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

Katherine G. Bishop is a doctoral candidate in the Department of Anthropology at the University of Alberta (13-15 Tory Building, Edmonton, Alberta, T6G 2H4 [kbishop@ualberta.ca]).
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 (yuca ssp.), 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 (mocochos ssp.), gourd, yuca, and corn (maíz ssp.). 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), mollusces (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 Huantar 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 (12C) weighs less than a carbon isotope with seven neutrons (13C), 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 13C/12C is measured in parts per mille (%) within the sample, and is recorded as a delta value (δ13C) in relation to an international standard (Hoefs 2009:28). Carbon’s standard (Vienna Pee Dee Belemnit, or VPDB) is naturally 13C-enriched and causes most sample δ13C values to be expressed as negative values (Hoefs 2009).

Bioavailable carbon can come from atmospheric CO2 and dissolved inorganic carbon, and the analysis of δ13C 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 C3 photosynthetic pathway and are referred to as C3 plants. The C3 photosynthetic pathway discriminates against 13C, giving C3 plants a 13C-depleted carbon isotope ratio (δ13C between -30‰ and -25‰) (DeNiro and Schoeninger 1983) (fig. 1). Wild grasses and a few cultivars (e.g. maize) use the C4 photosynthetic pathway and are referred to as C4 plants. The C4 photosynthetic pathway does not heavily discriminate against 13C compared to C3 plants, giving C4 plants a comparably 13C-enriched carbon isotope ratio (δ13C 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 N2, 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 15N and 14N, and the ratio (15N/14N) is most frequently used to illustrate differences in predator-prey relations as they relate to available nitrogen resources (DeNiro and Epstein 1981). Predators are 15N-enriched when they consume prey (δ15N 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
food chain, so consumers of aquatic resources will illustrate subsequently higher $\delta^{15}N$ 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 $\delta^{13}C$ and $\delta^{15}N$ 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 $\delta^{15}N$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ and $\delta^{15}N$ 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.

Figure 1. Trophic level representation illustrating relative $\delta^{13}C$ and $\delta^{15}N$ for different plants and animals (from Schwarcz and Schoeninger 2011:732)
**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                                                                                                                                 |
|---------------------------|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Marine Protein            | Increase$^2$ Increase Variable$^3$ | Craig *et al.* 2006; Nehlich *et al.* 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 *et al.* (2009); Richards, Fuller, and Molleson 2006 |
| Fungi                     | Increase Decrease N/T          | Millard *et al.* 2011                                                                                                                                 |
| Maize, Kiwicha            | Increase - N/T                 | Cadwallader *et al.* 2012; Krueger and Sullivan 1984; Schwarcz and Schoeninger 2011                                                                                                                                 |
| Shallow Water Organisms   | Decrease Increase Decrease     | Craig *et al.* 2006; Miller, Capriles, and Hastorf 2010; Nehlich *et al.* 2011                                                                 |
| Salt Marsh Grazing        | - Increase Increase            | Britton *et al.* 2008; Madgwick *et al.* 2013; Weinstein *et al.* 2000                                                                 |
| Freshwater Protein        | - Increase Variable            | Craig *et al.* 2006; Katzenberg 1989; Linderholm and Kjellström 2011; Nehlich *et al.* 2011                                                                 |
| Terrestrial Protein       | - Increase -                  | Katzenberg 1989; Nehlich *et al.* 2011; Richards *et al.* 2003; Schwarcz 2000                                                                 |
| Manured Cultigens         | - Increase Variable            | Bogaard *et al.* 2007; Mizota and Sasaki (1996)                                                                                                                                 |
| Legumes$^4$               | - Decrease N/T                 | DeNiro and Epstein 1981                                                                                                                                 |
| Sea-Sprayed Cultigens     | - - Increase                  | Horn *et al.* 2009; Richards, Fuller, and Hedges 2001; Richards *et al.* 2003                                                                 |
| Geographic Change         | - - Variable                  | Craig *et al.* 2006; Nehlich *et al.* 2011; Richards, Fuller, and Hedges 2001, 2003; Wilson *et al.* 2007                                                                 |

