# STABLE ISOTOPES AND MULTIPLE TISSUE ANALYSIS: RECONSTRUCTING LIFE HISTORIES FOR INDIVIDUALS FROM THE DAKHLEH OASIS, EGYPT

by

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# ABSTRACT

Stable isotope analysis is often used to evaluate elements of the lives of past peoples, such as diet and health status, at a societal level. Analysis at an individual level is exceptionally rare, and has not been conducted using a variety of tissues representing both early life and life approximate to death. In this study, $\delta^{13}C$ and $\delta^{15}N$ isotope signatures are used to create life histories for single individuals from Romano-Christian period Kellis 2 cemetery in the Dakhleh Oasis, Egypt. Samples are obtained from several different tissues, including tooth dentin, bone collagen, hair, nail, skin, and gut content, all of which have been previously researched, but have not been studied at such an individualistic level. By using data and previous research conducted by Drs. Tosha Dupras and Lana Williams, this research uses isotopic values from the aforementioned tissues, and the differing turnover rates of these tissues, to develop lifetime timetables for 15 individuals (female, male, and juvenile). Results show that individual analysis is possible, informative, and can enlighten researchers not just concerning the individual, but about the population as a whole. The methods presented can serve as a model for reconstructing individual life histories using isotope data from multiple tissues.

“The drops of rain make a hole in the stone not

by violence but by oft falling.”

Lucretius

Dedicated to Jeremy and Isaac, with love.

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# CHAPTER 1: INTRODUCTION

Stable isotope analysis has been used by bioarchaeologists for over three decades to help determine the diet of historic and prehistoric peoples. The analysis of carbon and nitrogen stable isotopes in particular has allowed for the reconstruction of ancient diets. Traditionally, samples come from bone tissue and enlighten researchers as to what a population was eating over time. The first study involving the analysis of stable isotopes and human diet was conducted by Vogel and van der Merwe (1977), who used carbon stable isotopes from bone to demonstrate that those consuming a diet consisting of a large portion of corn (a $C_4$ plant) had consistently higher $\delta^{13}C$ values than those consuming predominately $C_3$ plants. This study was a breakthrough, allowing researchers to determine what was being consumed rather than relying on conjectural floral, faunal, and artifactual evidence alone. Since that time, stable isotopes have become a routine part of archaeological studies, used to analyze a multitude of aspects of past people's lives.

By the early nineties, tissues other than bone had begun to be incorporated into standard stable isotope research from archaeological contexts. The first isotopic research regarding another human tissue was by Nakamura et al. (1982), which demonstrated that dietary changes directly affect $\delta^{13}C$ values in hair. Tieszen et al. (1983) conducted a similar study on animals comparing several tissues (hair, fat, muscle, liver, and fat) and also found that changes in diet do affect $\delta^{13}C$ values, although with different fractionation and turnover rates. The analysis of

tissues with fast turnover rates, such as hair, makes them useful indicators of short-term diet and dietary changes. This makes it possible for researchers to analyze not only what one was eating over a lifetime, but also just prior to death. Other tissues with fast turnover rates that have now been shown to produce reliable isotopic data include nail and skin (O'Connell and Hedges, 1999; Samman, 1995; White et al., 1999).

The focus of isotope research within bioarchaeology has also evolved from being concerned only with diet, to assessing an array of issues: from migration, to health status, to season of death. Interpretation and reconstruction of diet remains to be at the forefront of stable isotope studies in archaeology; however, expanding research on how isotopic composition is affected by other aspects of human biological processes is growing significantly. Health status and season of death will be focused on throughout this study, although the scope does not include stable oxygen isotopes or migration studies. Nitrogen isotopes in particular are useful for identifying or corroborating pregnancy and metabolic diseases, whereas carbon stable isotopes help identify changes in diet and seasonality of death.

While many different tissues have now been incorporated into stable isotopic studies, most focus solely on the total population of people being studied, giving broad statistics and analyses (e.g. O'Connell and Hedges, 1999; O'Connell et al., 2001). These studies do not elaborate on individuals within the population. In fact, only a handful of studies are published concerning life histories, such as Sealy et al. (1995), Sealy and Cox (1997) and Knudson et al. (2010), and the first two do not include multiple short-term tissues. Knudson et al. (2010) present

the first study to use multiple short term and long term values and to look at isotopes at an individual level in an archeological population. In this study, analysis is centered at the individual level by creating life histories based on the analysis of both long term and short term stable isotope values that cover the individual's life span. The research objectives of this thesis include: (1) attempting to create meaningful isotopic individual life histories for males, females, and juveniles of various ages; (2) developing a comprehensible model for displaying and analyzing stable isotope data from multiple long and short term tissues; and (3) recognizing and interpreting any trends noted in the isotopic histories.

The stable isotope data used in this thesis was generated from skeletal material excavated from the unique environment of the Dakhleh Oasis, Egypt. Located in central Egypt, within the Western Desert (see Figure 1), the Dakhleh Oasis is extremely arid with very little rainfall. These conditions allow for exceptional preservation of tissues, rarely found elsewhere in the world. Naturally mummified human remains, as well as botanical and faunal, are plentiful at the numerous sites located with the Oasis. This rare availability of various mummified tissues makes analyzing both multiple long term and short term tissues possible.

Figure 1: Map showing the location of the Dakhleh Oasis within Egypt

The structure of this thesis is of a traditional nature. The second chapter reviews the previous literature that has been published concerning carbon and nitrogen stable isotopes, as well as the different tissues that will be used to create life histories. The primary goal is to provide a thorough scientific background that will be used in forming the life histories. A basic explanation of stable isotopes is followed by more detailed descriptions of how carbon and nitrogen stable isotopes can be used in archaeological studies and the advantages and limitations of each. All of the tissues that will be included in this study are also detailed, including their turnover rates, fractionation values and any other information relevant to the histories.

Chapter 3 details the material and methods that were used in creating life histories. This begins in a broad fashion, giving a background and history of the Dakhleh Oasis and Dakhleh

Oasis Project, and narrows, first describing Kellis and the Kellis 2 cemetery and then the specific samples collected by Drs. Dupras and Williams that are the used in this study. The methods are explained next, including sample preparation, and the methods used to create the life histories. The latter consists of different statistical analyses, such as population and gender specific comparisons, and the specific methods used to create timetables, such as turnover rates, and the development of interpretations pertaining to life histories.

The results are detailed in Chapter 4. This chapter includes a presentation of the 15 life histories produced. The individuals analyzed are described in detail using a narrative format, beginning with a description of the location of the burial, biological profile (sex and age at death), and any noted pathological conditions. Following this initial description, long-term history will be discussed that includes the data from the teeth and bone collagen. Following a long-term analysis, a short-term analysis will ensue, presenting data from the hair, skin, nails, and gut content.

Chapters 5 and 6 are the discussion and conclusion sections, respectively. The discussion relates the work completed in this study to previous published studies, compares the methods for analyzing and displaying data, and notes and explains trends found in the results section. The conclusion reiterates the findings, the usefulness of the study, and makes suggestions for future studies.

# CHAPTER 2: REVIEW OF CARBON AND NITROGEN STABLE ISOTOPE AND MULTIPLE TISSUE ANALYSIS

## Introduction

Every atom on earth is composed of a nucleus, electrons, protons, and neutrons. The protons and neutrons are located within the nucleus, while the electrons are located outside of the nucleus on the perimeter. Any two atoms with an identical number of protons in their nuclei belong to the same chemical element. Atoms with equal numbers of protons, but a different number of neutrons, are different isotopes of the same element. Isotopes of an element, therefore, have different atomic mass numbers, which is the total mass of protons, neutrons and electrons in a single atom (Katzenberg, 2000).

Isotopes can be either radioactive or stable in nature. Radioactive isotopes, such as $^{14}C$ used for radiocarbon dating, decay at constant rate. Stable isotopes, on the other hand, have not been observed to decay over time. For example, in a deceased animal the amount of $^{14}C$ will decrease constantly (e.g., half-life), while the amount of $^{13}C$ (a stable isotope) will remain constant. Eighty elements are known to have at least one stable isotope and about two thirds of these elements have more than one stable isotope (Katzenberg, 2000).

Because isotopes of the same element have the same chemical composition, they behave in almost identical ways. The notable difference between stable isotopes is that mass differences, due to a variance in the number of neutrons, result in partial separation of the light isotopes from

the heavy isotopes during chemical reactions, otherwise known as fractionation. Isotopes with higher masses generally react slightly more slowly than lighter isotopes (Katzenberg, 2000). Fractionation, therefore, results in differing ratios of heavy and light isotopes, which is measurable by an isotope ratio mass spectrometer (Schoeninger, 1995).

Elements are analyzed with an isotope ratio mass spectrometer (IRMS) and are then measured against a universal standard, with a ratio established against that standard. The standard for nitrogen is atmospheric $N_2$ (AIR) and the standard for carbon is PeeDee belemnite (PDB). All ratios are expressed in terms of 'δ', or delta values, and in parts per mil (‰) and expressed with the notation seen in Equation 1:

$$\delta \text{ in } ‰ = \frac{\mathrm{R(sample)} - \mathrm{R(standard)}}{\mathrm{R\ (standard)}} \times 1000 \tag{1}$$

$\delta^{13}C$ values from biological samples are negative because the samples are less enriched than the PDB standard, while nitrogen samples are generally positive because samples are more enriched in $^{15}N$ than $N_2$ (Schoeninger, 1995). Both carbon and nitrogen stable isotopes and their applications will be discussed in more detail below.

## Carbon

Carbon is the most well studied and documented element with isotopes, due to the fractionation that occurs during photosynthesis in terrestrial plants (Gannes et al., 1998). Carbon has 16 documented isotopes, with $^{12}C$ and $^{13}C$ being stable, and of these $^{13}C$ is the heaviest stable isotope. When plants convert $CO_2$ into glucose, the amounts of $^{12}C$ and $^{13}C$ differ depending on which pathway they take. They can follow one of three pathways: $C_3$ (Calvin-Benson) cycle, $C_4$ (Hatch-Slack) pathway, or CAM models. Plants that follow the $C_3$ cycle fix $CO_2$ from the air via the enzyme Rubisco, which is turned into a three-carbon molecule. These plants are greatly depleted of the heavy $^{13}C$ isotope relative to the carbon standard of $CO_2$ and their $\delta^{13}C$ values range from -33‰ to -22‰ (Katzenberg, 2000). Approximately 85% of plant species are $C_3$ plants and include species such as wheat, rice, rye, beans, tubers, nuts, barley, oats, nuts, and most trees and shrubs, fruits and vegetables, and wetland grasses (O'Leary, 1995).

Plants that follow the $C_4$ pathway use the enzyme phospheonol pyruvate carbozylase to fix the $CO_2$ and have less fractionation of atmospheric carbon, thus are enriched in $^{13}C$ relative to $C_3$ plants. Their $\delta^{13}C$ values range from -16‰ to -9‰, about 5.5‰ more enriched than $C_3$ plants, and major crops that use this pathway include sorghum, millet, maize and sugar cane (O'Leary, 1995). Lastly, the CAM pathway can use either enzyme depending on the environment. CAM plants include cacti, agave, yucca, pineapple, and prickly pear (O'Leary, 1995). These values can tell us numerous things about the diet, including the ratio of $C_3$ to $C_4$ plants eaten and the diet of the herbivores that are being consumed (Schwarcz et al., 1985).

As the isotopic composition of plants is passed on to consumers, the isotopic composition of the whole body of an animal reflects the isotopic composition of its diet. The animal, however, is on average enriched in $\delta^{13}C$ relative to the diet. The relationship between the $^{13}C/^{12}C$ ratio of a tissue and diet depends on the type of tissue being analyzed (DeNiro, 1978). Traditionally, carbon can be isolated from bone in the organic portion of bone (collagen) or carbonate in the mineral portion of bone or teeth (hydroxyapatite ($Ca_{10}(PO_4)OH_2$)). The δ values retrieved from bone collagen are typically +5‰ greater than that of the diet, while $^{13}C$ from apatite is +12‰ greater than diet (Katzenberg, 2000). For this study, $\delta^{13}C$ values were obtained from additional soft tissues of the body, including hair, nail, skin, and gut content. These tissues will be discussed in more detail in later sections.

## Nitrogen

Nitrogen isotopes are also commonly used to assess diet and health and occur as the stable isotopes $^{14}N$ and $^{15}N$, with $^{15}N$ being the heavier and less abundant isotope. The standard that $^{15}N$ is measured against is $N_2$ to atmospheric nitrogen. Most biological material is enriched in $^{15}N$ compared to $N_2$ and therefore has positive $\delta^{15}N$ values. These values, like those of $\delta^{13}C$, have been shown to vary according to the tissue sampled and are known to vary dependent upon trophic level, or one's place in the food chain (Ambrose and DeNiro, 1986; O'Connell et al., 2001). Plants are in one of two groups: legumes that fix nitrogen via bacteria that live in the roots, or other plants that get nitrogen from decomposed organic matter and break it down into

ammonia ($NH_2$) or nitrate ($NO_3$) (Hopkins and Hunter, 2004). This leads to legumes having lower $\delta^{15}N$ values than other plants. Once herbivores have consumed a plant, their $\delta^{15}N$ values increase by approximately 3‰, with herbivores consuming legumes having $\delta^{15}N$ values lower than those consuming other plants (Schoeninger, 1995). The nitrogen values of carnivores consuming the herbivores are then increased again, with $\delta^{15}N$ values 3‰ higher than herbivores. This is known as the trophic level effect and reflects an individual's place relative to other organisms in their food web (Katzenberg, 2000). The degree of enrichment, while traditionally thought to be +3‰ per trophic level, has also recently been shown to possibly be as high as +5‰ for bone and from +1‰ to +3‰ for tissues like hair and nail (Bocherens and Drucker, 2003; O'Connell et al., 2001). Breastfeeding infants are also a tropic level (an average of 2-3‰) above their parents because they receive their protein from their mother's milk (Fogel et al. 1997; Dupras and Tocheri, 2007). Additionally, those consuming aquatic resources have higher $\delta^{15}N$ values due to the fact that aquatic food chains are longer than terrestrial ones (Dufour et al., 1999).

While the trophic level effect has been demonstrated, it has also been shown that there are other aspects that affect $\delta^{15}N$ values. While the carbon in collagen mostly comes from ingested protein, the nitrogen in collagen can come from ingested protein or recycled tissues in the body and can be influenced by environmental and physiological factors in addition to diet (Ambrose, 1991; Schwarcz et al., 1999; Sealy, 2001). Arid environments increase the amount of $^{15}N$ present in human tissues due to a physiological adaptation to conserve water and result in higher $\delta^{15}N$ values. This fractionation effect can result from water or heat stress on the urinary

system (Ambrose, 1991; Schwarcz et al., 1999), isotopically light ammonia evaporating from the soil **(**Schwarcz et al., 1999), or from the effects of plant forage over time (Hedges et al., 2007). Studies have shown that animals suffer the same effect; they have higher $\delta^{15}N$ values when they live in areas with minimal rainfall (Ambrose and DeNiro, 1986; Heaton et al., 1986). Due to the extreme aridity of the part of Egypt where these samples were obtained, the $\delta^{15}N$ values are very high (Schwarcz et al., 1999; Dupras et al., 2001; Williams et al., 2011). The high $\delta^{15}N$ values documented in desert environments (Schwarcz et al., 1999) can have a large effect on the trophic level effect of food webs, and in turn on the interpretation of isotopic data.

Nitrogen isotope values and nitrogen pools have also been found to be affected by changes occurring in the metabolic state of individuals through mechanisms such as disease and pregnancy. Nitrogen balance is positive during periods of growth or tissue repair (such as recovery from injury), when the body is ingesting more nitrogen than is being excreted, resulting in a reduction of $\delta^{15}N$ values (Fuller et al., 2005). Katzenberg and Lovell (1999) found that following trauma from a fracture, values were lower during the trauma and higher during the body's repair process. During pregnancy $\delta^{15}N$ values decrease due to nutritional demands and the anabolic state of the female's body. This trend has been specifically demonstrated in hair, where multiple samples can be taken from one strand. Fuller et al. (2005) demonstrated this by longitudinally measuring $\delta^{15}N$ values during pregnancy and found a significant decrease in $\delta^{15}N$ values throughout pregnancy. Williams et al. (2011) used this knowledge, in conjunction with hair cycles, to suggest pregnancy in archaeological sample B307, discussed later in this study.

While a decrease in $\delta^{15}N$ values cannot verify pregnancy in and of itself, it can certainly be used as a corroborating factor alongside other supportive evidence.

While a positive nitrogen balance often results in reduced $\delta^{15}N$ values, negative nitrogen balance, associated with periods of stress, disease, and injury, often results in increased values, when less nitrogen is being ingested than is needed to maintain and replace proteins in the body (White and Armelagos, 1997; Katzenberg and Lovell, 1999). Katzenberg and Lovell (1999) showed elevated $\delta^{15}N$ values in bone diseased by AIDS compared with healthy bone, and White and Armelagos (1997) showed similar results from individuals with osteoporosis. Hauber et al. (2005) and Mekota et al. (2006) have also demonstrated that nitrogen values become more enriched with starvation. During period of extreme stress, such as a fracture and repair, $\delta^{15}N$ values may either decrease (when less nitrogen is being ingested than is needed to maintain the body) or increase (when recycled nitrogen is being used for newly deposited tissues) (Katzenberg and Lovell, 1999). However, due to the aridity in the Dakhleh Oasis and the paucity of research available concerning nitrogen balance in human tissues, particularly short-term tissues, caution must be used when analyzing nitrogen results.

## Bone Collagen

Due to the rarity of soft tissue preservation in the archaeological record, bone is most commonly sampled for stable isotope analysis (Lee-Thorp et al., 1989). The first archaeological

studies using stable isotope analysis used collagen as the component from which the carbon and nitrogen were drawn, which makes up 85 to 90% of the organic portion of bone and constitutes about 30% of the total weight of bone (Katzenberg, 2000). The main reasons for this were that collagen can survive for thousands of years, and there were already reliable archaeological methods available for extracting collagen (Katzenberg, 2000). Bone collagen still remains the most commonly used tissue for archaeological isotopic studies.

Bone collagen in adults has a turnover rate of roughly more than 10 years (although rates can vary widely); therefore, samples reflect long-term diet (Sealy et al., 1995; Katzenberg, 2000; Cho et al., 2006). A study by the International Commission on Radiological Protection (1975) attempting to estimate what radiation does to the body is one of the only studies that calculate the bone turnover rate in healthy individuals. According to this source, young children have higher turnover rates than adults: 100 to 200% at one year, 10% at 3-7 years, and 1% at 8 years. Turnover slows down during adolescence and is between 0.3 to 3% for adults (Sealy and Cox, 1997).

Collagen carbon isotopes are on average +5‰ enriched compared to diet; therefore, people eating $C_3$ plants would have values around -20‰ and those eating $C_4$ plants around -7‰. There is some debate, however, on whether bone collagen accurately reflects the entire diet. Some experiments have demonstrated that collagen is derived mainly from dietary protein due to the fact that collagen is composed of a mix essential and nonessential amino acids, which are enriched by approximately +4‰ over carbohydrates (Krueger and Sullivan, 1984; Ambrose et

al., 1997). While bone collagen is often used for isotope studies, it has been argued that the inorganic portions of bone and teeth are more suitable for isotope analysis because they do not degrade over time.

## Teeth

Carbon can be found in the inorganic portions of teeth, and both carbon and nitrogen can be found in the organic portion of teeth. Samples from adults and juveniles in this study were taken from dentin, or organic portion, of the tooth. The dentin is located beneath the enamel, between the enamel and pulp chamber, and helps to support the enamel. The dentin in the permanent dentition is laid down with the initial formation of the tooth during childhood, while the dentin of primary teeth is laid down during gestation or childhood (Hillson, 1996). Carbon and nitrogen from the dentin comes from the organic portion and closely resembles collagen from bone. Like bone, collagen $\delta^{13}C$ values are enriched +5‰ compared to dietary protein.

Samples from the dentin of the tooth reflect roughly the time period in which the tooth crown was forming and give a snapshot of that window of time. Unlike bone collagen, dentin does not undergo remodeling, and thus represents the time period in which it formed (Sealy et al., 1995). Teeth begin formation in utero and development extends into adult life. Individual teeth form, develop, and emerge at varying, somewhat predictable times. They go through different stages of mineralization, including the development of the crown, root and apex

(Hillson, 1996). At birth, all of the deciduous teeth and the first molars have begun to mineralize. By the age of one year all deciduous teeth have their crown complete. Permanent molars have a wide range of ages of mineralization. Permanent first molars, as mentioned above, begin formation by birth. The crown is usually complete by the age of 2 and ½. Second molars begin formation around age 3.8 and the crown completes by age 6. Third molars are much more variable. Formation usually begins around age 9.5 and the crown completes at age 12 (Scheuer and Black, 2000). Dental formation stages and age ranges used in this study have been derived from studies by Liversidge et al. (1993), Smith (1991), and Garn et al. (1959).

## Hair

Hair fibers are composed of keratin, a protein structure which can preserve isotopic information for thousands of years (Lubec et al., 1987). Like teeth, the hair is a static tissue once it has formed and it remains unchanged by further metabolic action, thus retaining information from the time it was produced. Due to these static properties, hair is very useful for determining short-term, seasonal diet as well as potential metabolic changes (O'Connell and Hedges, 1999). Hair from the scalp on average grows at a constant rate of approximately 0.35 mm a day (Saitoh et al., 1970). Isotopic information generally first appears in the hair 6 – 12 days after ingestion, with $\delta^{13}C$ values enriched by +1‰ to +5‰, and $\delta^{15}N$ values enriched by +2‰ to +3‰ relative to dietary protein (O'Connell et al., 2001; Williams et al., 2011).

There are three different phases of hair growth within the growth cycle: anagen, catagen, and telogen phases. The anagen phase is the active growth phase, when fiber is being produced with prolonged stable growth; the catagen and telogen phases are the transitional and rest/dormant phases, respectively (Paus and Costarelis, 1999). During the latter two stages, the hair is dormant and does not represent diet right before death, as anagen hairs do. Hairs next to each other, and assumed to have been formed at the same time, may in fact have been formed at different times and be in different phases of the growth pattern (Williams et al., 2011). Therefore, the percentage of anagen, catagen and telogen hairs on the scalp and phase identification of hair, in conjunction with isotopic data, is important in determining the status of past peoples.

It is estimated that the normal adult has 85-90% actively growing hairs and 10-15% inactive hairs (Dawber and Van Neste, 2004). While the "normal" adult may have the distribution cited above, there are many factors that regulate the cyclic growth of hair, including intrinsic modulators, hormonal modulators (e.g., androgens, estrogens, and prolactin), and systemic modulators (e.g., seasonality, injury, illness, and diet change) (Williams, 2008; Williams et al., 2011). In hair samples with a mixed growth phase, Williams et al. (2011) found that the isotopic signal is delayed between 0 - 3 months compared to anagen hairs. This must be taken into account when analyzing hair samples, especially those from individuals with high telogen rates (Williams et al., 2011).

## Nail

Nail is another indicator of short term diet that has been shown to accurately reflect short-term human diet and physiology. It is very similar to hair, and the only difference is that nail keratin is on average enriched +.0.6‰ over hair nitrogen values. Carbon values are virtually the same (O'Connell and Hedges, 1999; O'Connell et al., 2001). Fingernails grow an average of 3 mm per month and while growth is consistent within the individual, it is variable between individuals (Dawber and Baran, 1994). In an adult, the fingernail completely replaces itself approximately every 5 – 6 months, thus isotope samples represent from 1 - 6 months of diet. In infants, the fingernails grow much more quickly and replace themselves in 6 - 8 weeks (Samman, 1995).

## Skin

Human skin, another indicator of short term diet, is also strongly influenced by diet. Studies indicate that skin is enriched in $^{13}C$ by +1‰ to 4‰, and enriched in $^{15}N$ by +5‰ relative to dietary protein (White et al., 1999). Skin has a turnover rate of approximately 2% per day and thus represents about 1 to 1 ½ months of diet (White, 1993; El Harake et al., 1998; Williams, 2008).

## Gut Content

Samples from the human gut represent the diet within the last 50 – 72 hours before death (Cummings et al., 1976). Because it has not yet been incorporated into tissue, the nitrogen in gut content samples represent the crude protein content of dietary plant foods (Williams, 2008), and it demonstrates a negative diet-feces fractionation, with $\delta^{13}C$ values of -0.4‰ in pigs and -1.9‰ in cows relative to diet (Sponheimer et al., 2003). $\delta^{15}N$ values ranged from +3‰ to +4‰ enriched compared to diet (Sponheimer et al., 2003). Comparative human data is not available at this time due to the fact that fecal material is very rarely preserved archaeologically (Williams, 2008). Stable isotopes of gut content from 8 individuals are included in this study.

## Previous Studies Presenting Life Histories

Sealy et al. (1995) and Sealy and Cox (1997) were the first studies to trace life histories using isotopic analysis of teeth and bone using $^{13}C$, $^{15}N$, and $^{87}Sr$ from historic and prehistoric samples. The first study (Sealy et al. 1995) traces five individuals, and the samples from each individual included a tooth formed in early childhood, a third molar, and bone collagen from a long bone and a rib. The authors conclude that isotope measurements from various tissues can be used to reflect diet at different times during an individual's life and suggest that changes in $\delta^{13}C$ and $\delta^{15}N$ may be due to diet, but point out that for the first few individuals analysis of further skeletons from the population would be necessary to distinguish between changes in diet and

normal variation. For the final 2 samples in the study, however, the authors are able to show a trend of enriched $\delta^{13}C$ and $\delta^{15}N$ values as the females aged, concluding that they consumed more seafood as adults.

The second study (Sealy and Cox, 1997) focuses on the life histories of historic shipwreck victims off the coast of South Africa, demonstrating values consistent with a terrestrial $C_4$ based diet and changes over time consistent with enslavement. These studies, however, do not attempt to answer questions about short-term diet from tissues with fast turnover rates. Nor do they present data in an easily comprehensible way for someone unfamiliar with the study of stable isotopes.

Recently, an article was published by Knudson et al. (2010) using stable isotope analysis of enamel, bone, and hair that constructed the life history of an adult male from an uninhabited area of the northern Chilean coast. The authors used carbon, nitrogen, strontium and oxygen stable isotopes from tooth enamel, bone, and hair in their analysis to reconstruct diet and mobility. Knudson et al. (2010) determined that the individual was likely consuming a large amount of marine resources, but switched between higher and lower trophic level resources as a result of trips to the coast. Using the hair data, they also determine that he likely traveled during the last 20 months of his life, eating a coastal diet for 2 – 3 months, then a terrestrial, inland diet for 8 – 12 months and a coastal, marine based diet again in the last 6 - 8 months of his life. However, they did not incorporate a separation of the different stages of hair growth (anagen, telogen, and catagen); therefore, results may be flawed. This research contributes to the

understanding of pre-Columbian life in northern Chile by using long and short term tissues, and represents one of the first publications to look at isotopes at an individual level.

# CHAPTER 3: MATERIALS AND METHODS

## The Dakhleh Oasis

The Dakhleh Oasis is one of five major depressions in the Western Desert of Egypt. It is located in western Egypt, around 660km southwest of Cairo and extends 80 km east-west and 25 km north-south and can be seen in Figure 2 (Kleindienst et al., 1999; Dupras and Tocheri, 2007). The significance of the depression is that the Oasis is low enough to provide access to the Nubian Sandstone Series, a water bearing stratum underlying the western Saharan desert. In the western part of Egypt, where the Dakhleh Oasis is located, the average rainfall is only 0.3 mm per year (Sutton, 1947). This water access is vital to survival the maintenance of a population within the Oasis (Schwarcz et al., 1999). Although the Oasis is extremely arid and its inhabitants depend on wells and springs to access water, people have been living in the region for thousands of years (Schwarcz et al., 1999; Dupras, 1999).

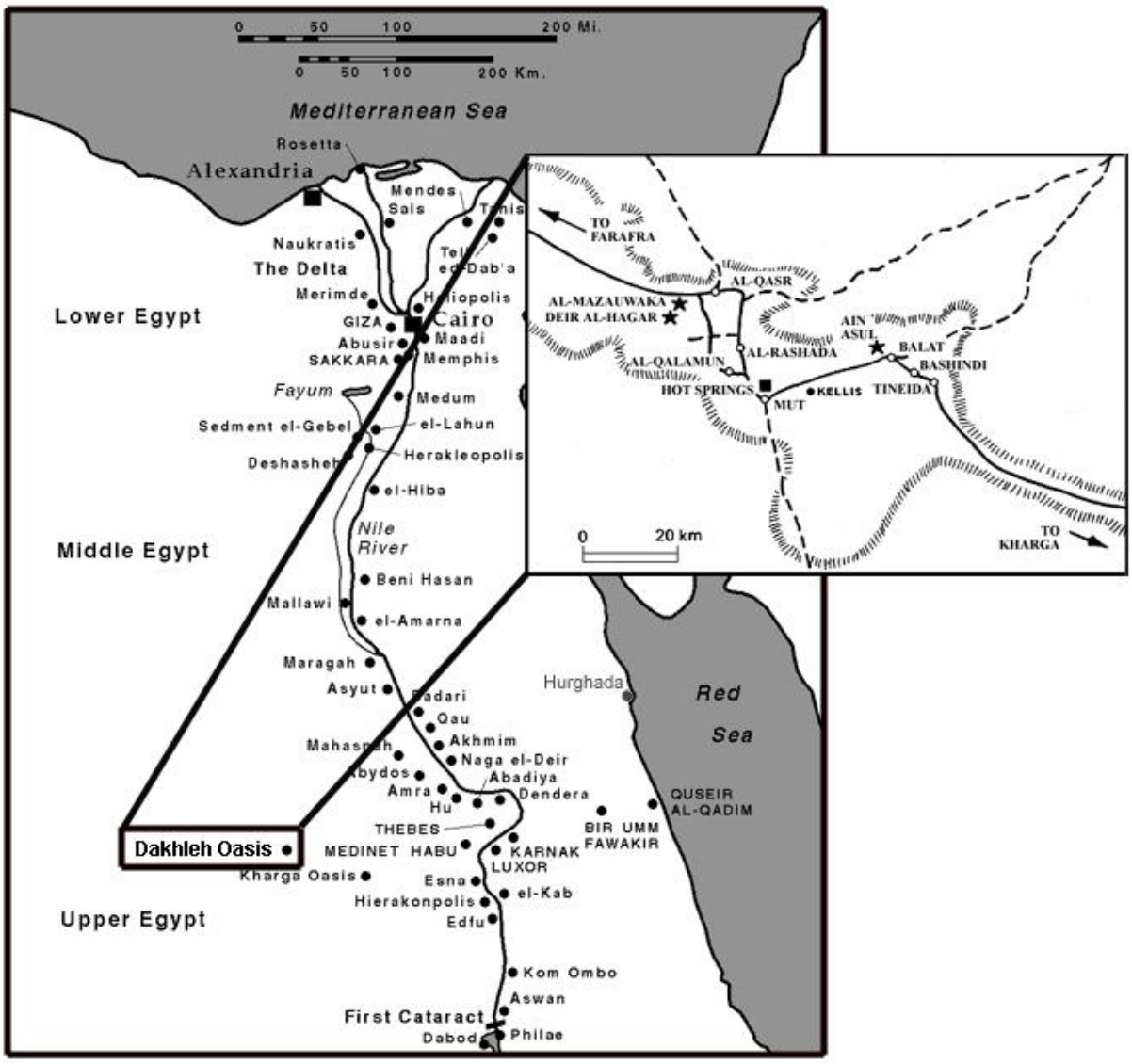


Figure 2: Location of the Dakhleh Oasis in Egypt

Communication between the Nile River Valley and the Dakhleh Oasis is possible via the Libyan Plateau, the Kharga Oasis, or the Farafra Oasis. It is evident that during the Roman occupation of Egypt, the time period in which the sample in the study is dated, contact and trade

were common between the Oasis and the Nile River Valley populations. Before this time, communication may have been restricted due to the fact that camels had not yet been introduced to the area; although due to the specialized nature of the ecology within the Oasis, some trade may have been mandatory for mere survival (Bulliet, 1975; Dupras, 1999).

The main resource produced within the Dakhleh Oasis was date palm, which was the second largest commodity cultivated in the Egyptian oases after salt, with olives also being a valuable commodity (Dupras, 1999). Populations in the Nile River Valley and throughout the Mediterranean sought these valuable resources. Field crops were also produced in the Oasis, principally barley and wheat. Due to the irrigation used at the Dakhleh Oasis, crops could be growing throughout the year, unlike those living on the Nile River who depended on the Nile flood to grow crops (Wagner, 1987; Williams, 2008). During Roman occupation, agricultural technologies and incentives drew many to the Oasis, and the population during this time may have been as many as 35,000, larger than the modern population (Mills, 1984; Fairgrieve and Molto, 2000; Williams, 2008).

## Kellis and Kellis 2 Cemetery

While the Dakhleh Oasis itself has been occupied for thousands of years, archaeological excavations and radiocarbon dating show that the ancient town of Kellis, seen in Figure 3, reached its height in the fourth century AD and was located along the trade route of the oasis

(Hope 1998; Hope, 2001). The site contains many structures from the Romano-Christian period including churches, temples, a bathhouse, tombs, and two cemeteries. Kellis is considered to have been an important economic and political center of the Oasis at this time (Hope, 2001; 2002; 2003). The Kellis 2 Cemetery, located northeast of the site of Kellis, contains Romano-Christian burials that have been suggested to date between AD50 – 450, although there is ongoing research concerning the dating of this cemetery (Bowen, 2003; Stewart et al., 2003; Molto et al., 2006). The burial style, consisting of single interment burials in an east-west orientation with the head facing west, is that of a Christian style burial and is different from the pagan style burials see in Kellis 1 cemetery to the west of Kellis (Bowen, 1998; Bowen 2003). To date, 760 burials have been excavated (Dupras, pers. Comm.) and the entire cemetery may contain as many as 3,000 to 4,000 graves (Molto, 2002).

Figure 3: Kellis and Kellis 2 Cemetery within the Dakhleh Oasis.

Information regarding the food available in ancient Kellis can be derived from archaeozoological and archaeobotanical analyses, and the Kellis Agricultural Account Book, a codex that contains accounts of fourth century agricultural entities, available goods, and income and expenditures (Bagnall, 1997). These sources show that the major grains available were wheat, barley, and millet. During this period of Roman occupation of the Oasis, wheat was the largest crop produced and was harvested from April until June. Barley was harvested in the spring and winter and millet in the spring, summer, and autumn (Williams, 2008). Wheat is noted as the main staple and was of a high quality. It was used for payment in business, as a trade item, and as fodder for pigs and chickens (Worp, 1995). The main protein sources available were pig, cow, goat and chicken. Other foods consumed included dates, broad beans, lentils, turnips, onions, garlic, artichokes, celery, gourds, cucumbers, figs, grapes, olives, apples, peaches, pomegranates, citron, and nuts (Dupras, 1999). While these sources can show that all of these items were certainly available, they cannot prove what foods were actually ingested and by whom.

It has been demonstrated that the diet at Kellis during the Roman period consisted of both $C_3$ and $C_4$ plants (Dupras, 1999; Dupras et al., 2001; Williams, 2008). With $\delta^{13}C$ values ranging from -25.6‰ to -17.6‰, the main components of the diet were $C_3$ foods such as wheat and barley, and animal proteins of pig, cow, and goat (with the consumption of goat, which has an average $\delta^{13}C$ value of -15.7‰, accounting for the higher $\delta^{13}C$ values). The only $C_4$ plant available for consumption was millet (with an average $\delta^{13}C$ value of -9.9‰). Within the Kellis 2 population, it has been demonstrated that there is a discrepancy between the $\delta^{13}C$ values of males

and females, with males being more enriched than females (Dupras, 1999). This difference probably indicates that males ate more meat (i.e., cows and goats that consumed millet), compared to females, who had a diet that relied more on grains like wheat and barley.

The $\delta^{15}N$ values from Kellis 2 are extremely high and it may appear that they were eating marine resources, which creates high levels of $^{15}N$. However, there is little evidence that the people at Kellis were consuming any aquatic resources, and considering the location of the Dakhleh Oasis, this is not surprising. The high $\delta^{15}N$ are much more likely a result of the arid conditions in the desert (Schwarcz et al., 1999). The aridity also complicates the trophic level effect, making it difficult to decipher. The effect can be seen, however, between humans and components of their diet (e.g., wheat, pigs, and goats). For example, the $\delta^{15}N$ values for pigs average 13.3‰, cows 13.1‰ and goats 13.4‰ (Dupras, 1999).

Dupras (1999), Dupras et al. (2001), and Dupras and Tocheri (2007) have also shown that children under the age of 2.5 have $\delta^{15}N$ values that are enriched compared to the rest of the population. The trophic level effect can be seen; at 6 months of age children value reach a peak and are approximately 3‰ more enriched than adults and gradually decline to the average female by 3 years of age. This is due to exclusively breastfeeding up until 6 months and gradually introducing goat/cow milk or pearl millet into the diet. Carbon isotopes also show a trend with small children. $\delta^{13}C$ values are enriched in children between birth and six months old, reach a maximum of -17.8‰ in children age 6 months to 1.5 years, and slowly declines until by age 3.5 the value is in between the average male and female. The introduction of milk/millet when being

weaned also accounts for this trend in high carbon values in young children because milk is enriched in $^{13}C$ (cows were fed millet), although recent studies have shown that modern infants who are breastfeeding and have no access to $C_4$ foods have a 1‰ increase in $\delta^{13}C$ as well, indicating a trophic level effect (Fuller et al., 2005; Richards et al., 2006). To summarize, children began the weaning process sometime before six months and were then introduced to alternative foods. Breastfeeding continued in part until age 3, when a diet similar to the rest of the population was reached.

Lastly, Dupras and Schwarcz (2001) used nitrogen, in combination with oxygen, isotopes to demonstrate migration into the Dakhleh Oasis during the Roman occupation. Some individuals, particularly young males, with abnormally low $\delta^{15}N$ values were shown to be from outside the Dakhleh Oasis, probably the Nile Valley, where values are much lower. The values of the individuals were in between that of the Dakhleh Oasis and the Nile Valley, presumably because they lived for a period of time in each location.

## Materials

The data used in this study was obtained from Dr. Tosha Dupras (University of Central Florida) and Dr. Lana Williams (University of Central Florida), who are both a part of the Dakhleh Oasis Project in Egypt. The Dakhleh Oasis Project has intensively studied the Oasis since 1978 to better understand the relationship between humans and the harsh desert

environment. The project is under the direction of Anthony Mills, and is an international, multidisciplinary collaboration (Dupras, 1999). The samples used were obtained from individuals interred in the Kellis 2 cemetery, a Romano-Christian cemetery located to the northeast of the ancient town of Kellis, dating from approximately AD50 – AD 450 (Stewart et al. 2003). Maps of the general location are available, as well as detailed maps of the cemetery, denoting the exact location and directionality of each individual burial (see Figure 4) (Williams, 2008). The map shows the excavated part of the cemetery thus far, with the inset showing the excavated section in respect to the entire surveyed extent of the cemetery. The excavated section is located more or less in the middle of the entire surveyed cemetery. All of the individuals that are analyzed in this study are located in the northern half of the excavated section of the cemetery. Each of the individual burials analyzed are highlighted in red on the map below.

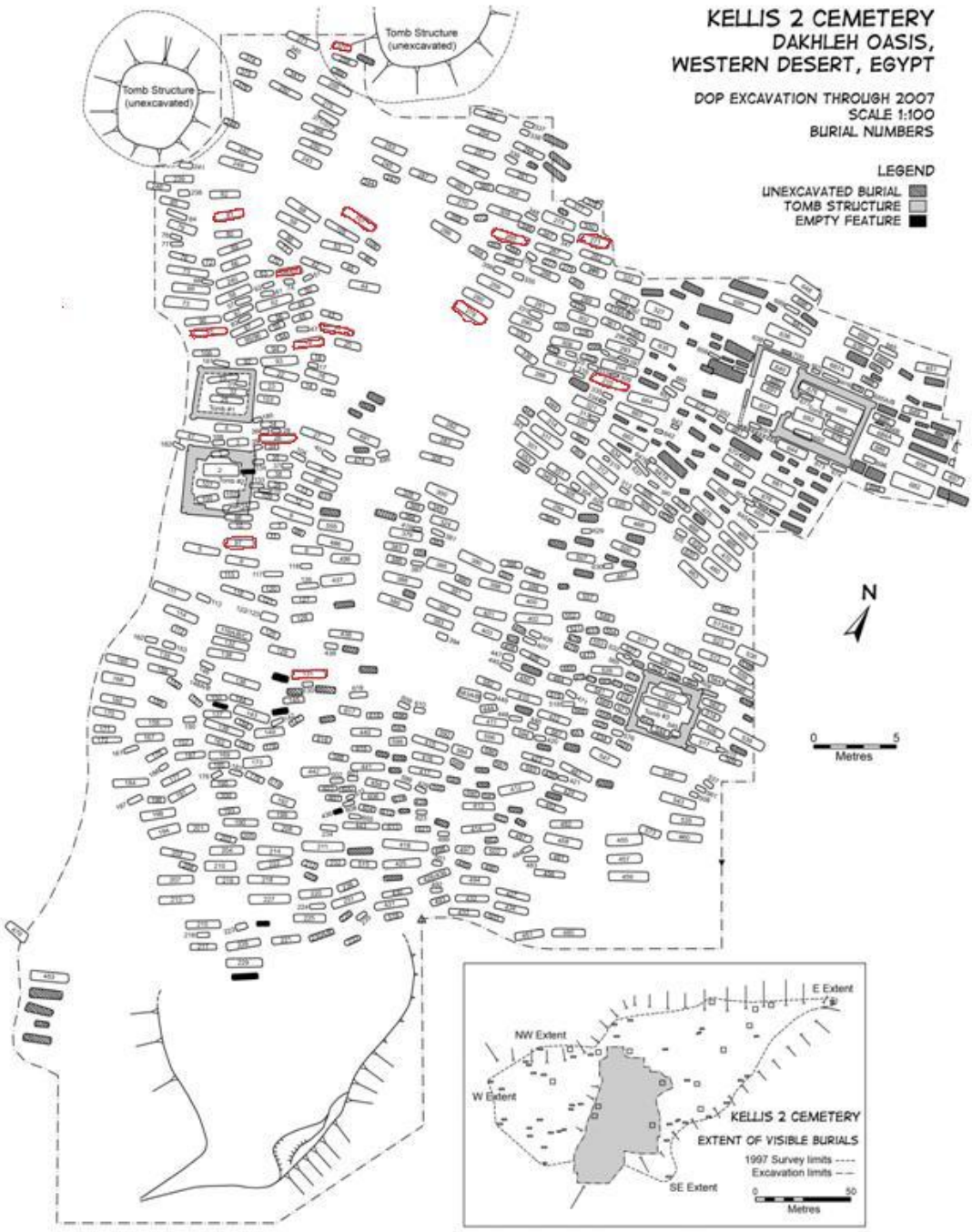


Figure 4: Excavated area of Kellis 2 cemetery from Williams (2008). Individuals examined in this thesis are highlighted in red.

To date the following tissues have been analyzed for their carbon and nitrogen stable isotope values: bone collagen (80 females, 54 males and 37 juveniles), teeth (64 adults, 27 juveniles), hair (47 females, 43 males, and 126 juveniles), nails (6 females, 4 males, and 51 juveniles), skin (40 females, 30 males, and 73 juveniles), and gut content (4 females, 2 males, and 2 juveniles) (see Table 1). From the teeth, samples were taken from the dentin of numerous teeth. For adults, samples of dentin were taken from the $1^{st}$, $2^{nd}$, and $3^{rd}$, upper molars and consist of 159 samples: $M^1 = 64$, $M^2 = 62$ and $M^3 = 33$. Dentin from 27 juveniles was sampled from different deciduous and primary teeth in various stages of development.

Table 1: Data available from various tissues

| | Bone Collagen | Teeth | Hair | Nails | Skin | Gut Content |
|---|---|---|---|---|---|---|
| Female | 80 | 25 | 47 | 6 | 40 | 4 |
| Male | 54 | 28 | 43 | 4 | 30 | 2 |
| Juvenile | 37 | 27 | 126 | 51 | 73 | 2 |
| Unknown | | 14 | | | | |
| Total | 171 | 94 | 216 | 61 | 143 | 8 |

## Methods

All of the data used in this study were collected by Drs. Tosha Dupras and Lana Williams. The bone collagen was analyzed by Dr. Dupras and the extraction techniques are those detailed in Dupras (1999). Samples from the teeth were extracted by Dupras and Tocheri (2007)

and can be referred to for detailed analysis. Hair, nail, skin, and gut content isotopes were all extracted by Williams (2008).

All of the stable isotope data were organized into one spreadsheet using Microsoft Excel 2007. Several different tabs exist within the file to organize data by categories: bone collagen, dentition, hair, nails, skin and gut, pathology, and charts/timelines. This allows for greater ease when comparing and analyzing data. For each tissue, the average of the total population, females, males, and juveniles was calculated, as well as the standard deviation for each average. For some of the tissues, these values have already been calculated by Dr. Williams (2008) and by Dupras and Tocheri (2007). The estimation of age at death of individuals was determined in the field through suture closure, dental wear, and pubic symphysis morphology. For juveniles, dental eruption and long bone lengths were used. The sex of adults was determined by using the Phenice technique, which involves analyzing characteristics of the pubis bone.

For this thesis, a total of 15 individuals, with isotopic values available for four or more tissues (must include bone, teeth, hair, and one additional short term tissue), were used for the reconstruction of life histories. Having data from each of these tissues is extremely beneficial when the goal is to represent an individual's lifespan as thoroughly as possible. To create an individual history, the data from all of the different tissues was collected for a single individual. Due to the fact that the turnover rates for all the tissues analyzed are different, the isotope value from each tissue represents a different point in time. For example, the isotope values from an adult first molar represents birth – 2.5 years of age, the second molar 3.8 - 6 years of age, the

third molar 9.5-12 years of age, bone collagen the last 10 years of life, hair one month increments from time of death, nail 6 – 1 month before death, skin one month before death, and gut content only a few days before death. For dentition, the time period in which different teeth represent was formulated from a chart developed by Dupras and Tocheri (2007), seen in Figure 5. The chart illustrates when the crown and root is formed in various permanent and deciduous teeth. For purposes of this study, the crown development is particularly relevant because that is approximately when the primary dentin is formed in the tooth. While the dentin is formed after the enamel, and may in fact represent a delayed formation than what is represented in the chart, there are no studies presently available which denote exact times when dentin development spans. The chart was derived from Schour and Massler (1940), Lunt and Law (1974), and Smith (1991).

Table 2: Individuals with Multiple Tissues (4 or more)

| | Sex | Age | Bone | Teeth | Hair | Nail | Skin | Gut |
|---|---|---|---|---|---|---|---|---|
| B019 | F | 45 | x | x | x | | x | |
| B021 | F | 45 | x | x | x | | x | |
| B026 | F | 19 | x | x | x | | x | |
| B064 | | 6 | x | x | x | x | x | |
| B081 | M | 40 | x | x | x | | x | |
| B091 | F | 55 | x | x | x | x | x | x |
| B097 | | 6 | x | x | x | x | | |
| B107 | M | 27 | x | x | x | | x | |
| B131 | F | 23 | x | x | x | | x | |
| B265 | M | 50 | x | x | x | x | x | |
| B269 | F | 55 | x | x | x | x | x | |
| B271 | F | 31 | x | x | x | x | x | |
| B279 | F | 23 | x | x | x | x | x | |
| B310 | M | 21 | x | x | x | | x | |
| B370 | | 5 | x | x | x | x | x | |

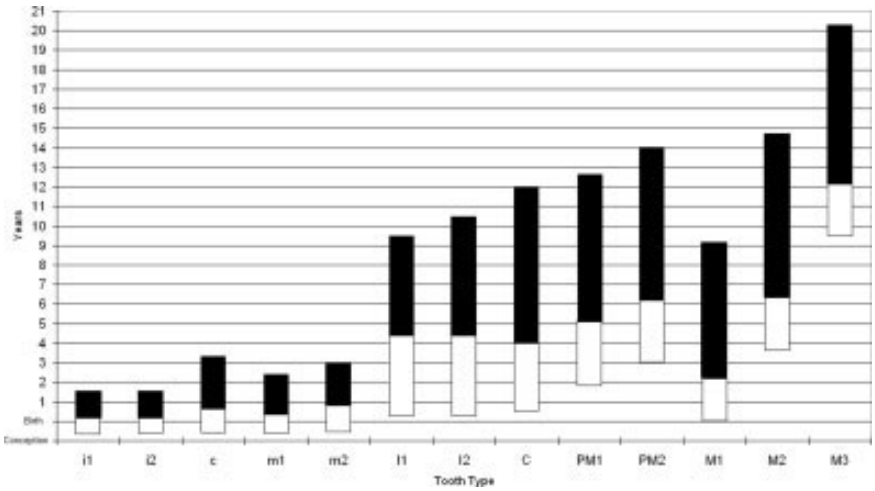


Figure 5: Chart illustrating dental crown (white) and root (black) formation of numerous deciduous (lowercase) and permanent (uppercase) teeth in relationship to age.

