur has a $\delta^{34}\text{S}$ of $\sim 21\text{‰}$, whereas freshwater sulphur ranges from $\delta^{34}\text{S}$ -22‰ to $+22\text{‰}$, and is reflected in the tissues of fauna that live within each niche (fig. 3, 4) (Richards, Fuller, and Hedges 2001; Richards *et al.* 2001; 2003). This $\delta^{34}\text{S}$ value for marine environments ($+20\text{‰}$ to $+21\text{‰}$) has also been documented in other studies (Nehlich, Barrett, and Richards 2013; Thode, Monster, and Dunford 1961).

Figure 4. Environmental and cultural influences of human sulphuric isotope composition. (created according to the information presented in Nehlich 2015).

New Isotopes in Conjunction with Old Isotopes

Sulphur isotopes are recorded from the protein portion of bone (collagen) and hair (keratin), making them ideal to study in conjunction with carbon and nitrogen (Nehlich and Richards 2009). When plants grow, they incorporate nutrients into their roots based on those available in the soil, and according to growing conditions (Bogaard *et al.* 2007; van Klinken, Richards, and Hedges 2000). Ground nutrients influence $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$, whereas growing conditions and plant type will influence $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$ values in organisms (table 1). Regional temperature, humidity, and environment can all influence which plants will grow in each niche, and whether they will be available for human consumption (Heaton 1999). Similarly, aquatic reservoirs will also influence the $\delta^{13}\text{C}$ and $\delta^{34}\text{S}$ recorded in aquatic food chains (fig. 5). Accordingly, carbon, nitrogen, and sulphur isotopes recorded in human and faunal bone will

change in different feeding niches (Lee-Thorp and Beaumont 1995; Schwarcz 2000). Table 1 illustrates the relative influence of different environments and food types on carbon, nitrogen, and sulphur isotope values recorded in bone collagen.

Mococho

Consuming *mococho* would enrich ^{13}C , reflect marine sulphur values (elevated to no more than 20‰), and can marginally enrich the ^{15}N in collagen. The study conducted by Richards, Fuller, and Molleson (2006) on the Newark Bay Viking site (600-1450 CE) in Scotland included the remains of animals that may have consumed seaweed, or cultigens that were fertilized with seaweed. Pig remains with recorded carbon and nitrogen isotope values of $-20.6 \pm 1.3\text{‰}$ and $+8.4 \pm 1.6\text{‰}$, respectively, indicated direct seaweed consumption (Richards, Fuller, and Molleson 2006). Alternatively, sheep/goats with

Figure 5. Relative impacts of various reservoirs on $\delta^{13}\text{C}$ and $\delta^{34}\text{S}$ values of archaeological bone collagen (adapted from Nehlich 2015).

measured isotope values consistent with increased average nitrogen values ($+7.0 \pm 0.9\%$), which did not demonstrate significantly increased carbon values ($-21.8 \pm 0.8\%$) indicated animals that consumed manured cultigens (refer to Table 1 on manuring effects) (Richards, Fuller, and Molleson 2006). In Peru, Finucane, Agurto, and Isbell (2006) suggested that elevated $\delta^{13}\text{C}$ in mice was due to consumption of seaweed from coastal sources. Madgwick *et al.* (2013) identified fauna that fed on halophytes (saline-loving plants) grown in salt marshes due to their isotope values which reflected a trophic level shift in $\delta^{15}\text{N}$ values, ^{13}C enrichment, and $\delta^{34}\text{S}$ values consistent with marine source consumption. Salt marsh grazers would have isotopic values that are different from those due to manuring because of increased $\delta^{34}\text{S}$ values attributed to aquatic sediments (Madgwick *et al.* 2013). Isotopic analysis of carbon, nitrogen, and sulphur can be

used to effectively identify halophytic foods in palaeodiet.