1 Isotopically ‘normal’ here refers to a small-bodied herbivore that consumes C$_3$ 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
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 $^{13}$C enrichment in Peru. According to Cadwallader et al. (2013), multiple plant sources can elevate $\delta^{13}$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 mococha 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 $\text{SO}_2$, 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...
occurring sulphur isotopes are $^{34}\text{S}$ and $^{32}\text{S}$, 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 (~12‰ and ~6‰, 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 ~21‰, whereas freshwater sulphur ranges from $\delta^{34}\text{S}$ -22‰ to +22‰, 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‰ to +21‰) has also been documented in other studies (Nehlich, Barrett, and Richards 2013; Thode, Monster, and Dunford1961).
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 $\delta^{15}N$ and $\delta^{34}S$, whereas growing conditions and plant type will influence $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ 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 $\delta^{13}C$ and $\delta^{34}S$ 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±1.3‰ and +8.4±1.6‰, respectively, indicated direct seaweed consumption (Richards, Fuller, and Molleson 2006). Alternatively, sheep/goats with...
measured isotope values consistent with increased average nitrogen values (+7.0±0.9‰), which did not demonstrate significantly increased carbon values (-21.8±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 δ¹³C 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 δ¹⁵N values, ¹³C enrichment, and δ³⁴S values consistent with marine source consumption. Salt marsh grazers would have isotopic values that are different from those due to manuring because of increased δ³⁴S 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 ³⁴S- and ¹³C-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, $\delta^{34}$S values were roughly -20‰ to -17‰ and $\delta^{13}$C was approximately -30‰ (Craig et al. 2006; Nehlich et al. 2011). Isotope signatures of $\delta^{34}$S and $\delta^{13}$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
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 $\delta^{34}$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 $\delta^{34}$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 $^{34}\text{S}$ when oxidized ($\delta^{34}\text{S} \sim -16\%$). 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%) (illustrated in red, fig. 6).

Volcanic lakes or other bodies of water within the Andes Mountains will likely be $^{34}\text{S}$-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% 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% (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 $^{34}\text{S}$-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 $^{34}\text{S}$ 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% to +15%, 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 cameldid, other fauna: collagen ($\delta^{13}C$, $\delta^{15}N$) and carbonate ($\delta^{13}C$) | (1) Maize as staple crop; (2) two distinct cameldid management strategies         | Elevated mice $\delta^{13}C$ likely due to seaweed; raises questions about human $\delta^{13}C$ values | Analyze contribution of marine sources: $\delta^{34}S$ elevated from baseline values (+20‰) |
| Wilson et al. (2007)          | Volcán Sara Sara (1430-1530 CE)  | 1 Human: hair keratin ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$)       | (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 $\delta^{34}S$.                         |
| Horn et al. (2009)            | Monte Grande, Pueblo Viejo, Paracas and Los Molinos (500 BCE-1000 CE) | Multiple mummies and cameldid wool: hair keratin ($\delta^{13}C$, $\delta^{15}N$, $\delta^{34}S$) | (1) Sites had different access to marine resources; (2) evidence of mococho being fed to cameldids | Overall trends analyzed; no account for seasonality or migration.                  | Analyze (monthly) segments of hair $\delta^{34}S$.                                |

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

Finucane, Agurto, and Isbell (2006) examined archaeological remains from Conchopato 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 palearctic diet. This was accomplished by examining the mean difference of $\delta^{13}C$ 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 $\delta^{34}$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 $\delta^{34}$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 $\delta^{34}$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
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 $^{13}\text{C}$ 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 $^{34}\text{S}$ however the Peruvian mummy illustrated a 5.2‰ decrease in $^{34}\text{S}$ roughly 12 months prior to death (fig. 7e). This $^{34}\text{S}$ depletion

---

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

has been attributed to a change in subsistence niche for Sarita while travelling to Cusco (Wilson et al. 2007). Marked decreases in δ\(^{34}\)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 \(\delta^{34}\)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 \(\delta^{15}\)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 \(\delta^{13}\)C, \(\delta^{15}\)N, and \(\delta^{34}\)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 $\delta^{15}N$ vs. $\delta^{34}S$ 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 $\delta^{34}S$ range of +2‰ to +3‰ (anticipated -10‰ to +10‰). Los Molinos A and C are located roughly 90 km from the Pacific Ocean and 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 $\delta^{34}S$ 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 $\delta^{34}S$ 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 (1994:172) 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 $^{34}$S-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 $\delta^{34}$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.