In this way, histories can be formed that span the length of time represented by the tissues analyzed. Figure 6 displays a timeline constructed in Microsoft PowerPoint 2007 which demonstrates how isotopic values from different tissues represent different times in an individual's life. The tissues, with $\delta^{13}C$ and $\delta^{15}N$ values underneath, are located in boxes with lines showing relative periods in life that each tissue would represent (the hair and nail values show the distal value on the left and the proximal value on the right). For this study, carbon and nitrogen stable isotope values are charted using this methodology and then interpreted for single individuals.

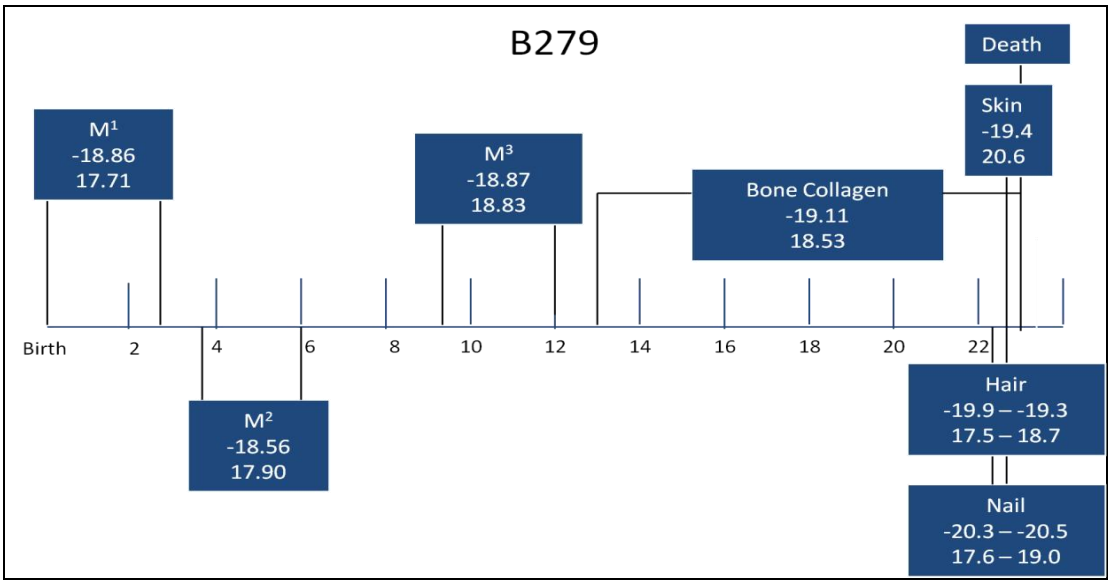


Figure 6: Timeline demonstrating during what time in life each tissue represents with $\delta^{13}C$ and $\delta^{15}N$ values underneath. Based on B279 (23 year old female)

To reconstruct and interpret the life histories of each individual, the stable isotopic values are analyzed in a number of ways. They are compared against the average of the total population and the average of the specific group in which the individual belongs (female, male, or juvenile) for each tissue from which data is available, as well as against the averages of other groups when desired. Averages will be calculated before and after removing extreme outliers, or those more than two standard deviations above or below the mean. Calculating the averages and identifying the outliers allows individuals to be accurately compared to the population, which in turn, reveals additional information about the individual. Bar graphs are constructed comparing these values.

For each individual analyzed, trends can be established, or a lack of an evident trend noted, both between and within tissues. X/Y scatter plots are constructed for both long-term and short-term diet, with either $\delta^{13}C$ or $\delta^{15}N$ values on the x axis. For plots depicting long-term values, the y-axis represents the relative tissue (different teeth and bone collagen), and the y-axis of plots depicting short-term values represents months since death. These plots allow for comparison, both between and within tissues, by showing the rise and fall of $\delta$ values over time.

The percentage of $C_4$ plants in the diet is calculated using a formula created by Schwarcz et al. (1985). This formula was created for use in bone collagen samples, but this study adjusts the formula to calculate the percentage of $C_4$ foods in teeth, hair, nails, and skin as well by changing the fraction factor for each tissue. The fraction factor is the difference in the isotope ratio between diet and the tissue being examined. In bone collagen the fraction factor is -5‰;

however, in hair it ranges from -1‰ to -4‰, with nails it is -1.6‰ to -5.6‰, and with skin is -1‰ to -4‰.The formula presents as follows:

$$\frac{PC4 = (\delta c - \delta 3 + \Delta dc)}{\delta 4 - \delta 3} \times 100 \quad (2)$$

$\delta_c$ is the measured value of collagen sample
$\delta_3$ is the average $\delta^{13}C$ value for $C_3$ plants (-26.5)
$\delta_4$ is the average $\delta^{13}C$ value for $C_4$ plants (-11.5)
$\Delta_{dc}$ is the fraction factor between diet and collagen (-5‰)

Individuals analyzed are described in detail using a narrative format, beginning with a description of the location of the burial, biological profile (sex and age at death), and any noted pathological conditions. Following this initial description, long-term history is discussed, which includes the data from the teeth and bone collagen. This data is then used to determine such things as the percentage of $C_4$ foods in the diet and possibly indicate breastfeeding/weaning at early ages. Following the long-term analysis, a short-term analysis ensues, analyzing data from the hair, skin, nails, and gut content. In this section, short-term diet will be examined, as well as season of death and health status. For seasonality of death, a study by Williams (2008) is cited and for some of the individuals, the season calculated. Williams (2008) used grave azimuth to demonstrate that graves at Kellis 2 cemetery were aligned to the solar arc, allowing for the season of death to be discerned. After all analysis is complete, a timeline depicting the individual's lifespan is presented, which chronicles events during life based on tissue turnover.

# CHAPTER 4: RESULTS & INTERPRETATION OF STABLE ISOTOPE ANALYSES - LIFE HISTORIES OF 15 INDIVIDUALS FROM THE DAKHLEH OASIS, EGYPT

## Burial 19

Burial 19, located in the northwest portion of the excavated area, contained the remains of a 45 year old female with no notable pathologies. The tissues available for analysis include $M^1$, bone collagen, hair, and skin. Due to the scarcity of tissues available compared to other individuals, the analysis is relatively brief. Her $\delta^{13}C$ and $\delta^{15}N$ tissue values can be seen in Table 3, while the life timeline illustrates what time periods each tissue represents (Figure 7). All $\delta^{13}C$ and $\delta^{15}N$ averages compared to B19 are illustrated in Figures 8, 9, 10, and 11.

Table 3: B19's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -18.9 | 18.1 |
| Bone Collagen | -18.7 | 19.0 |
| Hair (2) | -17.9 | 19.4 |
| Hair (1) | -17.7 | 19.2 |
| Skin | -21.4 | 20.5 |

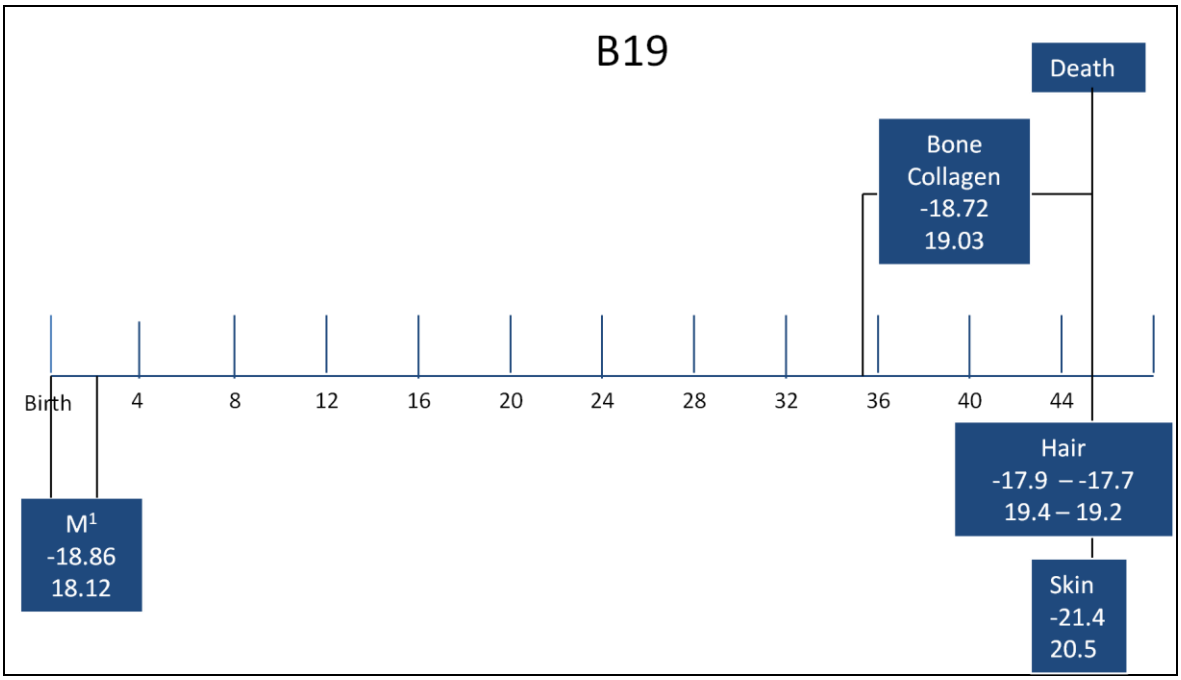


Figure 7: Timeline for B19 illustrating the ages each tissue represents

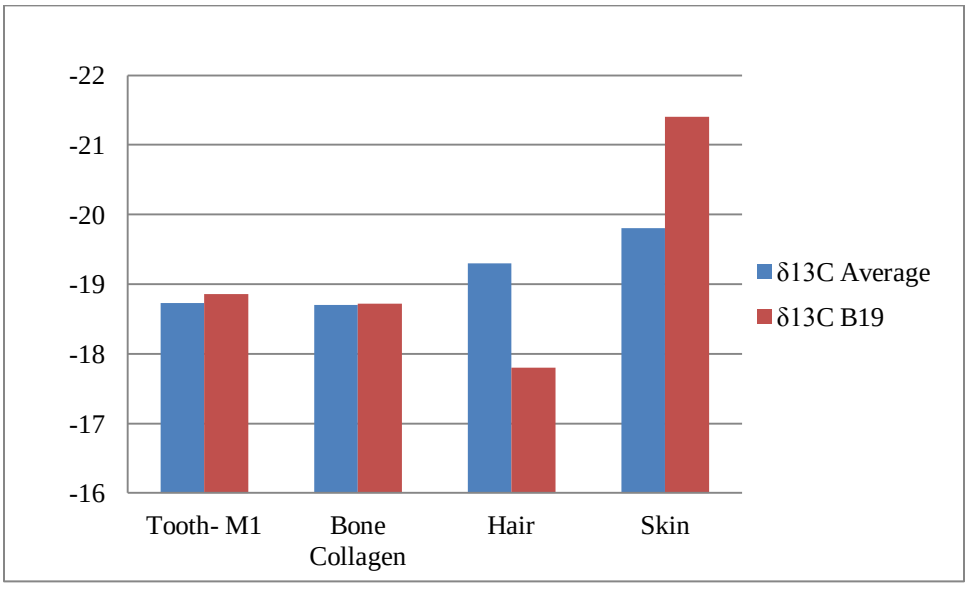


Figure 8: Graph comparing B19's $\delta^{13}C$ values with the rest of the population

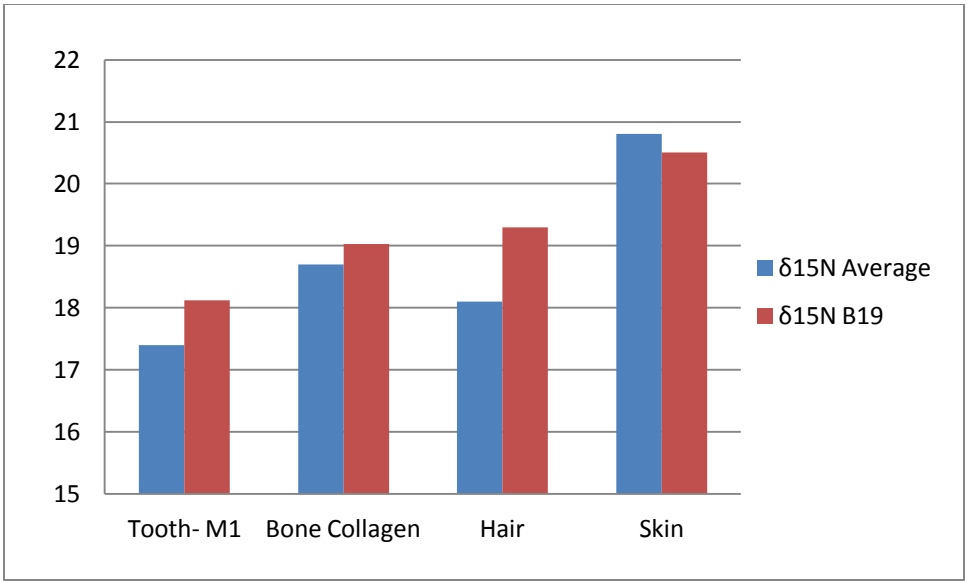


Figure 9: Graph comparing B19's $\delta^{15}N$ values with the rest of the population

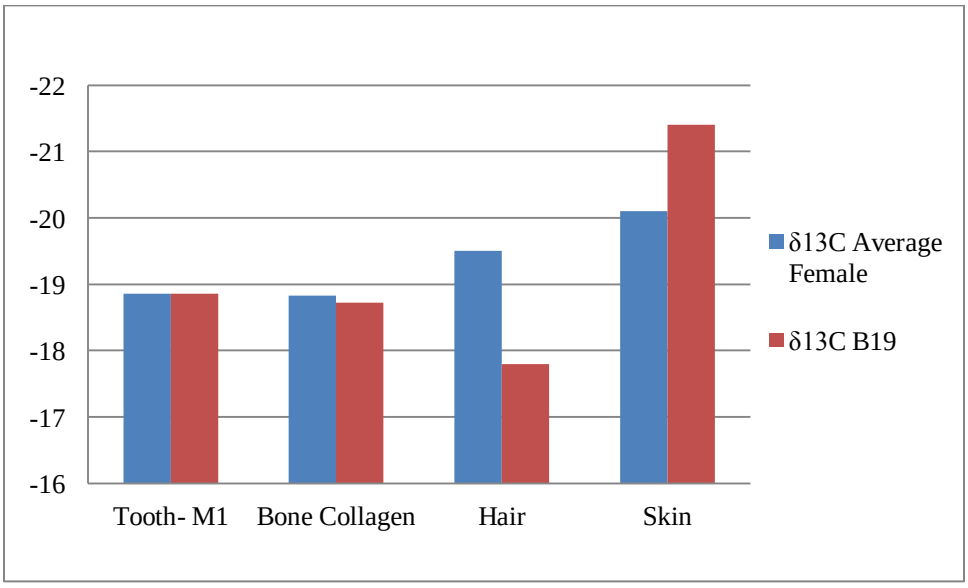


Figure 10: Graph comparing B19's $\delta^{13}C$ values with the average female

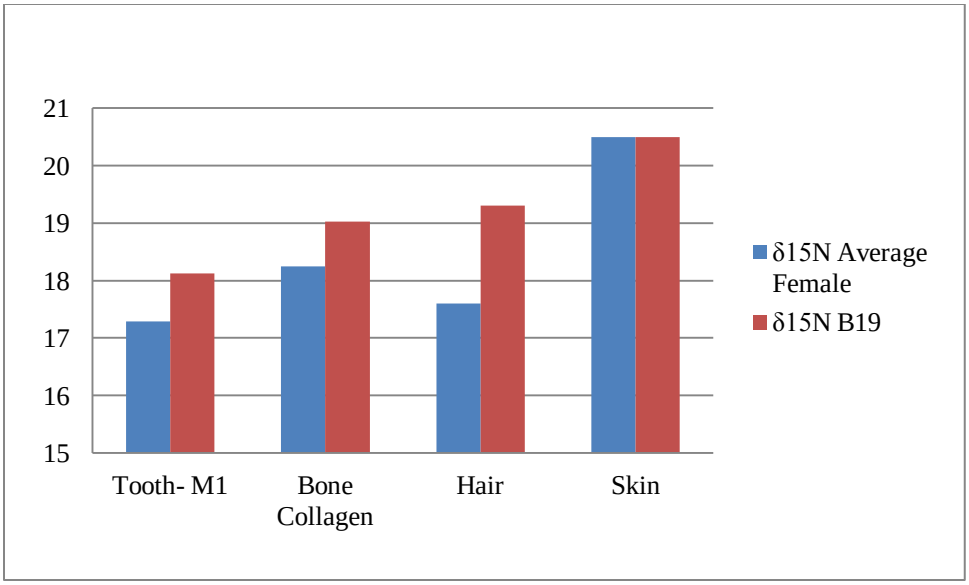


Figure 11: Graph comparing B19's $\delta^{15}N$ values with the average female

The first lower molar, $M^1$, is the only tissue for B19 which represents childhood. The dentin would have formed sometime between birth and two years of age. The $\delta^{13}C$ value,-18.86‰ is very close to the average for the population (-18.73‰), and the same as the average female. Using the formula presented in Schwarcz et al. (1985) it can be estimated that her diet was comprised of approximately 17.6% $C_4$ foods at this time. Her bone collagen (-18.72‰), also a long-term tissue, but representing from approximately 35- 45 years of age, is likewise very close to the average population, and only 0.11‰ higher than the average female. During this broad time span, B19 was consuming slightly more $C_4$ foods than in childhood (18.5%), as can be seen in Figure 12. Her long term $\delta^{15}N$ value also increases from childhood ($M^1$) to the last part of her life (represented by bone collagen). Both values, however, are higher than average. Her $M^1$ value of 18.12‰ is higher than the average of 17.4‰, which may be low due to the

trophic level effect seen in young children. It then jumps to 19.03‰ in adulthood, as seen in Figure 13.

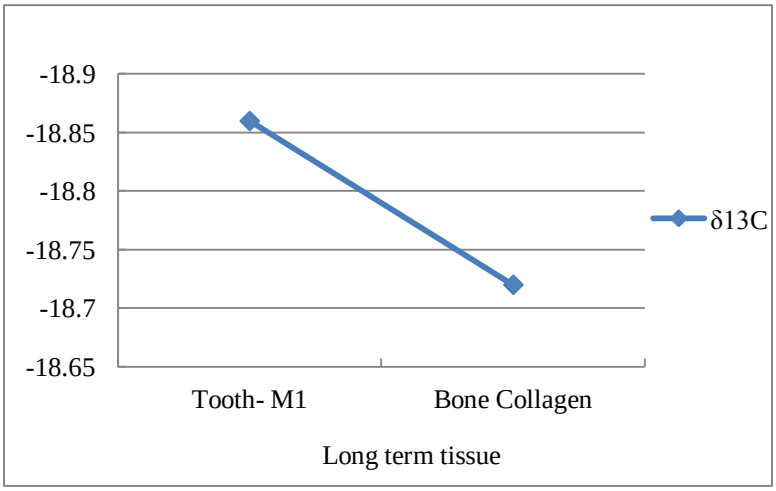


Figure 12: Line-graph depicting the long-term $\delta^{13}C$ values from B19

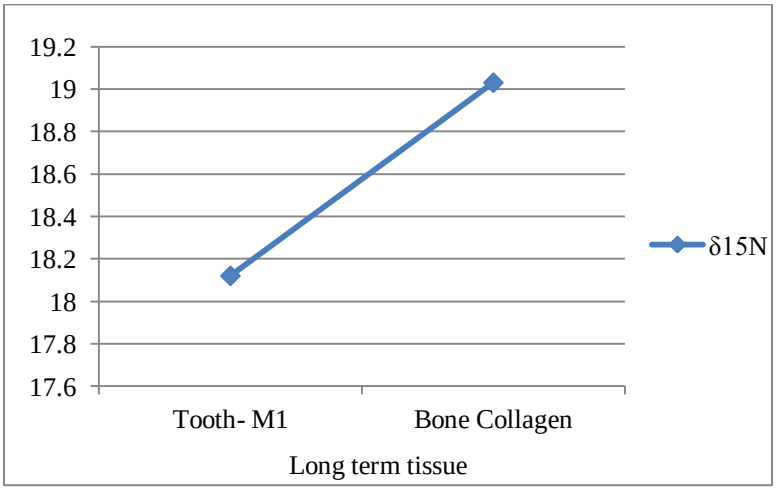


Figure 13: Line-graph depicting the long-term $\delta^{15}N$ values from B19

Short-term values available include only two hair samples and a skin sample and are plotted in Figures 14 and 15. Her $\delta^{13}C$ hair values(-17.9‰ and -17.7‰) rise slightly, but both values are well above, although not quite a standard deviation (±1.8‰) away from, the average of -19.3‰ and the average female of -19.5‰. Her skin value, on the other hand, is 1.3‰ lower than average, in a trend wherein hair and skin values are inversed that is repeated throughout this thesis. She was consuming 30.7 - 52% C4 foods one to two months before death. This is a higher percentage of millet and meat than the 20 – 40% consumed by the average population. This could potentially be due to time of year she passed or due to a special diet, such as millet pap, consumed because of illness.

The interpretation of her short-term $\delta^{15}N$ values (Figure 15) is also interesting. Her hair values (19.4‰ and 19.2‰) are higher than average (18.1‰) and show a very slight drop right before death. Her skin value (20.5‰), once again, is incongruent with the hair values and is slightly lower than average (20.8‰) and equivalent with the average female. If judging by hair values alone, it would be noted that her nitrogen balance was high, being over one standard deviation away from the average female a couple of months before death. This negative nitrogen balance, which results in high nitrogen values, can be associated with illness or injury. As she had high long term values as well, it may be due to a chronic ailment.

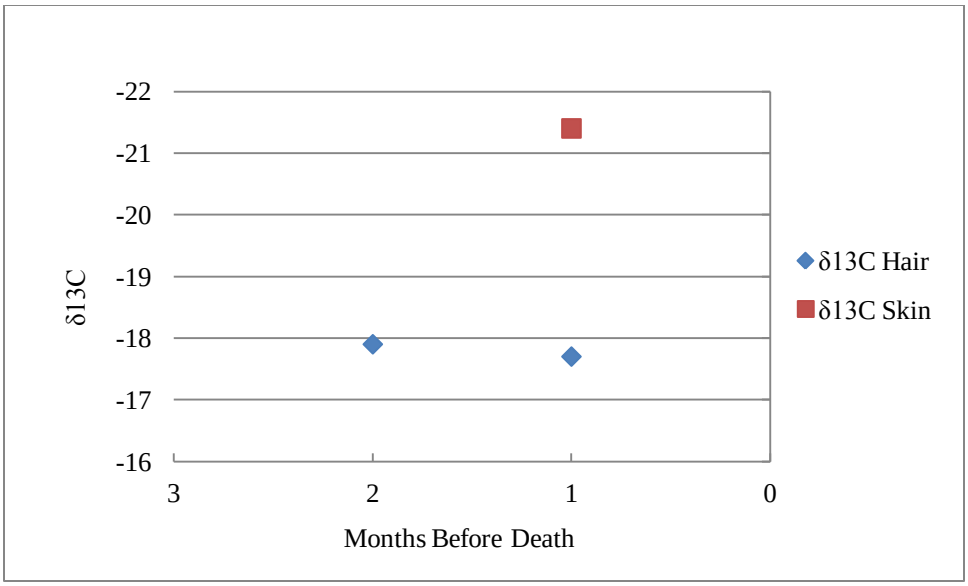


Figure 14: Scatter plot depicting short-term $\delta^{13}C$ values from B19

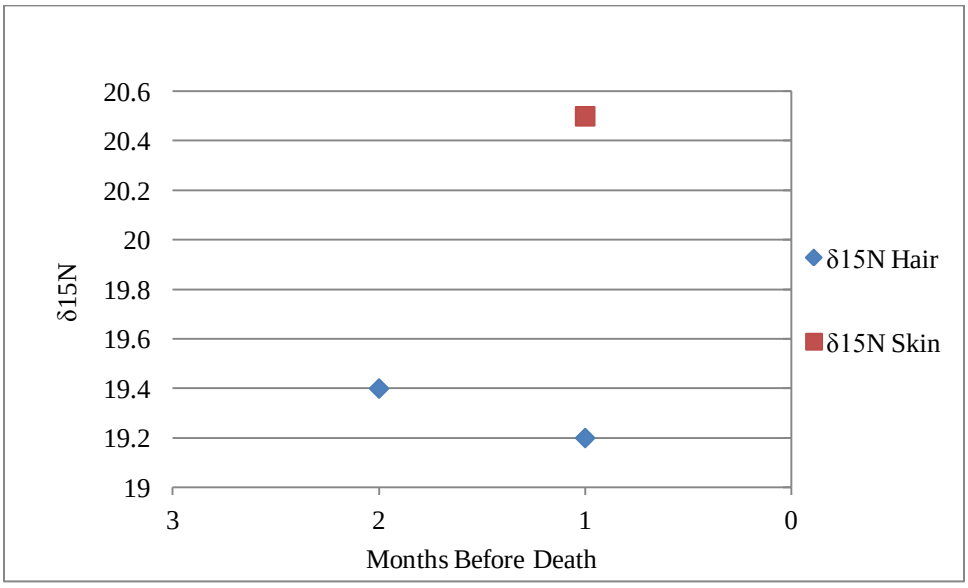


Figure 15: Scatter plot depicting short-term $\delta^{15}N$ values from B19

## Burial 21

The remains in B21 are estimated to be those of a 45 year old female with no pathologies. Her burial is located in the northwest section of the currently excavated part of Kellis 2 cemetery. The tissues available for B21 are $M^1$, $M^2$, bone collage, hair, and skin with the $\delta^{13}C$ and $\delta^{15}N$ values are noted in Table 4. These values are presented in a timeline of B21's life in Figure 16. Figures 17, 18, 19, and 20 present a comparison of these values with the population and the average female.

Table 4: B64's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -19.0 | 16.1 |
| M2 | -18.9 | 17.1 |
| Bone Collagen | -18.8 | 17.5 |
| Hair (2) | -19 | 17.6 |
| Hair (1) | -19.5 | 17.1 |
| Skin | -19.4 | 19.8 |

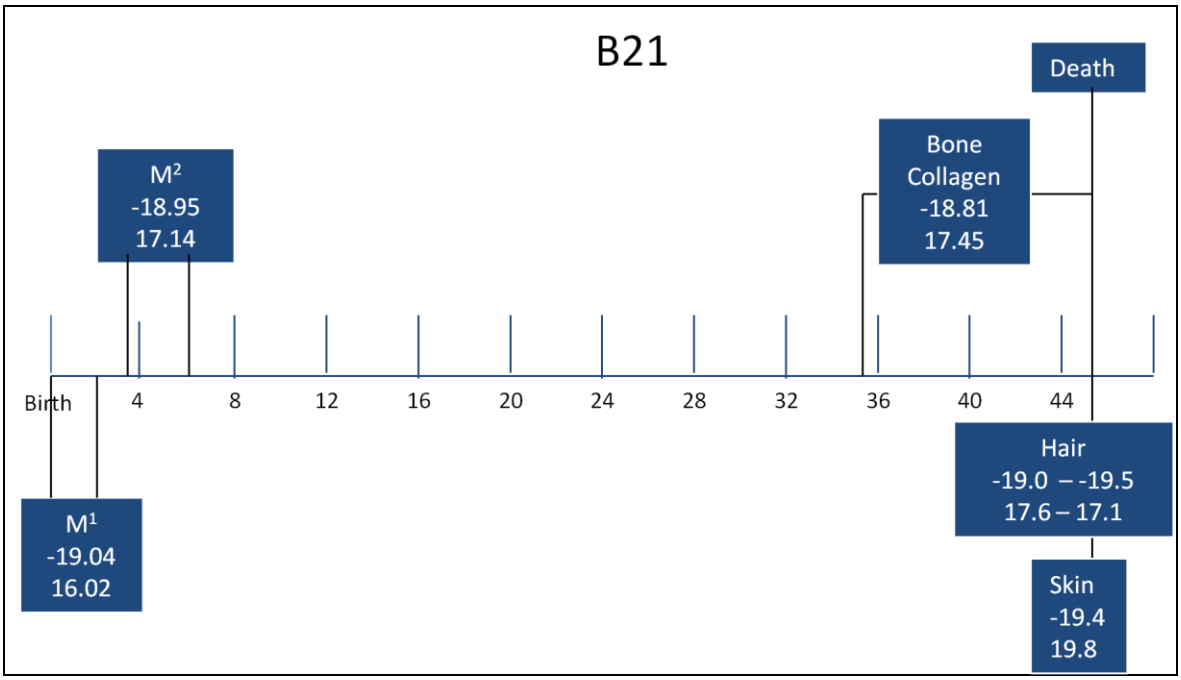


Figure 16: Timeline for B21 illustrating the ages each tissue represents

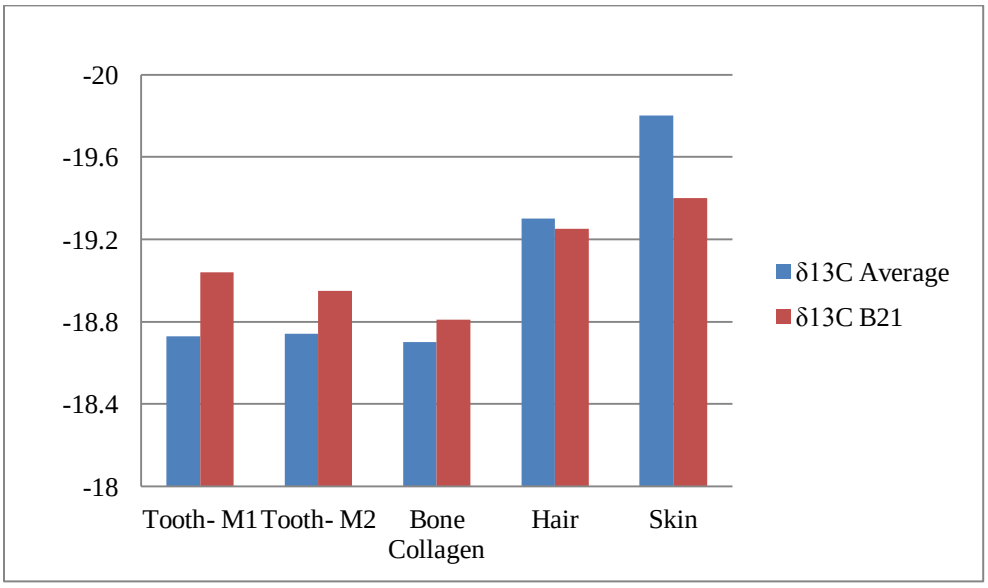


Figure 17: Graph comparing B21's $\delta^{13}C$ values with the rest of the population

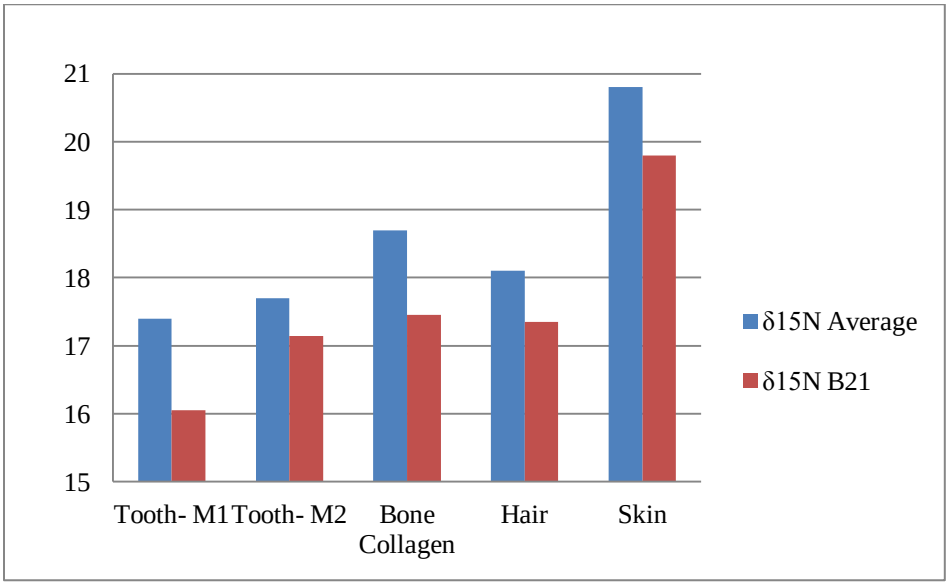


Figure 18: Graph comparing B21's $\delta^{15}N$ values with the rest of the population

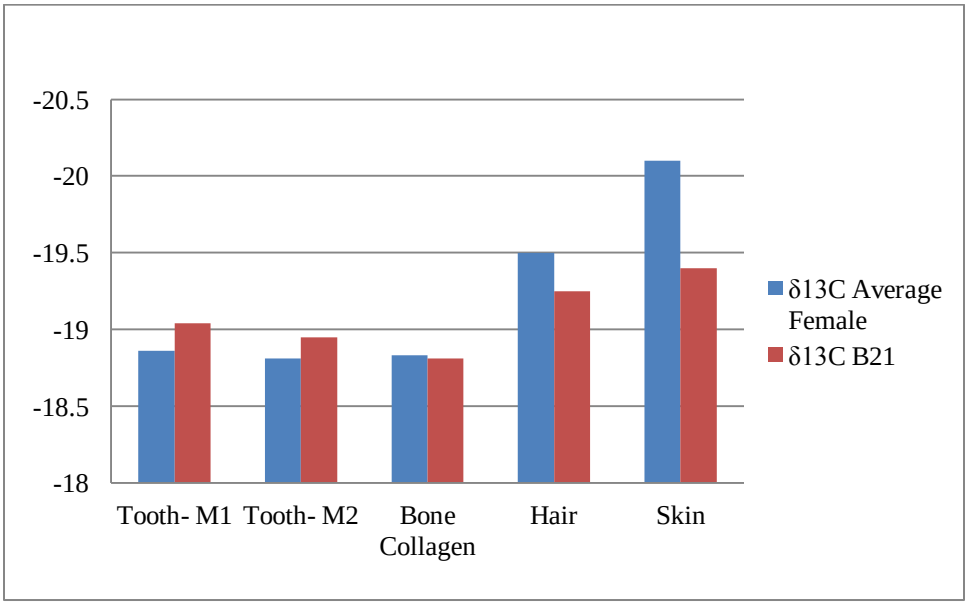


Figure 19: Graph comparing B21's $\delta^{13}C$ values with the average female

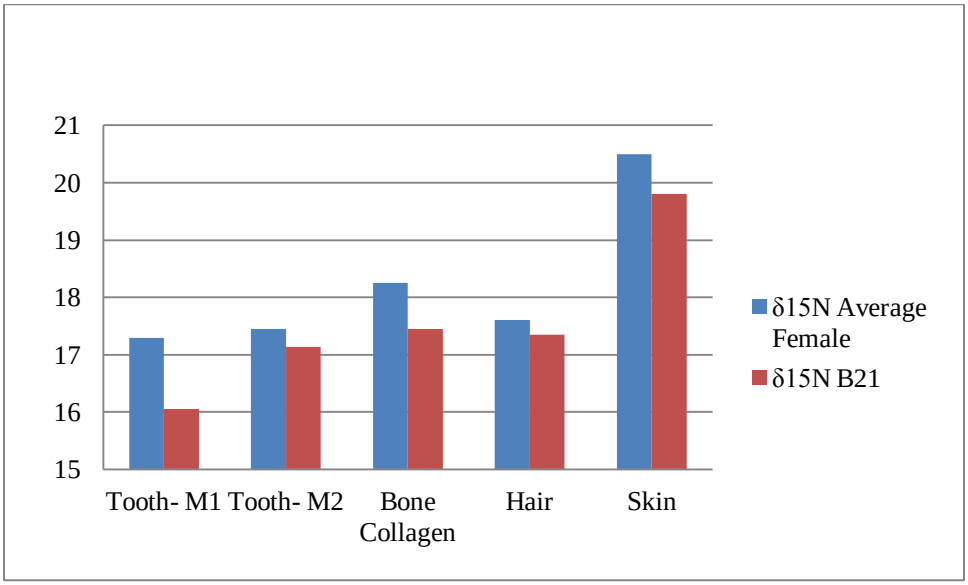


Figure 20: Graph comparing B21's $\delta^{15}N$ values with the average female

B21's long-term values are shown in Figure 21, and there is a distinct enrichment in $^{13}C$ over time. Her earliest value, $M^1$ (-19.0‰), represents birth - 2.5 years of age and is 0.3‰ lower than average (-18.7‰) and only 0.2‰ lower than the average female (-18.9‰). At this point she was consuming approximately 16.4% $C_4$ foods. By 3.8 – 6 years of age, the value enriches slightly, to -18.9‰, now 0.2‰ lower than average and 0.1‰ lower than the average female. By adulthood, as depicted by bone collagen (-18.8‰), she is 0.1‰ higher than average (-18.7‰), but in line with the average female (-18.8‰). She would have been consuming 17.9% $C_4$ foods; more millet and meat than in childhood.

Nitrogen values also became more enriched over time (Figure 22); from 16.1‰ at birth - 2.5 years of age, up to 17.1‰ by 3.8 – 6 years of age, and 17.5‰ in adulthood. All the values, however, are lower than averages of (17.4‰, 17.5‰, and 18.7‰). Her $M^1$ and bone collagen values are more than a standard deviation (±1.0‰ and ±1.6‰) lower than average. This may indicate that she was in ill health and recovering from illness or disease and in positive nitrogen balance, but with no recorded pathologies it is impossible to be certain. It is also possible that she spent time away from the Oasis, and thus her values reflected a less arid environment. Only oxygen isotope values could corroborate this theory.

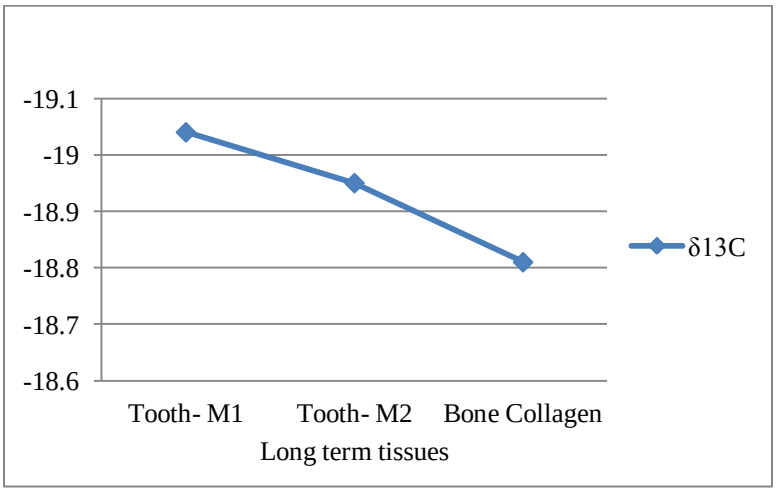


Figure 21: Line-graph depicting the long-term $\delta^{13}C$ values from B21

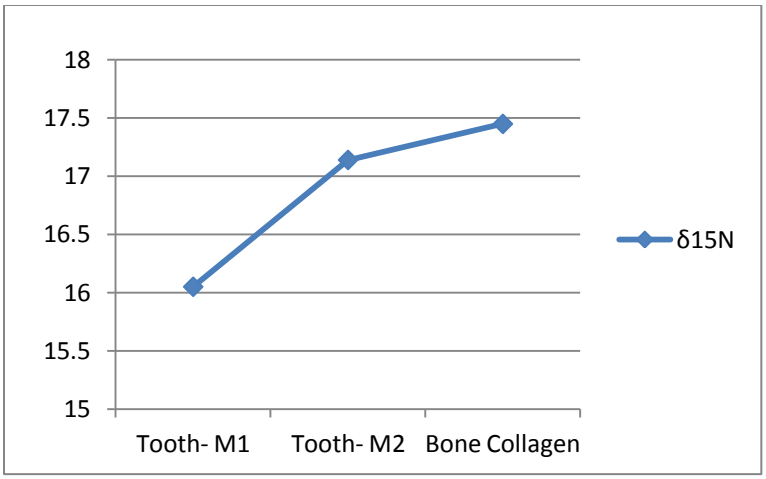


Figure 22: Line-graph depicting the long-term $\delta^{15}N$ values from B21

Only two hair samples and a skin sample are available to assess B21's life shortly before death and are shown in Figures 23 and 24. Her $\delta^{13}C$ hair values show that she began consuming less millet and meat right before death, as her value falls from -19.0‰ two months before death to -19.5‰ one month before death. Her grave azimuth of 74° and the decrease in her $\delta^{13}C$ value may suggest that she died in the spring months, when the spring wheat harvest began and the spring millet harvest had ended (Williams, 2008). Both values are very close to the average value of -19.3‰ for the population and -19.5‰ for the average female. Her skin value (-19.4‰) is also close to average (-19.8‰). All of B21's short-term $\delta^{15}N$ values are below the mean, although not significantly below the average female values. This trend is documented in both her long and short-term values. Her hair $\delta^{15}N$ value lowers by 0.5‰ one month before death.

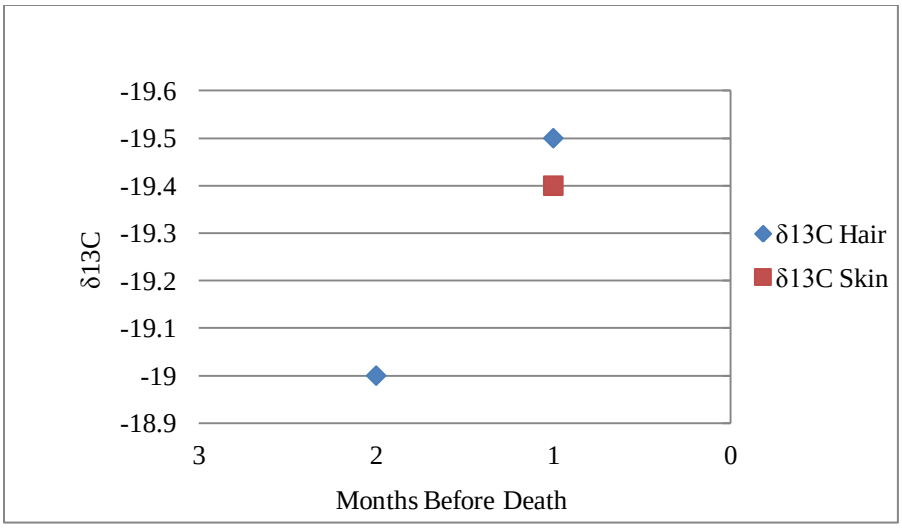


Figure 23: Scatter plot depicting short-term $\delta^{13}C$ values from B21

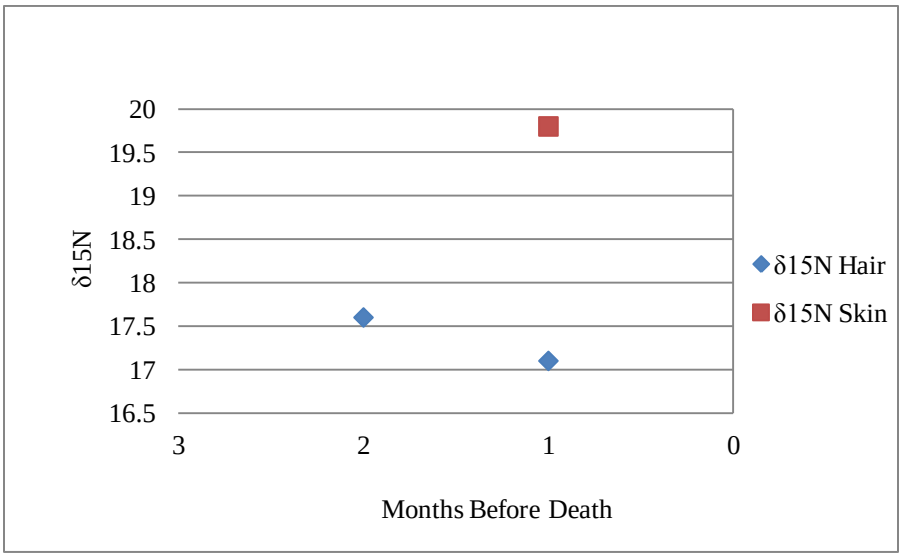


Figure 24: Scatter plot depicting short-term $\delta^{15}N$ values from B21

## Burial 26

Located in the northwestern section of the K2 cemetery and close to an excavated tomb structure, B26 is a 19 year old female with noted degenerative erosion of the left femoral and tibial medial condyles. B26 has isotope samples for $M^1$, $M^2$, $M^3$, bone collagen, six hair samples, and skin, as recorded in Table 5 and Figure 25. Figures 26 - 29 show B26's values compared with the population average and average female values.