Shallow Water Sources

Studies also investigated how isotopic values vary in aquatic environments according to water depth. Craig *et al.* (2006) analyzed faunal remains in northern Europe along the Baltic Sea (ca. 3900 BCE) and demonstrated that their sample had ^{34}S - and ^{13}C -depleted collagen compared to fauna in other aquatic environments. Shallow water niches have depleted heavy sulphur sources because of microbial sulphur cycling into sediments (Bottrell and Raiswell 2000). Heavy carbon depletion was due to reduced concentration of dissolved inorganic carbonate (Craig *et al.* 2006), which has also been documented in other studies involving shallow aquatic niches (Richards 2001). Shallow water environments were also investigated by Nehlich *et al.* (2011) using isotopes recorded in

fauna from four sites in Oxfordshire, United Kingdom: Barrow Hills (100-300 CE), Tubney Wood Quarry (200-600 CE), Queenford Farm (400-600 CE), and Queens' College (1400-1500 CE). In both studies, $\delta^{34}\text{S}$ values were roughly -20‰ to -17‰ and $\delta^{13}\text{C}$ was approximately -30‰ (Craig *et al.* 2006; Nehlich *et al.* 2011). Isotope signatures of $\delta^{34}\text{S}$ and $\delta^{13}\text{C}$ that are similar to those recorded by Nehlich *et al.* (2011) are unique, and would likely illustrate a shallow water source. Shallow water sources can be natural, as both studies documented, and form specific niches in the Peruvian lowlands near Lake Titicaca.

Sulphur Variation in Peru

Every ecological niche has a unique isotopic baseline value (Nehlich 2015). Currently there are no baseline sulphur isotope values (modern or ancient) that have been established in Peru. According to ecological studies of sulphur isotope pathways (Böttcher 2001; Hollingsworth 2006; Mossmann *et al.* 1991; Mizota and Sasaki 1996; Sakai and Matsubaya 1977; Shearer *et al.* 1996; Trust and Fry 1992), known geochemical properties of sulphur (Bottrell and Raiswell 2000; Krouse and Coplen 1997; Sakai 1957; Thode, Monster, and Dunford 1961), and previous archaeological applications of sulphur in other contexts (Craig *et al.* 2006; Nehlich *et al.* 2010; Nehlich *et al.* 2014; Privat, O'Connell, and Hedges 2007; Richards, Fuller, and Hedges 2001; Richards *et al.* 2001; 2003), Figure 6 was created to illustrate proposed isotopic trends in Peru. There are three isotopically distinct features about the Peruvian landscape which all impact regional sulphur variation.

Coastal Influences (Pacific Ocean)

According to all sources, oceanic sulphur is very uniform “due to the constant cycling of water through all oceans” (Nehlich 2015:4). Estuaries,

which stem from coastal systems and have joint impact from freshwater sources, will demonstrate more variable sulphur isotope values due to soil and rock leaching, erosion, groundwater, and geological formations (Hollingsworth 2006). The entire western coast of Peru is impacted by the sulphur content of the Pacific Ocean, and any marine protein sources would similarly reflect ^{34}S enrichment to roughly 20‰. According to Bottrell and Raiswell (2000:102) the Peru Margin, located along the Pacific coast of Peru, “is unusual in possessing an extensive thickness of dissolved, sulphide-bearing pore-waters, which combined with sedimentation rate, give several millions years of sediment exposure to dissolved sulphide.” Not only would coastal resources be expected to reflect the ^{34}S -enriched niche, but there would be a marked sea-spray effect inland from the coast. Average sea-spray effects have been measured roughly 30 km inland (Nehlich 2015:10), but this value is expected to be larger along the Pacific coast of Peru due to the Peru Margin documented by Bottrell and Raiswell (2000). Accordingly, Figure 6 has a projected sea-spray niche impact of up to 100 km from the Pacific coast (marked in yellow). In this niche, vegetation will reflect ^{34}S enrichment up to +20‰ because of evaporated oceanic sulphates absorbing into the local landscape (Horn *et al.* 2009).

Volcanic Rock and the rest of the Andes Mountains

Information related to the sulphur isotopic content of the Andes Mountains is limited however the available geochemical and soil-based information for this region is sufficient for an extrapolation of probable baseline sulphur values. For example, the Andes Mountains are composed of volcanic rock and many active volcanic systems (Stewart 2015). If the sulfur of the Andes Mountains was derived from marine sulfur during

Figure 6. The proposed contour lines representing the overall variability and ranges of sulphur isotopic composition in Peru based on the values and discussion provided in text (e.g., Craig *et al.* 2006; Fornander, Eriksson, and Lidén 2008; Nehlich 2015). Site names refer to the case studies discussed below.