Acknowledgements

This project stems from my MA Research (Bishop 2013) and was refined during my Doctoral coursework. Considerable thanks go to both of my supervisors, Tracy Prowse and Sandra Garvie-Lok, respectively. Many colleagues at Western University are referenced here with earnest thanks. Gratitude is also given to four anonymous reviewers, and colleagues Victoria and Christina, who were always available to provide insight on previous drafts.

References Cited

Ambrose, S.H., and L. Norr. 1993. Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In, Prehistoric Human Bone. Springer: Berlin, Germany, pp.1-37.

Beresford-Jones, D.G., S.T. Arce, O. Q. Whaley, and A.J. Chepstow-Lusty. 2009. The role of Prosopis in ecological and landscape change in the Samaca Basin, lower Ica Valley, south coast Peru from the early horizon to the late intermediate period. Latin American Antiquity 20(2):303-332.

Bishop, K.G. 2013. Meat, bones, and isotopes: Faunal remains in Roman subsistence analysis. (Unpublished MA Thesis). McMaster University, Hamilton, Ontario.

Bocherens, H., D.G. Drucker, and H. TaPoublard. 2011. Preservation of bone collagen sulphur isotopic compositions in an early Holocene river-bank archaeological site. Palaeogeography, Palaeoclimatology, and Palaeoecology 310:32-38.

Bogaard, A., H.E. Heaton, P. Poulton, and I. Merbach. 2007. The impact of manuring on nitrogen isotope ratios in cereals: Archaeological implications for reconstruction of diet and crop management practices. Journal of Archaeological Science 34:335-343.

Böttcher, M.E. 2001. Sulfur isotope fractionation in the biogeochemical sulfur cycle of marine sediments. Isotopic Environmental Health Studies 37:97-99.

Bottrell, S.H., and R. Raiswell. 2000. Sulphur isotopes and microbial sulphur cycling in sediments. In, Microbial Sediments. Riding, R.E., and S.M. Awramik, Eds. Springer-Verlag Berlin Heidelberg Publishing, Berlin, Germany, pp. 96-104.

Bray, T.L. 2003. Inka pottery as culinary equipment: Food, feasting, and gender in Imperial state design. Latin American Antiquity 14(1):3-28.

Burger, R.L., and N.J. van der Merwe. 1990. Maize and the origin of highland Chavin Civilization: an isotopic perspective. American Anthropologist 92(1):85-95.

Cadwallader, L., D.G. Beresford-Jones, O.Q. Whaley, and T.C. O’Connel. 2012. The signs of maize? A reconsideration of what $^{13}$C values say about paleodiet in the Andean region. Human Ecology 40:487-509.

Christenson, B., and F. Tassi. 2015. Gases in volcanic lake environments. In, Volcanic Lakes, Rouvet, D., B. Christenson, F. Tassi, and J. Vandemeulebrouck, Eds. Springer Heidelberg, New York, New York, pp. 125-154.

Craig, O.E., B. Ross, S.H. Andersen, N. Milner, and G.N. Bailey. 2006. Focus: Sulphur isotope variation in archaeological marine fauna from northern Europe. Journal of Archaeological Science 33:1642-1646.

DeNiro, M.J., and S. Epstein. 1981. Influence of diet on the distribution of nitrogen isotopes in animals. Geochimica et Cosmochimica Acta, 45:341-351.

DeNiro, M.J., and M.J. Schoeninger. 1983. Stable carbon and nitrogen isotope ratios of bone collagen: Variations within individuals, between sexes, and within populations raised on monotonous diets. Journal of Archaeological Science 10:199-203.

Downey, J. (2015). Statecraft in the Virú Valley, Peru in the First Millenium A.D. (Unpublished PhD Dissertation). Western University, London, Ontario.
Duncan, N.A., D.M. Pearsall, and R.A. Benfer, Jr. 2009. 
Gourd and squash artifacts yield starch grains of 
feasting foods from preceramic Peru. *Proceedings of the 
National Academy of Science* 106(32):13202-13206.

Fernández, J., H.O. Panarelo, and J. Schobinger. 1999. The 
Inka mummy from Mount Aconcagua: Decoding the 
geographic origin of the “messenger to the deities” by 
means of stable carbon, nitrogen, and sulfur isotope 
analysis. *Geoarchaeology* 14:27-46.