Table 5: B26's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -18.8 | 16.9 |
| M2 | -18.8 | 17.9 |
| M3 | -19.3 | 18.6 |
| Bone Collagen | -18.7 | 18 |
| Hair (6) | -19.9 | 16.8 |
| Hair (5) | -19.8 | 16.5 |
| Hair (4) | -19.8 | 16.1 |
| Hair (3) | -19.7 | 15.9 |
| Hair (2) | -19.6 | 16 |
| Hair (1) | -19.5 | 15.7 |
| Skin | -19.8 | 24.5 |

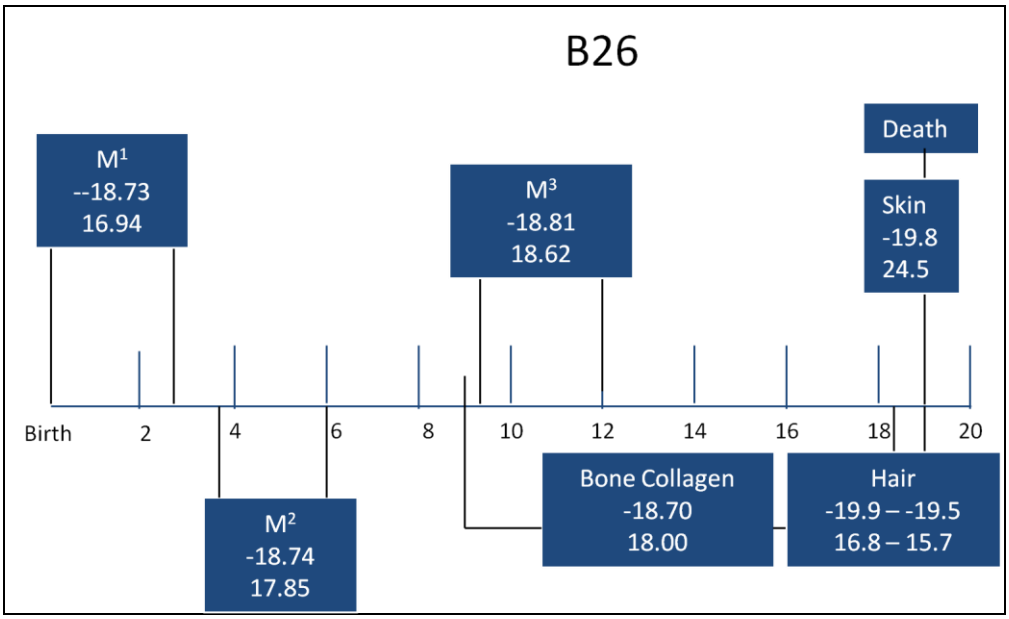


Figure 25: Timeline for B26 illustrating the ages each tissue represents

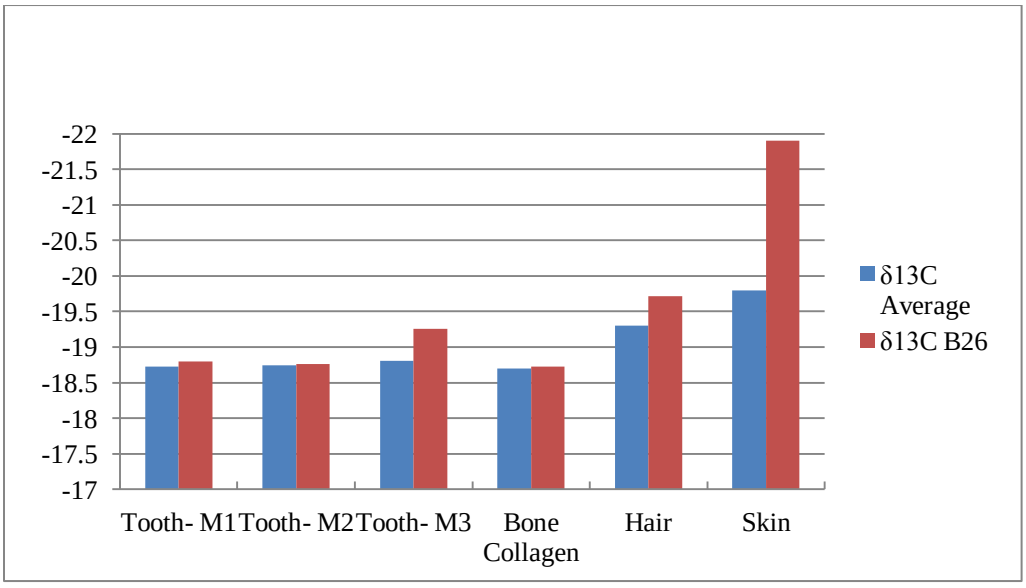


Figure 26: Graph comparing B26's $\delta^{13}C$ values with the rest of the population

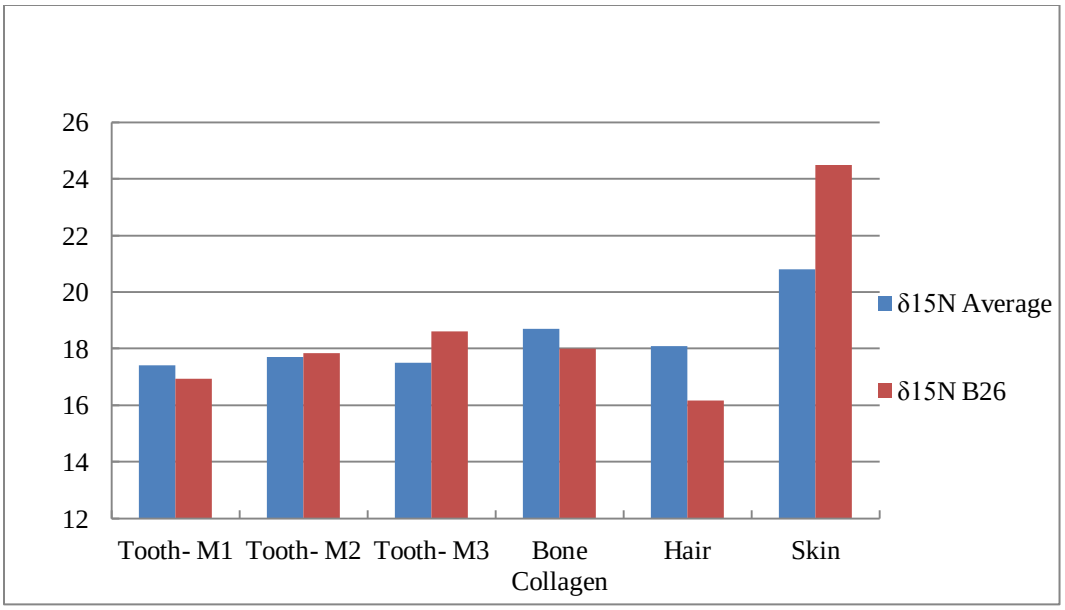


Figure 27: Graph comparing B26's $\delta^{15}N$ values with the rest of the population

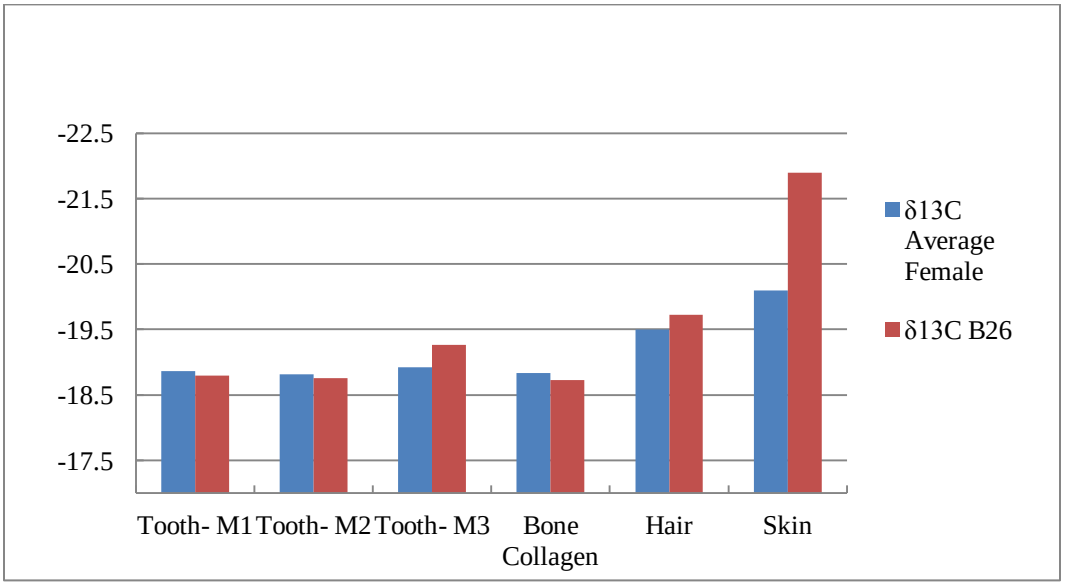


Figure 28: Graph comparing B26's $\delta^{13}C$ values with the average female values

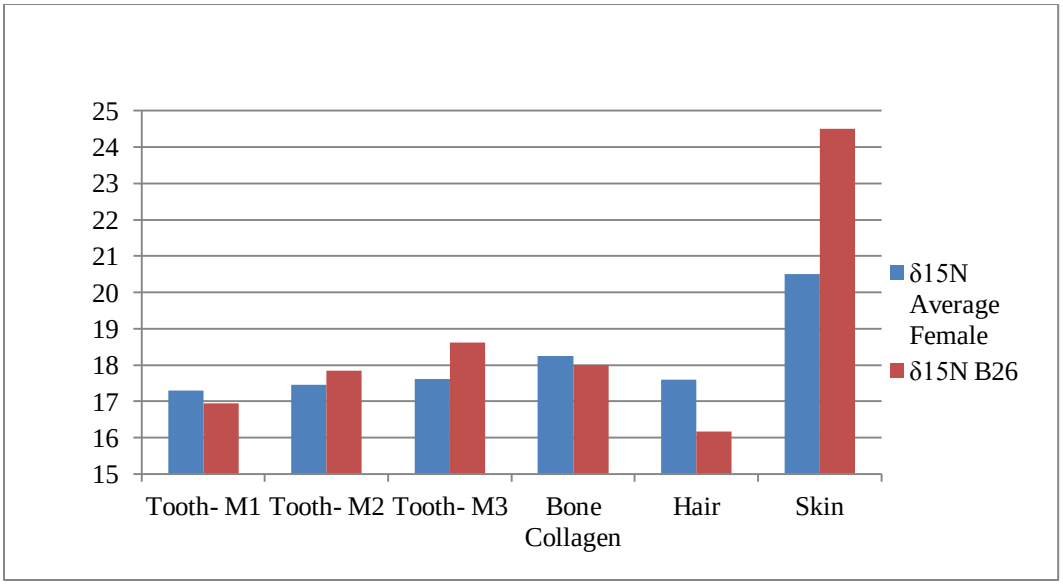


Figure 29: Graph comparing B26's $\delta^{15}N$ values with the average female values

B26's $M^1$ and $M^2$ $\delta^{13}C$ values (both -18.8‰), representing early and mid-childhood, are very close to the population average (-18.7‰) and the average female (-18.9‰) values (Figure 30). She was consuming approximately 18 - 18.3‰ $C_4$ foods during this time. Her $M^3$ values drops to -19.3 ‰, when she was approximately 9.5 - 12 years old. This indicates that when this tooth formed, B26 was only consuming 14.9% $C_4$ foods (millet and meat). In comparison, population averages indicate that less $C_4$ foods are consumed at this age than in early childhood, although B26's values are somewhat lower than both the population average (18%), and the average female (17.2%). Interestingly, her bone collagen value, which is long term but represents late childhood and adolescence, becomes more enriched than average at -18.0‰. This is the only $\delta^{13}C$ value from B26 that is higher than average (-18 7‰), but it does represent the longest time period, ages 9 – 19.

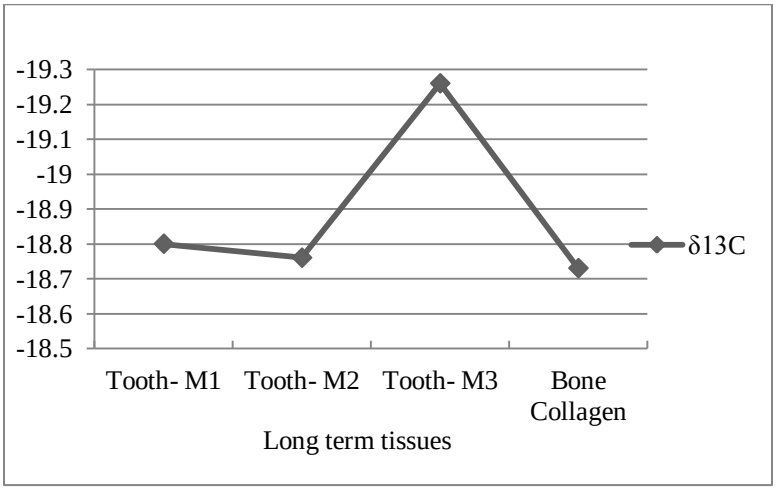


Figure 30: Line-graph depicting the long-term $\delta^{13}C$ values from B26

Long term nitrogen values for B26 show a marked enrichment from $M^1$ (16.9‰) to $M^2$ (17.9‰) to $M^3$ (18.6‰) (Figure 31). The population averages for $M^1$ (17.4‰) and $M^2$ (17.5‰) $\delta^{15}N$ values indicate that $M^1$values are approximately the same than those for $M^2$, which is surprising given the age at which the dentin forms in these teeth. B26's $M^1$ value is much lower than the averages of 17.4‰. This may indicate migration from elsewhere, but would have to be corroborated with other evidence, such as $^{18}0$ isotope analysis. Her $M^2$ $\delta^{15}N$ value rises to 17.9‰, which is actually slightly above average (17.5‰). $M^3$, formed at 9.5 – 12 years of age, increases to 18.62‰, almost a standard deviation (± 1.0‰) higher than the mean of 17.7‰. This may indicate that some sort of illness ailed her at this time. Her bone collagen $\delta^{15}N$ value, however, representing the last 10 years of her life is 18.0‰, 0.7‰ lower than the average (18.7‰).

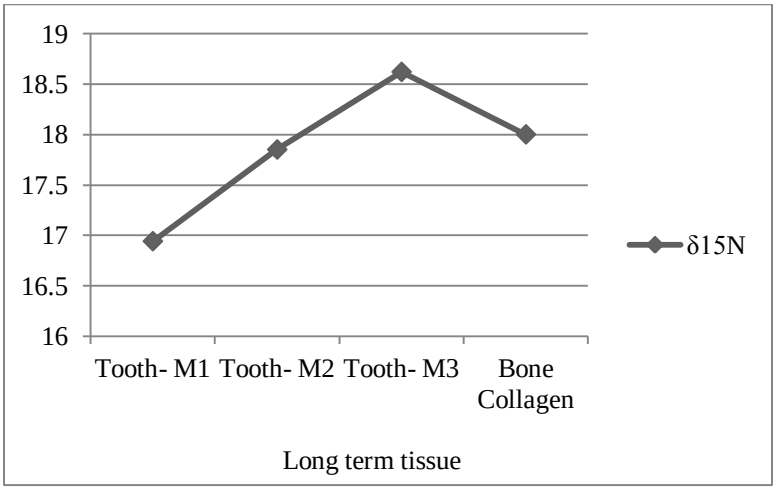


Figure 31: Line-graph depicting the long-term $\delta^{15}N$ values from B26

In the six months prior to death, there is a steady enrichment in B26's $\delta^{13}C$ values (Figure 32). In the six hair samples that are available, values rise from -19.9‰ - -19.5‰, increasing approximately 0.1‰ per month. Due to the small increase overall, this may not be significant. These values are all close to the population $\delta^{13}C$ average value of -19. 3‰ and average female $\delta^{13}C$ value of -19.5‰, and indicate that B26 was consuming from between 37.3% - 17.3% $C_4$ foods six months before death, and 40% – 20% $C_4$ foods one month before death. Her skin value of -21.9‰, however, is much higher than the average value of -19.8‰ The enrichment before death and a grave azimuth of 72° suggests that B26 most likely died in the early summer, after the spring wheat harvest and in the midst of the summer millet harvest (Williams, 2008). This would explain the enrichment in $\delta^{13}C$ values before death.

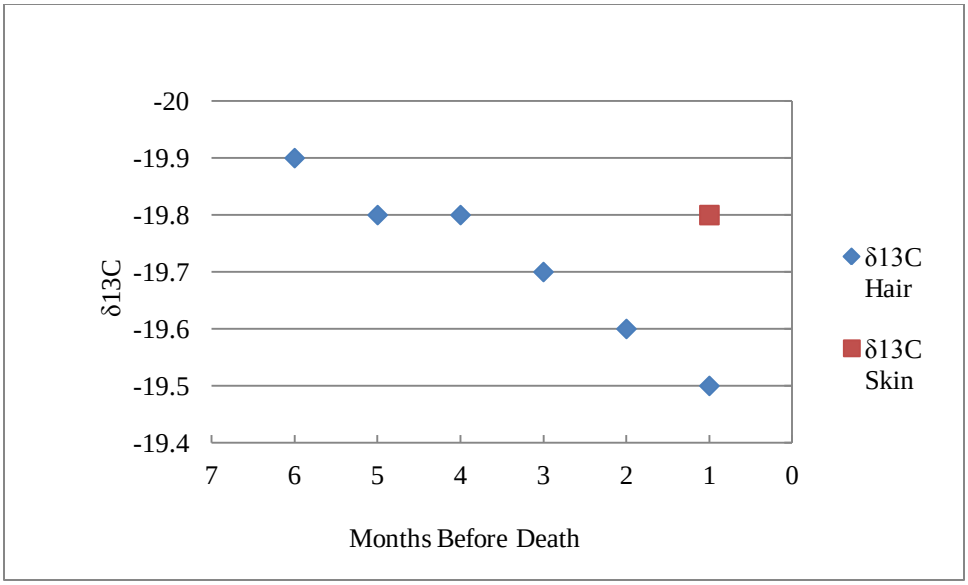


Figure 32: Scatter plot depicting short-term $\delta^{13}C$ values from B26

B26's short-term $\delta^{15}N$ tissue values show a distinct decrease in the months before B26's death (Figure 33 and 34). Figure 34 is a more detailed graph showing how the hair $\delta^{15}N$ values decrease over time, from 16.8‰ down to 15.7‰ in six months. These values, even at six months before death are well below the population $\delta^{15}N$ average value of 18.1‰, with the last three values over 3 standard deviations (0.7‰) away from the mean. Positive nitrogen balance with a trend of longitudinally decreasing $\delta^{15}N$ values has been associated with pregnancy and B26 would have been of childbearing age (Fuller et al., 2005). While this cannot be corroborated, it is a distinct possibility, given her age and lack of skeletal lesions. Negative nitrogen with low values has been associated with periods of extreme stress, such as a fracture event. No fractures are visible on the skeleton, however, and the values never raise indicating re-growth. Positive nitrogen balance can be cause by conditions such as the healing of an injury and result in low

values. Without further evidence, it cannot be said for certain what caused the decreasing $\delta^{15}N$ values in the months before death. Her skin value is 24.5‰, much higher than the average of 20.5‰, again the opposite of the trend seen in the hair.

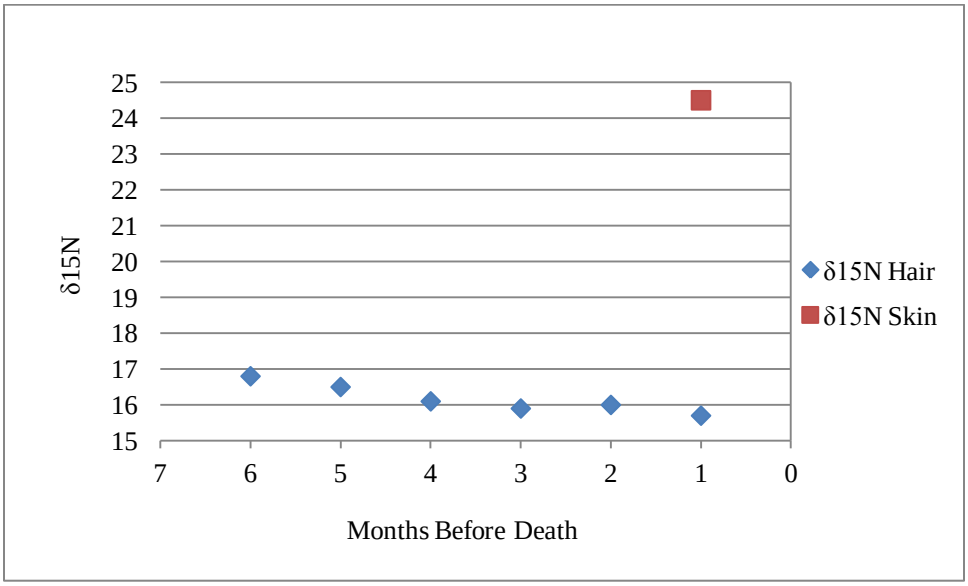


Figure 33: Scatter plot depicting short-term $\delta^{15}N$ values from B26

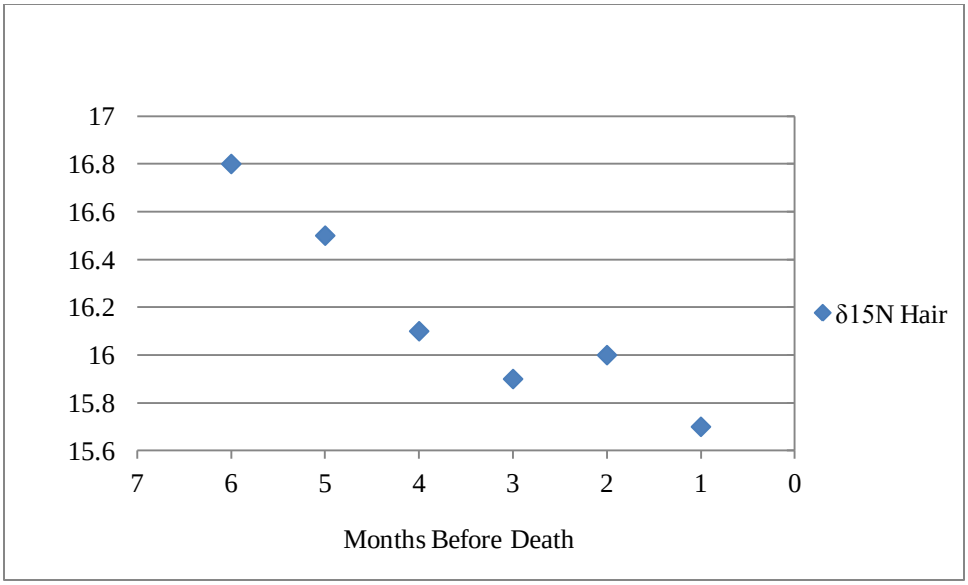


Figure 34: Scatter plot depicting hair $\delta^{15}N$ values from B26

## Burial 64

A young child aged 7 ± 2 years with no pathologies was located in Burial 64, in the north-west section of the cemetery. The tissues available for analysis include $dm^1$, $dm^2$, $M_1$, C, $PM_1$, $PM_2$, $M_2$, bone collagen, hair, nails, and skin. Table 6 displays all of B64's $\delta^{13}C$ and $\delta^{15}N$ values and Figure 35 presents a timetable which shows the time periods that each tissue represents. Because B64 was only 7 years old at death, some of his/her long term tissues and short term tissues are close in proximity. B64's values are compared to the population means in Figures 36 and 37.

Table 6: B64's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| $m_1$ | -17.5 | 19.9 |
| $m_2$ | -17.9 | 20.9 |
| $M_1$ | -18.2 | 17.9 |
| C | -18.3 | 18.2 |
| $PM_1$ | -18.7 | 17.9 |
| $PM_2$ | -19.1 | 17.9 |
| $M_2$ | -17.8 | 17.4 |
| Bone Collagen | -19.0 | 18.0 |
| Hair (2) | -19.6 | 17.5 |
| Hair (1) | -19.7 | 19.1 |
| Distal Nail | -19.9 | 15.9 |
| Proximal Nail | -19.9 | 18.6 |
| Skin | -20.0 | 22.5 |

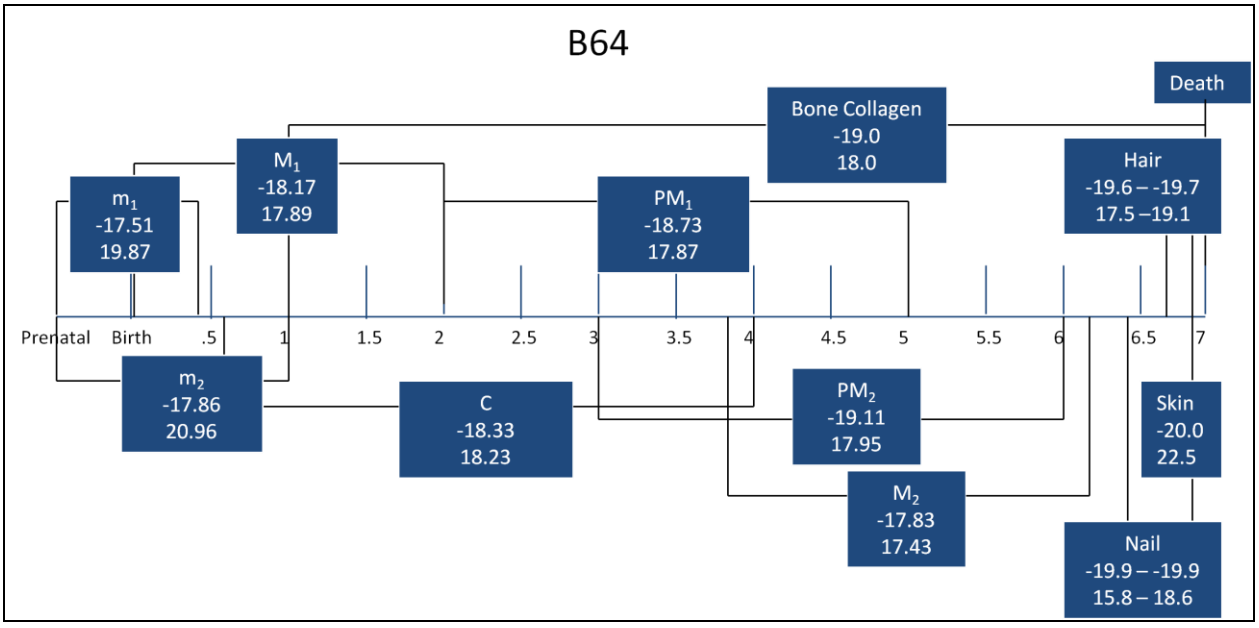


Figure 35: Timeline for B64 illustrating the ages each tissue represents

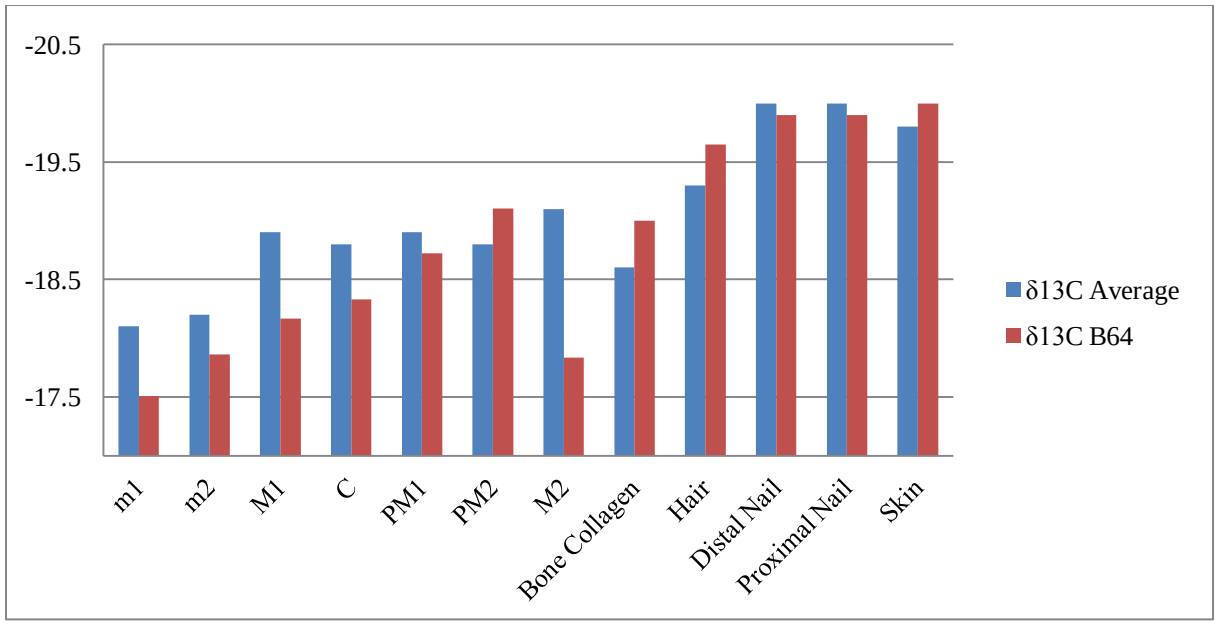


Figure 36: Graph comparing B64's $\delta^{13}C$ values with the rest of the population $\delta^{13}C$ average values

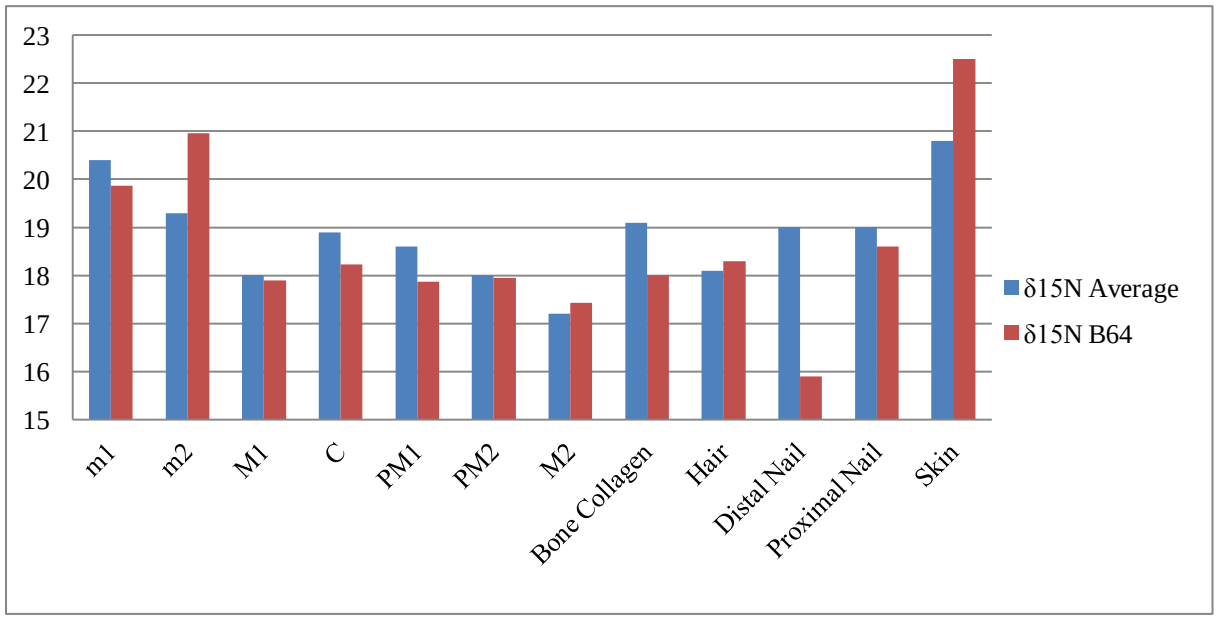


Figure 37: Graph comparing N64's $\delta^{15}N$ values with the rest of the population $\delta^{15}N$ average values

B64's long term $\delta^{13}C$ values are displayed in Figure 38 and show a distinct negative trend in relationship to age. His/her earliest $\delta^{13}C$ value is $dm_1$ (-17.5‰) that begins to form prenatally until about 4 months of age. The values slowly become less enriched until the $PM_2$ (ages 3 – 6) reaches a low point at -19.1‰, a total decrease of 1.6‰, indicating that at birth B64 was consuming as much as 26.7% $C_4$ foods early in life and 15.9‰ $C_4$ foods by age 3 - 6. This decrease of $\delta^{13}C$ values from birth through age 3 perfectly illustrates the trend documented in Dupras (1999), Dupras et al. (2001), and Dupras and Tocheri (2007) whereby infants and young children have higher $\delta^{13}C$ values than the rest of the population, which fall gradually until age three when they become consistent with the rest of the population. This is due to a $^{13}C$ trophic level effect seen in breastfeeding children, and may also reflect a weanling diet consisting of goat/cow's milk and millet gruel. After $PM_2$, the $M_2$ value rises to -17.8‰, an entire standard deviation (1.1‰) away from the mean value of -19.1‰. His/her $M_2$ value represents ages 3.8 – 6, but due to the overlapping ages with $PM_2$, it is likely that this sudden rise in $^{13}C$ enrichment occurred closer to age 6. At this point in time he/she was consuming 24.5% $C_4$ foods, much higher than the population average. The value once again falls with bone collagen to -19.0‰. However, it must be noted that this does not truly depict a fall in $^{13}C$, because bone collagen While bone turnover rate is faster in juveniles, it still represents almost the entirely of B64's life and thus spans over many of the other values.

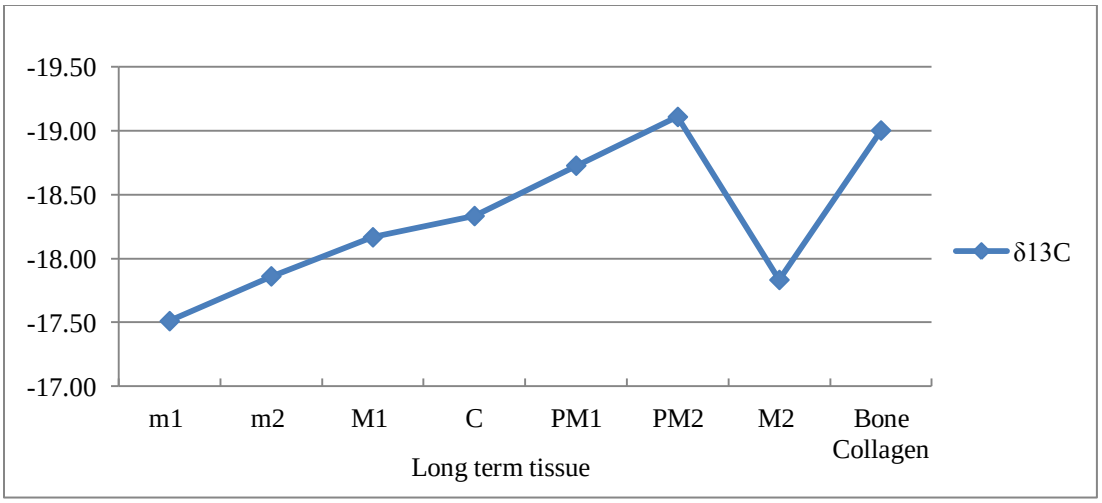


Figure 38: Line-graph depicting the long-term $\delta^{13}C$ values from B64

The long term $\delta^{15}N$ values show an inverse correlation, with values becoming less enriched over time (Figure 39). The child's earliest deciduous $\delta^{15}N$ values ($m_1$ and $m_2$) are the highest at 19.9‰ and 20.9‰. The values then fluctuate a little throughout ages 1 - 6, before finally reaching a low of 17.4‰ with $M_2$. Dupras (1999), Dupras et al. (2001), and Dupras and Tocheri (2007) found that there is a $^{15}N$ trophic level effect in breastfeeding infants in the Dakhleh Oasis, that peaks after birth and gradually declines until age 3, as seen in B64. Once again the bone collagen $\delta^{15}N$ value rises, but as stated above, it represents six of B64's seven years. Most of B64's $\delta^{15}N$ values are consistent with the population $\delta^{15}N$ average values, except for $m_2$ , corresponding with the prenatal period through one year, which is over a standard deviation (1.4‰) higher than the mean (19.3‰). Teeth $m_1$, $M_1$, and C all overlap with this timeframe and are typical, meaning that this high $\delta^{15}N$ value which could be due to some sort of acute, short lived illness.

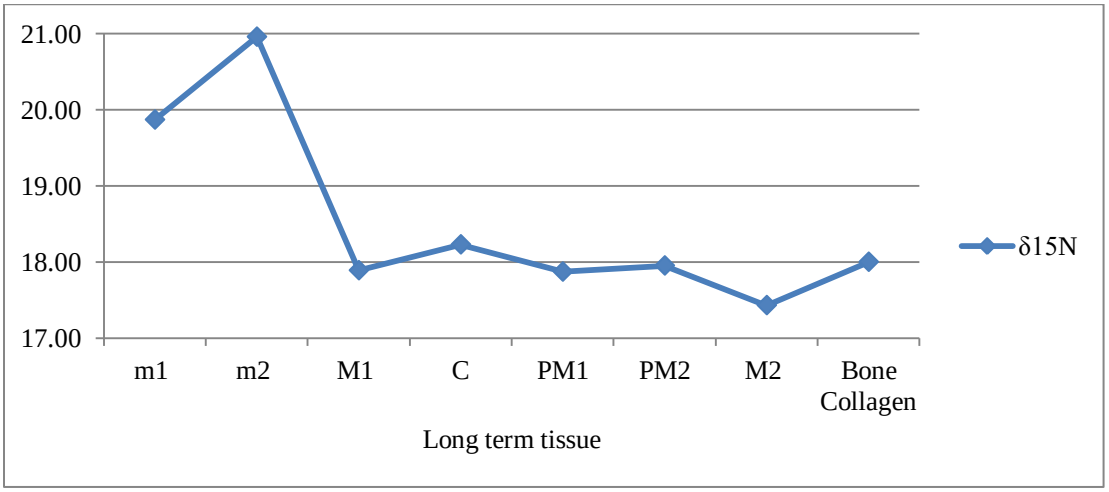


Figure 39: Line-graph depicting the long-term $\delta^{15}N$ values from B64

B64's short term $\delta^{13}C$ values show little to no change and are all very close to the mean population $\delta^{13}C$ values (Figure 40). His/her hair values only decreases one tenth, -19.6‰ to -19.7 ‰, from the distal sample to the proximal sample and are close to the population $\delta^{13}C$ average value (-19.3‰). The proximal and distal nail samples are the same at -19.9‰ and close to the population $\delta^{13}C$ mean of -20‰. The skin sample (-20‰) is also very close to the population $\delta^{13}C$ mean of -19.8‰. Therefore, not much can be said about his/her diet right before death other than the fact that he/she was consuming between 17.3% and 37.3% $C_4$ foods, or millet/meat, in the six months before death.

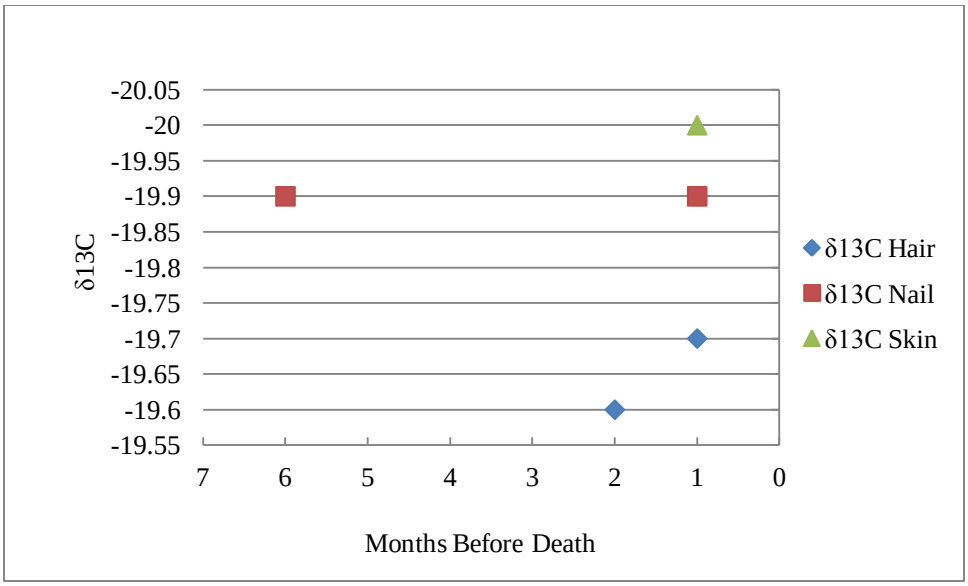


Figure 40: Scatter plot depicting short-term $\delta^{13}C$ values from B64

B64's $\delta^{15}N$ values, on the other hand, show a distinct enrichment. Figure 41 shows that the hair $\delta^{15}N$ values increase from 17.5‰ to 19.1‰, from below average to above average, and the nail $\delta^{15}N$ values from 15.9‰ to 18.6‰. The distal nail $\delta^{15}N$ value (15.9‰, six months before death) is over two standard deviations (1.2‰) below the population mean $\delta^{15}N$ value (19.0‰) and then increases to just below the population mean $\delta^{15}N$ value. Her skin value is 22.5‰, 1.7‰ above average. The low $\delta^{15}N$ value, then sharp increase right before death, has been documented in other individuals and is likely indicative of the presence of some sort of acute disease or metabolic disturbance that did not leave any visible evidence on the remaining skeleton. In children, illness quickly results in negative body nitrogen balance, as seen here, and usually persists until death (Beisel, 1975; Williams, 2011).

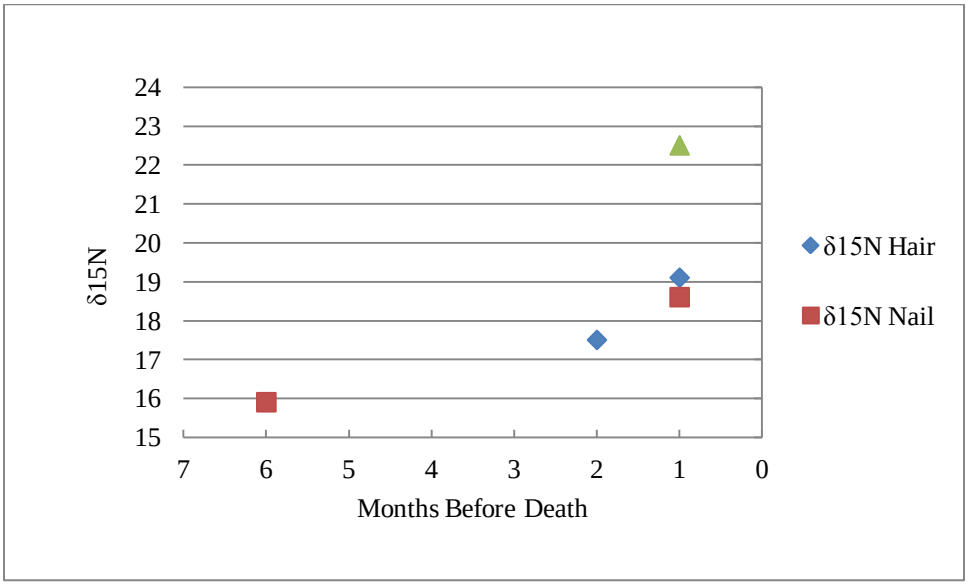


Figure 41: Scatter plot depicting short-term $\delta^{15}N$ values from B64

## Burial 81

Burial 81 contained the remains of an approximately 40 year old male, and it is located in the western half of the cemetery. It is noted that this individual had anklyosing spondilitis, which is an inflammatory disease that affects the spine and pelvis, eventually causing the joints to fuse together (Aufderheide and Rodriguez-Martin, 1998). It is noted that B81's sacrum is fused to the L5 vertebra. Tissues available for analysis include $M^1$, bone collagen, three hair samples, and skin. These values can be seen in Table 7 and his timeline in Figure 42. Charts plotting values against population averages are available in Figures 43 – 46.

Table 7: B81's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -18.6 | 16.5 |
| Bone Collagen | -18.7 | 18.1 |
| Hair (3) | -19.5 | 18 |
| Hair (2) | -19.5 | 18.4 |
| Hair (1) | -19.4 | 18.3 |
| Skin | -18.9 | 20 |

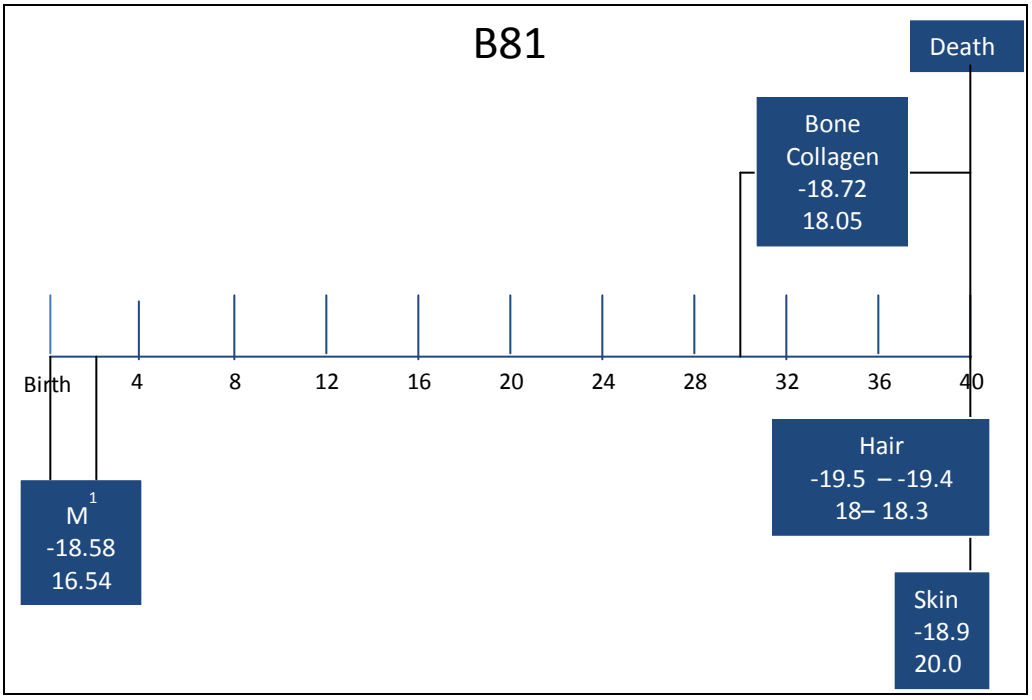


Figure 42: Timeline for B81 illustrating the ages each tissue represents

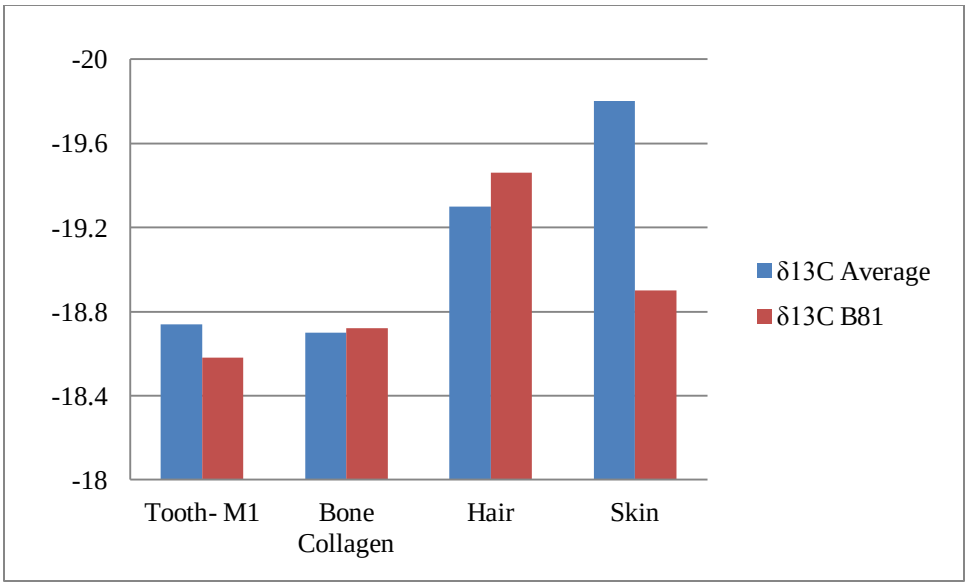


Figure 43: Graph comparing B81's $\delta^{13}C$ values with the rest of the population

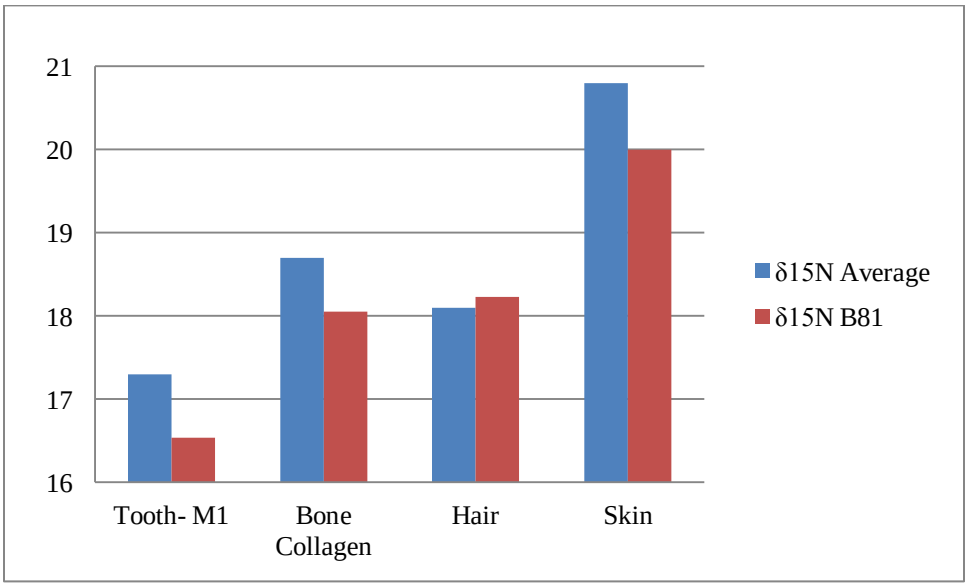


Figure 44: Graph comparing B81's $\delta^{15}N$ values with the rest of the population

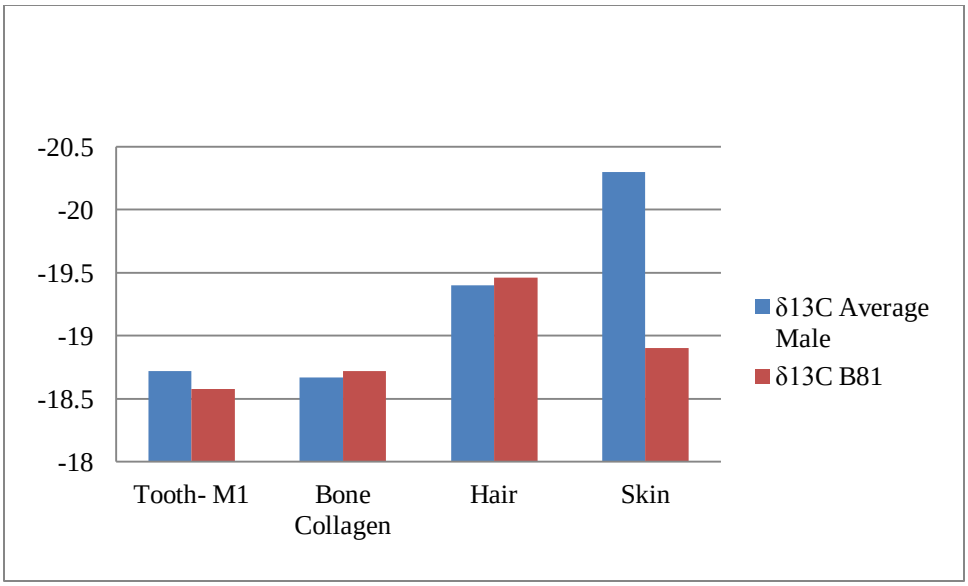


Figure 45: Graph comparing B81's $\delta^{13}C$ values with the average male values

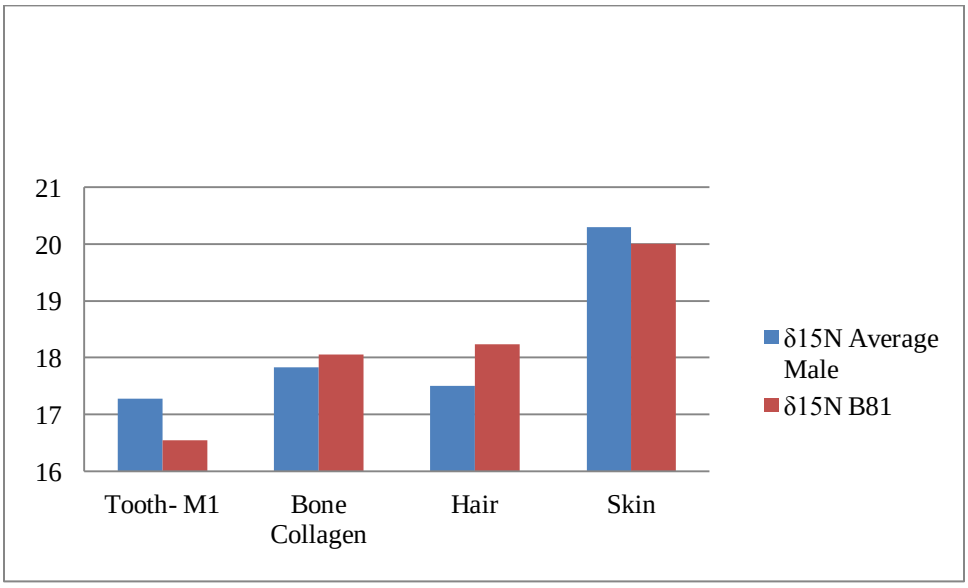


Figure 46: Graph comparing B81's $\delta^{15}N$ values with the average male values

The only two tissues available for long term analysis are $M^1$ and bone collagen (Figures 47 and 48). This gives a very limited perspective of B81's life; $M^1$ represents very early childhood and bone collagen ages 30 – 40. His $\delta^{13}C$ values (-18.9‰ and -18.7‰) are both very close to the population (-18.7‰ and -18.7‰) and average male values (-18.7‰ and -18.7‰). He was consuming around 19.5% $C_4$ foods from birth - age 2, and 18.5% C4 foods in the last ten years of his adulthood. This is a larger drop than is seen in the average population $\delta^{13}C$ value and is the opposite of the average male $\delta^{13}C$ value, whom typically shows $^{13}C$ enrichment with the bone collagen value in adulthood. Over the same time period his $\delta^{15}N$ values rise by 1.51‰, from 16.5‰ to 18.1‰. Both values are lower than the population average (17.3‰ and 18.7‰), although his bone collagen value is not lower than the average male $\delta^{13}C$ value (17.8‰), who show lower $\delta^{15}N$ values in general.