eruption, Lalonde and Beaudoin (2015) argue that the isotopic values would measure between 0‰ and +10‰. Alternatively, other studies of volcanic lakes have indicated that “sulphide minerals of igneous origin... are depleted in the heavy sulphur”, due to “the isotopic exchange reaction between native sulphur and hydrogen sulfide” (Sakai 1957:153, 160). Christenson and Tassi (2015:129) have identified that “the $\delta^{34}\text{S}$ signature of bulk mantle [sulphur] is similar to that of the internationally accepted standard value

derived from the Canyon Diablo Troilite meteorite” (CDT), suggesting that the bulk mantle of the Andes Mountain will average around 0‰. Varying quantities of gypsum and pyrite within volcanic terrains will also cause ^{34}S depletion, as these rock types also have stereotypically lower $\delta^{34}\text{S}$ values (fluctuating between -10‰ and +10‰) (Sakai and Matsubaya 1977). According to Bottrell and Raiswell (2000:99), volcanic pyrite undergoes “limited diagenetic alteration”, but will become depleted

in ^{34}S when oxidized ($\delta^{34}\text{S} \sim -16\text{‰}$). Overall, this suggests that the Andes Mountains will be mostly depleted in heavy sulphur at higher altitudes where there is less impact from marine sulphur and more impact from oxidized pyrite (ranging from -10‰ to $+10\text{‰}$) (illustrated in red, fig. 6).

Volcanic lakes or other bodies of water within the Andes Mountains will likely be ^{34}S -enriched due to freshwater influences (e.g., weathering of rock, atmospheric sulphurous gases) (Konhauser, Fyfe, and Kronberg 1994). Aquatic sources that are found at lower elevations are expected to illustrate a gradient of sulphur values, likely from -10‰ at higher elevations to $+10\text{‰}$ at lower elevations (illustrated in lime green, fig. 6) (Christenson and Tassi 2015). Volcanic lakes also impact the sulphur content of nearby terrestrial sediments, but not to the same extent that has been recorded for sea-sprayed niches adjacent to coastal sources (Hollingsworth 2006).

Lowland Freshwater Sources (Lake Titicaca and the Amazon River)

Unlike marine environments, niches impacted by freshwater sources will have more variable sulphur content across the landscape (Sayle *et al.* 2013). The Amazon River system in the northeast and Lake Titicaca's freshwater system in the southeast regions of Peru will likely vary in heavy sulphur and cause $\delta^{34}\text{S}$ values of 0‰ to $+15\text{‰}$ (Nehlich 2015; Privat, O'Connell, and Hedges 2007). In particular, the Amazon River system is known for being highly fertile and would be expected to have ^{34}S -enriched isotopic niches because of its biotic activity (Bottrell and Raiswell 2000; Konhauser, Fyfe, and Kronberg 1994). According to Nehlich (2015:4) freshwater sulphur values will "vary according to site geochemistry and sulphate reduction or sulphide oxidation." Some of these riverine systems may have also had connections with the Pacific Ocean,

which will also vary as a result of the recycled sulphur composition within the water sources (Bottrell and Raiswell 2000). Because of this, and due to the close proximity of the active Andes Mountains, freshwater influences may range in $\delta^{34}\text{S}$ from 0‰ to 15‰ (illustrated in green, fig. 6) (Nehlich 2015).

Despite isotopic variability anticipated across freshwater sources, no sulphurous influence is expected to raise values higher than 20‰ , as they are not currently connected to marine resources. Similar to the sea-spray effect along marine coasts, available sulphur along the lowland 'terrestrial' eastern half of Peru will be impacted by the riverine systems (Bocherens, Drucker, and TaPubald 2011). The leeward side of the Andes Mountains are projected to have ^{34}S depletion due to the minimal erosion of sulphur-bearing rocks and minerals, but will increase in $\delta^{34}\text{S}$ with increasing distance from the mountains (anticipated $+5\text{‰}$ to $+15\text{‰}$, illustrated as purple in fig. 6) (Rafter, Kaplan, and Hulston 1960 in Thode, Monster, and Dunford 1961). Additional studies will be required to sample ancient baseline sulphur isotope values at different niches throughout Peru.