Finucane, B., P.M. Agurto, and W.H. Isbell. 2006. Human 
and animal diet at Conchopata, Peru: Stable isotope 
evidence for maize agriculture and animal management 
practices during the middle horizon. *Journal of 
Archaeological Science* 33:1766-1776.

Fornander, E., G. Eriksson, and K. Lidén. 2008. Wild at 
heart: Approaching pitted ware identity, economy and 
cosmology through stable isotopes in skeletal material 
from the Neolithic site Korsnäs in Eastern Central 
Sweden. *Journal of Anthropology and Archaeology* 
27:281-297.

Froehle, A.W., C.M. Kellner, and M.J. Schoeninger. 2010. 
FOCUS: Effect of diet and protein source on carbon 
stable isotope ratios in collagen: Follow up to Warinner 
and Tuross (2009). *Journal of Archaeological Science* 
37:2662-2670.

Goldstein, P.S. 2003. From stew-eaters to maize-drinkers: 
The chicha economy and the Tiwanaku expansion. In, 
*The Archaeology and Politics of Food and Feasting in 
Early States and Empires*, Bray, T. L. Ed. Kluwer 
Academic/Plenum Publishers, New York, pp. 143–172.

Hastorf, C.A., and S. Johannessen. 1993. Pre-Hispanic 
political change and the role of maize in the central 
Andes of Peru. *American Anthropologist* 95(1):115-138.

Heaton, T.H.E. 1999. Spatial, species, and temporal 
variations in the $^{13}$C/$^{12}$C ratios of C$_3$ plants: Implications 
for palaeodiet studies. *Journal of Archaeological Science* 
26:637-649.

Hoefs, J. 2009. *Stable Isotope Geochemistry*, 6th ed. 
Springer: Berlin, Germany.

Hollingsworth, E.R. 2006. *Elemental and isotopic 
chemistry of the Uzon Caldera: The evolution of 
thermal waters, gas, and mineral precipitation.* 
(Unpublished MA Thesis). The University of the South, 
Athens, Georgia.

Horn, P., S. Hölzl, S. Rummel, G. Åberg, S. Schiegl, D. 
Biermann, U. Struck, and A. Rossmann. 2009. Humans 
and camelids in river oases of the Ica-Palpa-Nazca 
region in pre-Hispanic times: Insights from H-C-N-O-S-
Sr isotope signatures. In, *New Technologies for 
Archaeology: Multidisciplinary Investigations in Palpa 
and Nasca, Peru*, Reindel, M., and Wagner, G. A. Eds. 
Natural Science in Archaeology. Springer, Berlin, pp. 
173–192.

Izeta, A.D., A.G. Laguens, M.B. Marconetto, and M.C. 
Scattolin. 2009. Camelid handling in the meridional 
Andes during the first millennium AD: A preliminary 
approach using stable isotopes. *International Journal of 
Osteoarchaeology* 19:204-214.

Kellner, C.M., and M.J. Schoeninger. 2008. Wari’s 
Imperial influence on local Nasca diet: The stable 
isotope evidence. *Journal of Anthropological 
Archaeology* 27:226-243.

Knudson, K.J., A.E. Aufderheide, and J.E. Buikstra. 2007. 
Seasonality and paleodiet in the Chiribaya polity of 
southern Peru. *Journal of Archaeological Science* 
34:451-462.

Konhauser, K.O., W.S. Fyfe, and B.I. Kronberg. 1994. 
Multi-element chemistry of some Amazonian waters 
and soils. *Chemical Geology* 111:155-175.

Krouse, H.R., and T.B. Coplen. 1997. Reporting of relative 
sulfur isotope-ratio data. *Pure and Applied Chemistry* 
69(2):293-295.

Krueger, H.W., and C.H. Sullivan 1984. Models for carbon 
isotope fractionation between diet and bone. *Stable Isotopes in Nutrition* 258:205-220.

Lambert, P.M., C.M. Gagnon, B.R. Billman, M.A. 
Katzenberg, J. Carcelén, and R.H. Tykot. 2012. Bone 
chemistry at Cerro Oreal: A stable isotope perspective 
on the development of a regional economy in the Moche 
Valley, Peru during the early intermediate period. *Latin American Antiquity* 23(2):144-166.