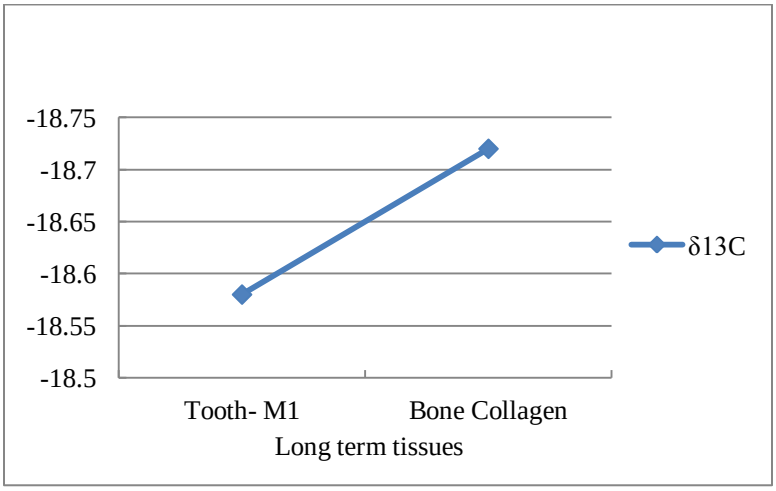


Figure 47: Line-graph depicting the long-term $\delta^{13}C$ values from B81

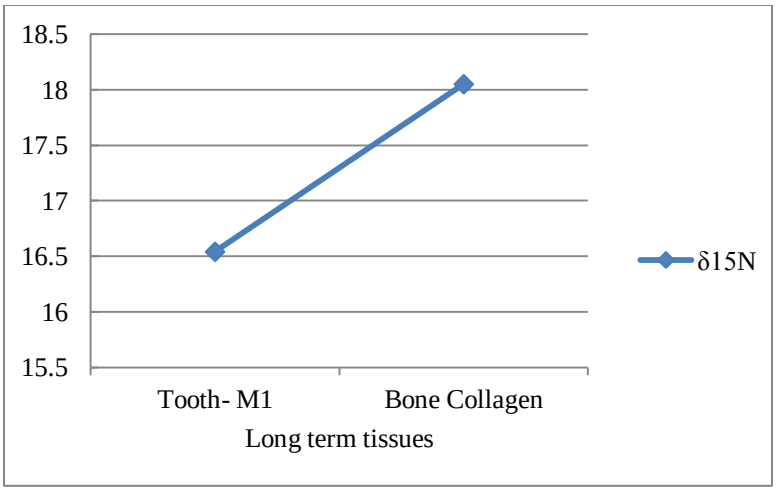


Figure 48: Line-graph depicting the long-term $\delta^{15}N$ values from B81

Overall, short term values do not show much fluctuation in $\delta^{13}C$ or $\delta^{15}N$ values (Figures 49 and 50). Hair $\delta^{13}C$ values (-19.5‰, -19.5‰ and -19.4‰) only drop 0.1‰ in the three months before death and are all close to the population average $\delta^{13}C$ value of -19.3‰ and the average male $\delta^{13}C$ value of -19.4‰. He was consuming between 20 - 40.6% $C_4$ foods before death. His $\delta^{13}C$ skin value (-18.9‰) is 0.9‰ higher than average (-19.8‰). His hair $\delta^{15}N$ values increase before death, from 18.0‰ three months before death, to 18.3‰ and 18.4‰ one and two months before death. This shift, however, is not large. The $\delta^{15}N$ hair values are consistent with the population $\delta^{15}N$ average value of 18.1‰, but higher than the average male's $\delta^{15}N$ mean value of 17.5‰. His skin value, at 20‰, is 0.8‰ lower than average (20.8‰). These values show little evidence of prolonged disease or even acute illness, even though this individual showed signs of anklyosing spondylitis. B81 may have died suddenly and therefore his values were not affected.

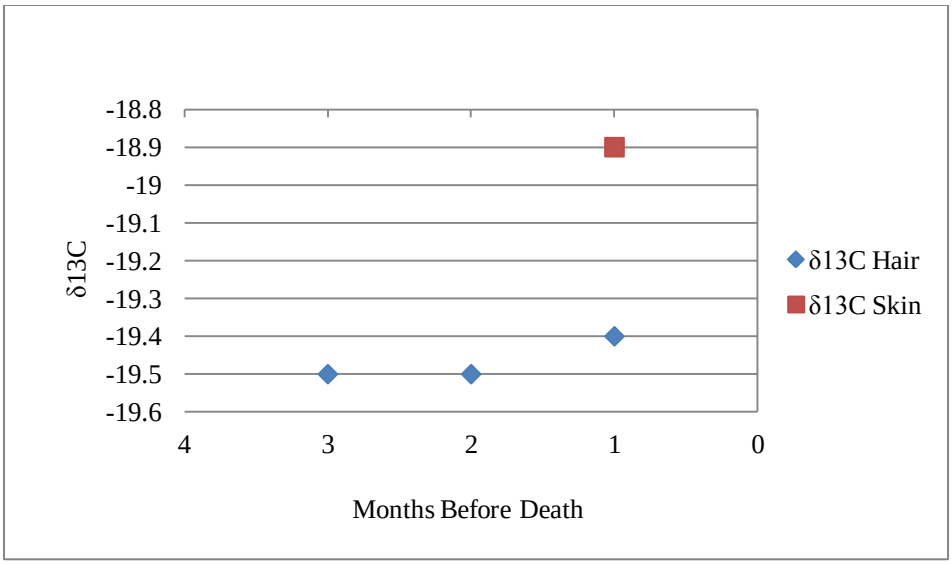


Figure 49: Scatter plot depicting short-term $\delta^{13}C$ values from B81

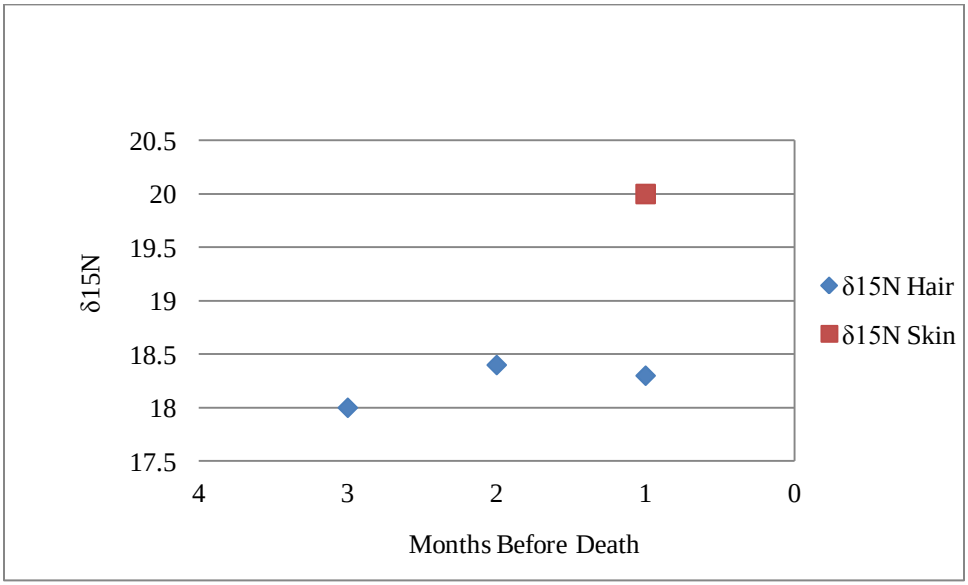


Figure 50: Scatter plot depicting short-term $\delta^{15}N$ values from B81

## Burial 91

Burial 91, which is located in the northwestern area of the excavated cemetery, contains a female who was approximately 55 ± 14.6 years old at her time of death. Noted pathological conditions include osteomas and spina bifida occulta, both of which are benign. Osteomas are benign bone tumors typically found on the skull, and spina bifida occulta consists of incomplete fusion of the posterior neural arch and is a mild form of the disease which produces little no symptoms (Jackson et al., 1977; Aufderheide and Rodriguez-Martin, 1998). Neither of these conditions would have effected B91 in life or been related to her death. The samples collected for B91 include $M^1$, $M^2$, $M^3$, bone collagen, 4 hair samples, proximal and disal nail, skin, and gut content. Her $\delta^{13}C$ and $\delta^{15}N$ values are displayed in Table 8. Figure 51 shows a timline for B91, and graphs showing comparisons of B91's isotopic values with population and female mean values are shown in Figures 52 - 55.

Table 8: B91's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -18.8 | 16.8 |
| M2 | -19.3 | 17.2 |
| M3 | -19.0 | 17.1 |
| Bone Collagen | -18.8 | 18.4 |
| Hair (4) | -19.3 | 17.7 |
| Hair (3) | -19.5 | 17.9 |
| Hair (2) | -19.4 | 17.9 |
| Hair (1) | -19.5 | 18.3 |
| Proximal Nail | -20.2 | 18.6 |
| Distal Nail | -20 | 17.6 |
| Skin | -19.8 | 19.9 |
| Gut Content | -23.8 | 26.5 |

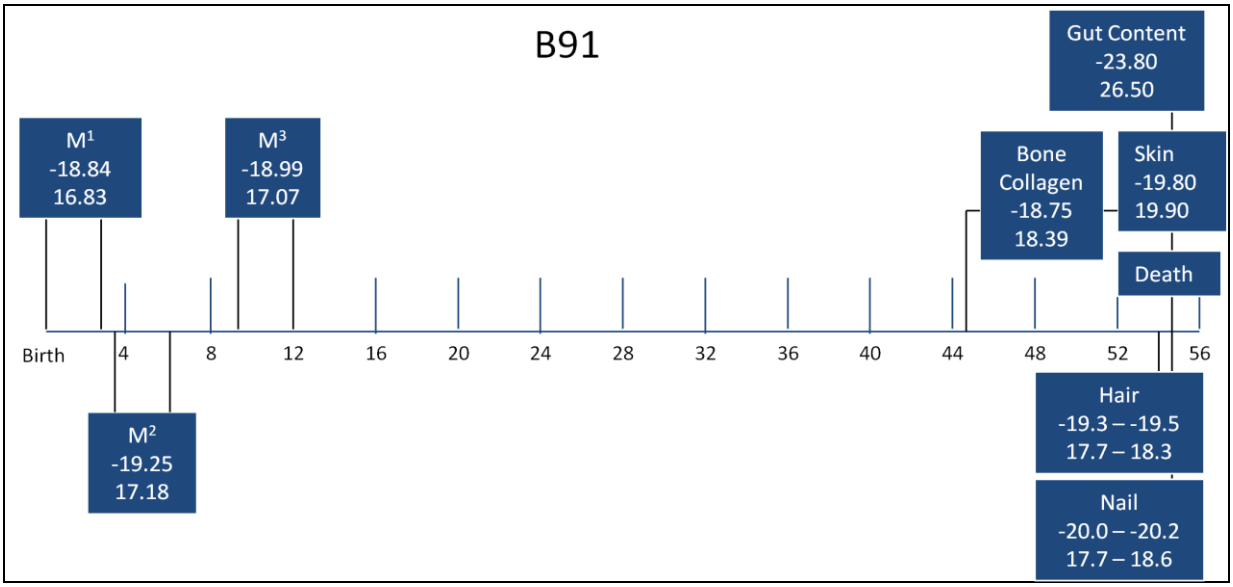


Figure 51: Timeline for B91 illustrating the ages each tissue represents

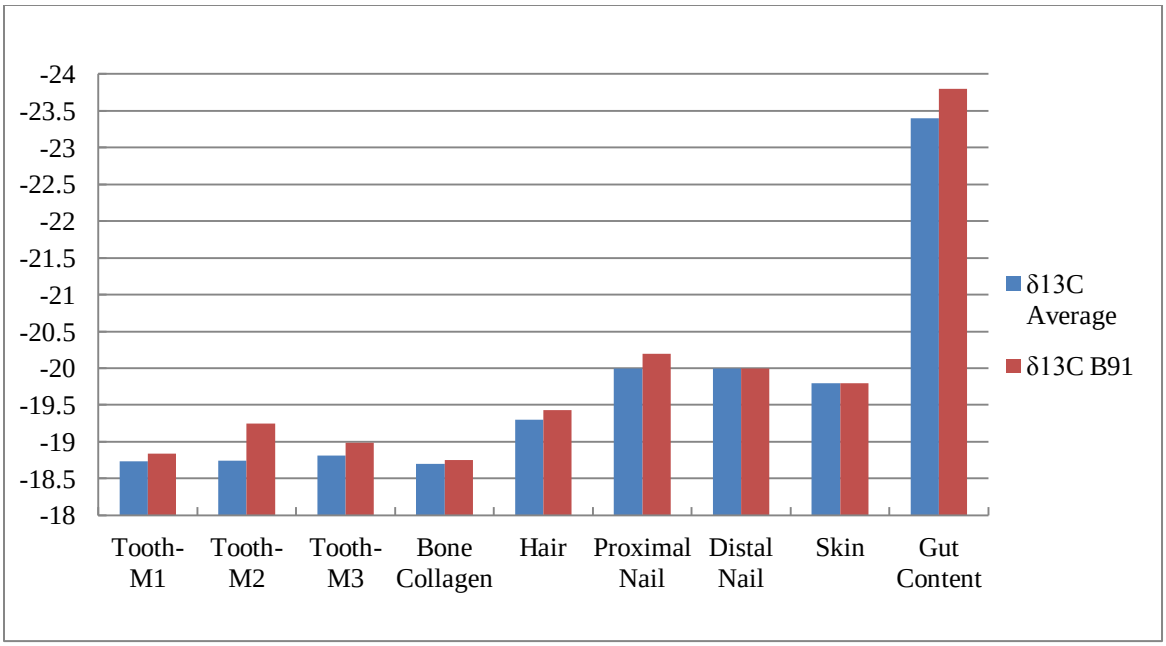


Figure 52: Graph comparing B91's $\delta^{13}C$ values with the rest of the population average values

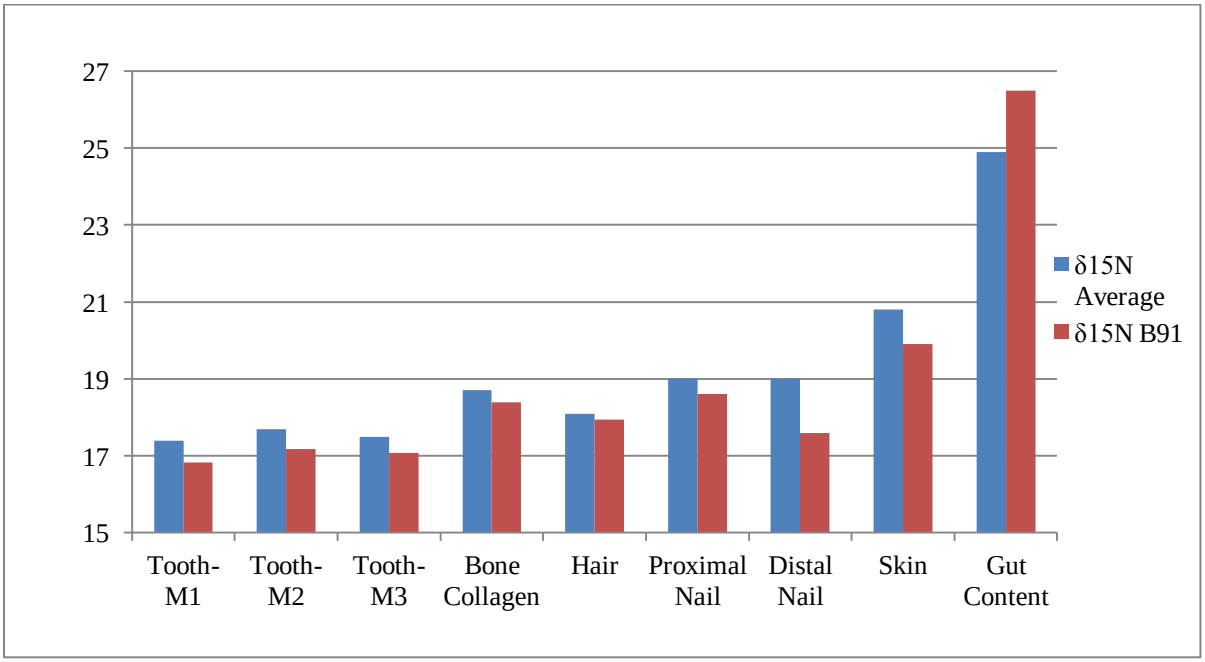


Figure 53: Graph comparing B91's $\delta^{15}N$ values with the rest of the population average values

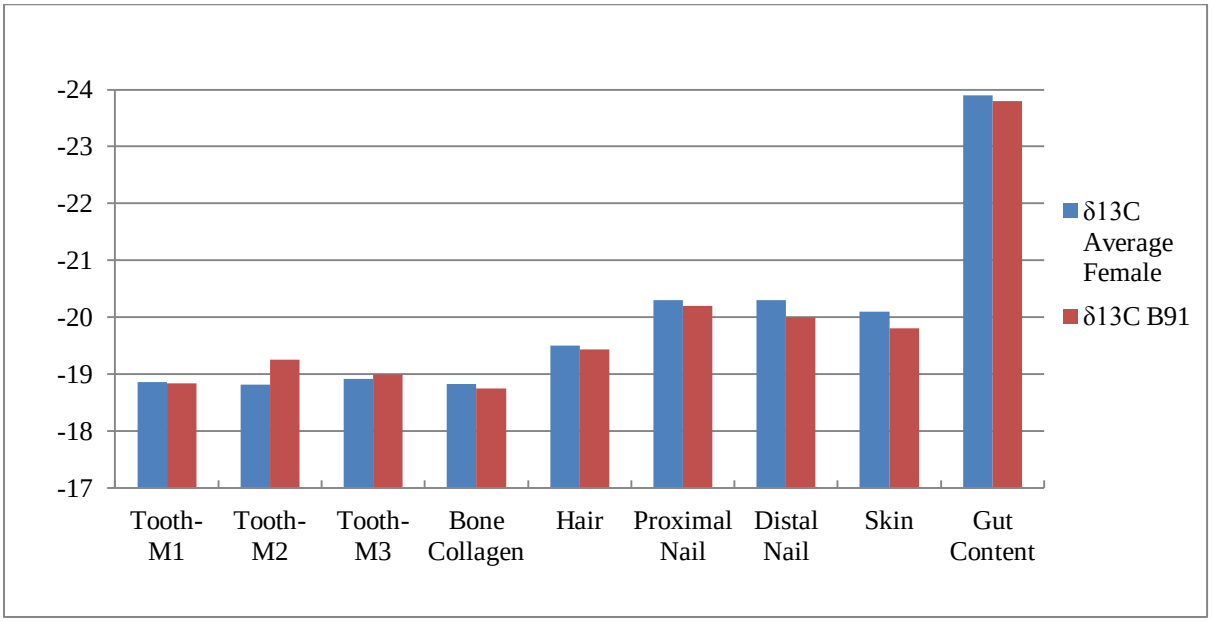


Figure 54: Graph comparing B91's $\delta^{13}C$ values with the female population average values

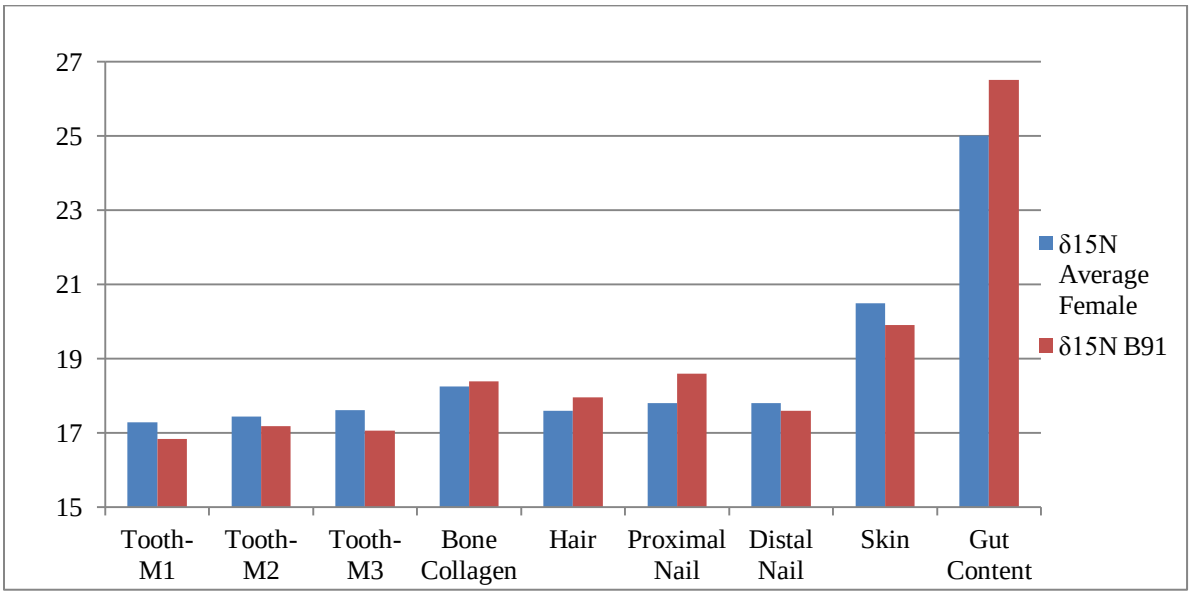


Figure 55: Graph comparing B91's $\delta^{15}N$ values with the female population average values

When analyzing long term diet, the molars and bone collagen are examined (Figures 56 and 57). Early in life, from birth - age 2, B91 shows a $\delta^{13}C$ value (-18.9‰) very consistent with that of the average female (-18.9‰) and only slightly lower than that of the average for the population (-18.7‰). This value is enriched compared to her other long term values, which is typical for young breastfeeding children. However, at some point after the age of 2, her $\delta^{13}C$ value is well below the average, down to -19.3‰. While the average person's diet consists more largely of $C_3$ foods after the age of 3, her value indicated that she was consuming less than average for this time period, from age 2 - 6 years of age. The average juvenile's $\delta^{13}C$ value is 18.6‰, indicating they consumed around 19.6% $C_4$ foods, while B91 was consuming only around 15% $C_4$ foods. After age 6, which is represented by $M^3$, B91's $C_4$ consumption goes up some (-19.0‰), but still remains slightly lower than the population.

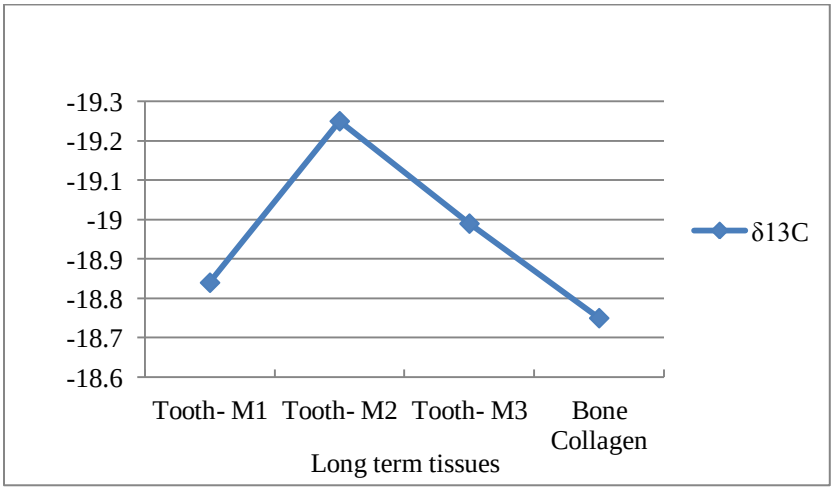


Figure 56: Line-graph depicting the long-term $\delta^{13}C$ values from B91

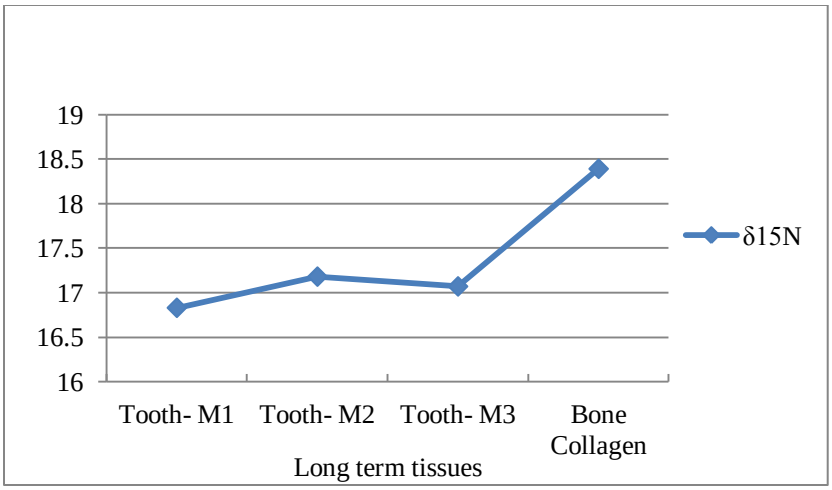


Figure 57: Line-graph depicting the long-term $\delta^{15}N$ values from B91

B91's long term $\delta^{15}N$ values, on the other hand, are consistently lower than the rest of the population during childhood and even in adulthood. Males and females do not have much difference in $\delta^{15}N$ values, and the general population has $M^1$, $M^2$, and $M^3$ values of 17.4‰, 17.5‰, and 17.7‰ respectively. B91's values for these teeth are 16.8‰, 17.2‰, and 17.1‰, all considerably lower. Her low $M^1$ value is consistent with young children being a trophic level lower than adults due to breastfeeding, but breastfeed cannot account for the other low values. While under different circumstances, this may indicate that she was eating foods with a lower trophic level (a vegetarian); however, the effect of the aridity at the Dakhleh Oasis make this type of analysis difficult. Pregnancy has been shown to lower $\delta^{15}N$ values, but as B91 was a child during this time pregnancy is not possible. Another possible explanation is a positive nitrogen balance due to tissue repair from injury, yet the span of low values throughout life make this unlikely as well. Dupras and Schwarcz (2001) argue that some individuals with low $\delta^{15}N$

values may, in fact, not originate from the Dakhleh Oasis at all. However, all of the individuals that she discussed were at least one standard deviation below the average. For example, B116, a male with leprosy who is assumed to have moved to the Oasis, has a $\delta^{15}N$ value of 14.52‰. B91, while her values are low, has no value that is below the standard deviations of 1.03‰ ($M^1$), 1.30‰ ($M^2$), and 1.04‰ ($M^3$). It remains possible, nevertheless, that B91 moved to the Dakhleh Oasis later in life. Only testing with $^{18}O$ isotopes could confirm this hypothesis.

Due to the age of B91, her bone collagen values represent from 45 years of age until the time of death. By this time in her life, her $\delta^{13}C$ value (-18.7‰) is no longer lower than the average female. Although her values are lower than juveniles (-18.6‰) and males (-18.7‰), females have been shown to eat more $C_4$ foods than both juveniles and males and this is consistent with the data (Dupras, 1999). Her $\delta^{15}N$ value also rises at this time (18.4‰) and is close to the average population $\delta^{15}N$ value (18.3‰) and the average female $\delta^{15}N$ value (18.3‰).

For assessing short-term isotopic analysis, the tissues available are hair, nail, skin, and gut content (Figures 58 and 59). B91 has an overall pattern of decreasing $\delta^{13}C$ values as she got closer to death. Her distal nail $\delta^{13}C$ value, representing 6 months before death, is -20.0‰, while her proximal nail, representing 1 month before death, becomes less enriched at -20.2‰. This change is not necessary significant, but it does follow the same pattern observed in the $\delta^{13}C$ values of her hair. Her skin value is exactly the same as the average person, at -19.8‰, and gut content very close to average at -23.8‰. Like nail, her hair $\delta^{13}C$ values also decrease the closer she gets to death, from -19.3‰ to -19.5‰. Williams (2008) proposed that B91 died in early

summer and her hair values, in fact, follow the harvests precisely. Her $\delta^{13}C$ values begin at 4 months before death at -19.3‰, then fall to -19.5‰, rise to -19.4‰, and finally fall again to -19.5‰. The harvest in March (four months before early summer) is spring barley, followed in April by millet, wheat in May, and millet again in the summer. This corresponds directly with the rising and falling of B91's $\delta^{13}C$ values and with a summer death. All of her $\delta^{13}C$ values are consistent with the rest of the population, including skin and gut content. All of her short term $\delta^{13}C$ values are slightly more enriched in $C_4$ than the average female and closer to the average male. Therefore, although she consumed more $C_3$ foods the closer she got to death, it was still a diet similar to a male. Dupras (1999) notes that females in the Dakhleh Oasis typically consume around 16.3% $C_4$ plants, while males consume around 18.2%. This may indicate that males consume more meat than females, but that they do consume similar foods overall. B91 was eating between 18 – 40% $C_4$ foods (probably closer to 18%) in her diet in the months leading up to death.

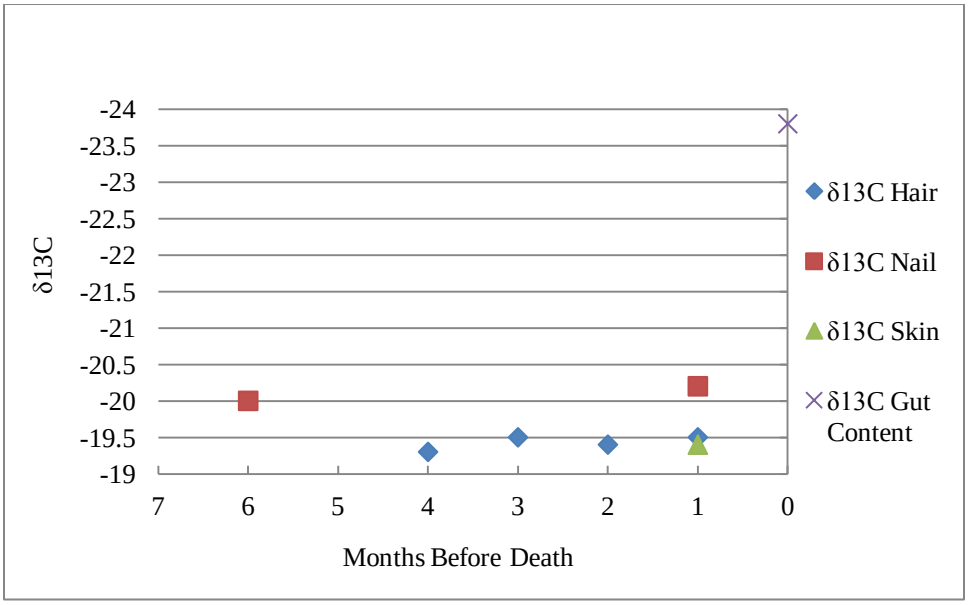


Figure 58: Scatter plot depicting short-term $\delta^{13}C$ values from B91

Her short term $\delta^{15}N$ values also show an interesting trend (Figure 59). From 6 months until 2 months her values seem typical and are actually below the average female. It must be noted that male nail $\delta^{15}N$ values have an average (18.8‰) considerably higher than females (17.8‰), and at 17.6 ‰ her distal nail at 6 months before death is normal for females. Then, at one month before death, her hair and nail $\delta^{15}N$ values both rise to 18.3‰ and 18.6 ‰ respectively. Her gut content sample is also higher than the average, although the scarcity of this type of sample makes this comparison difficult. This increase in $\delta^{15}N$ values and negative nitrogen balance right before death may be contributable to acute disease and metabolic distress.

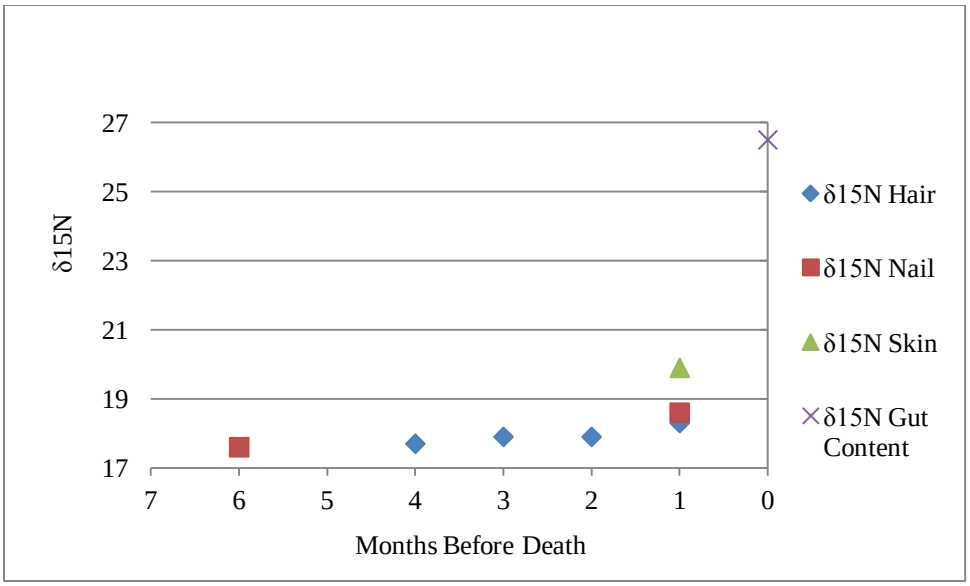


Figure 59: Scatter plot depicting short-term $\delta^{15}N$ values from B91

## Burial 97

With no notable pathologies, Burial 97 contained the remains of a 6 ± 2 year old child located in the west central section of the excavated cemetery within a tomb structure. The tissues available for B97 include $m_1$, $M_1$, $I_1$, C, $PM_2$, $M_2$, bone collagen, six hair samples, and distal and proximal nail. Table 9 and Figures 60 - 62 show a timeline of $\delta^{13}C$ and $\delta^{15}N$ values relative to B97's life and graphs which compare these values to the population mean $\delta^{13}C$ and $\delta^{15}N$ values.

Table 9: B97's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| $m_1$ | -19.4 | 20.2 |
| $M_1$ | -18.5 | 17.8 |
| $I_1$ | -20.9 | 20.9 |
| C | -19.3 | 17.5 |
| $PM_2$ | -19.2 | 18.6 |
| $M_2$ | -21.9 | 25.4 |
| Bone Collagen | -18.6 | 18.1 |
| Hair (6) | -19.1 | 17.8 |
| Hair (5) | -19.3 | 18.0 |
| Hair (4) | -19.0 | 19.4 |
| Hair (3) | -19.3 | 18.7 |
| Hair (2) | -19.6 | 17.3 |
| Hair (1) | -19.6 | 16.7 |
| Distal Nail | -19.0 | 18.2 |
| Proximal Nail | -18.6 | 20.9 |

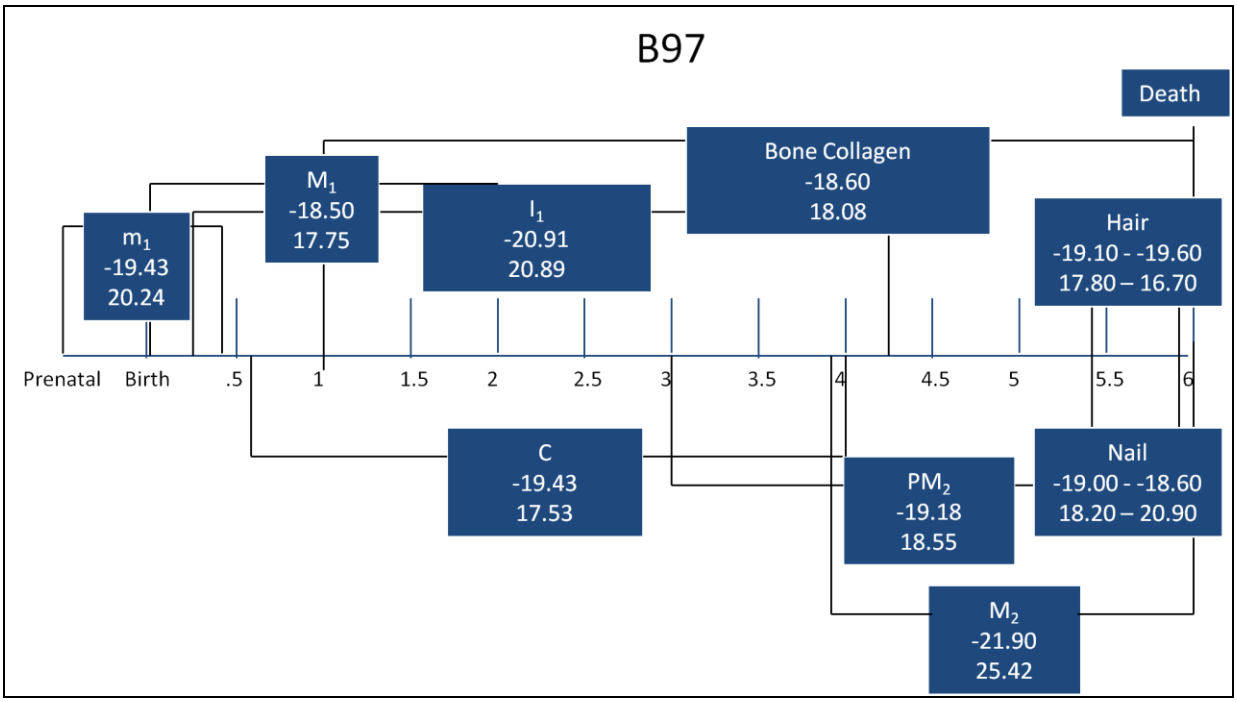


Figure 60: Timeline for B97 illustrating the ages each tissue represents

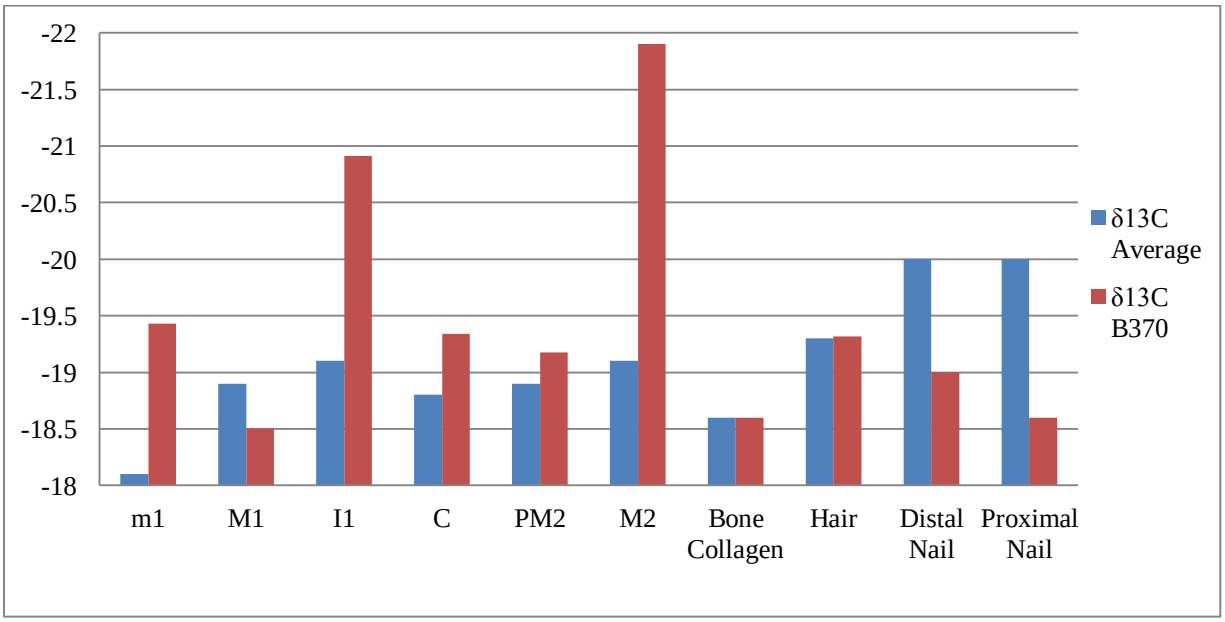


Figure 61: Graph comparing B97's $\delta^{13}C$ values with the rest of the population

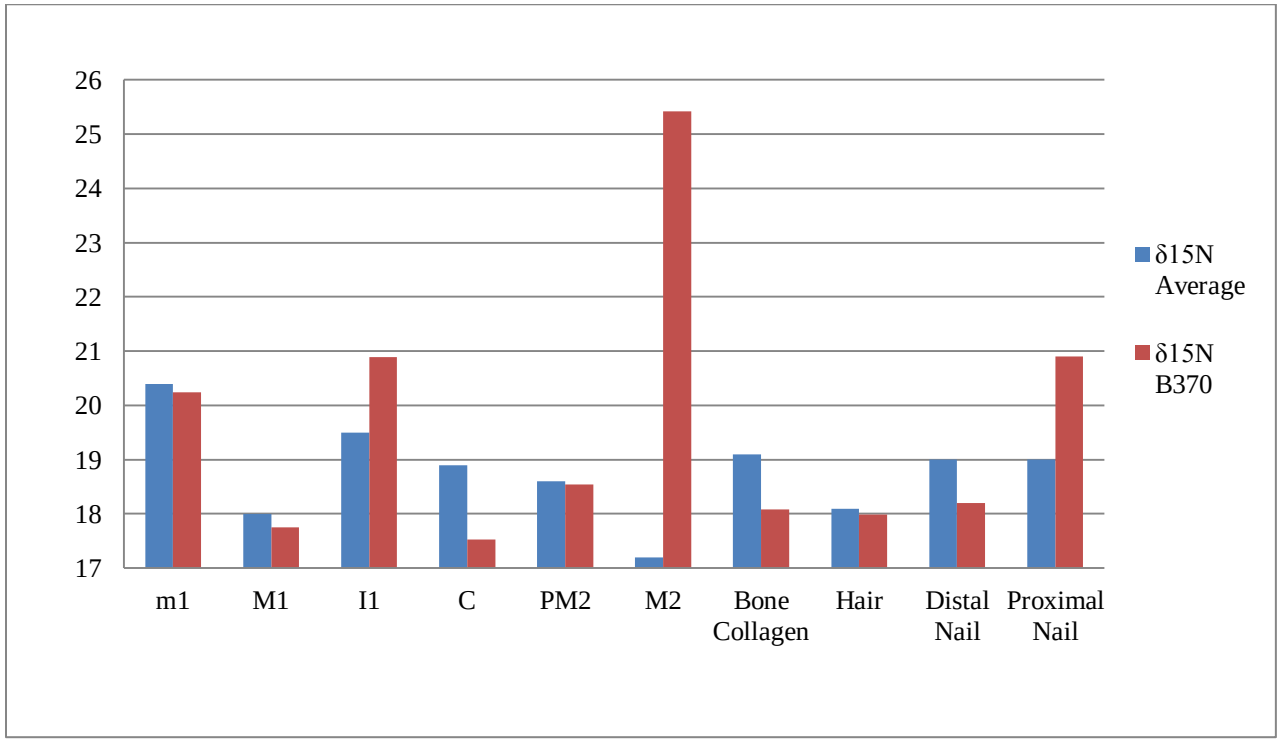


Figure 62: Graph comparing B97's $\delta^{15}N$ values with the rest of the population

During very early life, B97's $\delta^{13}C$ values fluctuate considerably and do not gradually become more enriched as seen in the other juveniles in this study (Figure 63). The first deciduous molar $\delta^{13}C$ value (-19.4‰), representing prenatal life, is low compared to other $m_1$'s in the sample, with the mean $\delta^{13}C$ value for the population at -18.1‰. His/her next chronological $\delta^{13}C$ value ($M_1$) rises to -18.5‰, slightly higher than the population $\delta^{13}C$ mean of -18.9‰. This may be due to a change in diet (millet pap used for infants) eaten during illness. The nitrogen value for this tooth also drops significantly; therefore, illness or trauma is a likely cause. Another

possible explanation for this inverse trend is that B97's dentin formed earlier than average and his/her $m_1$ value represents the mother's diet, with $M_1$ representing the first few months of life and a higher tropic level. The next teeth to develop in which $\delta^{13}C$ values are available are $I_1$ and C, representing 3 months – 4.25 years and 6 months – 4 years respectively. At this point, B97 was clearly eating more $C_3$ foods and breastfeeding less than in the timeframe represented by $M_1$. These values are both lower than the population $\delta^{13}C$ average, with $I_1$ (-20.9‰) being a standard deviation lower than the mean of -19.1‰. The values for $PM_2$ (-19.2‰) and $M_2$ (-21.9‰) remain higher than the population $\delta^{13}C$ average and represent 3 and 4 years of age up until death. The $M_2$ $\delta^{13}C$ value is in fact more than two standard deviations higher than the population $\delta^{13}C$ mean of -19.1‰; B97 was consuming practically no $C_4$ foods. This many also be due to a special diet eaten during illness. Interestingly, B97's bone collagen value, representing most of his/her short life, does not reflect these typically low values and at -18.6‰ is consistent with the $\delta^{13}C$ mean for the population.