Application: Case Studies

Three case studies were chosen to critically examine the applicability of sulphur isotope methodology in Peru (table 2). One example highlights the limitations of analyzing palaeodiet in Peru by only focusing on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in human and animal remains (Finucane, Agurto, and Isbell 2006). The second (Wilson *et al.* 2007) and third (Horn *et al.* 2009) examples examine carbon, nitrogen, and sulphur isotope values recorded in mummy scalp hair from Peru. The benefits and limitations of these two case studies highlight strategies that should be employed moving forward with palaeodietary analysis in this region.

TABLE 2. Case study contextual information, including major conclusions, limitations within each study, and the proposed sulphur isotope analysis findings.

Study	Context	Methods and Materials	Study Conclusions	Issues within Study	Proposed Solution
Finucane, Agurto, and Isbell (2006)	Conchopata (550-1000 CE)	40 Human and camelid, other fauna: collagen ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) and carbonate ($\delta^{13}\text{C}$)	(1) Maize as staple crop; (2) two distinct camelid management strategies	Elevated mice $\delta^{13}\text{C}$ likely due to seaweed; raises questions about human $\delta^{13}\text{C}$ values	Analyze contribution of marine sources: $\delta^{34}\text{S}$ elevated from baseline values (+20‰)
Wilson <i>et al.</i> (2007)	Volcán Sara Sara (1430-1530 CE)	1 Human: hair keratin ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{34}\text{S}$)	(1) No evidence of marine diet; (2) distinct movement of individual.	Small sample size. No baseline data. Suspected non-local.	Larger sample size. Analyze hair and bone $\delta^{34}\text{S}$.
Horn <i>et al.</i> (2009)	Monte Grande, Pueblo Viejo, Paracas and Los Molinos (500 BCE-1000 CE)	Multiple mummies and camelid wool: hair keratin ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{34}\text{S}$)	(1) Sites had different access to marine resources; (2) evidence of <i>mococho</i> being fed to camelids	Overall trends analyzed; no account for seasonality or migration.	Analyze (monthly) segments of hair $\delta^{34}\text{S}$.

Case Study #1: Mice, Mococho, and Management Strategies

Finucane, Agurto, and Isbell (2006) examined archaeological remains from Conchopata recorded to the Middle Horizon (AD 550-1000) (fig. 6, table 2). Researchers compared isotopes recorded from human bone collagen to those recorded in tooth enamel bicarbonate to establish the role of *maize* in palaeodiet. This was accomplished by examining the mean difference of $\delta^{13}\text{C}$ between paired samples of carbonate (full diet) in enamel and collagen (protein portion of diet) in bone. Based on their findings they assert that maize was a staple part of diet, and was not merely a ceremonial cultigen, which had been

argued elsewhere (e.g. Hastorf and Johannessen 1993). The second aim of this study was to examine the carbon and nitrogen isotopes in faunal bone collagen to determine if specialized animal management strategies were practiced. Supported by current ethnographic data, *Puna* camelid pastoralism during the Wari polity involved two major husbandry regimes that: (1) utilized maize fodder grazing locally in the *yunga* region (2200-2600m in elevation); and, (2) involved transhumance in the highland *puna* region (>4100m in elevation), well above maize growing altitude.

One major limitation of this study is that the authors failed to account for the marine influence

on human isotopic values. The spacing between carbonate and collagen did illustrate that ^{13}C enrichment was most likely due to C_4 plants; however, Finucane, Agurto, and Isbell (2006:1771) conclude that:

although the observed nitrogen isotope signatures could result from the consumption of marine protein, this is extremely unlikely considering the site's distance from the ocean and the high transportation costs associated with transporting fish or shellfish to the sierra from the Pacific [Ocean].

The authors deny the possibility of marine resource consumption by humans, but then later use marine sources to explain the elevated carbon and nitrogen values observed in a mouse bone collagen sample: “a diet composed primarily of marine plants would produce the observed isotopic value, yet leave little if any physical residue in the archaeological record” (Finucane, Agurto, and Isbell 2006:1773). This contradiction was one of the major limitations of their study, and illustrates issues with carbon and nitrogen isotope analyses in Peru.

If sulphur isotope values were recorded from the bone collagen fragments sampled in Finucane, Agurto, and Isbell (2006), it would aid in the discussion of access to marine resources. Conchopata is located in the high-lands of the Andes Mountains and would be expected to have a baseline sulphur isotope value of -10 to +10‰, depending on the erosion of volcanic sulphur and impact from rain patterns (Bottrell and Raiswell 2000) (fig. 6). Small-bodied herbivores would normally be tested to establish local baseline isotope values, however the anomalous mouse in Finucane, Agurto, and Isbell (2006) shows that this practice may generate misleading data. Fortunately, marine sulphur isotope signatures are so unique (~20‰), that any faunal or human isotope values that reflect ^{34}S enrichment would

be indicative of the consumption of food from a marine subsistence niche, or an individual who has migrated from that environment.