Leach, F, C. Quinn, J. Morrison, and G. Lyon. 2001. The 
use of multiple isotope signatures in reconstructing 
prehistoric human diet form archaeological bone from 
the Pacific and New Zealand. *New Zealand Journal of 
Archaeology* 23:31-98.

Lee-Thorp, J.L., and P.B. Beaumont. (1995). Vegetation 
and seasonality shifts during the late quaternary 
deduced from $^{13}$C/$^{12}$C ratios of grazers at Equus Cave, 
South Africa. *Quaternary Research* 43(3):426-432.

Lee-Thorp, J.L., and N.J. van der Merwe. 1987. Carbon 
isotope analysis of fossil bone apatite. *South African 
Journal of Science* 83(11):712-715.

Leonard, C., Vashro, L., J.F. O’Connell, and A.G. Henry. 
2015. Plant microremains in dental calculus as a record 
of plant consumption: A test with Twa forager-
horticulturalists. *Journal of Archaeological Science: 
Reports* 2:449-457.

Macko, S.A., M.H. Engel, V. Andrusевич, G. Lubec, T.C. 
O’Connell, and R.E.M. Hedges. 1999. Documenting the 
diet in ancient human populations through stable isotope 
analysis of hair. *Philosophical Transactions of the 
Royal Society B: Biological Sciences* 354(1379):65-76.

Madgwick, R., N. Sykes, H. Miller, R. Symmons, J. Morris, 
and A. Lamb. 2013. Fallow deer (*Dama dama dama*) 
management in Roman South-East Britain. *Archaeological and Anthropological Sciences* 5(2):111-122.

Masur, L.J. 2012. *Peanuts and prestige on the Peruvian 
north coast: The archaeology of peanuts at Huaca 
Galñinazo (V-59) and Huaca Santa Clara (V-67).* 
(Unpublished MA Thesis). The University of British 
Columbia, Vancouver, British Columbia.
Millaire, J.-F., and E. Eastaugh. 2014. Geophysical survey on the coast of Peru: The early prehispanic city of Gallinazo Group in the Virú Valley. *Latin American Antiquity* 25(3):239-255.

Miller, G.R., and R.L. Burger. 1995. Our father the Cayman, our dinner the Llama: Animal utilization at Chavín de Huántar, Peru. *American Antiquity* 60(3):421-458.

Miller, M.J., J.M. Capriles, and C.A. Hastorf. 2010. The fish of Lake Titicaca: Implications for archaeology and changing ecology through stable isotope analysis. *Journal of Archaeological Science* 37:317-327.

Mizota, C., and A. Sasaki. 1996. Sulfur isotope composition of soils and fertilizers: Differences between Northern and Southern hemispheres. *Geoderma* 71:77-93.

Moseley, M.E. 1975. *The Maritime Foundations of Andean Civilizations*. Cummings Publishing Company, Inc., Menlo Park.

Mossmann, J.-R., A.C. Aplin, C.D. Curtis, and M.L. Coleman. 1991. Geochemistry or inorganic and organic sulphur in organic-rich sediments from the Peru Margin. *Geochimica et Cosmochimica Acta* 55(12):3581-3595.

Nehlich, O. 2015. The application of sulphur isotope analyses in archaeological research: A review. *Earth-Science Reviews* 142:1-17.

Nehlich, O., and M.P. Richards. 2009. Establishing collagen quality criteria for sulfur isotope analysis of archaeological bone collagen. *Archaeological and Anthropological Science* 1:59-75.

Nehlich, O., D. Boric, S. Stefanovic, and M.P. Richards. 2010. Sulfur isotope evidence for freshwater fish consumption: A case study from the Danube Gorges, SE Europe. *Journal of Archaeological Science* 37:1131-1139.

Nehlich, O., B.T. Fuller, M. Jay, A. Mora, R.A. Nicholson, C.I. Smith, and M.P. Richards. 2011. Application of sulphur isotope ratios to examine weaning patterns and freshwater fish consumption in Roman Oxfordshire, UK. *Geochimica et Cosmochimica Acta* 75:4963-4977.

Nehlich, O., J.H. Barrett, and M.P. Richards. 2013. Spatial variability in sulfur isotope values of archaeological and modern cod (*Gadus morhua*). *Rapid Communication in Mass Spectrometry* 27:2255-2262.