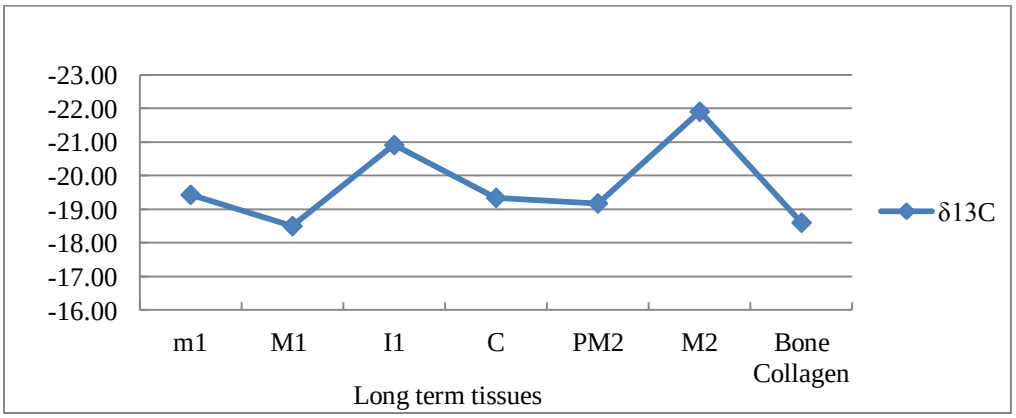


Figure 63: Line-graph depicting the long-term $\delta^{13}C$ values from B97

Long term $\delta^{15}N$ values (Figure 64) are very sporadic as well, fluctuating from high to low and above average to below average. The $m_1$ $\delta^{15}N$ value (20.2‰) is high, but not above the population $\delta^{15}N$ average for this tissue. Due to the trophic level effect seen in breastfeeding infants, it is expected that this value would be higher to reflect the consumption of breast milk. The $\delta^{15}N$ value for $M_1$ then decreases to 17.8‰, also close to the population $\delta^{15}N$ mean of 18.0‰. The next tissue, $I_1$, then increases to 20.9‰. The average population $\delta^{15}N$ value for $I_1$, 19.5‰, is actually higher than that of $M_1$, indicating that the dentin in $I_1$ may in fact form before the dentin in $M_1$, making a rise normal. However, B97's $I_1$ $\delta^{15}N$ value is 1.4‰ higher than the population $\delta^{15}N$ mean, more than a standard deviation (±1.2‰) above. The next forming tooth, C, has a $\delta^{15}N$ value of (17.5‰), which is 1.4‰ below the population $\delta^{15}N$ mean. With $PM_2$, the $\delta^{15}N$ value (18.6‰) rises to the population $\delta^{15}N$ average (18.6‰) and then dramatically increases with the last tooth, $M_2$. The M2 $\delta^{15}N$ value (25.4‰) is an entire 8.2‰ higher than the population $\delta^{15}N$ mean; 13 standard deviations (±0.6‰) above the mean. Representing up until after 6 years of age, this value may reflect the ailment responsible for B97's death. This tooth is still forming at death. As children have prompt catabolic response to illness, this sudden extremely low nitrogen imbalance indicates B97 was probably suffering from acute illness or infection right before death.

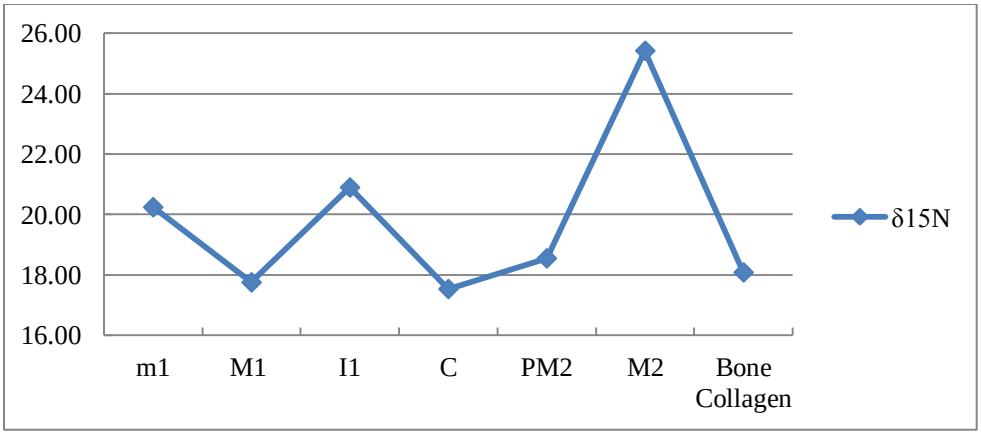


Figure 64: Line-graph depicting the long-term $\delta^{15}N$ values from B97

B97's short term history can be assessed using hair and nail values (Figures 65 and 66). His/her $\delta^{13}C$ hair values show a small increase and decrease in the 4 - 6 months prior to death, and then a general decrease in $\delta^{13}C$ values from 4 months - death. The $\delta^{13}C$ values, ranging from -19.0‰ to -19.6‰, indicate that as B97 got closer to death he/she was consuming less $C_4$ foods, like millet and meat. In conjunction with the grave azimuth, Williams (2008) used this trend to theorize that B97 died in the early summer. A death in early summer would correspond with the values becoming less enriched as a result of consumption of the spring wheat harvest. B97's nail $\delta^{13}C$ values (-19.0‰ and -18.6‰), on the other hand, become more enriched closer to death. However, it is noted that nail growth in children is faster than in adults, and because B97 was a child, his/her nail growth may represent the time directly before death (Samman, 1995). This enrichment, therefore, may represent the last few weeks before death, suggesting that an illness food such as millet pap/gruel may have been consumed.

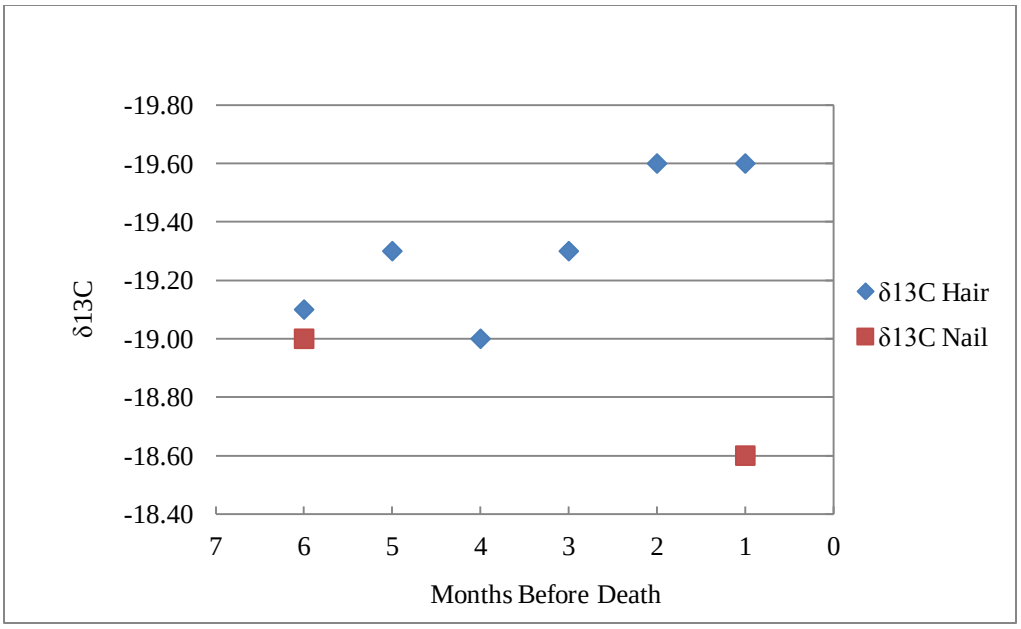


Figure 65: Scatter plot depicting the short-term $\delta^{13}C$ values from B97

Short term $\delta^{15}N$ hair values show an increase from six months - four months prior to death, and then a gradual decrease until death. At six months prior to death the $\delta^{15}N$ hair value (19.1‰) is close to the population $\delta^{15}N$ average of 18.1‰. At five months prior to death the $\delta^{15}N$ hair value (19.3‰) increases, and peaks at 19.0‰, a standard deviation (±1.8‰) above the mean, around four months prior to death. From this point until death, the $\delta^{15}N$ hair values decrease, falling two standard deviations below the population $\delta^{15}N$ hair value mean. The rise in $\delta^{15}N$ values and negative nitrogen balance may indicate metabolic stress or disease, and the following decrease in values and positive nitrogen balance a recovery from this ailment. His/her nail $\delta^{15}N$ values, on the other hand, are enriched from 6 months prior to up until the time of death. If nail growth is faster because this is a child, this may truly represent a time closer to

death and the spike indicates a quickly rising negative nitrogen balance. Overall, the fluctuating of B97's long and short term nitrogen values seem to indicate that he or she died from an acute disease or injury.

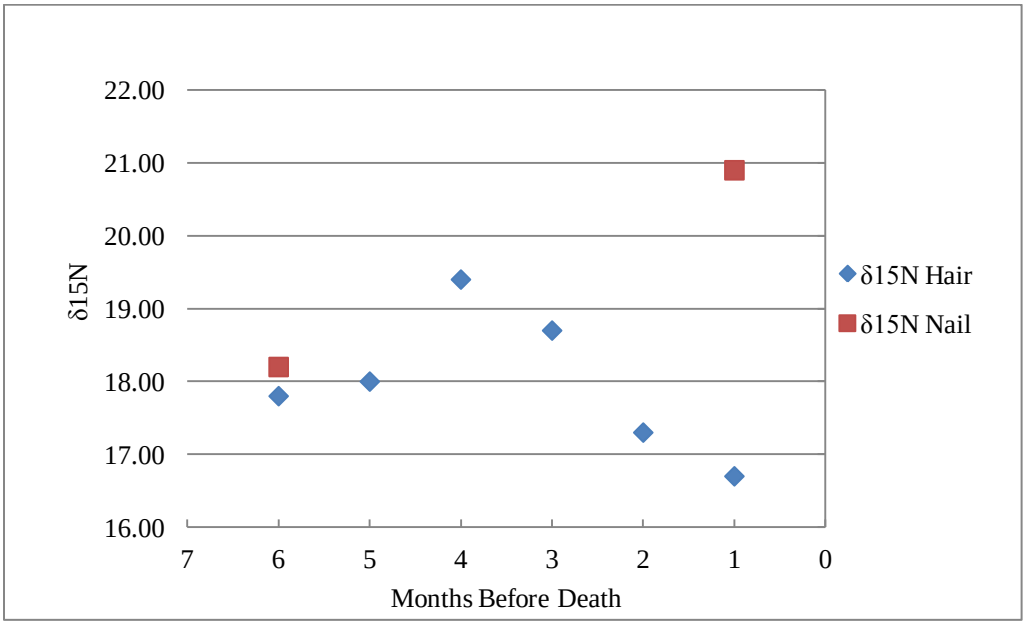


Figure 66: Scatter plot depicting the short-term $\delta^{15}N$ values from B97

## Burial 107

Burial 107 contained an approximately 27 year old male with no pathologies visible on the skeletal remains. He was buried in the western half of the Kellis 2 cemetery to the right of a large tomb structure. Samples were taken from $M^2$, bone collagen, hair, and skin. The $\delta^{13}C$ and $\delta^{15}N$ values from these samples can be viewed in Table 10, along with a timeline showing the

periods in B107's life these values would represent (Figure 67). Graphs comparing the values to the average population and male $\delta^{13}C$ and $\delta^{15}N$ values are shown in Figures 68 - 71.

Table 10: B107's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M2 | -18.4 | 18.3 |
| Bone Collagen | -18.8 | 19.4 |
| Hair (5) | -19.3 | 18.7 |
| Hair (4) | -19.2 | 18.8 |
| Hair (3) | -19.3 | 18.7 |
| Hair (2) | -19.5 | 17.6 |
| Hair (1) | -19.4 | 18.8 |
| Skin | -19.6 | 20.2 |

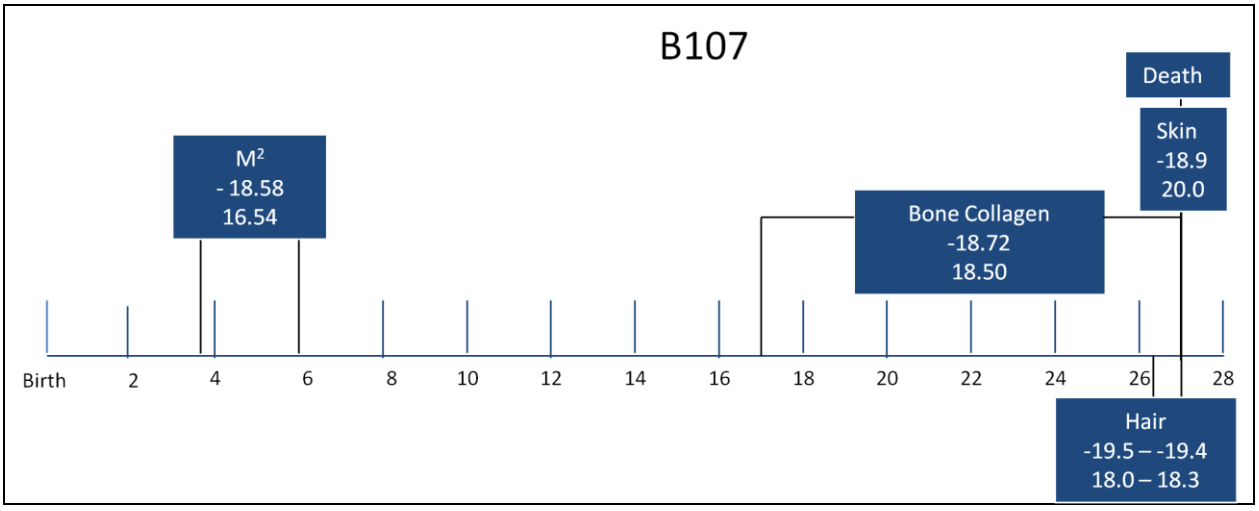


Figure 67: Timeline for B107 illustrating the ages each tissue represents

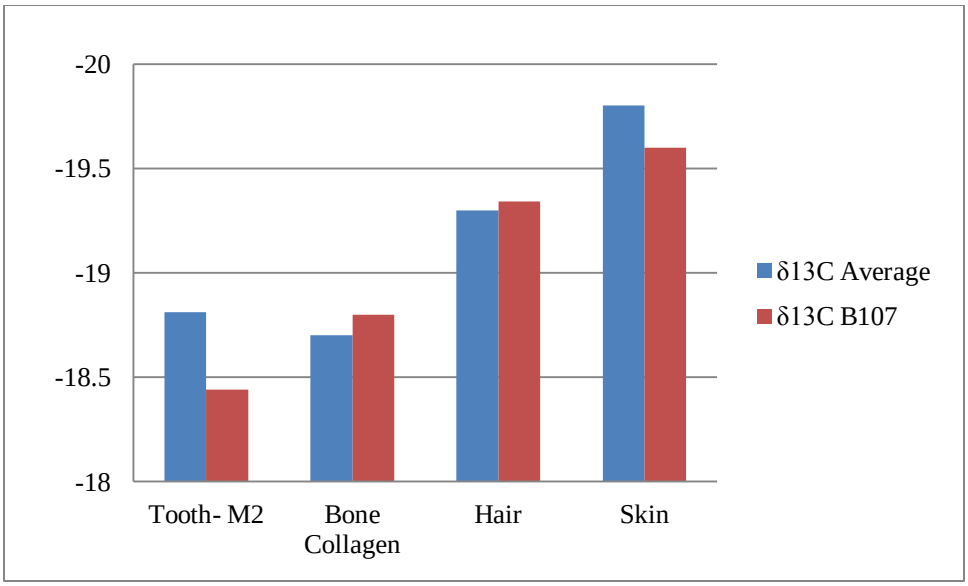


Figure 68: Graph comparing B107's $\delta^{13}C$ values with the rest of the population mean values

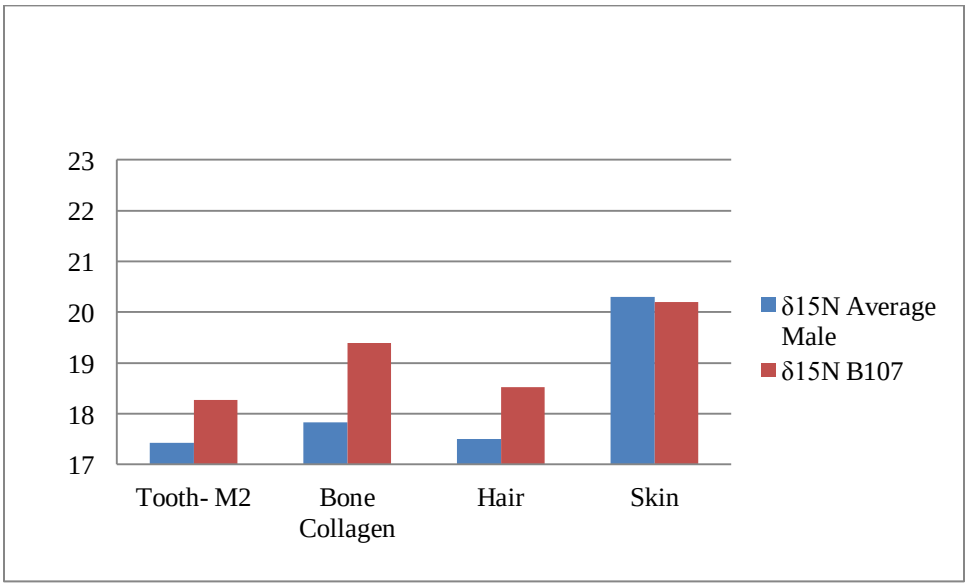


Figure 69: Graph comparing B107's $\delta^{15}N$ values with the rest of the population mean values

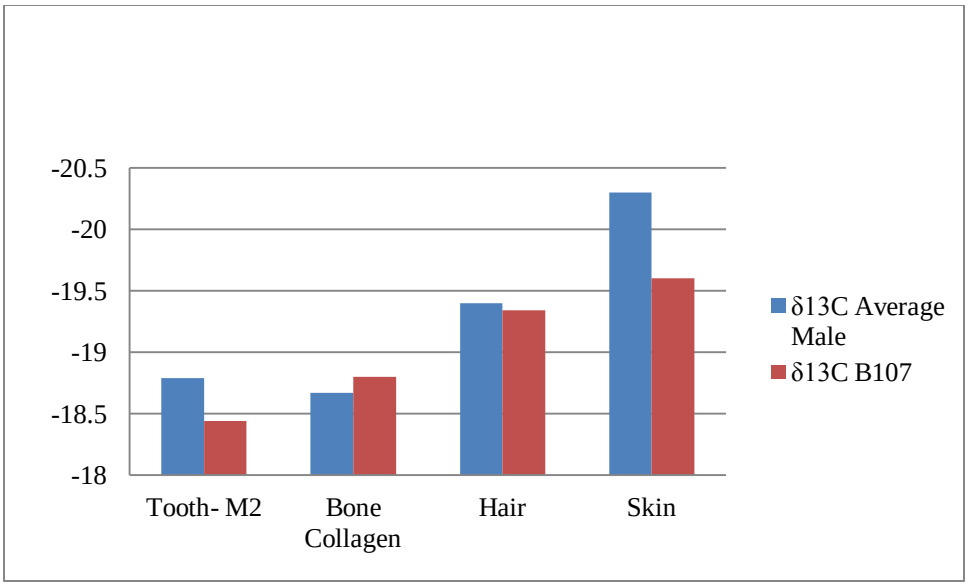


Figure 70: Graph comparing B107's $\delta^{13}C$ values with the average male values

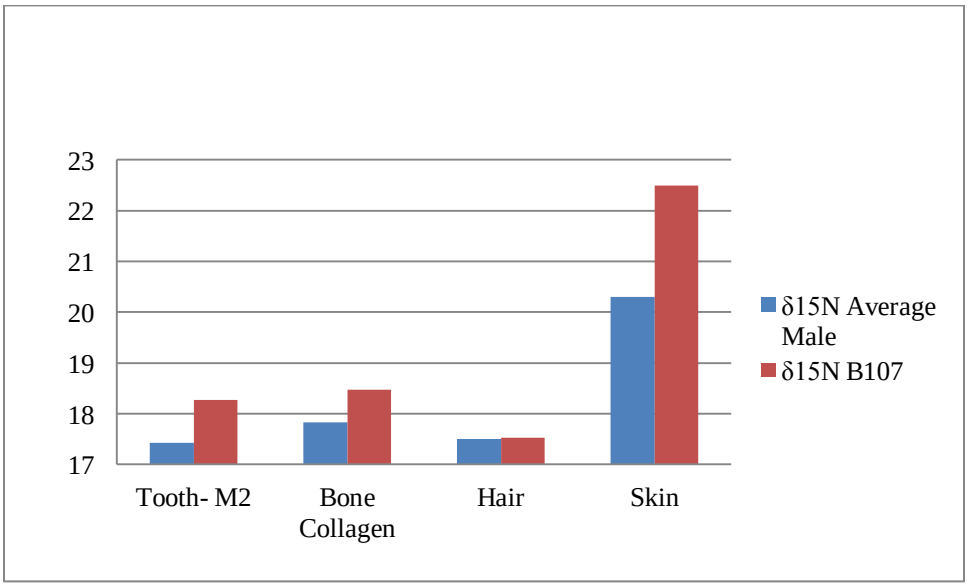


Figure 71: Graph comparing B107's $\delta^{15}N$ values with the average male values

For B107 there are only two tissues available for long term analysis (Figures 72 and 73), $M^2$ and bone collagen. His $M^2$ $\delta^{13}C$ value of -18.4‰, representing ages 3.8 – 6 years, is only slightly more enriched than the $\delta^{13}C$ mean for the population (-18.8‰) and average male $\delta^{13}C$ values (-18.8‰). He was consuming approximately 20.4% $C_4$ foods at this time. His bone collagen $\delta^{13}C$ value shows that through the ages of 17 – 27 his value decreases slightly to -18.8‰, whereas the average population $\delta^{13}C$ value (-18.7‰) becomes more enriched. He was then consuming less $C_4$ foods (18%) than average (20%), with a diet heavily dependent on $C_3$ foods.

B107's $M^2$ and bone collagen $\delta^{15}N$ values rise from 18.27‰ to 19.4‰, as does the general populations $\delta^{15}N$ values (17.5‰ and 18.7‰). However, both values are above the averages of 17.5‰ and 18.7‰. The average male's $\delta^{15}N$ bone collagen value is 17.8‰, and B107's $\delta^{15}N$ value (19.4‰) is over a standard deviation (±1.4‰) higher than this. High nitrogen values often indicate injury or disease, and perhaps B107 was suffering from some chronic ailment during his life.

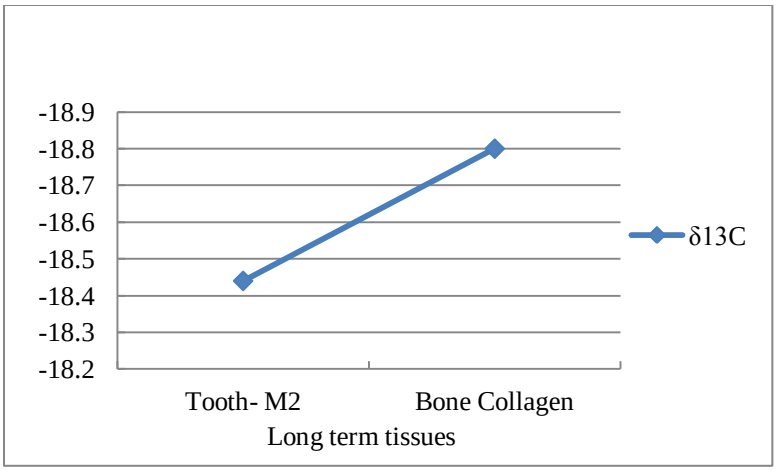


Figure 72: Line-graph depicting the long-term $\delta^{13}C$ values from B107

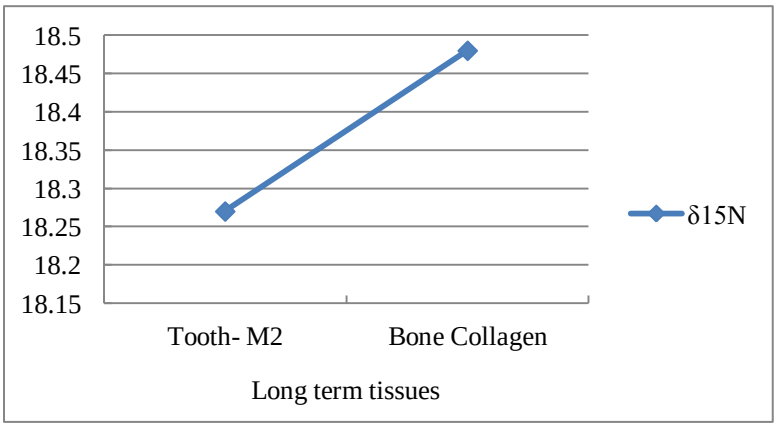


Figure 73: Line-graph depicting the long-term $\delta^{15}N$ values from B107

B107's hair $\delta^{13}C$ values (Figure 74) show that in the last five months of life the values increase, then decrease, then increase again right before death. However, it must be noted that the $\delta^{13}C$ values are all within a very small range of each other (-19.2‰ – 19.5‰) and the increases and decreases are only 0.1‰ or 0.2‰ each month. They are all right around the

average population hair $\delta^{13}C$ value of -19.3‰. These values indicate that he was consuming anywhere from 20 - 42% $C_4$ foods during these last months of life, a dramatic increase from that indicated by his long term tissues. His skin $\delta^{13}C$ value (-19.6‰), which turns over quickly, is very close to the population $\delta^{13}C$ average value of -19.8‰. When comparing hair and skin values close to death, it appears that he was eating less meat and millet as he got closer to death. His $\delta^{15}N$ values for hair (18.7‰, 18.8‰, 18.7‰, 17.4‰, and 18.8‰) are all very similar, except for two months before death when his value drops to 17.6‰. Something may have happened to cause this decrease at 2 months before death, such as an injury. Whatever the cause, it appears to have been only a short period of time because the value increases to 18.8‰ in the month before his death.

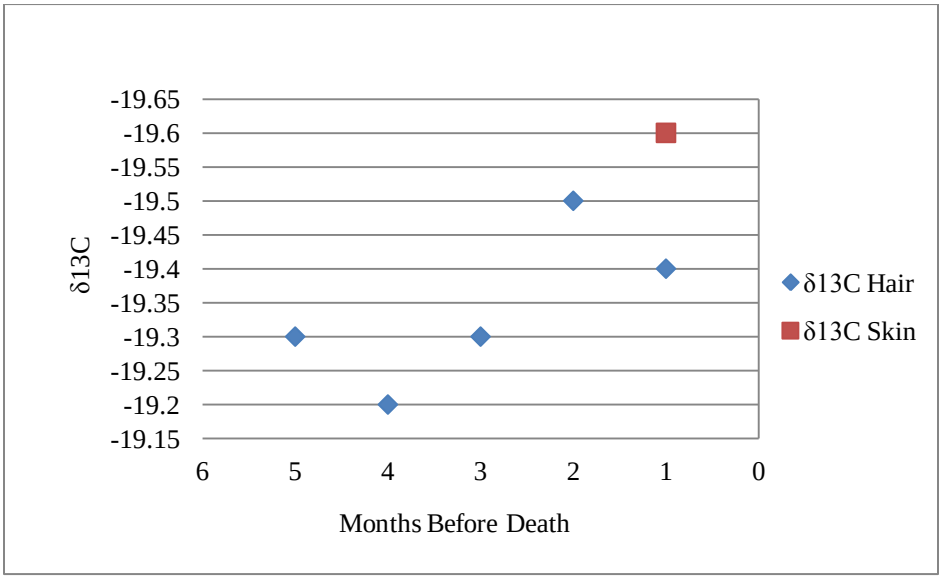


Figure 74: Scatter plot depicting short-term $\delta^{13}C$ values from B107

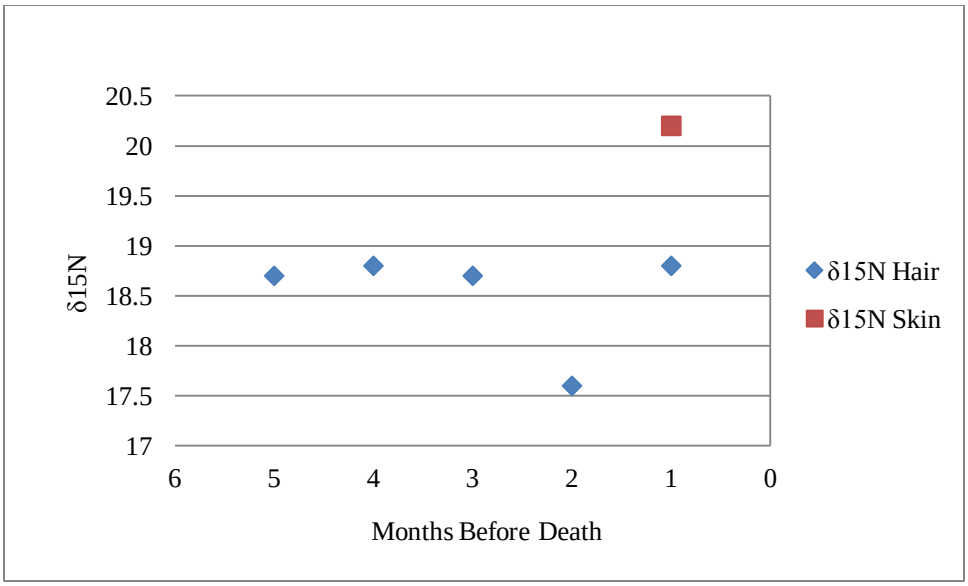


Figure 75: Scatter plot depicting short-term $\delta^{15}N$ values from B107

Burial 131

Located in the southwestern section of the excavated burial site, B131 is a 23 year old female with no skeletal pathologies. She has samples available from $M^1$, $M^2$, bone collagen, skin, and 15 hair segments (Table 11). Figure 76 shows a timeline displaying B131's lifetime and Figures 77 - 80 are bar graphs comparing her $\delta^{13}C$ and $\delta^{15}N$ values to the population and female average $\delta^{13}C$ and $\delta^{15}N$ values.

Table 11: B131's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -19.2 | 16.6 |
| M2 | -18.9 | 17.3 |
| Bone Collagen | -19.2 | 18 |
| Hair (15) | -19.9 | 17.1 |
| Hair (14) | -19.9 | 16.9 |
| Hair (13) | -19.9 | 16.6 |
| Hair (12) | -19.9 | 16.6 |
| Hair (11) | -19.7 | 16.8 |
| Hair (10) | -19.7 | 17 |
| Hair (9) | -19.6 | 17.3 |
| Hair (8) | -19.5 | 17.3 |
| Hair (7) | -19.6 | 17.1 |
| Hair (6) | -19.8 | 17 |
| Hair (5) | -20 | 16.7 |
| Hair (4) | -20 | 16.2 |
| Hair (3) | -20.1 | 16.4 |
| Hair (2) | -20 | 16.4 |
| Hair (1) | -20.2 | 16.6 |
| Skin | -20.8 | 23.2 |

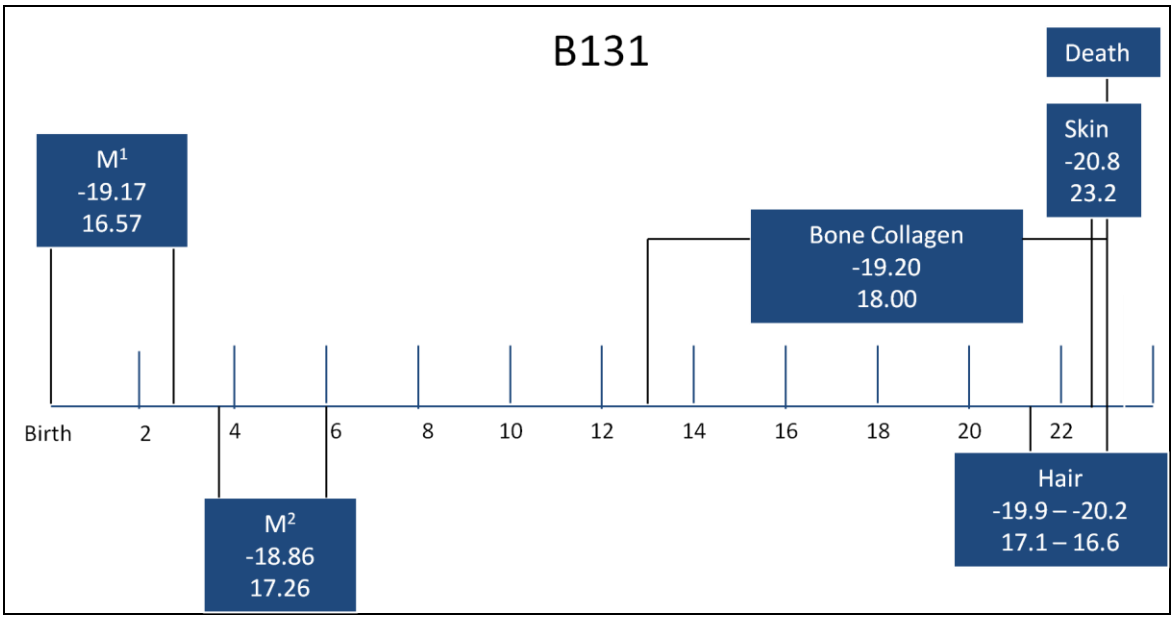


Figure 76: Timeline for B131 illustrating the ages each tissue represents

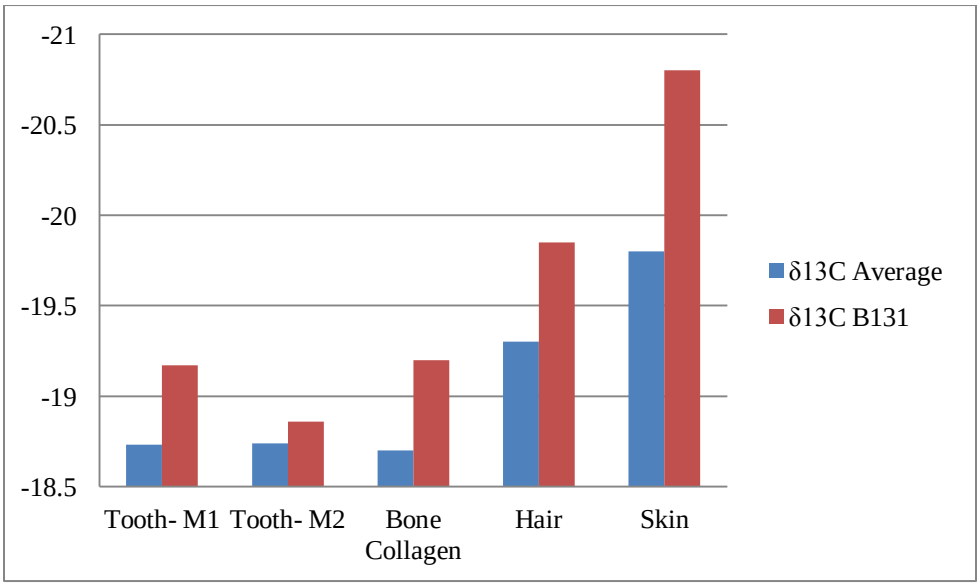


Figure 77: Graph comparing B131's $\delta^{13}C$ values with the rest of the population mean values

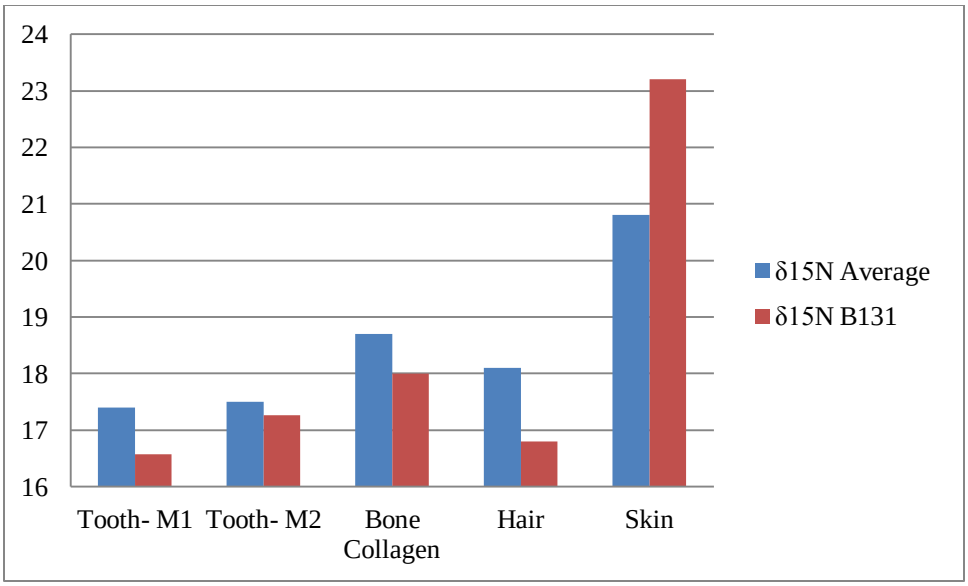


Figure 78: Graph comparing B131's $\delta^{15}N$ values with the rest of the population mean values

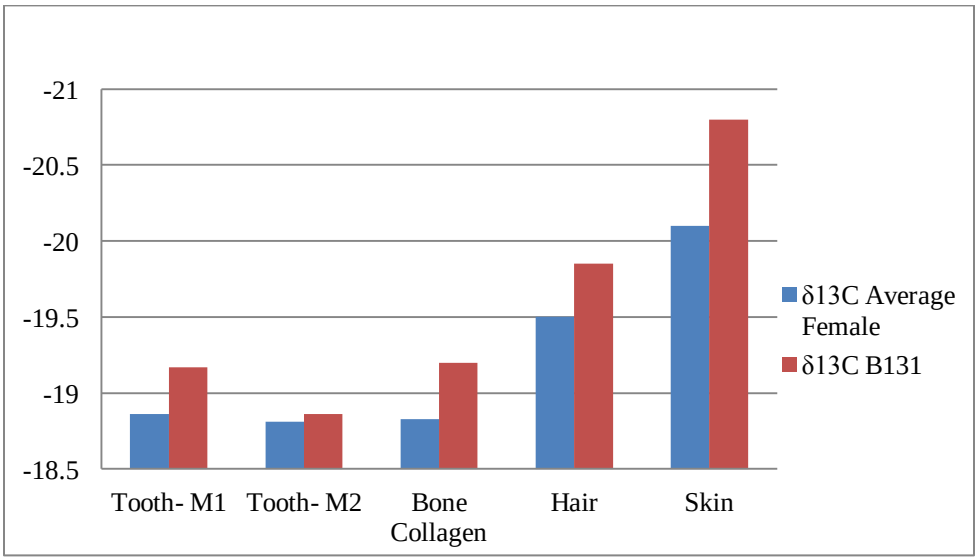


Figure 79: Graph comparing B131's $\delta^{13}C$ values with the average female values

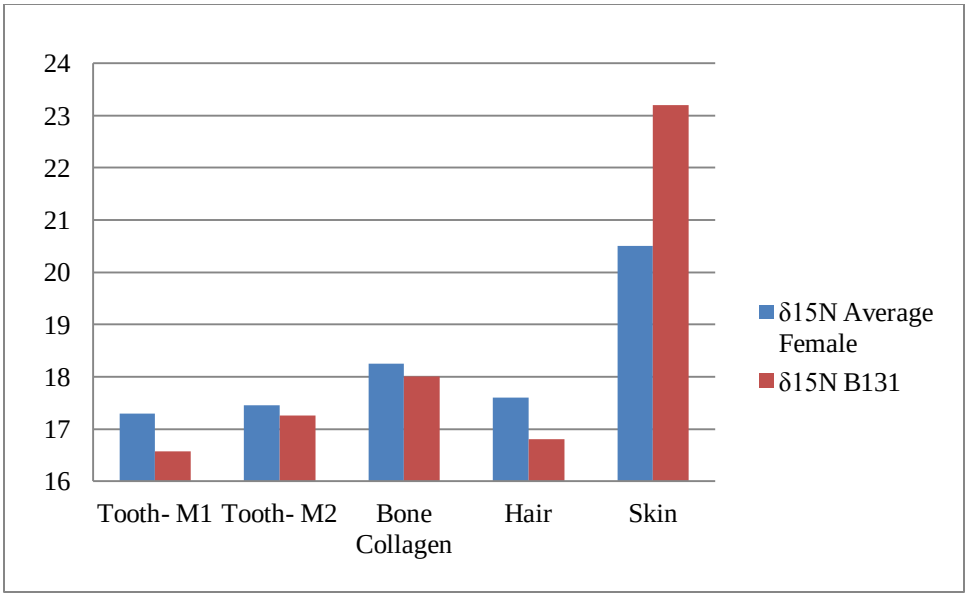


Figure 80: Graph comparing B131's $\delta^{15}N$ values with the average female values

B131's long-term analysis is represented by $\delta^{13}C$ and $\delta^{15}N$ values from $M^1$, $M^2$ and bone collagen. All three $\delta^{13}C$ values tissue values are less enriched than the population. Her $M_1$ value is -19.2‰, one standard deviation (0.4‰) away from the mean population value (-18.7‰), meaning she was consuming less $C_4$ enriched foods than the average 0 – 2.5 year old. She was consuming approximately 15.5% $C_4$ foods, as opposed to the average person who consumed 18.7%. By 3.8 – 6 years of age, represented by$M_2$, her $\delta^{13}C$ value was -18.9‰, closer to the average of -18.8‰ and average female of -18.81‰. Her bone collagen $\delta^{13}C$ value (-19.2‰) is 0.5‰ lower than average, and her diet was consistent with consuming mostly $C_3$ foods and 15.3% $C_4$ foods.

Her $\delta^{15}N$ values are also all lower than the average population. However, none of them are a complete standard deviation away from the mean. Her $\delta^{15}N$ values from increase over time: from $M^1$ (16.6‰), to $M^2$ (17.3‰), to bone collagen (18.0‰). The average person's values also increase from 17.4‰, to 17.5‰, to 18.7‰. Although the values are rising, these values may not be different enough from the average person and the trend to rise during this time to signify anything significant.

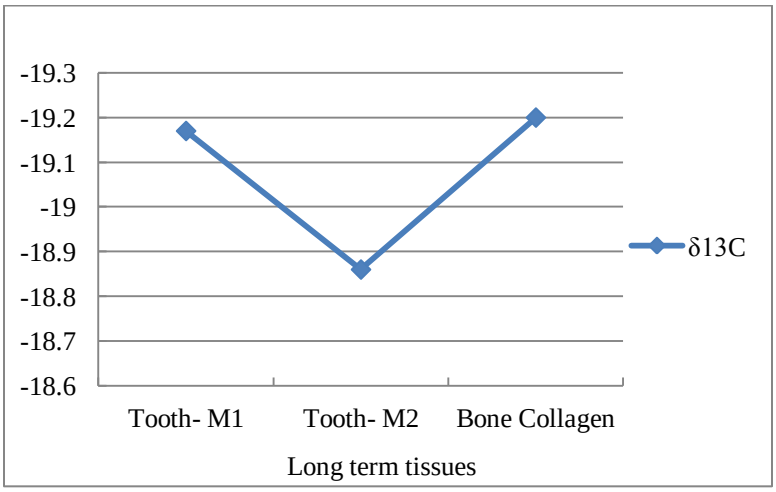


Figure 81: Line-graph depicting the long-term $\delta^{13}C$ values from B131

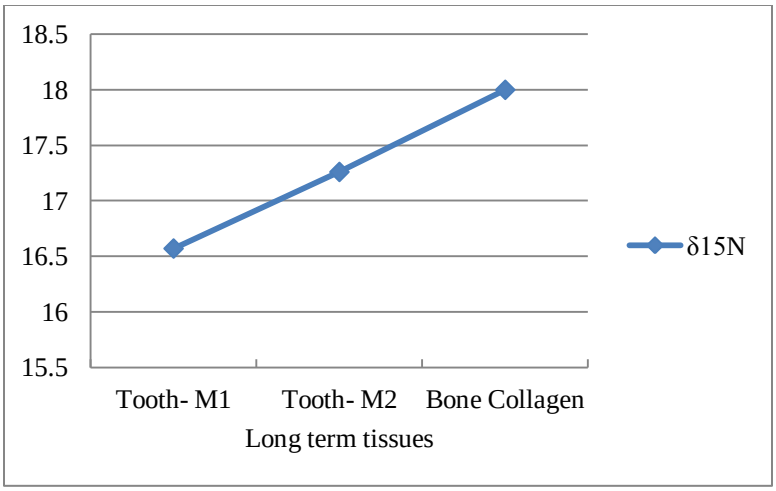


Figure 82: Line-graph depicting the long-term $\delta^{15}N$ values from B131

The 15 hair samples allow for the interpretation of short term history over the last 15 months before B131's death. Her $\delta^{13}C$ hair values (Figure 83) increase in the fifteenth through eighth month before death, from -19.9‰ to -19.5‰, and then decrease in the last seven months of life, from -19.5‰ to -20.2‰. All of her $\delta^{13}C$ hair values are lower than the population mean $\delta^{13}C$ hair value of -19.3‰. The highest $\delta^{13}C$ hair value occurs at 8 months before death, suggesting that she was consuming an elevated amount of $C_4$ foods at this point, approximately 20 – 40%. At one month before death she was consuming approximately 15.3 - 35.3% $C_4$ foods. She most likely died in early summer following the spring wheat harvest, corroborated by her burial at a 70° azimuth (Williams, 2008). Her $\delta^{13}C$ values also rise in corroboration with the time in which she was not pregnant and it is possible she was consuming a diet with more $C_3$ foods while pregnant. Her skin value, representing a month before death, is -20.8‰, which is 1.0‰ lower than the average of -19.8‰.

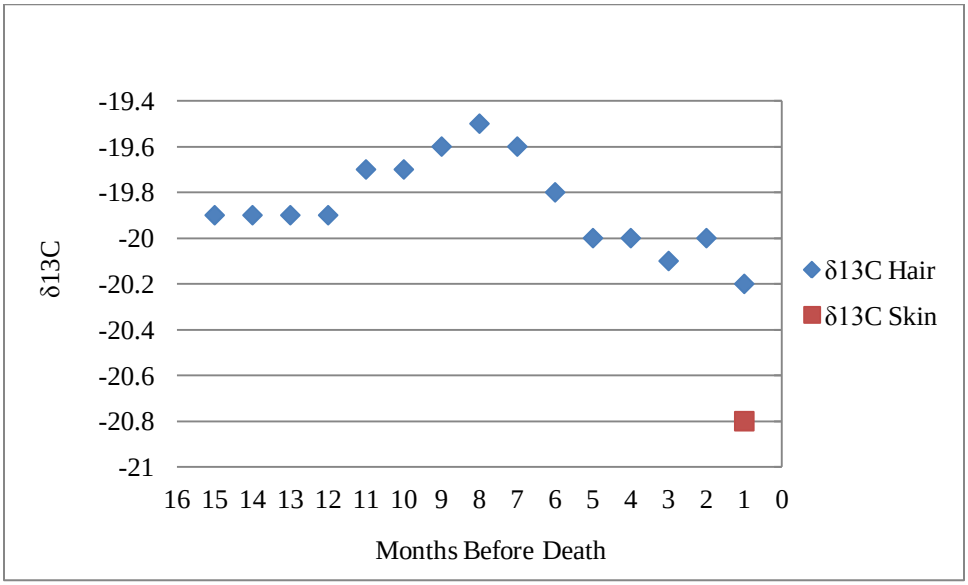


Figure 83: Scatter plot depicting short-term $\delta^{13}C$ values from B131

B131's short term $\delta^{15}N$ values (Figure 84) are more sporadic over the last 15 months of her life. The hair $\delta^{15}N$ values first decrease, then increase, decrease again, and beginning to increase again and are all below the population average of 18.7‰. Interestingly, this seemingly random pattern and positive nitrogen balance may represent pregnancy. Fuller et al. (2005) demonstrated that during pregnancy nitrogen values decrease steadily and then increase slightly before birth. This is due to the growth and nutritional demands during pregnancy; more $\delta^{15}N$ is being ingested than excreted (Katzenberg and Lovell, 1999). B131's $\delta^{15}N$ values decrease from 15 – 12 months before death and then increase until nine months before death. This may indicate a pregnancy and miscarriage/birth. It is likely a miscarriage because her levels never become as

depleted as in the following pregnancy and because a subsequent pregnancy only months following a full term birth would have been unlikely. Her levels then begin to decrease steadily until four months before death, and then increase until death. This may indicate another pregnancy in which the individual died in or around the time of childbirth. Fuller et al. (2005) charted a subject that conceived and birthed two children in a row and the pattern looks remarkably similar to that of B131. B131's age is estimated at 23 years, which would be appropriate for a pregnancy related death and she has no visible skeletal pathologies.