More local trends could be established using sulphur isotope analysis depending on how contained the sulphur isotope niche is around Conchopata. If this region has a unique sulphur isotope value that is distinct from nearby water sources or camelid migration routes, sulphur isotope values may be used to strengthen the examination of distinct camelid husbandry regimes in Finucane, Agurto, and Isbell (2006). Likely, the *yunga* region will reflect higher $\delta^{34}\text{S}$ values (0‰ to +10‰) due to organic matter in the soils from the irrigation systems used for *maize* agriculture (Mizota and Sasaki 1996). Alternatively, the *puna* grassland will likely reflect lower $\delta^{34}\text{S}$ values (-10‰ to 0‰) due to the erosion of volcanic pyrite in the volcanic highlands that already reflects ^{34}S depletion (Hollingsworth 2006). Ultimately, a marine dietary contribution, such as *mococho*, would be indicated by a much more elevated $\delta^{34}\text{S}$ value depending on the amount of halophytes consumed.

Case Study #2: Sarita, Sacrifice, and Capacocha Children

Wilson *et al.* (2007) examined five mummified children located at the sites of Volcán Sara Sara in Peru ($n=1$: Sarita), and Volcán Llullaillaco in northwest Argentina ($n=4$). Dated to the pre-conquest period (1430–1520 CE), Wilson *et al.* (2007) wanted to understand the final months of life for ritually killed *capacocha* children. Good preservation enabled scalp hair to be sampled for the analysis of carbon, nitrogen, oxygen, hydrogen, and sulphur isotopes (fig. 7), as well as mitochondrial DNA analysis (mtDNA). For the purposes of this analysis, I will only focus on the carbon, nitrogen, and sulphur isotope values recorded by Wilson *et al.* (2007). Based on their

Figure 7. Stable isotope values of $\delta^{15}\text{N}$ (a), $\delta^{13}\text{C}$ (b), and $\delta^{34}\text{S}$ (e) recorded from scalp hair (from Wilson *et al.* 2007:16457). Particular attention in-text is given to Sarita ($\blacklozenge$ -S).

results, individuals travelled from villages at lower altitudes to the highlands (likely Cusco) where they were fed special foods and prepared for their roles as tribute to the gods.

All samples recorded diets with increased protein sources and ^{13}C enrichment (attributed to

maize) roughly 12 months prior to death (fig. 7a, 7b, respectively). The four Argentinian mummies (LG, LB, LM, and LX) demonstrated little variation in $\delta^{34}\text{S}$ however the Peruvian mummy illustrated a 5.2‰ decrease in $\delta^{34}\text{S}$ roughly 12 months prior to death (fig. 7e). This ^{34}S depletion

has been attributed to a change in subsistence niche for Sarita while travelling to Cusco (Wilson *et al.* 2007). Marked decreases in $\delta^{34}\text{S}$ for all five individuals provided conclusive evidence that the children were not fed special marine-protein diets, disproving the original hypothesis. Ultimately this study provided a new approach to analyzing ritual sacrifice, examined the diets of *capacocha* children, and identified evidence of changes in subsistence niches.

Scalp hair is a more effective medium for isotopic analysis as it measures dietary protein on a monthly basis rather than a multi-year basis (Macko *et al.* 1999). According to Williams and Katzenberg (2012), hair grows roughly 0.35 mm / day, equating to roughly one centimetre of hair per month. Wilson *et al.* (2007) analyzed hair increments that represented 1.5 month periods. This incremental measurement was selected to ensure that a sufficient sulphur mass was recorded from each keratin sample. According to Nehlich (2015:7) keratin has a mass that is roughly 5% sulphur, compared to the ~1% sulphur content-by-mass value recorded in bone collagen. Fernández, Panarello, and Schobinger (1999) also analyzed isotope values recorded in scalp hair in other mummies in South America however their methods were based on an older approach (Macko *et al.* 1999). In this approach the entire hair sample was analyzed as a bulk sample to ensure sufficient sulphur content. In their study, sulphur values indicated individuals from more coastal regions (likely impacted by the sea-spray effect) compared to those that came from more highland or low-inland regions (Macko *et al.* 1999). Alternatively, newer and more refined methods of hair analysis have identified diet during a more specific period of life (Williams and Katzenberg 2012). Migration, seasonality, and more specific dietary trends can all be examined using isotopes analysed from hair samples.