Nehlich, O., V. Oelze, M. Jay, M. Conrad, H. Stäuble, W. Teegan, and M.P. Richards. 2014. Sulphur isotope ratios of multi-period archaeological skeletal remains from central Germany: A dietary and mobility study. *Anthropologie (BRNO)*, LII:15-33.

Pipeño, D.R., and T.D. Dillehay. 2008. Starch grains on human teeth reveal early broad crop diet in northern Peru. *Proceedings of the National Academy of Science* 105(50):19622-19627.

Privat, K.L., T.C. O’Connell, and R.E.M. Hedges. 2007. The distinction between freshwater- and terrestrial-based diets: Methodological concerns and archaeological applications of sulphur stable isotope analysis. *Journal of Archaeological Science* 34:1197-1204.

Raifer, T.A., I.R. Kaplan, and J.R. Hulston. 1960. Sulphur isotopic measurements on sulphur and sulphates in New Zealand geothermal and volcanic areas. *New Zealand Journal of Science* 1: 103-126.

Richards, M.P., B.T. Fuller, and R.E.M. Hedges. 2001. Sulphur isotopic variation in ancient bone collagen from Europe: implications for human palaeodiet, residence mobility, and modern pollutant studies. *Earth and Planetary Science Letters* 191:185-190.

Richards, M.P., B.T. Fuller, M. Sponheimer, T. Robinson, and L. Ayliffe. 2003. Sulphur isotopes in palaeodietary studies: A review and results from a controlled feeding experiment. *International Journal of Osteoarchaeology* 13:37-45.

Richards, M.P., B.T. Fuller, and T.I. Molleson. 2006. Stable isotope palaeodietary study of humans and fauna from the multi-period (Iron Age, Viking and Late Medieval site of Newark Bay, Orkney). *Journal of Archaeological Science* 33:122-131.

Richards, M.P., P.B. Pettitt, M.C. Stiner, and E. Trinkaus. 2001. Stable isotope evidence for increasing dietary breadth in the European mid-Upper Paleolithic. *Proceedings of the National Academy of Science* 98:6528-6532.

Sakai, H. 1997. Fractionation of sulphur isotopes in nature. *Geochimica et Cosmochimica Acta*, 12:150-169.

Sakai, H., and O. Matsubaya. 1977. Stable isotopic studies of Japanese geothermal systems. *Geothermics* 5:97-124.

Salque, M., G. Radi, A. Tagliacozzo, B. Pino Úria, S. Wolfram, I. Hohle, H. Stäuble, A. Whittle, D. Hofmann, J. Pechtl, S. Schade-Lindig, U. Eisenauer, and R.P. Evershed. 2012. New insights into the Early Neolithic economy and management of animals in Southern and Central Europe revealed using lipid residue analyses of pottery vessels. *Anthropozooologica*, 47(2):45-62.

Sayle, K.L., G.T. Cook, P.L. Ascough, H.R. Hastie, A. Einarssson, T.H. McGovern, M.T. Hicks, A. Edwald, and A. Fridriksson. 2013. Application of 34S analysis for elucidating terrestrial, marine and freshwater ecosystems: Evidence of animal movement/husbandry practices in an early Viking community around Lake Myvatn, Iceland. *Geochimica et Cosmochimica Acta* 120: 531–544.

Schoeninger M.J., M.J. DeNiro, and H. Tauber. 1983. Stable nitrogen ratios of bone collagen reflect marine and terrestrial components of prehistoric human diet. *Science* 220(4604):1381-1383.

Schwarz, H.P. 2000. Some biochemical aspects of carbon isotopic paleodiet studies. In, *Biogeochemical Approaches to Paleodietary Analysis*, Ambrose, A., and Katzenberg, A. Eds. Kluwer Academic/Plenum Publishers: New York, pp. 189-210.

Schwarz, H.P., and M.J. Schoeninger. 2011. Stable isotopes of carbon and nitrogen as tracers for paleodiet reconstruction. *Handbook of Environmental Isotope Geochemistry*, Advances in Isotope Geochemistry, Part 5, pp. 725-742, DOI: 10.1007/978-3-642-10637-8_34.
Shearer, C.K., G.D. Layne, JJ. Papike, and M.N. Spilde. 1996. Sulfur isotopic systematics in alteration assemblages in martian meteorites Allan Hills 84001. Geochimica et Cosmochimica Acta 60(15):2921-2926.