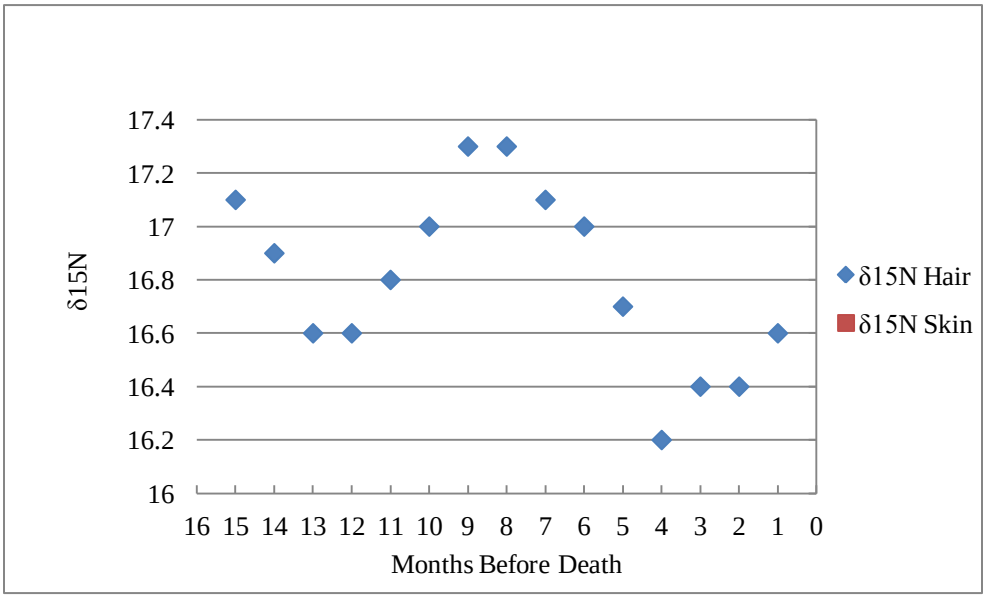


Figure 84: Scatter plot depicting short-term $\delta^{15}N$ values from B131

## Burial 265

Situated in the northwestern section of the excavated cemetery, Burial 265 contained the body of a 50 ± 5 year old male. The pathologies found on his skeleton include an infection of ankylosed vertebrae (fused vertebrae due to inflammatory arthritis) and lytic destruction of the vertebral centra, probably the result of tuberculosis (Aufderheide and Rodriguez-Martin, 1998). Tuberculosis is an acute or chronic infection of the soft or skeletal tissues by *Mycobacterium tuberculosis*. It usually occurs in two phases: a primary infection phase, usually occurring in childhood, and a reinfection/reactivation phase, more common in adults. *M. tuberculosis* initially attacks the lungs, can spread to other parts of the body, including the bones. Referred to as skeletal tuberculosis, 40% of skeletal tuberculosis lesions involve the spine and is then termed Pott's disease, which results in the infection of the spine, fever, weight loss, spasms, bone destruction and eventually vertebral collapse (Aufderheide and Rodriguez-Martin, 1998). This condition very well could have contributed to B265's death.

The tissues available for B265 included $M^2$, $M^3$, bone collagen, hair, nail and skin. Because M1 in not available, as with the other individuals, his analysis begins with M2, representing 2 – 8 years of age. Table 12 displays B265's values and a timeline showing the periods of time these different tissues represent is presented in Figure 85. Figures 86 - 89 show B265's $\delta^{13}C$ and $\delta^{15}N$ values in comparison to the average $\delta^{13}C$ and $\delta^{15}N$ values for the population and males.

Table 12: B265's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| $M^2$ | -19.1 | 18.3 |
| $M^3$ | -19.1 | 18.7 |
| Bone Collagen | -18.5 | 19.5 |
| Hair (3) | -18.6 | 15.3 |
| Hair (2) | -19.1 | 15.3 |
| Hair (1) | -19.2 | 16.5 |
| Proximal Nail | -19.2 | 20.1 |
| Distal Nail | -18.3 | 15 |
| Skin | -19.5 | 20.2 |

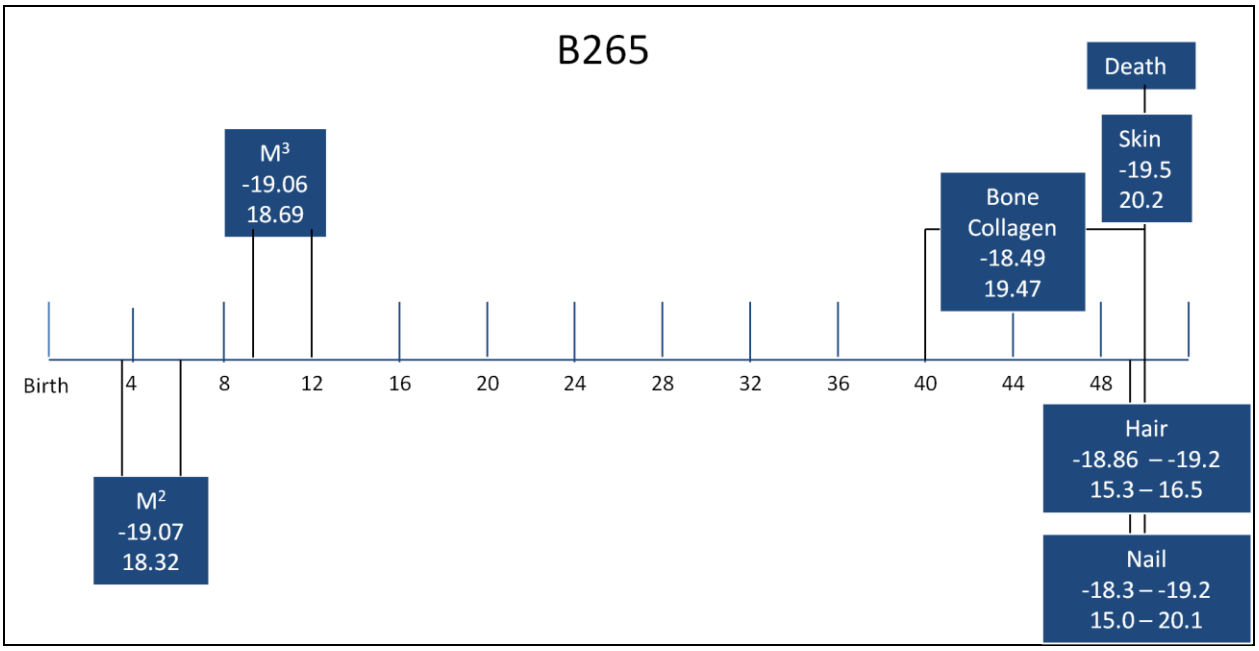


Figure 85: Timeline for B265 illustrating the ages each tissue represents

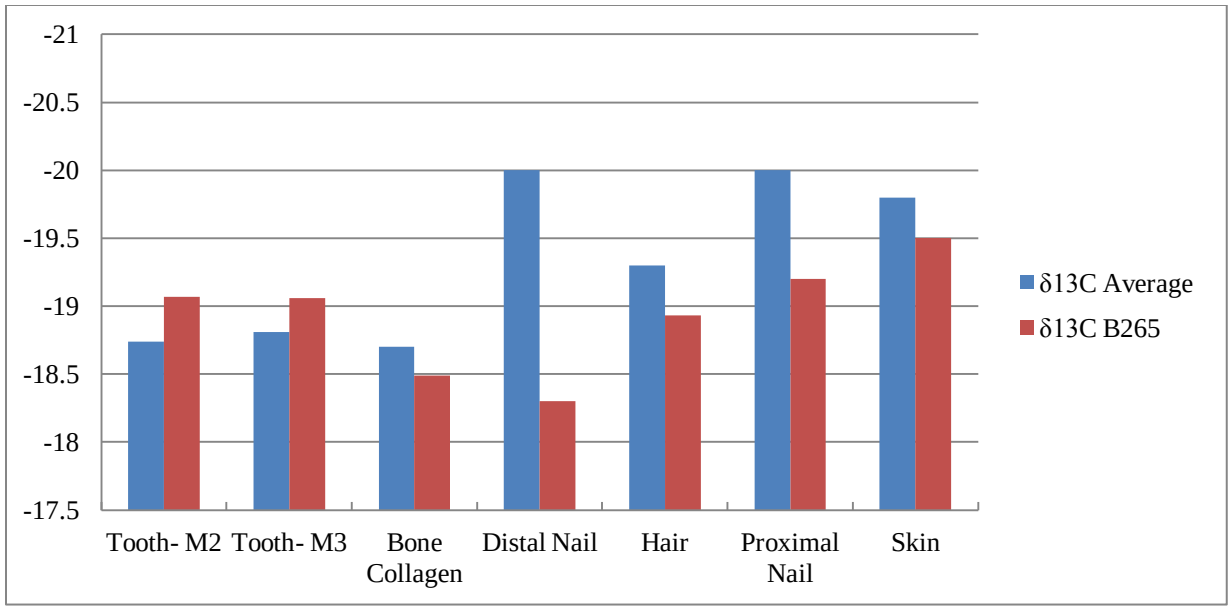


Figure 86: Graph comparing B265's $\delta^{13}C$ values with the rest of the population mean values

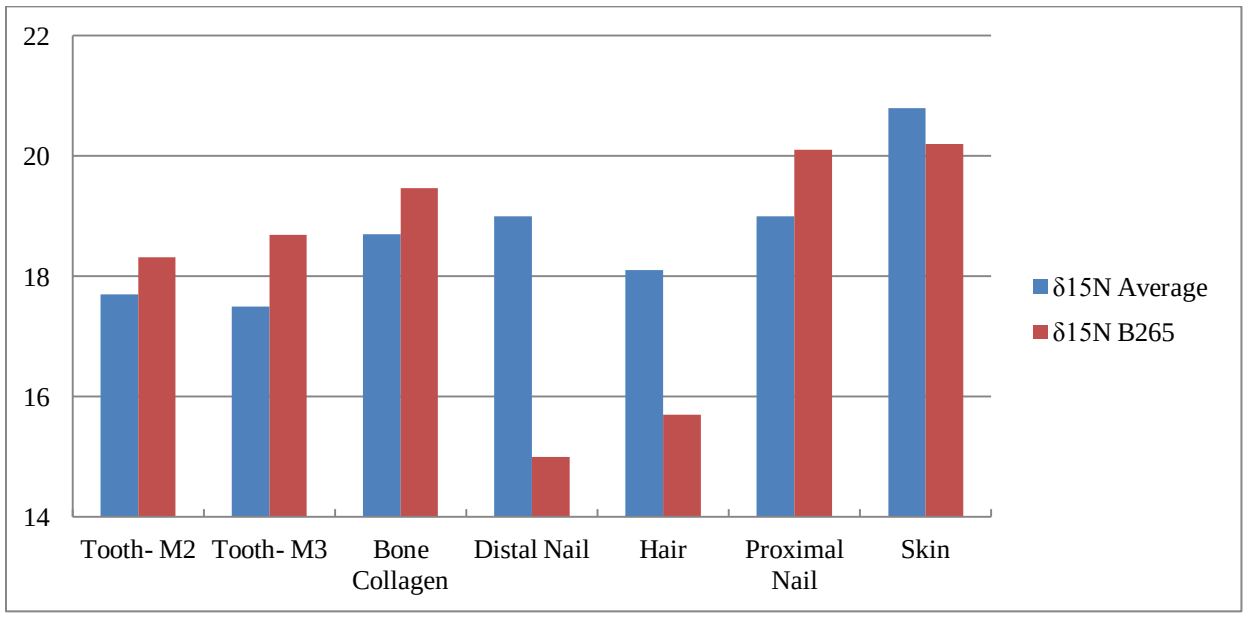


Figure 87: Graph comparing B265's $\delta^{15}N$ values with the rest of the population mean values

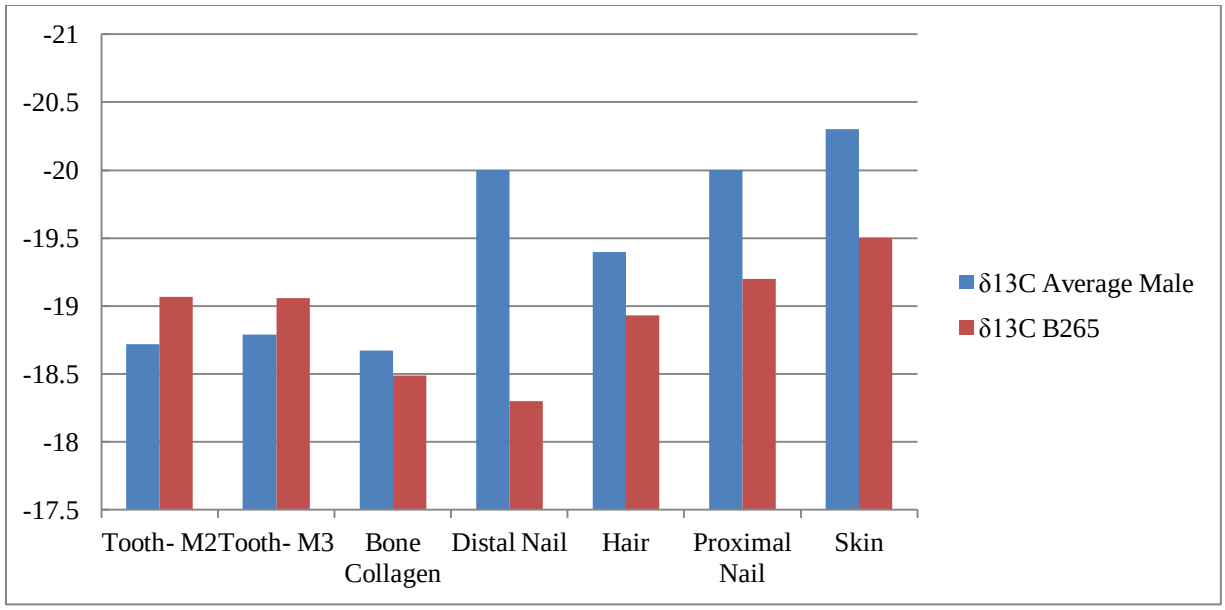


Figure 88: Graph comparing B265's $\delta^{13}C$ values with the average male values

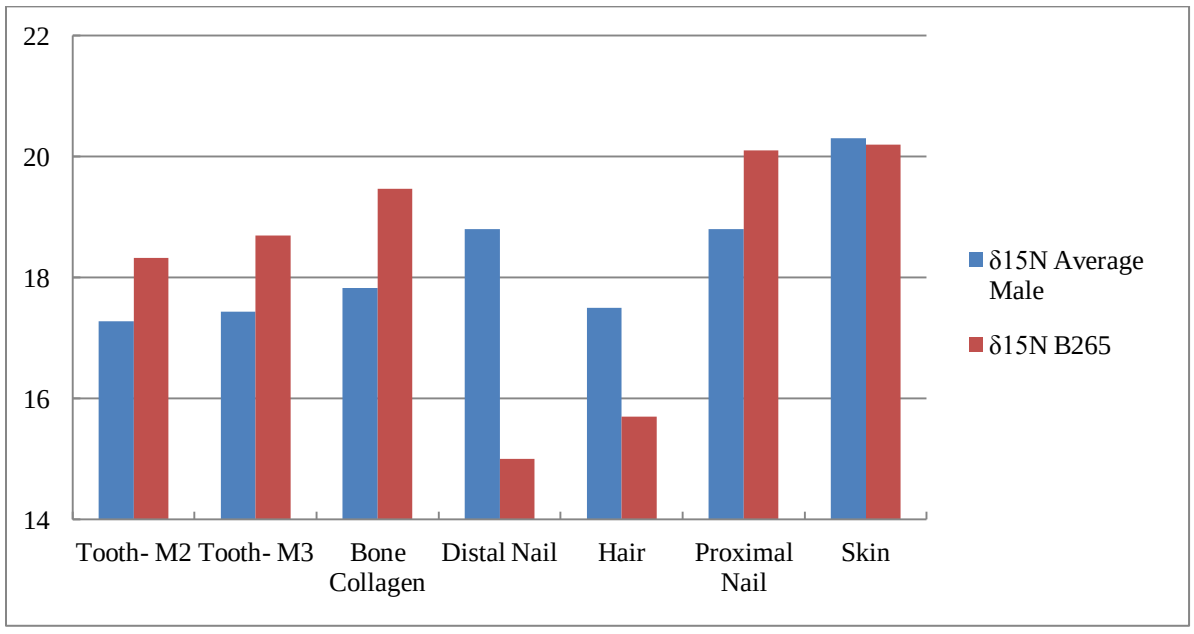


Figure 89: Graph comparing B265's $\delta^{15}N$ values with average male values

In early childhood, represented by $M^2$, B265's $\delta^{13}C$ value was -19.1‰, lower than the population $\delta^{13}C$ average (-18.7‰) and average $\delta^{13}C$ male value (-18.7‰) (Figure 90). His $M^3$ $\delta^{13}C$ value was also lower (-19.1‰), albeit closer to the population average $\delta^{13}C$ value (-18.9‰) and average $\delta^{13}C$ male value (-18.8‰). These values suggest that from ages 2 – 16 B265 was consuming approximately 16.2% $C_4$ foods in his diet, less than the average of 17.4 – 18.4%, suggesting he was eating mostly grains like wheat and barley for sustenance and not much millet or meat. His bone collagen $\delta^{13}C$ value (-18.5‰), which is also a long term value but represents much later period in his life (ages 40 – 50), transitions to being more enriched than the population $\delta^{13}C$ mean value at -18.5‰, though not remarkably so. He was now consuming approximately 20% $C_4$ foods, even more than the average for an adult male (18.9%).

While B265's long term $\delta^{13}C$ values were decreasing, his long term $\delta^{15}N$ values increased from 18.3‰ ($M_2$) to 19.5‰ (bone collagen) (Figure 91). His $M^2$ and $M^3$ $\delta^{15}N$ values are much more enriched than the population $\delta^{15}N$ average, but his bone collagen $\delta^{15}N$ value is over one standard deviation (±1.5‰) away from the average $\delta^{15}N$ male value (17.8‰). As mentioned previously, his $\delta^{13}C$ values indicate that towards the end of his life he was consuming more $C_4$ foods than average. His $\delta^{13}C$ and $\delta^{15}N$ values in combination with his skeletal pathological conditions indicate that during the time period represented by his bone collagen, 40 – 50 years old, he was already suffering from some kind of disease, probably tuberculosis.

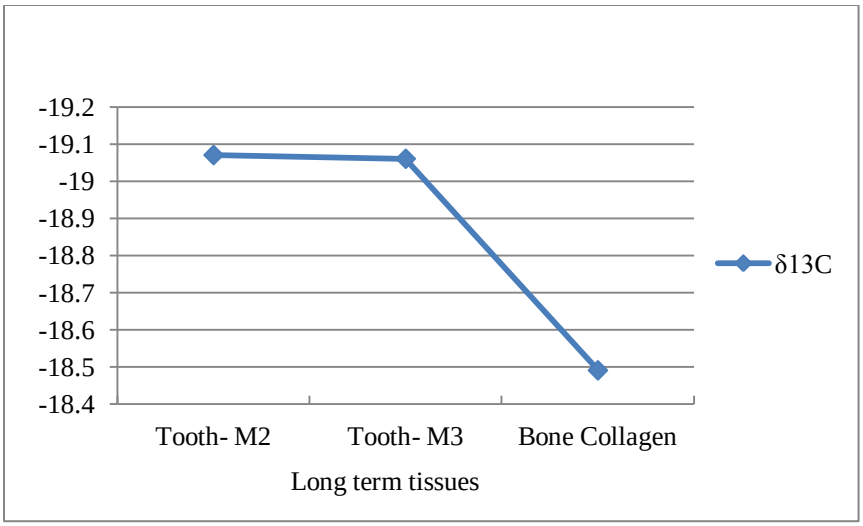


Figure 90: Line-graph depicting the long-term $\delta^{13}C$ values from B265

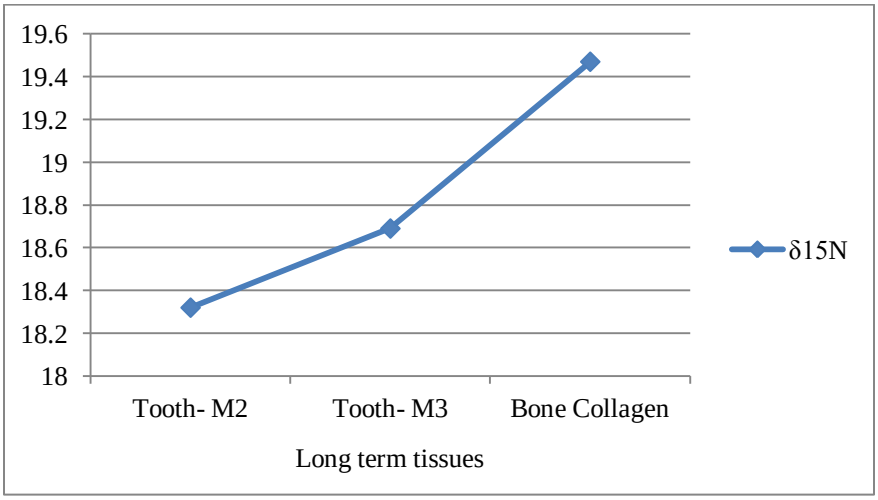


Figure 91: Line-graph depicting the long-term $\delta^{15}N$ values from B265

B265's short term diet is examined by analyzing three hair samples, proximal and distal nail, and skin (Figures 92 and 93). His $\delta^{13}C$ values become increasingly more enriched closer to

death (Figure 92). His distal nail sample, representing 6 months prior to death, has a $\delta^{13}C$ value of -18.3‰, which is considerably enriched compared to the population and male $\delta^{13}C$ averages, both -20‰. In fact, with a small standard deviation of ±0.3‰, it is over 2 standard deviations away from the average male $\delta^{13}C$ value. This suggests that B265 was eating considerably more millet and/or meat than most individuals in the population. His proximal nail sample, at one month prior to death, decreases to -19.2‰, but remains more enriched in $^{13}C$ than the population average. His hair $\delta^{13}C$ values are also more enriched than the population $\delta^{13}C$ average (-19.3‰), especially his third hair $\delta^{13}C$ value (3 months prior to death at -18.6‰). His hair values decrease over time, from -18.6‰ to -19.1‰ to -19.2‰. His skin $\delta^{13}C$ value (-19.5‰), is also above the population $\delta^{13}C$ average (-19.8‰). Williams (2008) did not discuss the season of B265's death, but based on her analysis, a trend where hair $\delta^{13}C$ values decrease prior to death indicate a death in either spring or autumn. B265 has a grave azimuth of 82° indicating a death in the spring. This corresponds with the spring wheat and barley harvests, when people would have been consuming more $C_3$ foods.

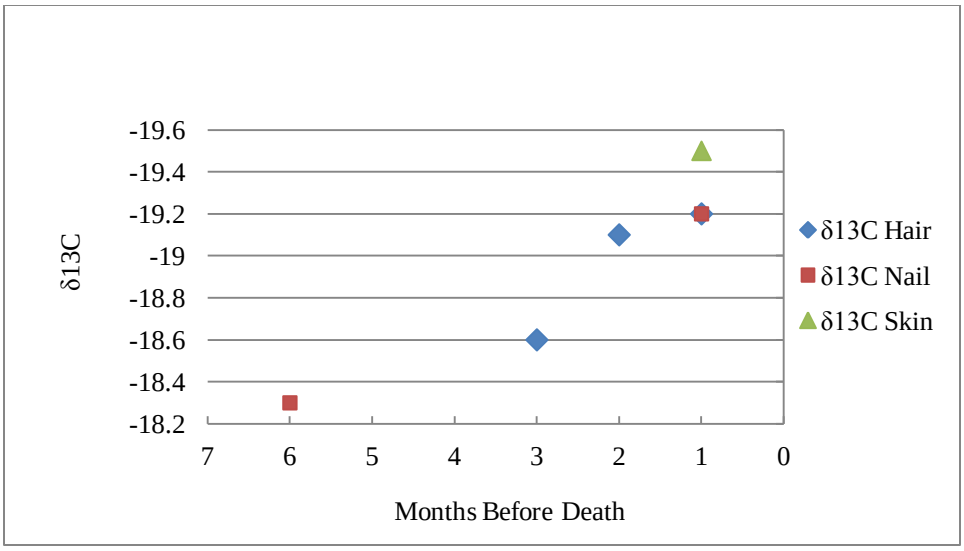


Figure 92: Scatter plot depicting short-term $\delta^{13}C$ values from B265

B265's short term $\delta^{15}N$ values are very interesting (Figure 93). His distal nail and hair $\delta^{15}N$ values are all well below the population average $\delta^{15}N$ value. At 15‰, his distal nail $\delta^{15}N$ value is over 3 standard deviations (±1.2‰) below the population $\delta^{15}N$ mean (19‰), and at 15.3‰ his second and third hair $\delta^{15}N$ values are 4 standard deviations (±0.7‰) below the population $\delta^{15}N$ mean (18.1‰). These extremely low values, not seen in B265's earlier life, are probably due to disease. His visible skeletal lesions strongly suggest an infection of tuberculosis and this probably affected his $\delta^{15}N$ values. Although it is possible that B265 was not in the Dakhleh Oasis when these tissues were formed (Dupras and Schwarcz, 2001), from 6 to 2 months prior to death, without corroboration from oxygen isotopes it may also be hypothesized that these $\delta^{15}N$ values are more likely due to disease. Tuberculosis results in destruction of tissue and, therefore creates a negative nitrogen balance. Regeneration of the bone is rare. At one

month before death both the hair and proximal nail $\delta^{15}N$ values increase to 16.2‰ and 20.1‰, respectively. The hair $\delta^{15}N$ value remains well below average, but the nail value is above the $\delta^{15}N$ average for the sample. His skin $\delta^{15}N$ value at 20.2‰ is also right around the population $\delta^{15}N$ average. This increase in $\delta^{15}N$ values and negative nitrogen balance are often seen before death in people with acute disease, and while we cannot speculate that B265 died directly from tuberculosis, is seems likely that he suffered from associated complications from his disease and organ failure.

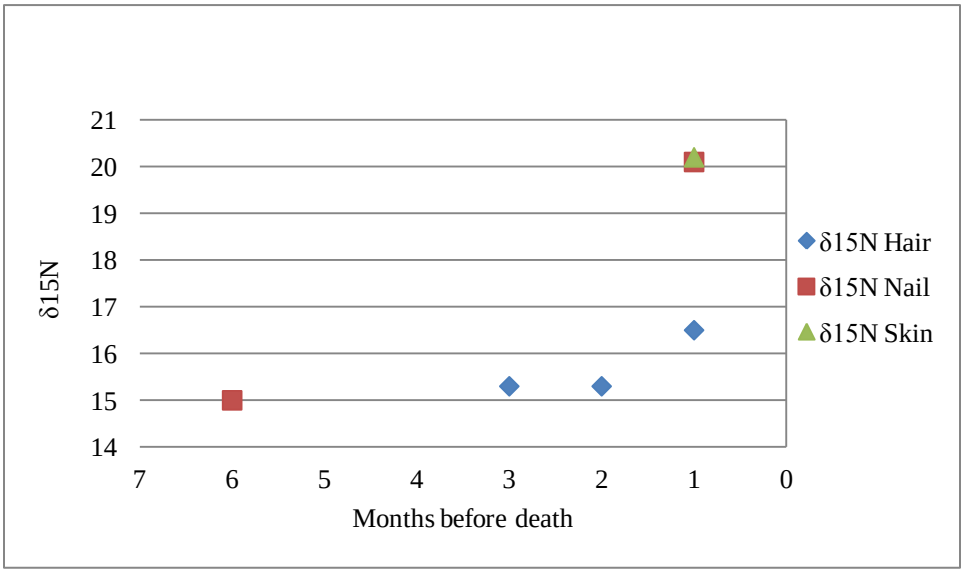


Figure 93: Scatter plot depicting short-term $\delta^{15}N$ values from B265

## Burial 269

Burial 269 contains the remains of a 55 ± 15 year old female and is located in the northeast corner of the cemetery. The notable pathologies on the skeleton are osteoporotic femoral fractures and chondromalacia, an irritation of the cartilage at the knee joint (Wiles et al., 1956). Osteoporosis, a condition that results in a reduction in bone density, is most common in menopausal women and because as it decreases the strength in bone, it increases the propensity of fracturing (Aufderheide and Rodriguez-Martin, 1998). These fractures can be painful or small and symptomless (Kanis et al., 1994). The evidence suggests that she suffered repeated injury at the fracture site, even while healing from previous fractures (Williams et al., 2011).

The tissues available for analysis are $M^1$, $M^2$, $M^3$, six hair samples, proximal nail, distal nail, and skin. The associated isotopic values for these tissues are listed in Table 13. The timeline showing the period in time each tissue corresponds with is shown in Figure 94. Figures 95 to 98 show a comparison of B265 isotopic values to those of the average population and female values.

Table 13: B269's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -19.1 | 17.0 |
| M2 | -18.7 | 17.0 |
| M3 | -19.0 | 16.9 |
| Bone Collagen | -19.2 | 18.2 |
| Hair (6) | -20.2 | 17.6 |
| Hair (5) | -19.8 | 17.8 |
| Hair (4) | -19.4 | 17.6 |
| Hair (3) | -19 | 16.3 |
| Hair (2) | -19.4 | 16.5 |
| Hair (1) | -19 | 17.4 |
| Distal Nail | -20.1 | 18.3 |
| Proximal Nail | -20.3 | 18 |
| Skin | -20.4 | 19.6 |

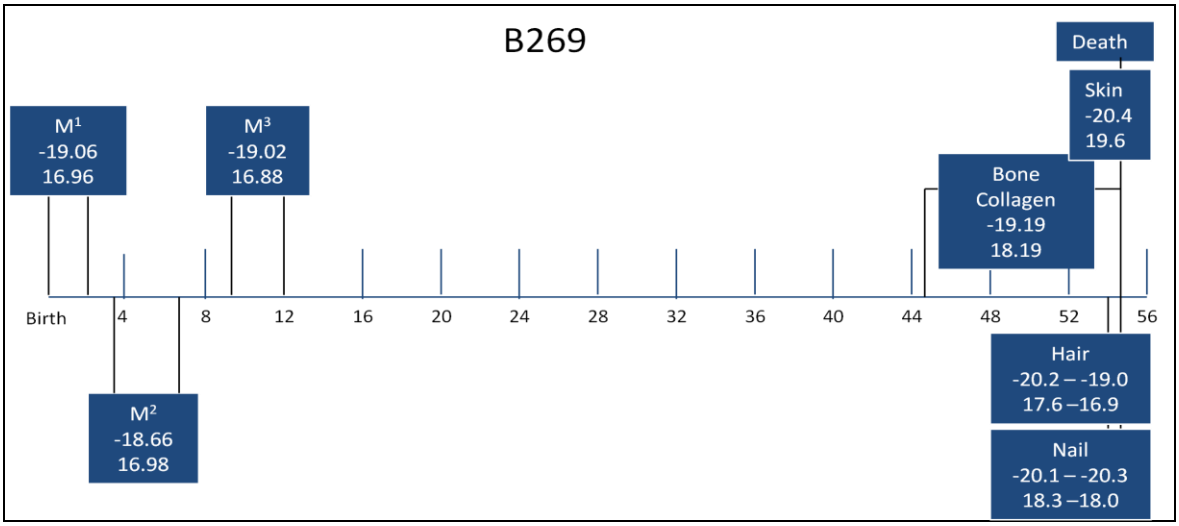


Figure 94: Timeline for B265 illustrating the ages each tissue represents

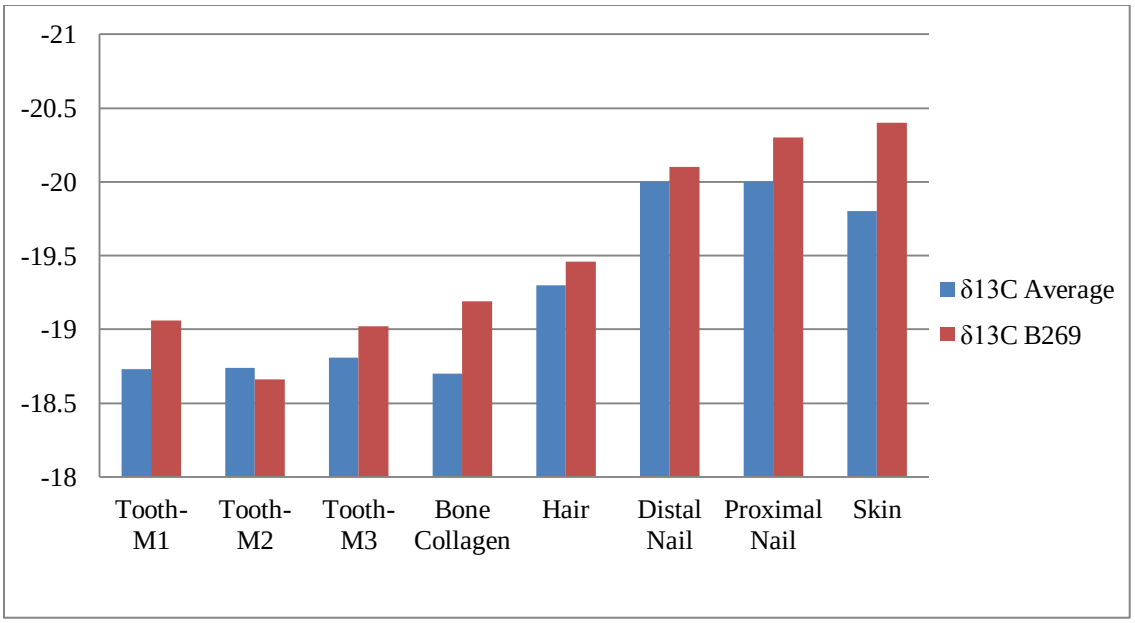


Figure 95: Graph comparing B269's $\delta^{13}C$ values with the rest of the population mean values

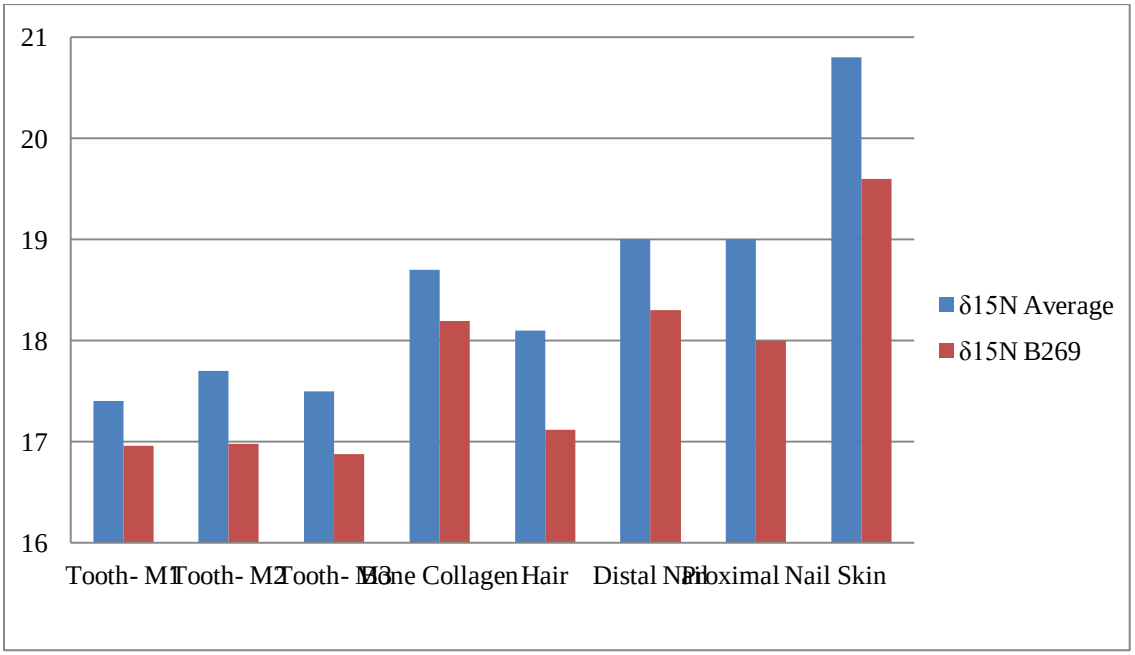


Figure 96: Graph comparing B269's $\delta^{15}N$ values with the population mean values

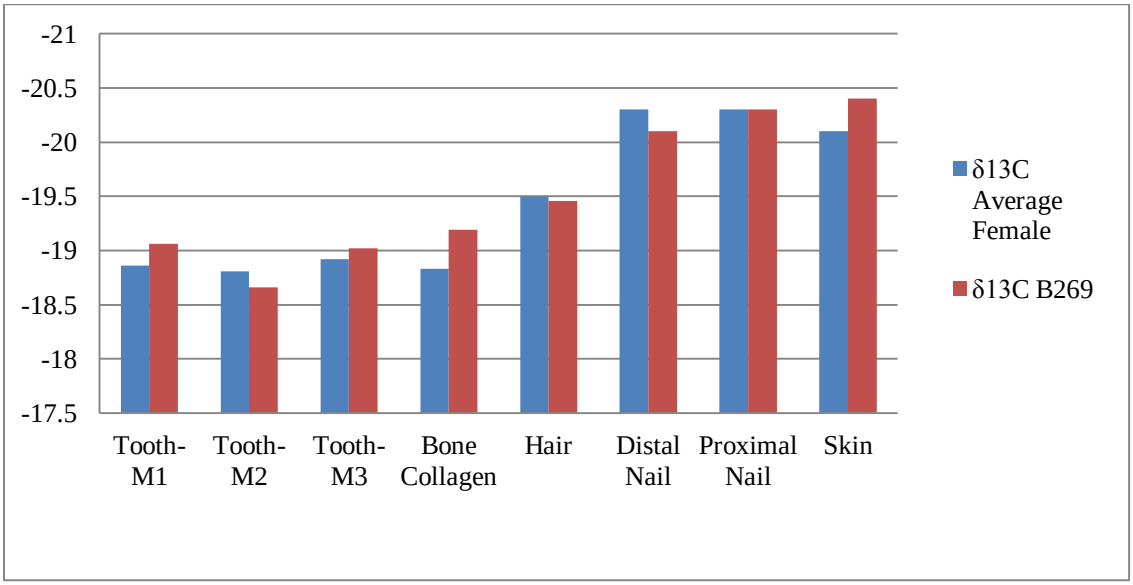


Figure 97: Graph comparing B269's $\delta^{13}C$ values with the average female values

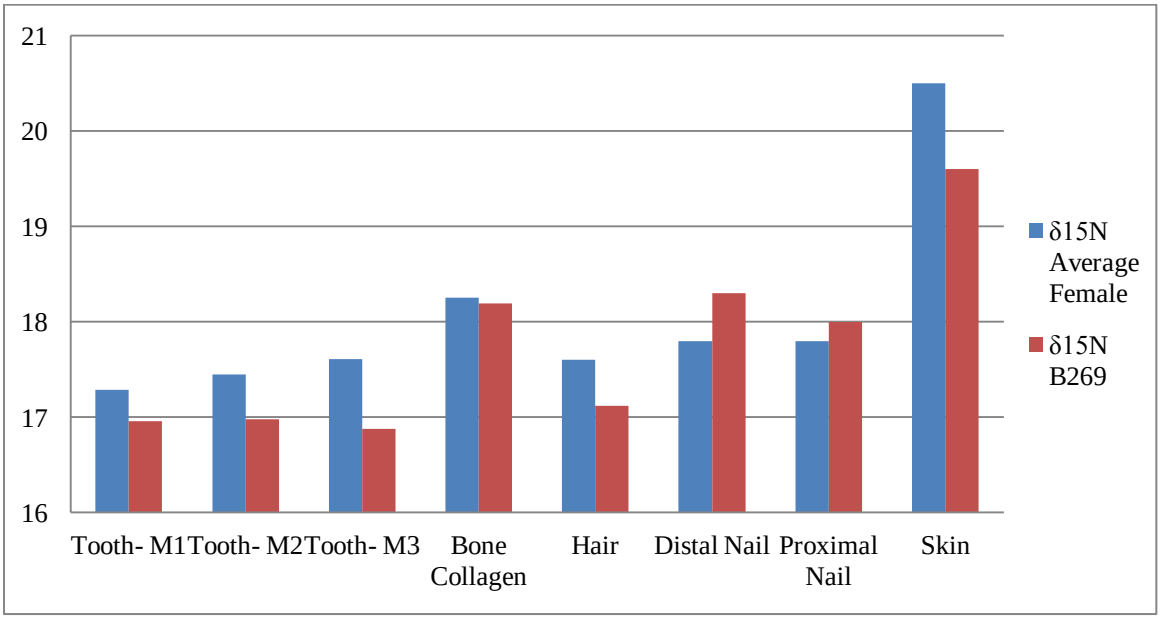


Figure 98: Graph comparing B269's $\delta^{15}$ values with the average female values

B269's long term $\delta^{13}C$ values show that as an infant, ($M^1$) with a value of -19.1‰, she was slightly more depleted in $^{13}C$ than the average population (-18.7‰) and mean female value (-18.8‰), and that as she got older (3.8 -6 years of age represented by $M^2$), she become more enriched in$^{13}C$ (-18.7‰). This $\delta^{13}C$ value is the same as the average population value (-18.7‰) and close to the average female (-18.8‰). As she gets older still and into adolescence ($M^3$), her $\delta^{13}C$ value decreases to -19.0‰. With juveniles being more enriched in $^{13}C$ than adults at Kellis 2, these $\delta^{13}C$ values are not surprising. The population mean $\delta^{13}C$ value for M3 also rises to -18.7‰ at this time. This pattern is seen in other individuals as well, wherein the $\delta^{13}C$ value is low prenatally, increasing in early childhood, and then decreasing again with age. Her bone collagen (representing 44-55 years of age) indicates another decrease (-19.2‰). Using the formula in Schwarcz et al. (1985), it can be determined that in early childhood she was eating between 16.5% and 18.9% $C_4$ foods and as an adult approximately 15.9% $C_4$ foods, indicating a diet heavily reliant on $C_3$ foods throughout her life.

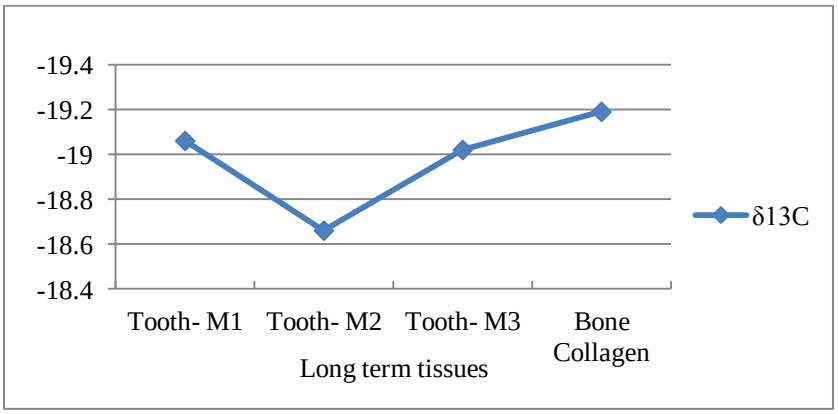


Figure 99: Line-graph depicting the long-term $\delta^{13}C$ values from B269

In comparison to the mean population and female $\delta^{15}N$ values, B269's childhood $\delta^{15}N$ values are all low (Figure 100). Her $\delta^{15}N$ values for $M^1$, $M^2$ and $M^3$ (17.0‰, 17.0‰, and 16.9‰, respectively) are lower than the population mean for these three tissues (17.4‰, 17.5‰, and 17.7‰) and the average female values (17.3‰, 17.5‰, and 17.6‰). While the $M^1$ $\delta^{15}N$ value (birth – 2.5 years of age) can be accounted for with breastfeeding, as with B91, the other low values (3.8 – 6 and 9.5 – 12 years of age) cannot be due to that. These $\delta^{15}N$ values are within a standard deviation, and are not so low as to presume her from elsewhere. Lower $\delta^{15}N$ values can also be indicative of metabolic states such as pregnancy or rebuilding tissue after injury or disease, but given the age span of these tissues, pregnancy is not the likely cause. Her bone collagen value (18.2‰), representing a longer period of time, is also more depleted than the average value of (18.7‰) It may be speculated that during childhood B269 was dealing with metabolic changes due to illness/disease.

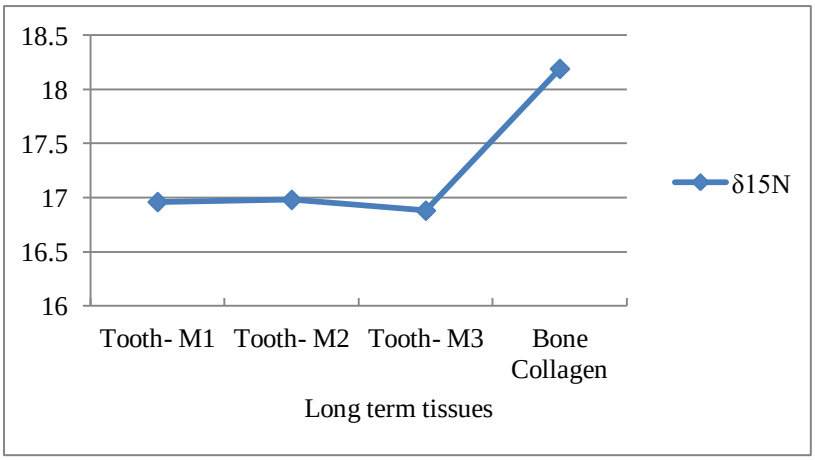


Figure 100: Line-graph depicting the long-term $\delta^{15}N$ values from B269

When assessing short term diet, the $\delta^{13}C$ values indicate that there is a gradual enrichment in $^{13}C$ from 6 months until 1.5-2 months prior to death (Figure 101). The hair $\delta^{13}C$ value at 6 months before death is -20.2‰, 0.8‰ less than the average female $\delta^{13}C$ value. This decrease continues to a $\delta^{13}C$ value of -19‰ (0.5‰ higher than the average female $\delta^{13}C$ value) at approximately three months prior to death. Her hair $\delta^{13}C$ values decrease to -19.4‰ two months before death, and then increase again one month prior to death (-19.0‰). This suggests that B269 was consuming between 15-35% $C_4$ foods six months prior to death, and 23-43% $C_4$ foods one month prior to death. Williams (2008) theorized that because B269 was buried at an 86° azimuth and her $\delta^{13}C$ values became more enriched closer to death that she died in the spring. This corresponds with her depleted values in the winter months (barely harvest) and enriched values in the spring months with the spring millet harvest. This enrichment could also be due to a special "sick" diet, such as millet pap, as her $\delta^{15}N$ values fall during this time as well. Her nail $\delta^{13}C$ values, on the other hand, show a depletion in $^{13}C$ from -20.1‰ to -20.3‰, both similar to at the mean $\delta^{13}C$ values for the population (-20‰) and average female (-20.3‰).