According to Sarita's isotope values, her diet was enriched in ^{15}N and some ^{13}C , and depleted in ^{34}S within the same 9 month period (12-21 cm distance from scalp, fig. 7). The carbon and nitrogen data for this timeframe would normally be identified as representing a marine-based diet, which should be accompanied by ^{34}S -enriched keratin. Based on Sarita's $\delta^{34}\text{S}$ value (~10‰), she was more likely consuming larger portions of C_4 cultigens (e.g. *maize* or *kiwicha*) and protein from a freshwater or terrestrial source, and was changing subsistence niches. Depending on nearby freshwater sources, a diet with increased freshwater protein from a shallow-water niche may also cause ^{34}S -depletion (Craig *et al.* 2006). Sarita's recorded $\delta^{15}\text{N}$ values nine months prior to death may also be interpreted as a diet based on seasonal protein sources, as illustrated by the sine-curved pattern (fig. 7a). This fluctuation is also observed among the four mummies from Argentina. Sarita and the other *capacocha* children had drastically different diets in the four to nine months prior to death, which would not have been visible in the osteological material, or according to full-strand isotopic analysis of hair.

Case Study #3: Large-Scale Mummy Study

Horn *et al.* (2009) conducted a large-scale isotopic study of mummy teeth, scalp hair, and camelid textiles from remains located at Los Molinos, Monte Grande, Paracas, and Pueblo Viejo from the Middle Paracas (500 BCE) to the end of the Wari culture (1000 CE) (fig. 6, table 2). Full strands of hair were sampled to indicate the average diet for each mummy, which was then illustrated as the average subsistence trend for each population (fig. 8). Based on the combined data recorded in $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$ values in hair and wool, Horn *et al.* (2009) concluded that individuals from Paracas had a marine-heavy diet, whereas Monte Grande may

Figure 8. Mean values for $\delta^{15}\text{N}$ vs. $\delta^{34}\text{S}$ analyzed on recent and archaeological hair and wool from various sites discussed in text. Based on values interpreted from Horn *et al.* (2009:184).

have had food items grown in a sea spray-affected niche.

Comparing the geographic locations of these four sites, the recorded sulphur values (fig. 6, 8) match the anticipated ranges outlined in Figure 6. Pueblo Viejo, which is the most elevated site sample, is located approximately 500 km from the Pacific Ocean, and would have volcanic sulphur sources. Accordingly, Pueblo Viejo human hair has a $\delta^{34}\text{S}$ range of +2‰ to +3‰ (anticipated -10‰ to +10‰). Los Molinos A and C are located roughly 90 km from the Pacific Ocean at the base of the Andes Mountains, and would be expected to have either a terrestrial sulphur source or a low-level volcanic influence (anticipated 0‰ to +16‰). The average range for both assemblages is +4‰ to +6‰ in human hair, supporting the values estimated in Figure 6. The Los Molinos averages were also too ^{34}S -depleted to indicate a sea-spray influence supporting the estimation of Nehlich (2015) that sea-spray only affects areas less than 30 km from a coastal niche.

Accordingly, Monte Grande, which is located less than 30 km from the coast, is identified as having some sea-spray influence (+8‰ to +9‰ in human hair) (Horn *et al.* 2009). Paracas, the only study sample located on the Pacific coast, had an average $\delta^{34}\text{S}$ of +13‰ to +14‰ in human hair, indicating that there was some marine influence on subsistence. The larger spread of sulphur values in wool was not discussed by Horn *et al.* (2009) (fig. 8), but may be indicative of expansive grazing niches throughout a larger space, similar to the management ‘zones’ recorded by Finucane, Agurto, and Isbell (2006).