Somerville, A.D., P.S. Goldstein, S.I. Baitzel, K.L. Bruwelheide, A.C. Dahlstedt, L. Yzurdiaga, S. Raubenheimer, K.J. Knudson, and M.J. Schoeninger. 2015. Diet and gender in the Tiwanaku Colonies: Stable isotope analysis of human bone collagen and apatite from Moquegua, Peru. American Journal of Physical Anthropology 158(3):408-422.

Szpak, P., J-F. Millaire, C.D. White, G.F. Lau, F. Surette, and F.J. Longstaffe. 2015. Origins of Prehispanic camelid wool textiles from the north and central coasts of Peru traced by carbon and nitrogen isotopic signatures. Current Anthropology 56(3):449-459.

Stewart, N. 2015. Andes Mountains. In, Encyclopaedia Britannica. Retrieved from http://www.britannica.com/place/Andes-Mountains.

Thode, H.G., J. Monster, and H.B. Dunford. 1961. Sulphur isotope geochemistry. Geochimica et Cosmochimica Acta 25:159-174.

Tomczak, P.D. 2003. Prehistoric diet and socioeconomic relationships within the Osmore Valley of Southern Peru. Journal of Anthropological Archaeology 22(3):262-278.

Trust, B.A., and B. Fry. 1992. Stable sulphur isotopes in plants: A review. Plant, Cell and Environment 15:1105-1110.

Turner, B.L., J.D. Kingston, and G.J. Armelagos. 2010. Variation in dietary histories among the immigrants of Machu Picchu: Carbon and nitrogen isotope evidence. Chumgara, Revista de Antropología 42(2):515-534.

Ugan, A., and J. Coltrain. 2011. Variation in collagen stable nitrogen values in black-tailed jackrabbits (Lepus californicus) in relation to small-scale difference in climate, soil, and topography. Journal of Archaeological Science 38:1417-1429.

van Klinken, G.J., Richards, M.P., and R.E.M. Hedges. 2000. An overview of causes for stable isotopic variations in past European human populations: Environmental, ecophysiological, and cultural effects. In, Biogeochemical Approaches to Paleodietary Analysis, Ambrose, A., and Katzenberg, A. Eds. Kluwer Academic/Plenum Publishers: New York, pp. 39-63.

Venet-Rogers, C. 2013. A study of faunal consumption at the Gallinazo Group Site, northern coast of Peru. (Unpublished MA Thesis). Western University, Ontario, London, Ontario.

Vika, E. 2009. Strangers in the grave? Investigating local provenance in a Greek Bronze Age mass burial using δ34S analysis. Journal of Archaeological Science 36:2024-2028.

Webb, E., C. White, and F. Longstaffe. 2013. Dietary shifting in the Nasca Region as inferred from carbon- and nitrogen-isotope compositions of archaeological hair and bone. Journal of Archaeological Science 40(1):129-139.

White, C.D., A.J. Nelson, F.J. Longstaffe, G. Grupe, and A. Jung. 2009. Landscape bioarchaeology at Pacatnamu, Peru: Inferring mobility from δ13C and δ15N values of hair. Journal of Archaeological Science 36(7):1527-1537.

Williams, J.S., and M.A. Katzenberg. 2012. Seasonal fluctuations in diet and death during the late horizon: A stable isotopic analysis of hair and nail from the central coast of Peru. Journal of Archaeological Science 39:41-57.

Wilson, A.S., T. Taylor, M.C. Ceruti, J.A. Chavez, J. Reinhard, V. Grimes, W. Meier-Augenstein, L. Cartmell, B. Stern, M.P. Richards, M. Worobey, I. Barnes, and M.T.P. Gilbert. 2007. Stable isotope and DNA evidence for ritual sequences in Inca child sacrifice. Proceedings of the National Academy of Science 104:16456-16461.

Zarrillo, S., D.M. Pearsall, J.S. Raymond, M.A. Tisdale, and D.J. Quon. 2008. Directly dated starch residues document early formative maize (Zea mays L.) in tropical Ecuador. Proceedings of the National Academy of Science 105(13):5006-5011.