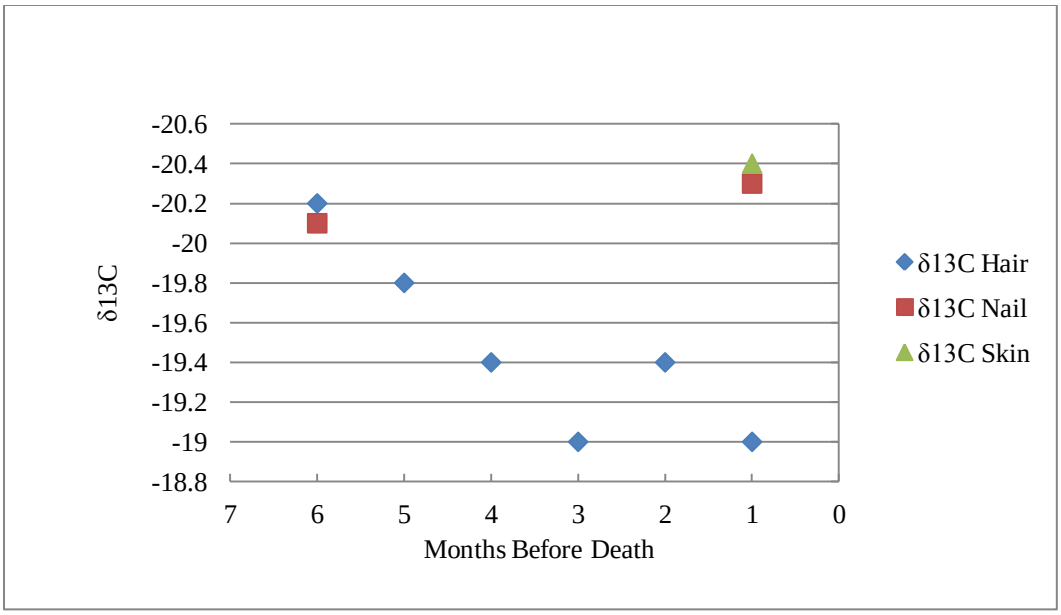


Figure 101: Scatter plot depicting short-term $\delta^{13}C$ values from B269

In fact, all of B269's nitrogen values, short term and long term, are lower than average. Her short-term values range from 1.8‰ -.7‰ lower than the mean (Figure 102). Her values at 6, 5, and 4 months before death are 17.6‰, 17.8‰ and 17.6‰, not far from the population average of 18.1‰. However, at three months and two before death, her hair value does show an interesting drop, to 16.3‰ and 16.5‰ and then sharply rises again to 17.4‰ one month before death. The values of 16.3‰ and 16.5‰ are two standard deviations (0.7‰) away from the mean (18.1‰) and this negative nitrogen balance is probably indicative of a fracture event. People suffering from femoral fractures often have negative nitrogen balance over the first few months post-trauma (Stableforth, 1986; Williams et al., 2011). Corroborating this hypothesis, Williams et al. 2011 found that B269 had 34% of hair in the telogen (or dormant stage) compared with the average of 10-15%. Telogen rates increase greatly in response to serious infection and trauma

(Klingman, 1961). The rise in $\delta^{15}N$ right before death and positive nitrogen balance is probably due to the facture healing and the body using recycled nitrogen for regrowth (Katzenberg and Lovell, 1999).

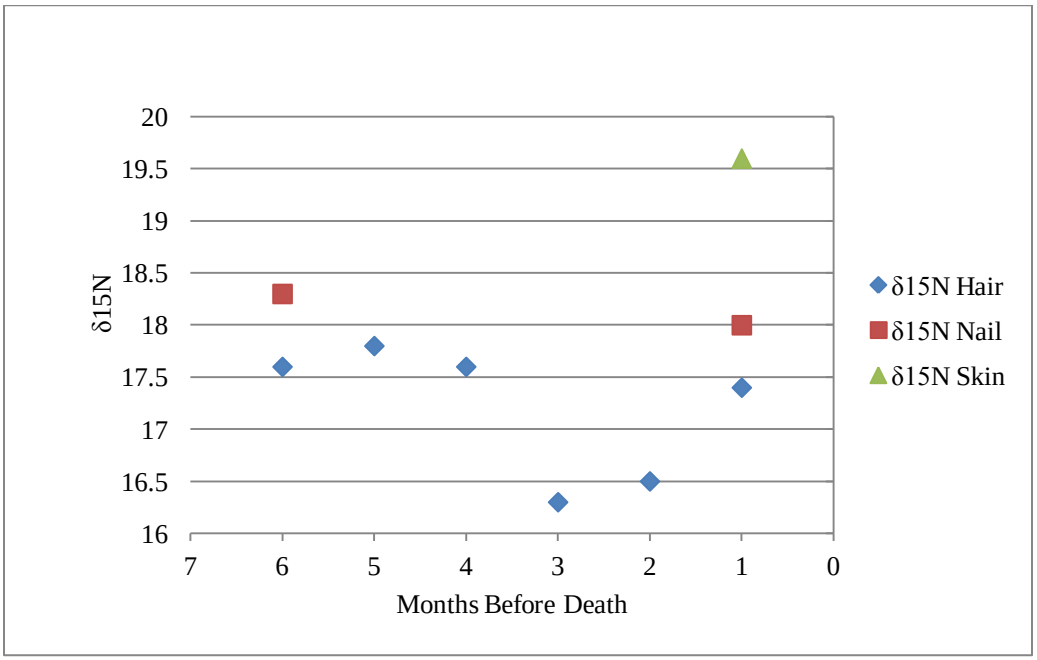


Figure 102: Scatter plot depicting short-term $\delta^{15}N$ values from B269

## Burial 271

Found in the north east section of the excavated cemetery at Kellis 2, Burial 271 contained a 31 ± 8 year old female with no notable pathologies. The tissues available for analysis include $M^1$, $M^2$, $M^3$, bone collagen, hair, nail, and skin, and this data can be seen in Table 14. A

timeline displaying the ages each tissue represents is shown in Figure 103. Figures 104 - 107 display the bar graphs comparing B271's $\delta^{13}C$ and $\delta^{15}N$ values to the mean population and female values.

Table 14: B271's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -18.6 | 20.1 |
| M2 | -19.0 | 15.3 |
| Bone Collagen | -18.5 | 19.6 |
| Hair (3) | -19.5 | 16.8 |
| Hair (2) | -19.4 | 16.6 |
| Hair (1) | -19.4 | 16.9 |
| Distal Nail | -20.7 | 18.1 |
| Proximal Nail | -19.3 | 18.8 |
| Skin | -19.5 | 20.5 |

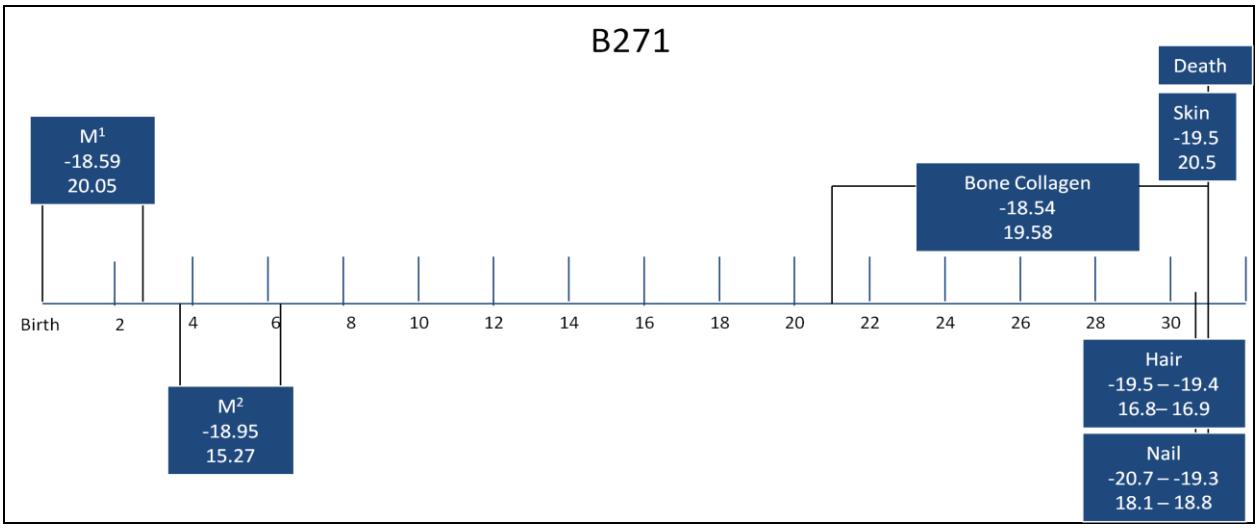


Figure 103: Timeline for B271 illustrating the ages each tissue represents

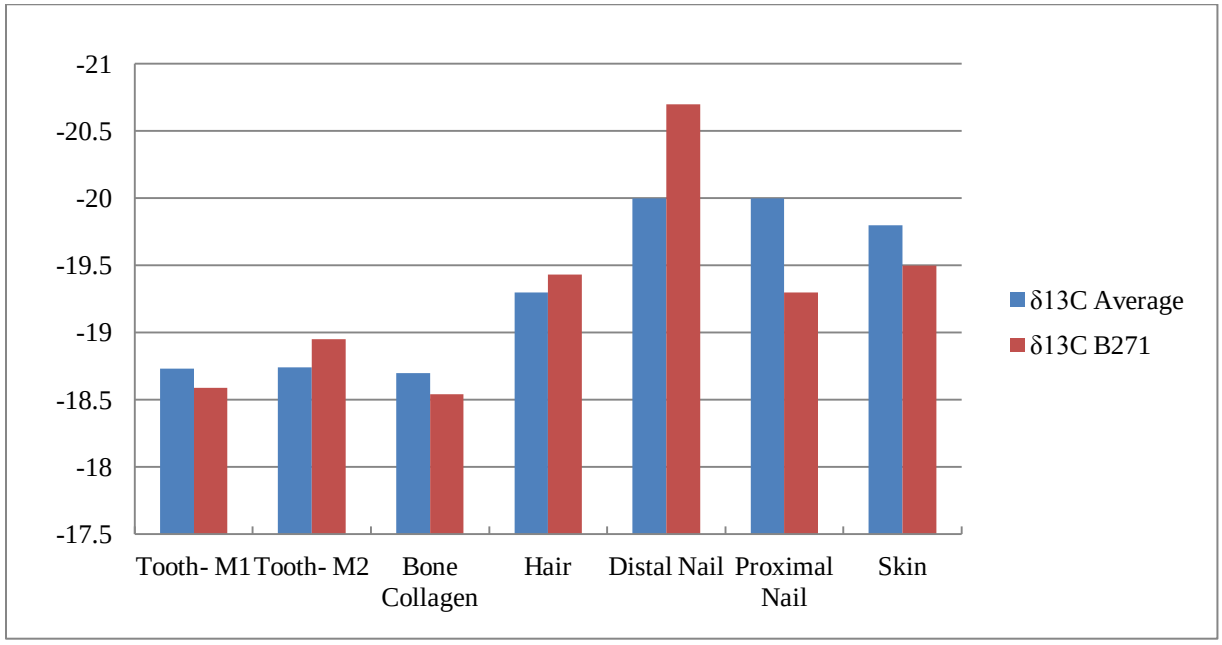


Figure 104: Graph comparing B271's $\delta^{13}C$ values with the rest of the population average values

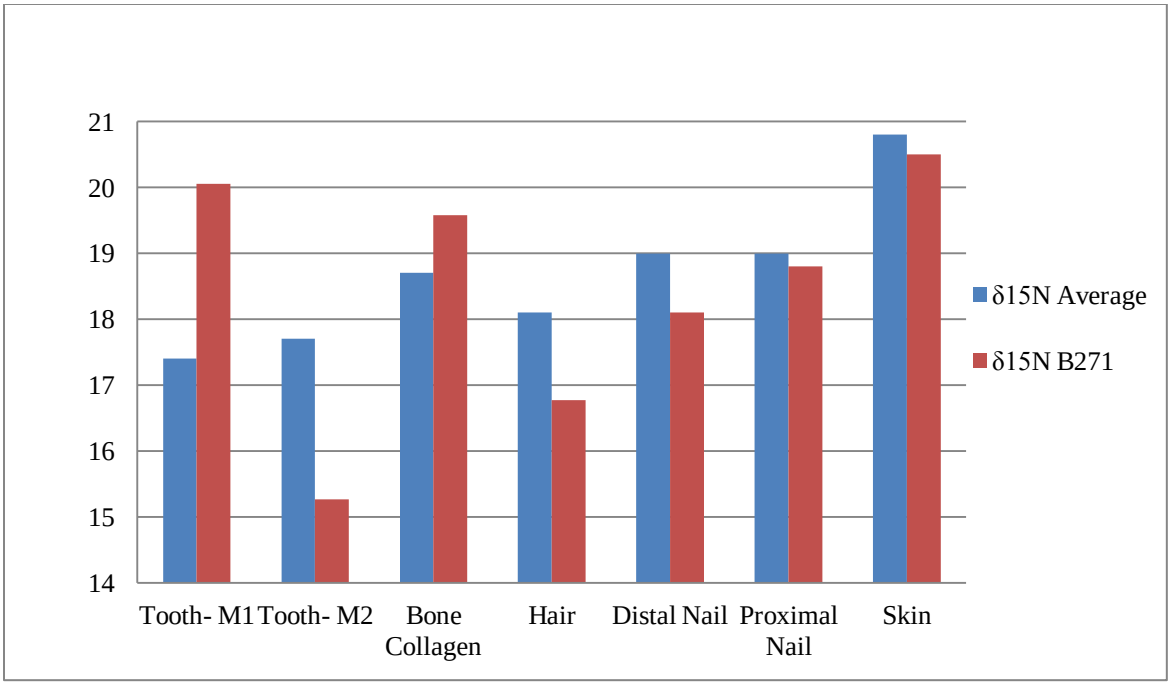


Figure 105: Graph comparing B271's $\delta^{15}N$ values with the population average values

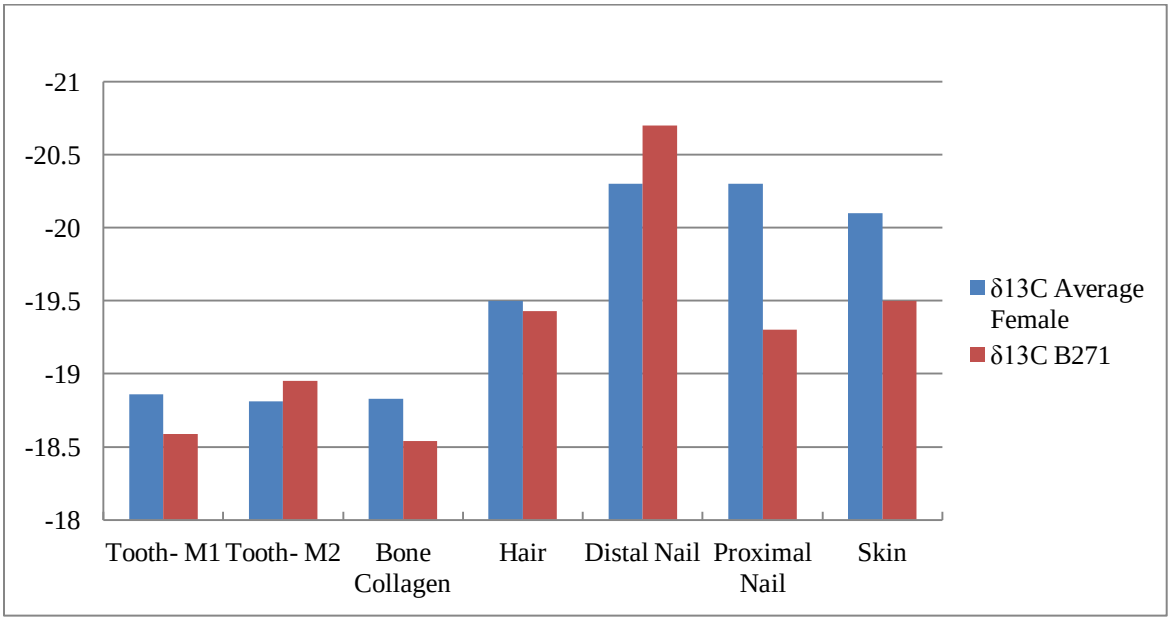


Figure 106: Graph comparing B271's $\delta^{13}C$ values with the average female values

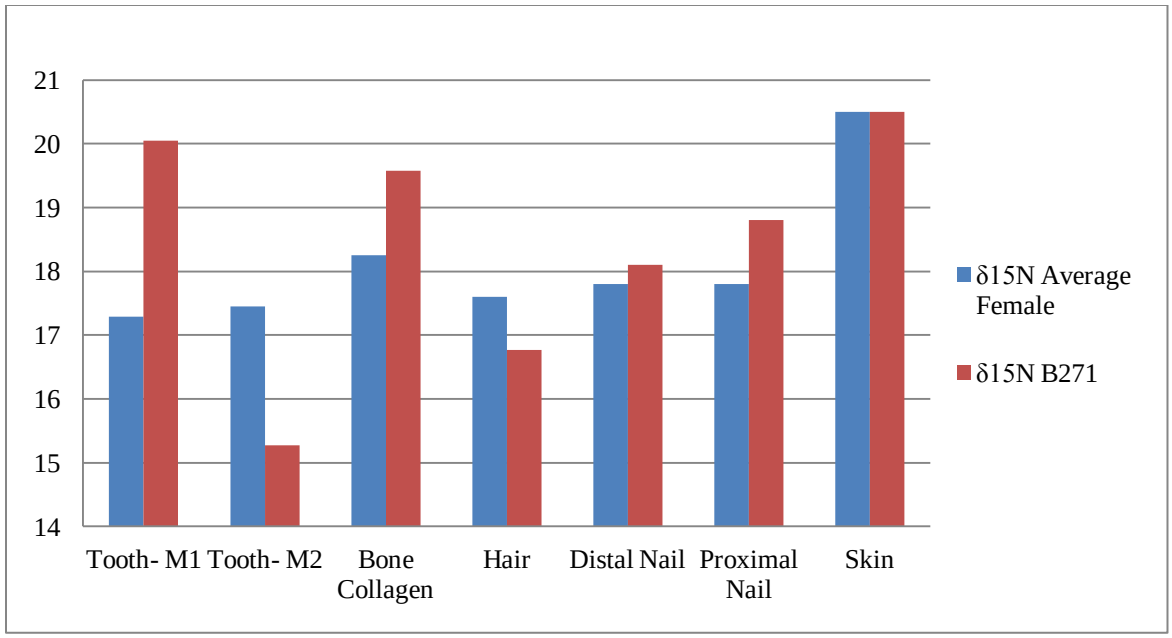


Figure 107: Graph comparing B271's $\delta^{15}N$ values with the average female values

When observing long term $\delta^{13}C$ values (Figure 108), B271's $M^1$ value at -18.6‰, representing birth – 2.5 years, is slightly lower than the population average (-18.7‰) and lower than her $M^2$ value of -19.0‰, which is also lower than the population average (-18.7). As shown by Dupras (2001), children under the age of 3 have more enriched $^{13}C$ values than the rest of the population due to a possible diet consisting of milk and millet. This can be seen in B271, as her $\delta^{15}N$ values decreases from $M^1$ (birth – 2 years of age) to $M^2$ (3 - 6 years of age). She transitioned between consuming 19.4% $C_4$ foods to 17% in these years. Her bone collagen $\delta^{15}N$ value (-19.5‰), representing ages 21 – 31, is once again a little lower than the average population and female $\delta^{15}N$ values. During these years she was consuming 19.7% $C_4$ foods; closer to the average male than the average female.

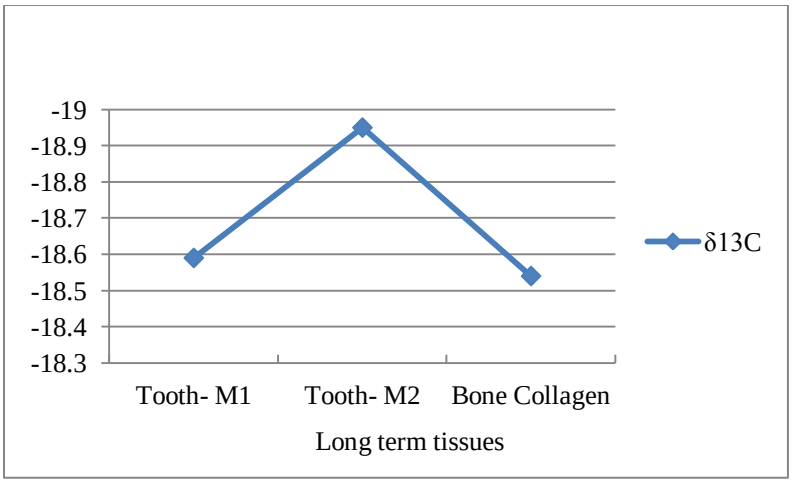


Figure 108: Line-graph depicting the long-term $\delta^{13}C$ values from B271

Her long term $\delta^{15}N$ values (Figure 109) start very high, with her $M^1$ value at 20.5‰; it is more than three standard deviations above the population mean value of 17.4‰. Young children, younger than 3, are expected to have $\delta^{15}N$ values that are higher than the rest of the population due to the tropic level effect and breastfeeding; her level, however, is higher than the average adult or juvenile $M^1$ or $M_1$ value. Her $M^2$ $\delta^{15}N$ value then decreases drastically, to 15.3‰. It is likely that B271 was not in the Dakhleh Oasis during this time and was rather in the Nile Valley, where values fall in this low range (Dupras and Schwarcz, 2001). Oxygen isotopes could be used in further studies to corroborate this hypothesis. Later in life, from ages 21 – 31, her nitrogen value raises again, up to 19.6‰, again more than two standard deviations above the mean. Unfortunately, with no skeletal pathologies visible, it is not possible to speculate as to the cause of these disparities in $^{15}N$ values; however, something was causing extreme negative nitrogen imbalance in B271 throughout life.

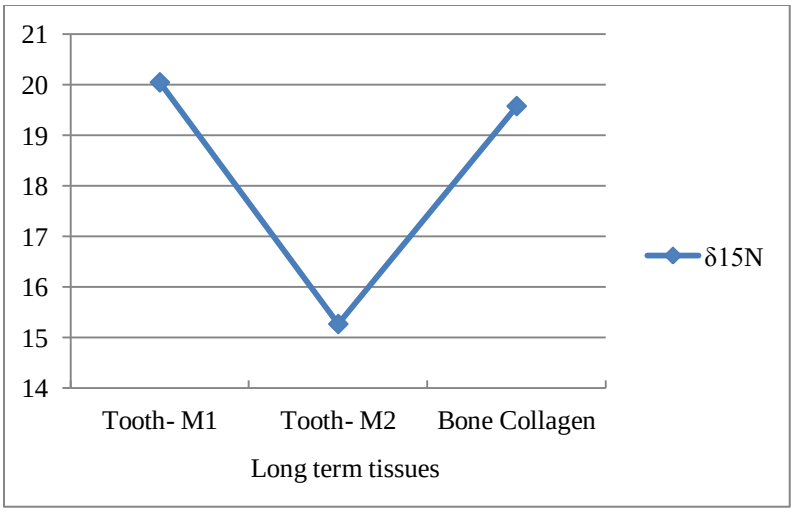


Figure 109: Line-graph depicting the long-term $\delta^{15}N$ values from B271

B271's short term tissues (Figure 110) indicate that her $^{13}C$ becomes more enriched from six months prior to and until death, with a distal nail $\delta^{13}C$ value of -20.7‰, and a proximal nail value of -19.3‰. Her hair $\delta^{13}C$ values show little change, with a $\delta^{13}C$ value of -19.5‰ three months prior to death and -19.4‰ one and two months prior to death. Her proximal nail and skin $\delta^{13}C$ values are both below the population and female $\delta^{13}C$ values. According to the formula used in Schwarcz et al. (1985), B271 was eating between 12 - 32% $C_4$ foods at six months prior to death, and 20 – 40% $C_4$ foods one month prior to death. She was buried at an 86° azimuth, and according to Williams (2008) B271's increase in $\delta^{13}C$ values suggests that B271 probably died in the spring, which corresponds with the spring millet harvest in March/April.

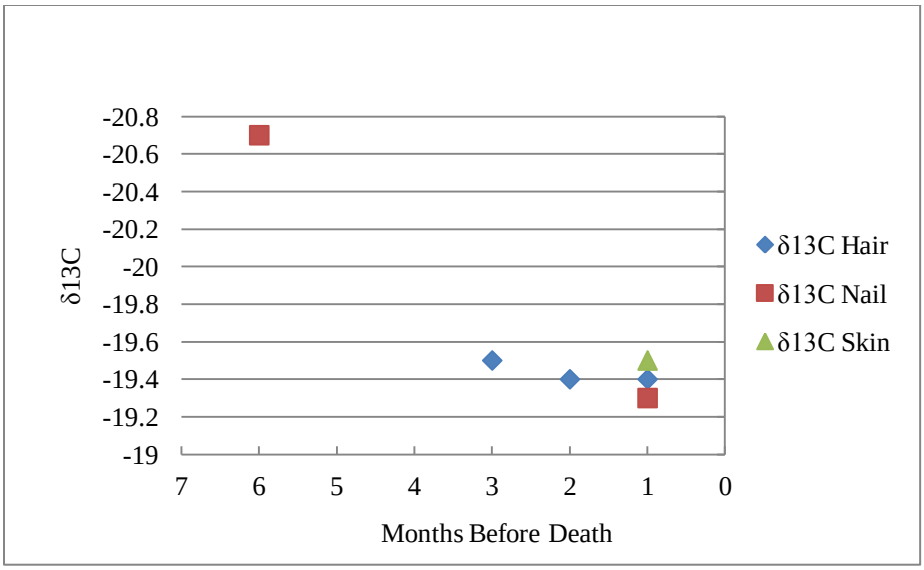


Figure 110: Scatter plot depicting short-term $\delta^{13}C$ values from B271

B271's short term $\delta^{15}N$ values are all lower than the population $\delta^{15}N$ average (Figure 111). The hair $\delta^{15}N$ values, 16.8‰, 16.6‰, and 16.9‰, are one standard deviation (0.7‰) below the population mean $\delta^{15}N$ value (18.1‰), but are within a standard deviation of the average female $\delta^{15}N$ value (17.8‰). Her nail $\delta^{15}N$ values, also below the population mean $\delta^{15}N$ value of 19.0‰, show enrichment from the distal nail (18.1‰) to the proximal nail (18.8‰). Her skin $\delta^{15}N$ value (20.5‰) is also slightly below the population average $\delta^{15}N$ value at 20.5‰. The $\delta^{15}N$ values appear to increase slightly before death, but the cause of this cannot be determined. As stated above, however, it is clear that her nitrogen balance is unstable close to death. Low nitrogen values are associated with pregnancy, as is a slight rise right before birth (Fuller et al. 2005). Given B271's age, it is possible this representative of the last few months before birth.

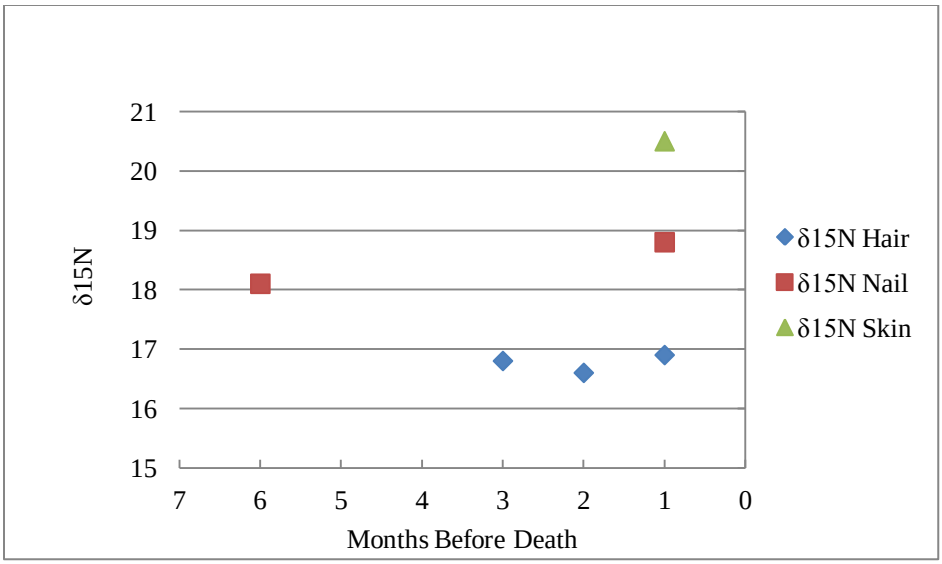


Figure 111: Scatter plot depicting short-term $\delta^{15}N$ values from B271

## Burial 279

Located in the northeast part of the Kellis 2 cemetery excavated section, Burial 279 (B279) held the remains of an adult female who was 23 ± 3 years old at time of death. The only notable pathology was healed cribra orbitalia, a lesion located on the orbital roof. Cribra orbitalia is a non-specific indicator of anemia, or low iron levels in the blood during childhood (Aufderheide and Rodriguez-Martin, 1998). Samples from B279 inlcude: $M^1$, $M^2$, $M^3$, bone collagen, nail, hair, and skin. From the nail there are distal and proximal samples, and from the hair there are five sequential 1 cm samples. The $\delta^{13}C$ and $\delta^{15}N$ values for each of these different samples are shown in Table 15, and Figure 112 illustrates the time in life the various tissues

represent for B279. The values for $\delta^{13}C$ and $\delta^{15}N$ are compared to the overall $\delta^{15}N$ average of the population and the average $\delta^{15}N$ values for females in the Kellis 2 cemetery (Figures 113 - 116).

Table 15: B279's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -18.8 | 17.7 |
| M2 | -18.5 | 17.9 |
| M3 | -18.9 | 18.8 |
| Bone Collagen | -19.1 | 18.5 |
| Hair (5) | -19.9 | 17.5 |
| Hair (4) | -19.7 | 17.5 |
| Hair (3) | -19.7 | 17.1 |
| Hair (2) | -19.7 | 17.4 |
| Hair (1) | -19.3 | 18.7 |
| Proximal Nail | -20.5 | 19 |
| Distal Nail | -20.3 | 17.6 |
| Skin | -19.4 | 20.6 |

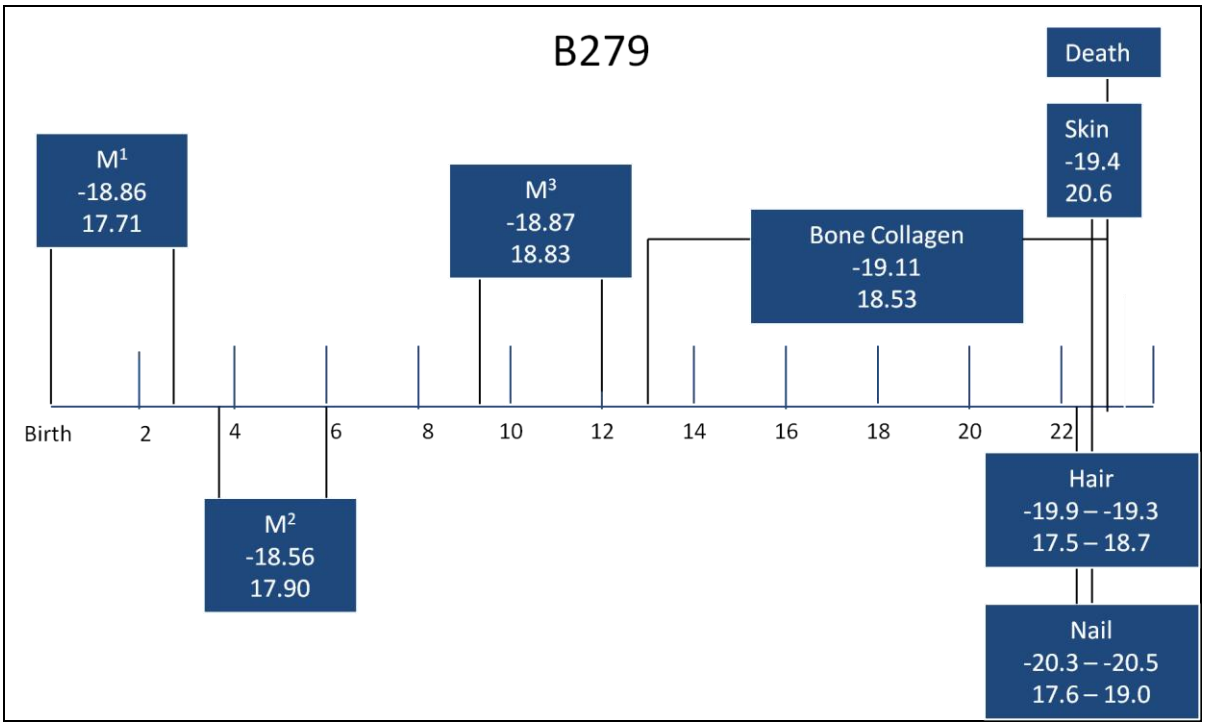


Figure 112: Timeline for B279 illustrating the ages each tissue represents

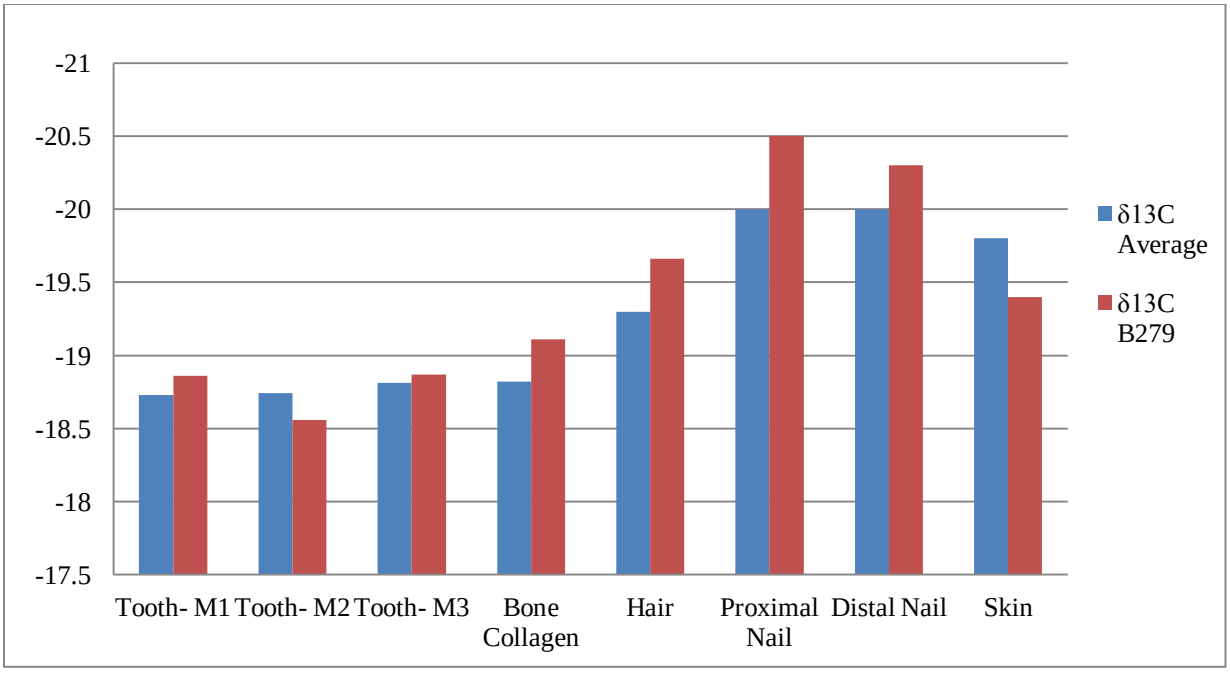


Figure 113: Graph comparing B279's $\delta^{13}C$ values with the population mean values

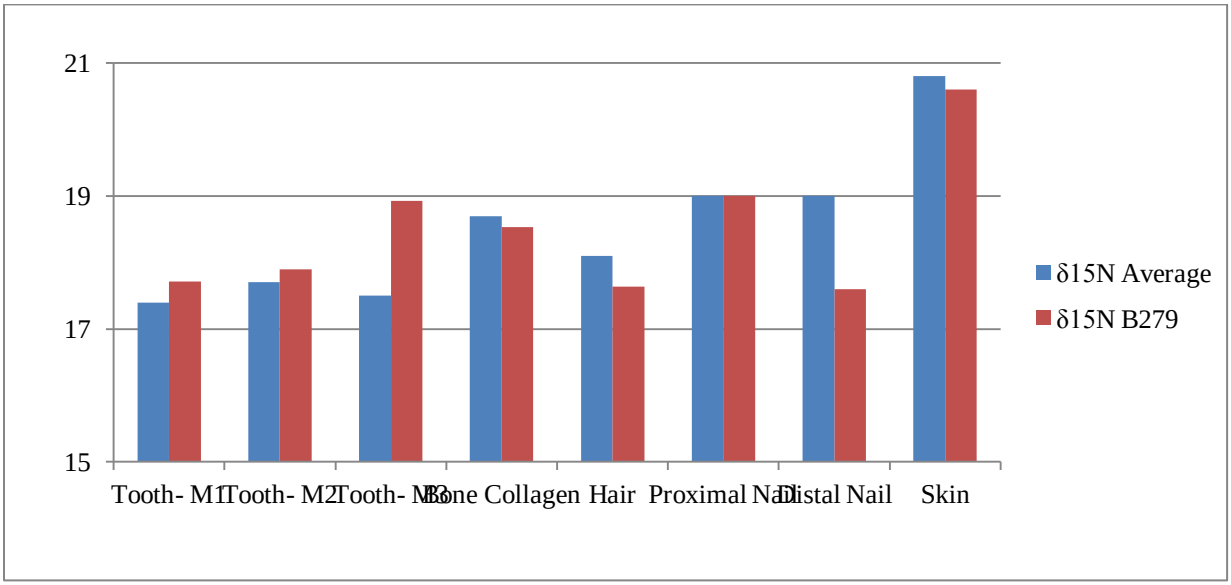


Figure 114: Graph comparing B279's $\delta^{15}N$ values with the population mean values

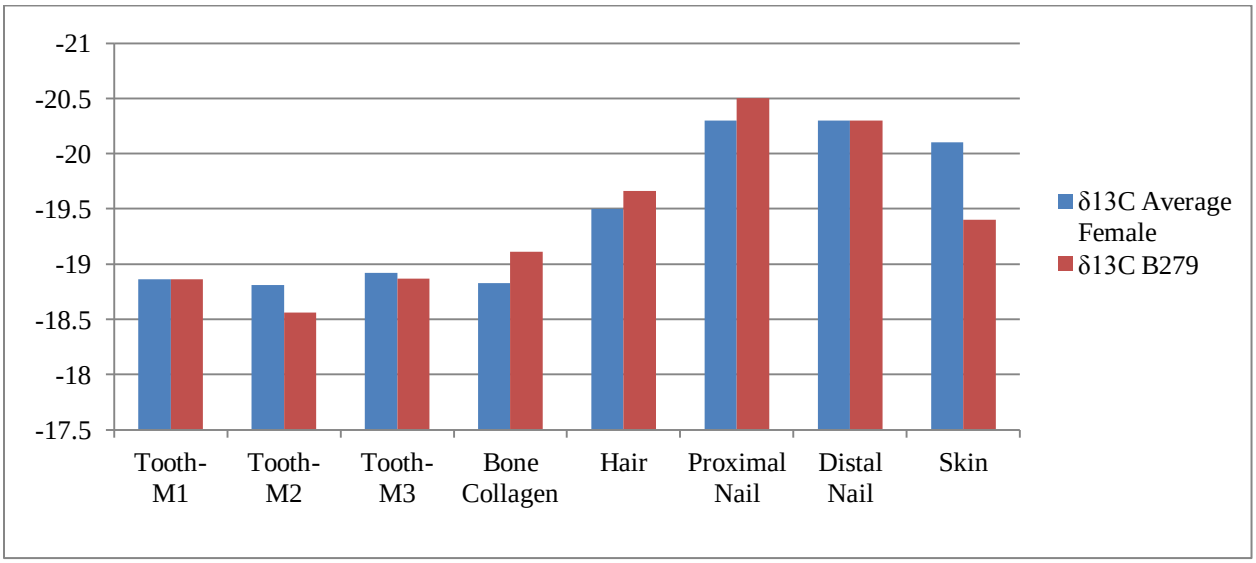


Figure 115: Graph comparing B279's $\delta^{13}C$ values with the average female values

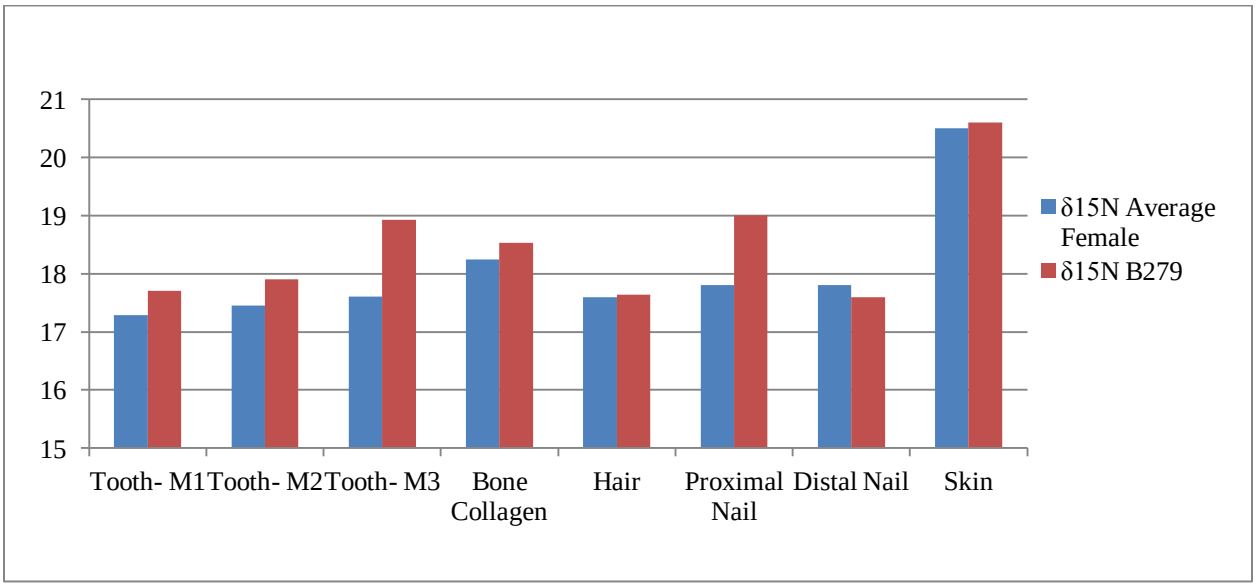


Figure 116: Graph comparing B279's $\delta^{15}N$ values with the female average values

When examining long-term diet, the samples from the $M^1$, $M^2$, $M^3$ and bone collagen are analyzed. Figures 117 and 118 illustrate the $\delta^{13}C$ and $\delta^{15}N$ values for the samples representing long-term diet. The samples that represents the earliest time in life are that of the dentin from the $M^1$ and $M^2$. The $\delta^{13}C$ values are -18.8‰ and -18.5‰, and denote birth – 2.5 and 3.8 – 6 years of age, respectively. Her $M^1$ $\delta^{13}C$ value is very close to the average $M^1$ value (Figure 113) for the population (-18.7‰). Her $M^2$ $\delta^{13}C$ value (-18.5‰) is more enriched than the $M^1$, and the population (-18.7‰) and female (-18.8‰) average values. Overall, as a child she was eating a diet consisting of $C_3$ and some $C_4$ foods, such as millet and animals that were fed millet (e.g., cows and goats) like the rest of the people in the population. After using the formula presented in Schwarcz et al. (1985), it can be deduced that at this point in her life, B279 was consuming between 17.6 - 19.6% $C_4$ foods (millet) in her diet. As B279 got older and reached adolescence and beyond, her $\delta^{13}C$ values began to decrease. This is illustrated by the $M^3$ (6-16 years of age) and bone collagen $\delta^{13}C$ values (13 years and older). Her $M^3$ $\delta^{13}C$ value is -18.8‰, and then there is a decrease to -19.1‰ with bone collagen. She was now only consuming around 15.9% $C_4$ foods in her diet.

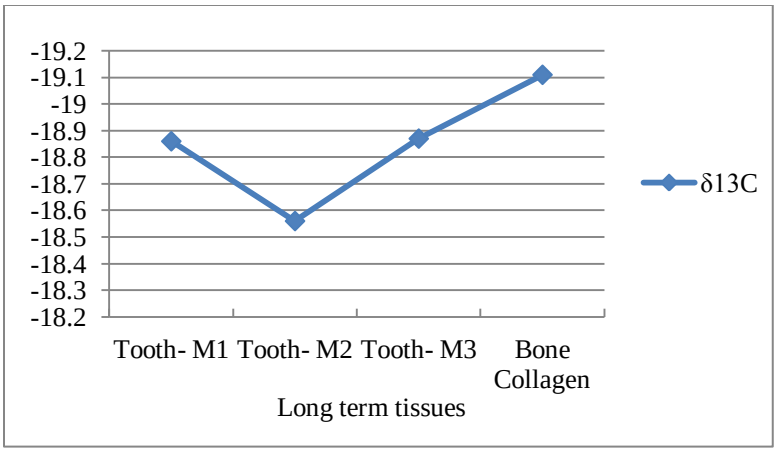


Figure 117: Line-graph depicting the long-term $\delta^{13}C$ values from B279

The long-term $\delta^{15}N$ values for $M^1$ (17.71‰), $M^2$ (17.9‰) are close to the rest of the population (17.4‰ and 17.5‰) and the average female (17.3‰ and 17.4‰). Her $M^3$ $\delta^{15}N$ value (18.83‰) representing approximately 9.5-12 years of age, however, increases sharply and is over 1 standard deviation away from the mean (17.7‰ ±1.04). This negative nitrogen balance may be a result metabolic stress suffered from an episode of anemia or some other illness that she experienced between ages 9.5 and 12. By adulthood, represented my bone collagen, her $\delta^{15}N$ value was congruent with the rest of the population (18.7‰), at 18.5‰ and may demonstrate that she had reached full recovery from the anemia.

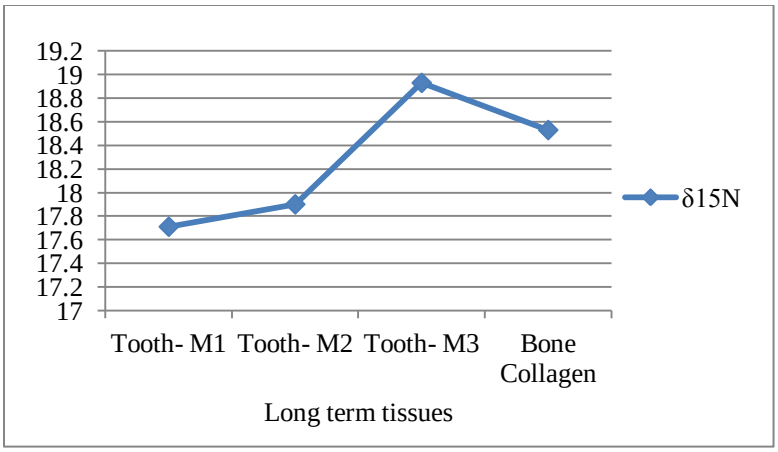


Figure 118: Line-graph depicting the long-term $\delta^{15}N$ values from B279

In terms of short term diet, B279 can be accessed from 6 months prior to and up to death (see Figures 119 and 120). There are 5 segments of hair that represent 5 months - 1 month prior to death, a distal nail that represents 5.5 – 6 months before death, a proximal nail that represents 1 month before death, and a skin sample that represents one month before death. The $\delta^{13}C$ values of the hair show an interesting trend (Figure 119). Her $\delta^{13}C$ values, which range from -19.3‰ to -19.9‰, are all very close to the average female value of -19.5‰ and suggest she was consuming between 11 - 41% $C_4$ foods. The samples become more $C_4$ enriched in the months before death, following a linear trend, with the $\delta^{13}C$ value of -19.3‰ one month before death and the $\delta^{13}C$ value of -19.9‰ five months before death. This means that B279 slowly began eating more and more $C_4$ grains or animals that fed on $C_4$ plants in the months leading up to death. Williams (2008) theorized that B279 died either during early spring or mid-autumn based on burial solar alignment and grave azimuth (98°). The short-term $\delta^{13}C$ values represent the 5 months leading up to death and therefore should correspond to either the months of November –

March or June - October. The three annual millet harvests take place in March/April, June/July, and October. If B279 died in October, her values would have been low in June with the summer millet harvest and remained low for the October harvest. Her $\delta^{13}C$ values seem to correspond better with an early spring death, as Williams theorized, with the autumn millet harvest being over in November and picking back up in March. Her skin $\delta^{13}C$ value of -19.4‰ is also higher than the average $\delta^{13}C$ population value of -19.8‰ (which represents the average of all times of year, Figure 114) or the average female's value of -20.1‰ (Figure 115), indicating that in the month before death she was eating more millet than usual.

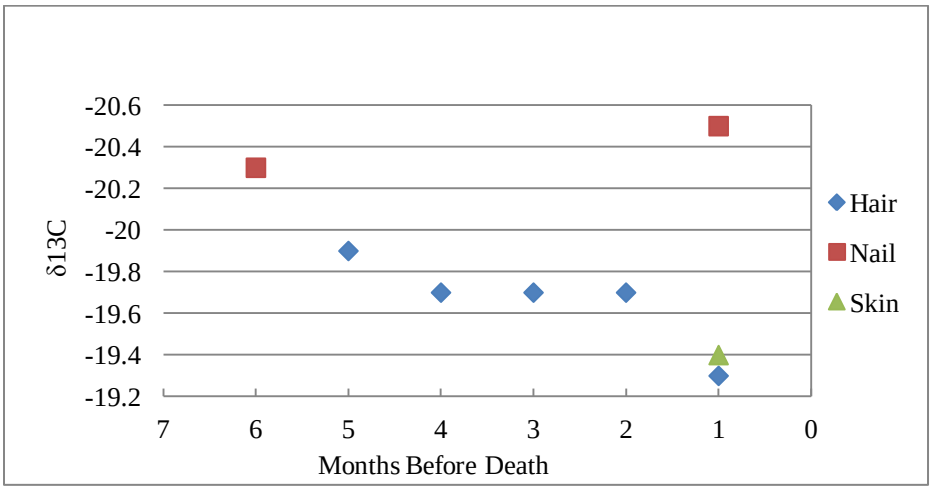


Figure 119: Scatter plot depicting short-term $\delta^{13}C$ values from B279

In the month prior to death, B279 experienced a sharp increase in $\delta^{15}N$ (Figure 120). Her hair $\delta^{15}N$ values jumped from 17.4‰ 2 months prior to death to 18.7‰ 1 month before death.