This study confirmed many of the $\delta^{34}\text{S}$ trends anticipated across different subsistence niches in Peru (fig. 6) but also highlighted some of the limitations of broad-scale sulphur isotope studies. Unlike Wilson *et al.* (2007), who examined monthly segments of scalp hair, Horn *et al.* (2009) recorded isotopes from full strands of hair. This method is similar to analyzing bone samples. Full strands of hair indicate the relative diet for

one to two years depending on the length of each strand, which may confound dietary differences indicative of seasonality (Williams and Katzenberg 2012), transhumance (White *et al.* 2009), and migration (Wilson *et al.* 2007). Alternatively, this study highlights discernible differences in baseline sulphur values for a small region in Peru, suggesting that other areas can also have unique sulphurous niches.

Cautionary Analysis Moving Forward

Sulphur isotope analyses require establishing baselines for each niche. Once established, deviations from the baseline can be interpreted as the inclusion of a dietary item from a different source. Figure 6 illustrates relative sulphur variability according to a number of sources for the Peruvian landscape. The geology of this landscape must first be considered. The Pacific Ocean is a large marine source that has been extensively studied and fauna that grow within this environment would be expected to reflect a sulphur isotope value of roughly +21‰ (Mossman *et al.* 1991). Small river valleys that stem from the Pacific Ocean, but turn into shallow-bedded estuaries, would have specific sulphur content based on the marine source and influence from local sedimentary sources (Böttcher 2001). Fauna that grow in estuary conditions will have site-specific values that should range between +10‰ and +25‰. Alternatively, freshwater sources east of the Andes Mountains would be expected to have more depleted sulphur values as they approach the Amazon riverbed (Bottrell and Raiswell 2000). According to Konhauser, Fyfe, and Kronberg (1994), the Amazon riverbed does not have recorded sediments of sulphur, and fauna that grow in these conditions would only get sulphurous content from other surrounding sediments and runoff from the Andes Mountains. The isotopic values for these areas would be

closer to 0‰ due to a lack of stored sulphur within the sediments. The Andes Mountains, according to Konhauser Fyfe, and Kronberg (1994:172) are geologically active areas “mixed with newly extruded mantle elements”, including sulphur. Due to the presence of pure sulphur, and the attrition of these elements throughout the Andes, the sulphuric content of vegetation and fauna living within these areas would be ³⁴S-depleted, reflecting a lower recorded value of -20‰ to 0‰. Each area within Peru will have a unique sulphuric value based on the available sources of geological sediments and rainwater-deposited aerosols (Nehlich 2015).

Due to modern anthropogenic contamination, the sulphur isotope content of each site location is unobtainable through modern sampling (Richards *et al.* 2003). Baseline isotope values must be established for each site using small-bodied (non-mobile) fauna recorded within each archaeological assemblage. In Peru this could involve recording sulphur isotope values in the collagen of rodents (except for guinea pigs¹), lagomorphs, and lizards from archaeological assemblages. Domesticated animals may provide local baseline values, but could also represent diets attributed to non-locally grown fodder, which will skew baseline isotope values (Millard *et al.* 2011). Once a representative sulphur niche baseline is established, values will provide a comparative measure for the proportion of locally grown flora and locally-raised fauna in the diet.

Conclusions

Stable isotope analysis enables a direct investigation of the foods consumed in the past, which is not possible using other methods of botanical and faunal analysis. The exact

¹ Recall Finucane, Augurto, and Isbell (2006): *cuy* can be raised domestically for consumption and may reflect non-local omnivore isotope signatures. They are not ideal for providing a baseline.

parameters of palaeodiet are unobtainable from one method alone. Sulphur isotope analysis permits an examination of palaeodietary sources but it can easily be confounded by local isotopic variability. Instead of analyzing sulphur isotopes in bone collagen, it would be most beneficial to examine $\delta^{34}\text{S}$ values measured in segments of hair from human and faunal archaeological remains. Numerous archaeological sites in Peru yield sufficient preservation for the recovery and sampling of hair remains, including hair samples already recorded by Horn *et al.* (2009); Knudson, Aufderheide, and Buikstra (2007); Szpak *et al.* (2015), Webb, White, and Longstaffe (2013), White *et al.* (2009), Williams and Katzenberg (2012), and Wilson *et al.* (2007). The previously established limitations in sulphur isotope analysis should not discredit the approach, but instead promote caution in its application. The type of isotope analyzed may limit palaeodietary analysis, but it can provide supplementary dietary information not evident from floral, ceramic, and faunal analyses alone.

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