This is an increase of 1.3‰. The average female has a $\delta^{15}N$ value of 17.6‰ (Figure 116). Accordingly, her distal nail $\delta^{15}N$ value was 17.6‰ about 5 - 6 months prior to death and it increased to 19.0‰ in the month before death, for an increase of 1.4%. Again, the short-term $\delta^{15}N$ value farthest from death (the distal nail) is much closer to the average female (17.8‰). With B279 being a 23 year old female, and of childbearing age, it might be suggested that this increase was due to pregnancy. However, studies by Fuller et al. (2005) demonstrated that during pregnancy $\delta^{15}N$ values decline, not rise. Williams (2008) found this was consistent with individuals at Kellis 2. Additionally, during pregnancy the amount the anagen hair (hair that is actively growing) is increased. B279 did not have increased anagen hairs when tested by Williams (2008). With the enrichment in $^{15}N$ not being attributable to pregnancy, this negative nitrogen balance in a short-term tissue is probably the result of an acute condition, such as dehydration from kidney disease or kidney stones shortly before and possible leading up to death.

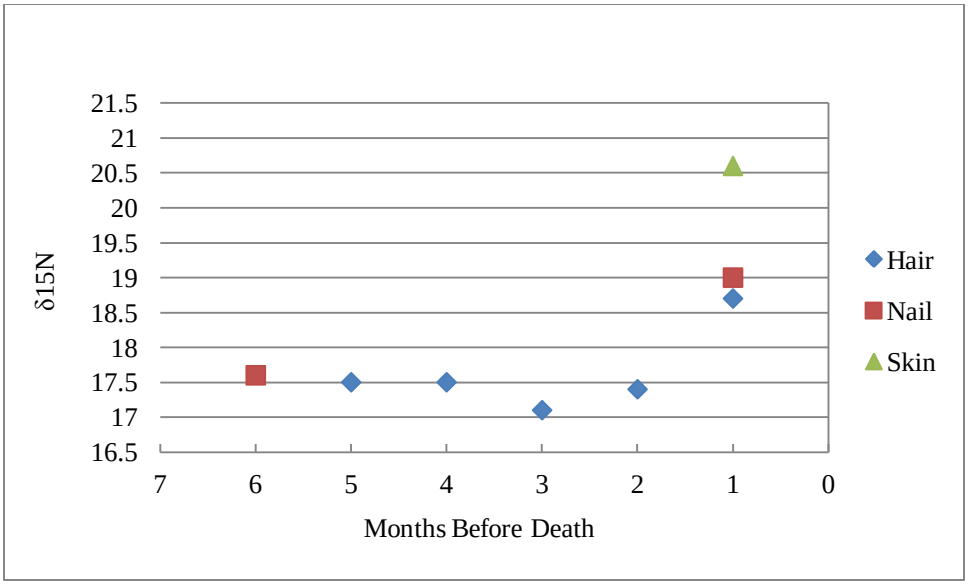


Figure 120: Scatter plot depicting short-term $\delta^{15}N$ values from B279

## Burial 310

This burial contained the remains of a 21 year-old male with no pathologies. His $\delta^{13}C$ and $\delta^{15}N$ values can be seen Table 16. They include two teeth ($M_1$ and $M_2$), bone collagen, four hair, and skin values. Figure 121 shows B310's lifespan and displays which periods of life each tissue represents. The bar graphs compare B310's isotopic values with the population and the average male values (Figures 122 - 125).

Table 16: B310's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| M1 | -19.1 | 17.7 |
| M2 | -19.0 | 17.7 |
| Bone Collagen | -18.8 | 18.5 |
| Hair (4) | -18.1 | 18 |
| Hair (3) | -18.7 | 17.7 |
| Hair (2) | -18.9 | 17.6 |
| Hair (1) | -19.4 | 16.8 |
| Skin | -21.2 | 22.5 |

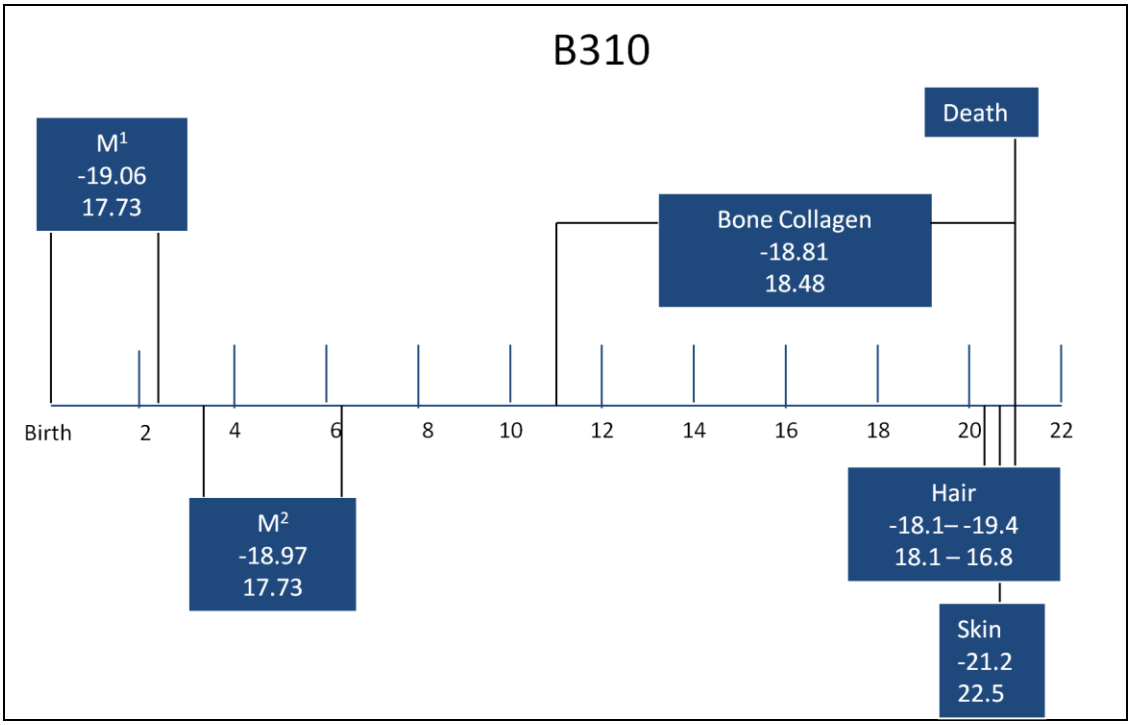


Figure 121: Timeline for B310 illustrating the ages each tissue represents

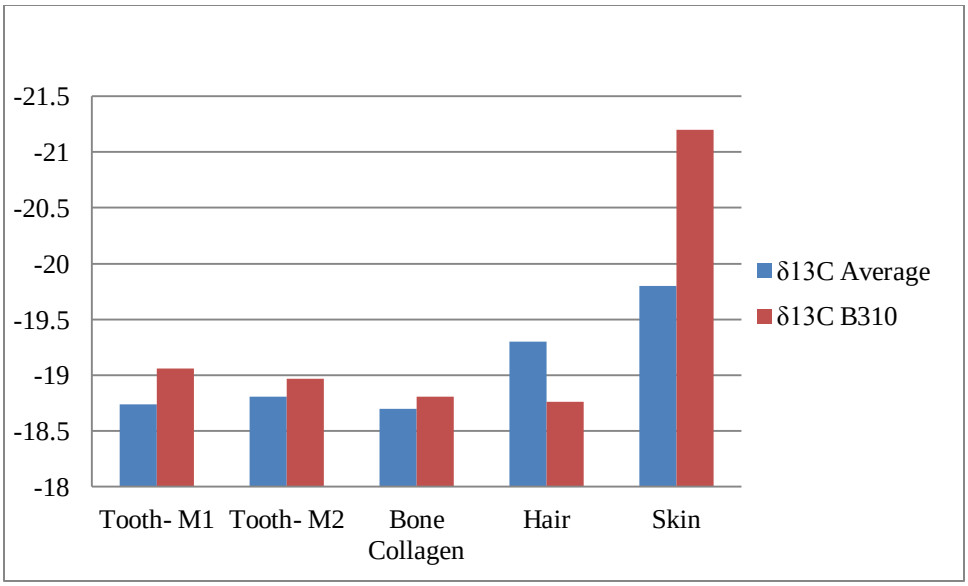


Figure 122: Graph comparing B310's $\delta^{13}C$ values with the population average values

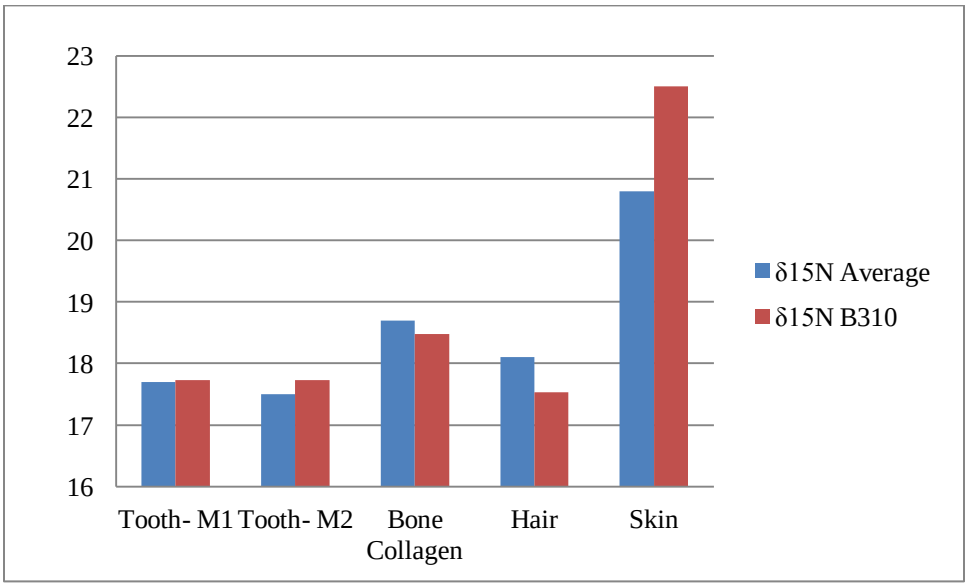


Figure 123: Graph comparing B310's $\delta^{15}N$ values with the population average values

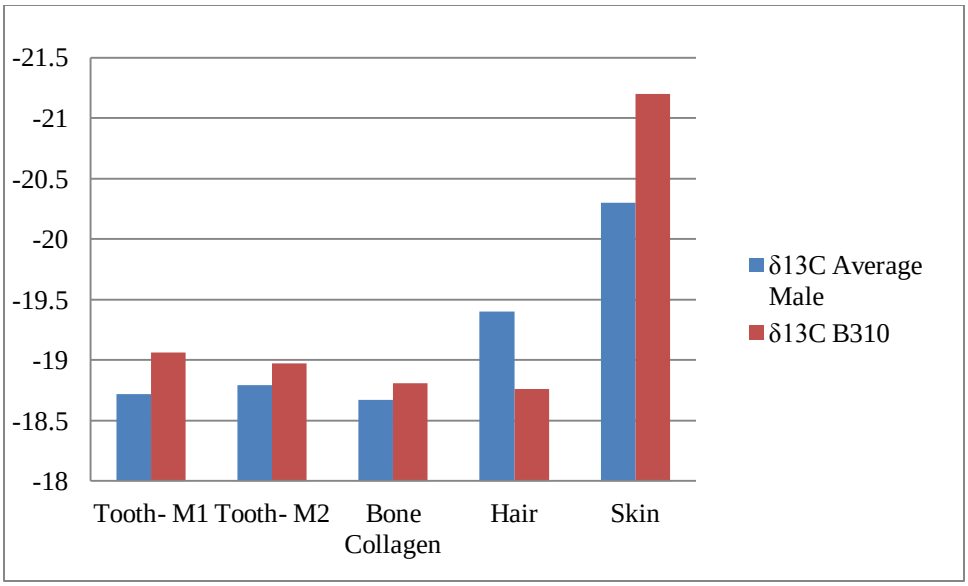


Figure 124: Graph comparing B310's $\delta^{13}C$ values with the average male values

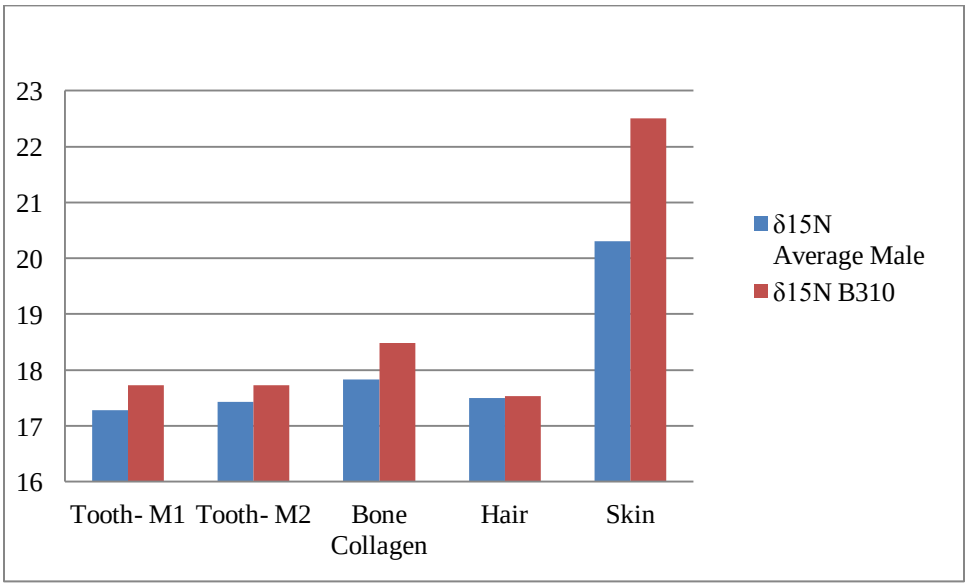


Figure 125: Graph comparing B310's $\delta^{15}$ N values with the average male values

All of B310's $\delta^{13}C$ long term values (-19.1‰, -19.0‰, and -18.8‰) (Figure 126) are slightly less enriched than the population $\delta^{13}C$ and the male average values, although not by a significant amount. The $\delta^{13}C$ values also become more enriched from $M_1$ (birth to just over 2 years of age) to $M_2$ (3.8 – 6 years of age) by 0.9‰, and by 0.16‰ with bone collagen (ages 11 – 21). Unlike the average person, whose $\delta^{13}C$ values decreases from $M_1$ to $M_2$, B310 was eating slightly more $C_4$ foods during this period, from 16.3% to 16.9%. Then, like the average person, he became even more enriched as an older child and adult, eating 17.9% $C_4$ foods.

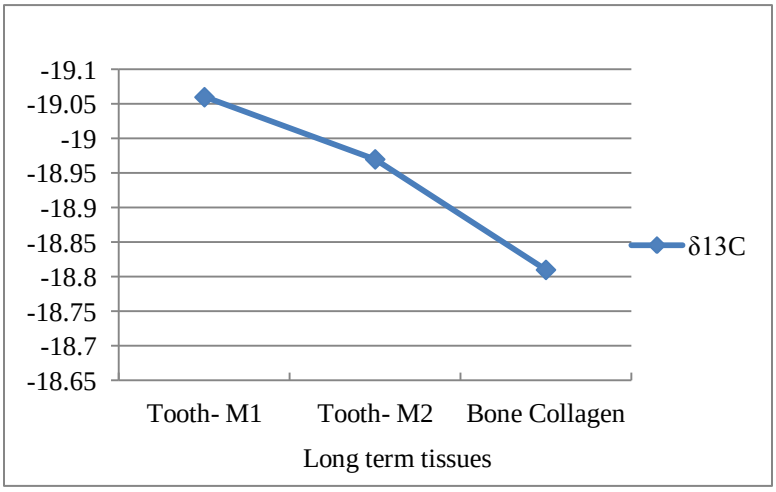


Figure 126: Scatter plot depicting long-term $\delta^{13}C$ values from B310

His long term $\delta^{15}N$ values (Figure 127) stay the same during childhood at 17.7‰, and these values are only 0.3 ‰ higher than the population average value. His bone collagen $\delta^{15}N$ value increases to 18.5‰, similar to the population average of 18.0‰. His long term $\delta^{15}N$

values, therefore, do not show any signs of illness or distress during the majority of his life, indicating he may have died a quick death as the result of accident.

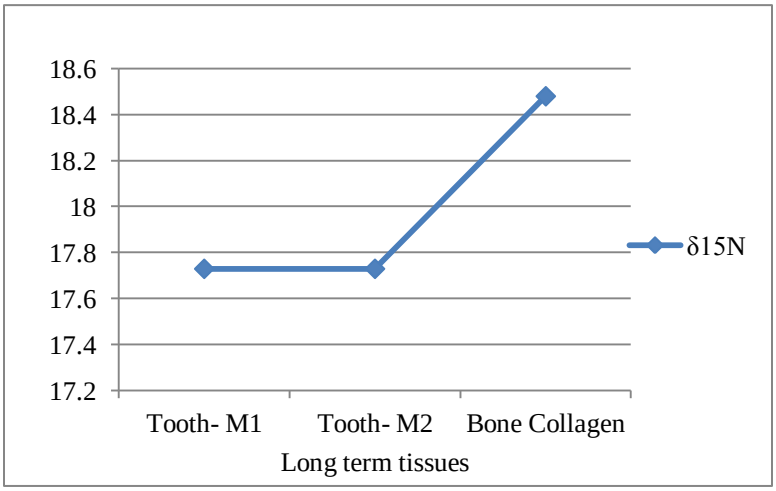


Figure 127: Scatter plot depicting long-term $\delta^{15}N$ values from B310

B310's short term values tell a different story (Figures 128 and 129). His $\delta^{13}C$ values begin much higher than average (1.2‰ higher at 5 months before death). This is not an entire standard deviation (±1.2‰) away from the mean, but he was consuming between 25.3% - 49.3% $C_4$ foods compared to the population average of 21.3% - 41.3%. Over the next few months his $\delta^{13}C$ values decreased, becoming less enriched (-19.4‰, the same as the average male). This suggests that he was eating more millet and meat right before death. This trend of decreased $\delta^{13}C$ values and his burial position of 92° suggest that he most likely died in autumn, during the autumn millet harvest.

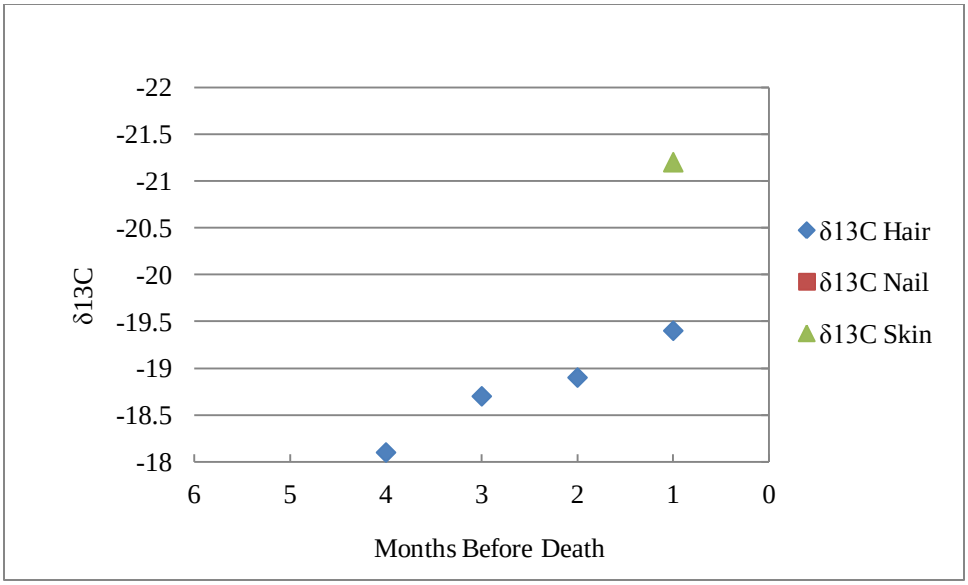


Figure 128: Scatter plot depicting short-term $\delta^{13}C$ values from B310

B310's short term $\delta^{15}N$ values also fall before death, from 18.0‰ 5 months prior to death, to 16.8‰ a month before death (Figure 129). His skin $\delta^{15}N$ value (22.5‰) is higher than the populations mean (20.8), but as shown in earlier individuals, this value is often the opposite of the hair and nail values. The average hair $\delta^{15}N$ value for the population is 18.1‰; therefore his last $\delta^{15}N$ value is almost two full standard deviations (±0.7‰) away from the mean. This decrease and positive nitrogen balance may indicate he was in the process of recovery from some acute illness or injury in the months before his death.

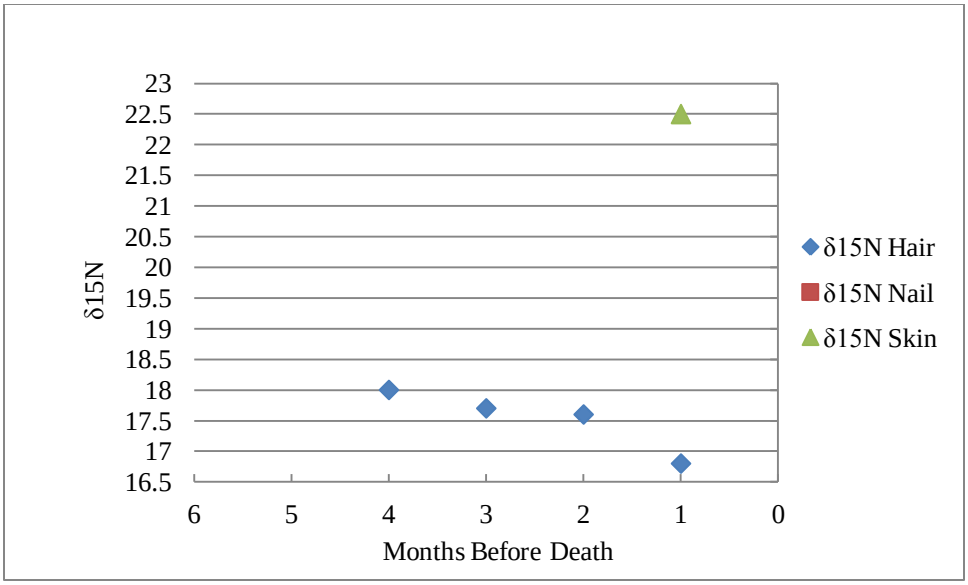


Figure 129: Scatter plot depicting short-term $\delta^{15}N$ values from B310

Burial 370

Located in the northernmost part of the excavated cemetery, directly beside the northern unexcavated tomb structure, B370 contained the remains of a 5 year-old child with no visible pathologies present. The tissues available for analysis include $i_1$, c, $m_1$, $M_1$, $I_1$, C, bone collagen, hair, nail and skin. The values are shown in Table 17 and the timeline representing B370's lifespan in Figure130. Figures 131 and 132 are below as well, which compare all of B370's values to the population means.

Table 17: B2370's $\delta^{13}C$ and $\delta^{15}N$ values

| Tissue | $\delta^{13}C$ (‰) | $\delta^{15}N$ (‰) |
|---|---|---|
| $i_1$ | -17.7 | 20.9 |
| c | -18.7 | 20.1 |
| $m_1$ | -18.2 | 19.9 |
| $M_1$ | -18.8 | 15.9 |
| $I_1$ | -20.3 | 19.6 |
| C | -19.2 | 19.3 |
| Bone Collagen | -18.7 | 19.4 |
| Hair (1) | -19.8 | 17.5 |
| Distal Nail | -20.3 | 18.0 |
| Proximal Nail | -20.1 | 18.0 |
| Skin | -19.3 | 22.7 |

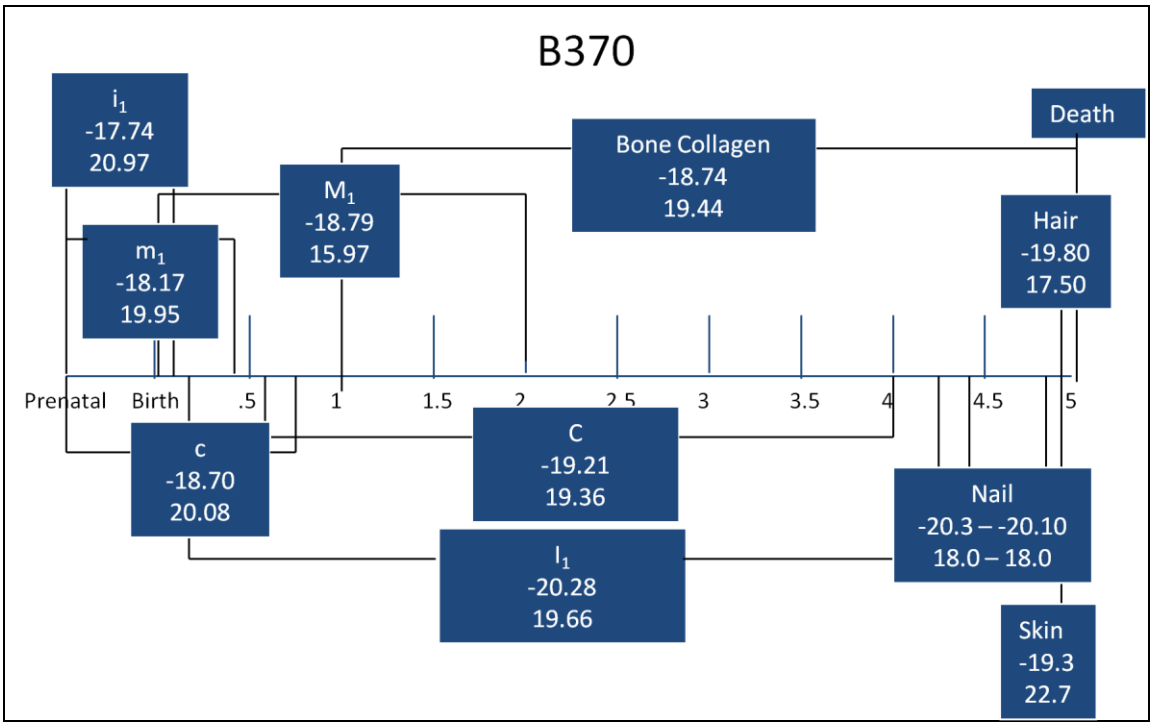


Figure 130: Timeline for B370 illustrating the ages each tissue represents

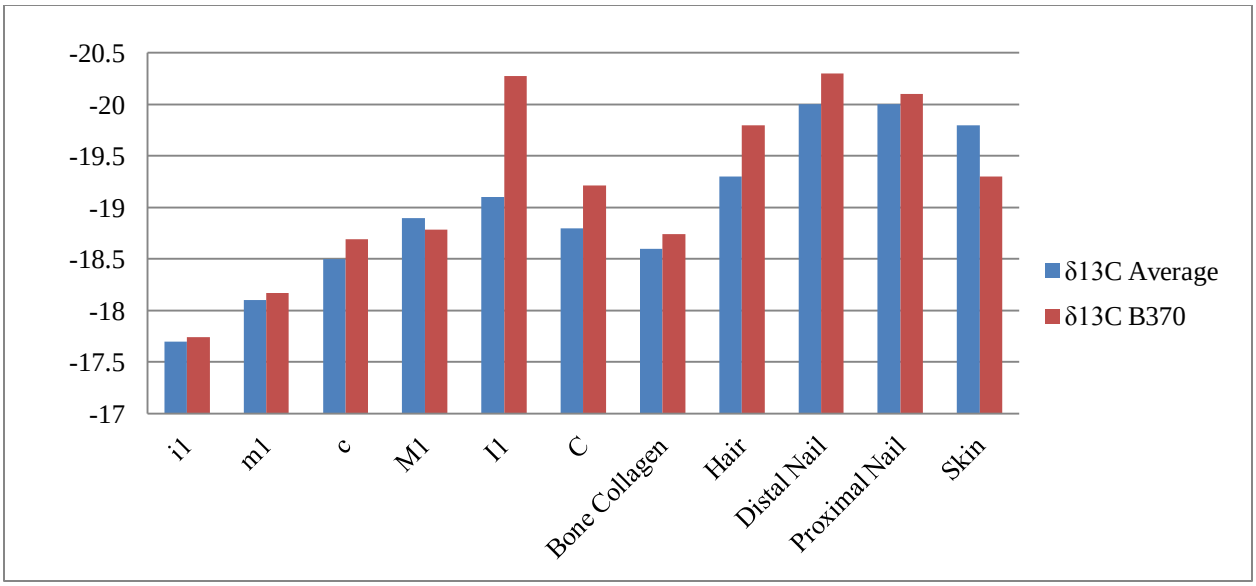


Figure 131: Graph comparing B370's $\delta^{13}C$ values with the population mean values

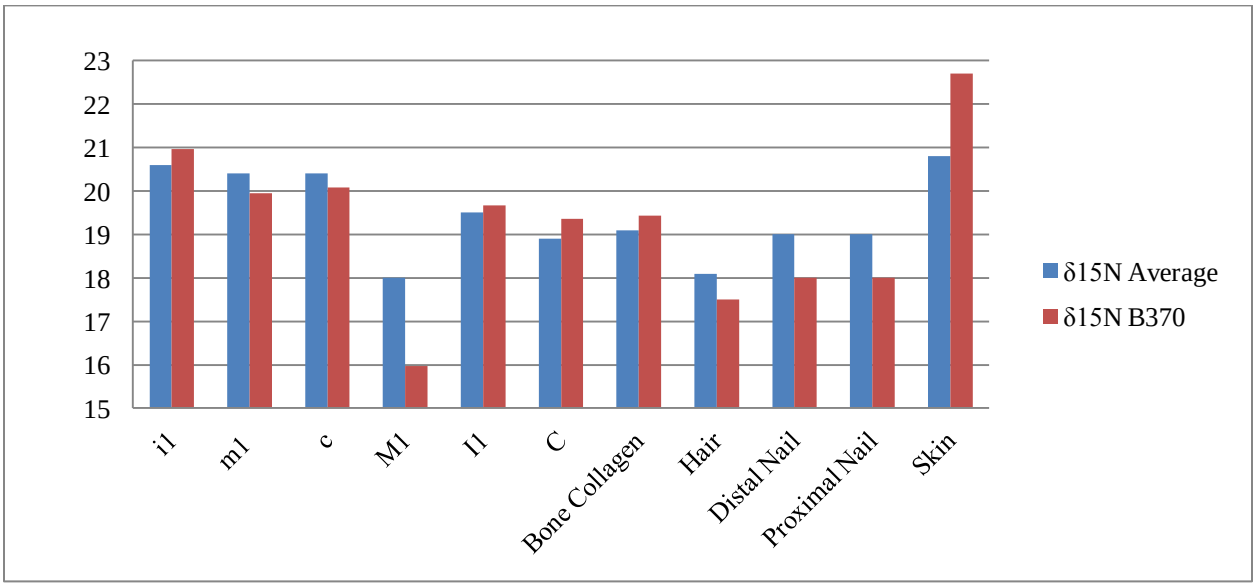


Figure 132: Graph comparing B370's $\delta^{15}N$ values with the population average values

When B370's first teeth are forming prenatally and through the first 6 months of life, $i_1$, $m_1$, and c, the $\delta^{13}C$ values are -17.7‰, -18.2‰, and -18.7‰ respectively, showing a trend of becoming less enriched over time (Figure 133). It is typical for young children who are breastfeeding and weaning have lower $\delta^{13}C$ values than the rest of the population (Dupras and Tocheri, 2007). During this time, B370 was consuming approximately 25.1% $C_4$ foods (millet/milk).The trend continues with the permanent teeth, $M_1$, $I_1$, and C (-18.79‰, -20.28‰, and -19.21‰). While the crown of $I_1$ begins to form earlier than C, it also forms for a longer period of time and the dentin forms toward the end of crown development. It may appear that the $\delta^{13}C$ value decreases then increases with these two teeth, but it is probably the fact that the dentin of C formed before that of $I_1$. This is corroborated with the population mean $\delta^{13}C$ values of these two teeth: -19.1‰ for $I_1$ and -18.8‰ for C, with C being more enriched and thereby earlier. Note that these two values, the only two representing an age over 3 and an end of breastfeeding, are enriched compared to the earlier values; B370 was only consuming between 15.3 - 8.1% $C_4$ foods at this period of time. These are both considerably lower than the population means and signify that B370 was eating more millet or animal products compared to the rest of the population. Lastly, his/her bone collagen $\delta^{13}C$ value, which represents the majority of B370's life, is -18.7‰, very close to the population $\delta^{13}C$ mean value of -18.6‰, and shows that overall the child was eating much like most of the population in Kellis 2.

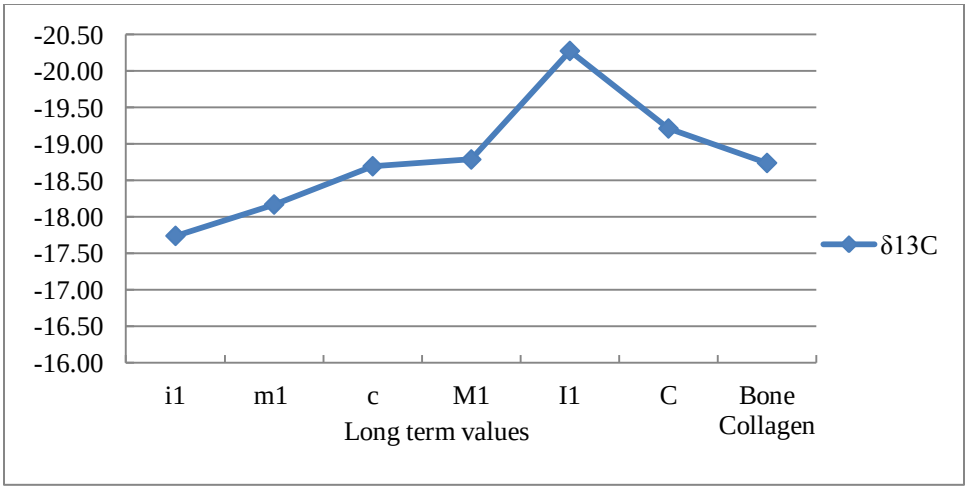


Figure 133: Line-graph depicting the long-term $\delta^{13}C$ values from B370

Long term $\delta^{15}N$ values begin very high, with values of 20.9‰, 19.9‰, and 20.1‰, but are all very close to the averages for $i_1$, $m_1$, and c. These first three values denote the prenatal period up to around 7 months of age are representative of the fact that breastfeeding children under the age of 3 have higher $\delta^{15}N$ values than the rest of the population because of a trophic level effect. His/her first permanent tooth $\delta^{15}N$ value, however, decreases considerably; $M_1$ has a value of 15.9‰. This tooth represents prenatal life through age 2; therefore, sometime between 7 months and 2 years of age B370 experienced this extreme nitrogen imbalance. The average $\delta^{15}N$ value for this tissue is 18.0‰, and B370's $\delta^{15}N$ value is an entire standard deviation below the mean (±1.6‰). It is unlikely that due to age he/she was traveling out of the oasis at this period, and therefore it is more likely that something else, presumably an illness, caused this decrease. B370's $I_1$ and C values, representing ages 3 months to 4.25 years and 7 months to 4 years, again increase to (19.6‰ and 19.3‰) right around the $\delta^{15}N$ average for the population. Sometime after

age 2 and before the age of 4, therefore, B370 recovered from whatever was causing the negative nitrogen balance seen in $M_1$.

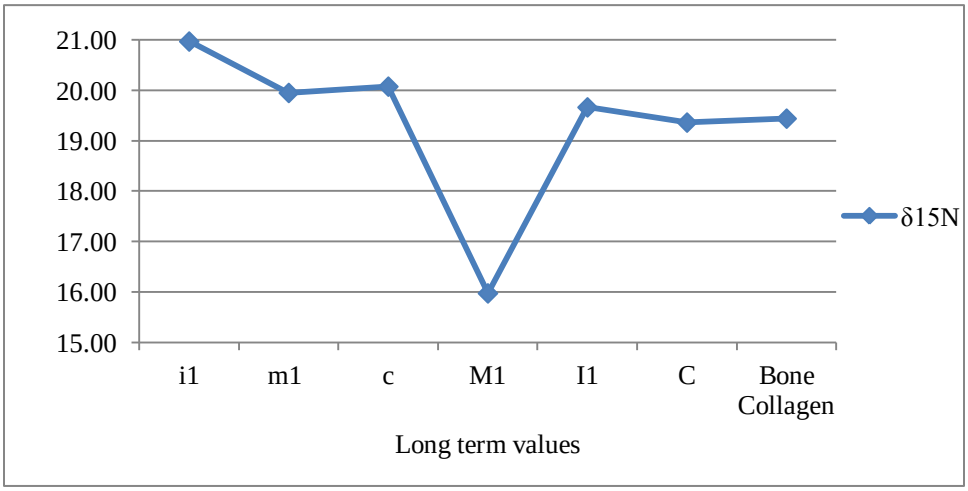


Figure 134: Line-graph depicting the long-term $\delta^{15}N$ values from B370

Short term tissue values can be viewed in Figures 135 and 136. Due to the absence of multiple hair samples, very little can be interpreted regarding trends in the period directly before death. A slight increase (from -20.3‰ to -20.1‰) can be seen in the distal nail to the proximal nail $\delta^{13}C$ values, however this does not appear to be a significant change. The proximal nail, at six months before death, is the most distant short term value and indicates that B370 was consuming between 14.7 and 34.7% $C_4$ foods during that time. Closer to death, the hair, skin and proximal nail, all represent one month prior to death. While the hair and nail $\delta^{13}C$ values are slightly below average, the skin value is slightly above average. Skin values tend to be out of

concurrence with hair and nail in most other individuals, therefore, it is likely B370 was consuming less $C_4$ foods than the rest of the population at death. Likewise, little can be said regarding short term nitrogen values (Figure 136). Proximal and distal nail values remain the same at 18.0‰. Both nail and hair values are below the averages of 18.1‰ and 19.0‰, but neither are a complete standard deviation (±0.7‰ and ±1.2‰) away from the mean. The skin sample, again not in concurrence with hair or nail, is in fact higher than the mean of 20.8‰, but also not a standard deviation higher (±2.2‰).

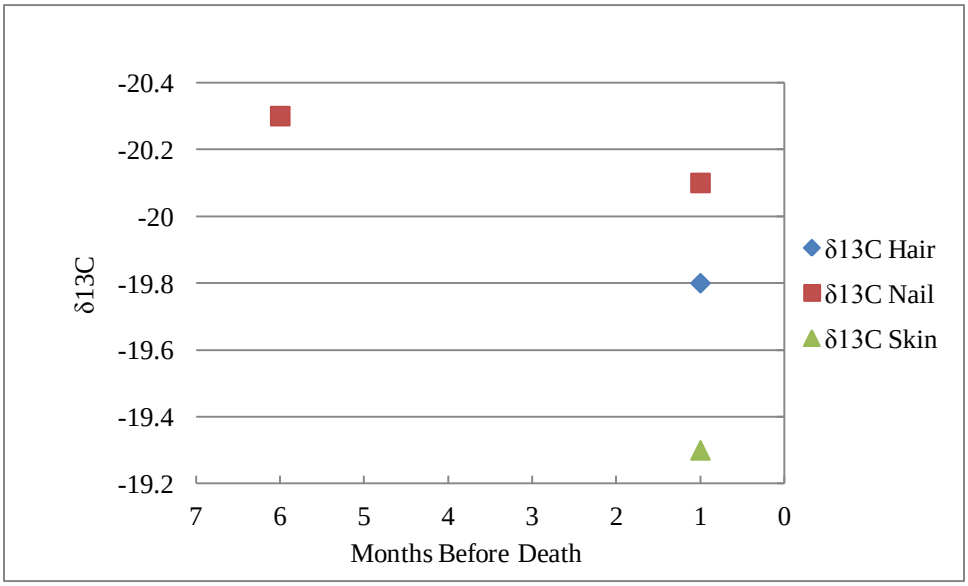


Figure 135: Scatter plot depicting short-term $\delta^{13}C$ values from B370

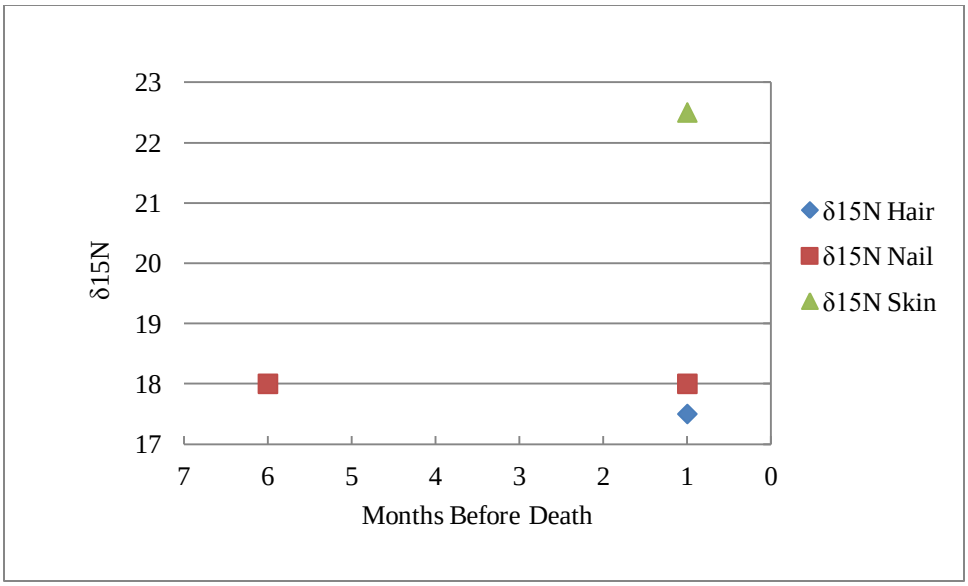


Figure 136: Scatter plot depicting short-term $\delta^{15}N$ values from B370

# CHAPTER 5: DISCUSSION AND FURTHER CONSIDERATIONS

Following the completion of the 15 life histories, it is clear that useful analysis and interpretation can be made using long and short term tissues stable isotope values. Former studies that have also used different tissues to analyze the life history of an individual or individuals, including Sealy et al. (1995), Sealy and Cox (1997), and Knudson (2010). Sealy et al. (1995), use $\delta^{13}C$ and $\delta^{15}N$ isotopes for analysis, but only use long term values from teeth and bone collagen and have no short term analysis. This allows for analysis many years before death, but not in the months close to death. The graphs used for results are also extremely difficult to comprehend, with $\delta^{15}N$ values on the y-axis and $\delta^{13}C$ values on the x-axis and very little labeling. This makes it nearly impossible to visualize any kind of trend from viewing the graphs themselves.

Knudson et al. (2010) is the most recent study and uses various isotopes of short and long term tissues to interpret paleodiet and paleomobility of a single individual, and uses only a single graph for displaying information. The one graph included plots $\delta^{13}C$ and $\delta^{15}N$ values together on the y-axis and months before death (0-20) on the x-axis. This graph can be confusing for two reasons. Firstly, the $\delta^{13}C$ and $\delta^{15}N$ isotope values are plotted together on the same graph. If space is not an issue, plotting them on separate graphs makes them more precise and easier to read. Secondly, the x-axis on this graph reads in reverse time order, from 0 months before death on the left to 20 months before death on the right. This means when reading the graph from left to right, you are viewing the values in opposite order compared to how they occurred in life.

The present study, though it does use some data that has already been published (including the isotope data itself), uses and presents the data in a new way. It attempts to reconstruct paleodiet, seasonality of death, and health status of individuals. The use of separate graphs for $\delta^{13}C$ and $\delta^{15}N$ and short term and long term tissues makes it much easier to comprehend the results. Also, the months before death are plotted on the axis so that they can be read from left to right, ending with death in chronological order. In addition, the timeline demonstrating the time in an individual's life each value represents makes understanding all of the information presented (long and short term tissues together) possible even for someone who in unfamiliar with stable isotope research altogether.

Breaking down the information and analyzing individuals also allowed for some information to be uncovered. Most importantly, in almost all of the individuals discussed, the skin values did not correlate with the hair and nail values for both $\delta^{13}C$ and $\delta^{15}N$ isotopes. When comparing to the population, more often than not the skin values would either be below or above average, while the hair and nail values would be the opposite. This was the case for eleven individuals of the fifteen. In fact, in five individuals both the $\delta^{13}C$ and $\delta^{15}N$ skin isotopes values were not congruent with the hair values, while four had only $\delta^{15}N$ values and two had only $\delta^{13}C$ that did not match with the rest of the data. This leads to the question of whether the skin samples are reliable and whether they need to be analyzed in a different way. Perhaps there is a reverse relationship between hair and skin: if the skin is utilizing the nitrogen, then the hair and nails are not receiving as much and vice versa. Unfortunately, there is a lack of research focused

on stable isotope analysis of human skin. Perhaps this relationship between skin and other tissues is something that could be further researched.

Another trend that was apparent with the individuals in this study is that $\delta^{13}C$ levels are more likely to stay more or less unchanged (values being within a few per mil throughout) as they approached death. This is true for seven of the fifteen burials. Five of the individuals had a decrease in $\delta^{13}C$ and only three had increasing values. This is probably due to the fact that the mortality peak in Egypt and Kellis 2 cemetery is in the spring and early summer (Williams, 2008). During the winter and early spring people were consuming barley and wheat from the winter and spring harvest, therefore the values would not change much. There is a spring millet harvest, but individual's tissues who died in the spring would not yet reflect the addition of millet to the diet. This may also be an indicator of different social ranks within the society. Wheat is a more substantial grain than either barley or millet, which is used primarily for animal fodder (Darby et al., 1977). People with access to higher quality food would eat the stores of wheat for a longer period before switching to millet, and thus their values would not become enriched for a longer period of time. People who began to eat millet sooner would have values that become enriched at an earlier date. The fact that some individual's values change abruptly while others do not may be indicative of these status differences.

It can also be observed that many of the individual's had a significant increase or decrease in their $\delta^{15}N$ values in the months before death. Six of the fifteen individuals had a change of 0.7‰ or higher during the last few months before death. Only five individuals had

little to no change and four had a small change. Of the five individuals in this study that had noted skeletal pathologies, three had changes over 1.0‰, and the other two had changes of 0.7‰ and 0.4‰. None of the individuals with little to no change had a noted pathology. This heavily suggests that when the body is in distress due to illness or injury, the nitrogen balance of that individual is altered. Whether the change is positive or negative depends of many factors, including the nature of the distress.

The last thing apparent when viewing the results of these 15 individuals is really a lack of trends or discrepancies between or within groups. There were no notable differences between males, females, and juveniles regarding $\delta^{13}C$ and $\delta^{15}N$ values throughout time or closer to death. Each group was just as likely as the other to have high or low $\delta^{13}C$ and $\delta^{15}N$ at any time during life, increasing or decreasing $\delta^{13}C$ values, and a large change in $\delta^{15}N$ values close to death (positive or negative). This is probably because the population of Kellies at its maximum only reached several thousand people, they were consuming more or less the same diet, with only small, short-term seasonal differences, and they lived in an Oasis far from the Nile River Valley with probably relative independence (Williams, 2008). With the 15 individuals sampled, these differences could not be discerned. The differences were as likely to be within groups as between groups.

# CHAPTER 6: CONCLUSION

While the use of stable isotope analysis to uncover the past has been used by researchers for several decades now, it has not been used to its full potential. Traditionally, this information has been used to analyze large groups of people and make inferences about that entire group as a whole. In some cases, this may be all that is possible given the sample size, preservation, and other factors. However, in select cases it is possible to take the data at hand and make deductions about a single individual in that sample, even over a period of time. It is also possible to cohesively plot and graph that information in a way that can be understood by all who encounter it.

In this study, 15 individuals were analyzed according to $\delta^{13}C$ and $\delta^{15}N$ values for both long-term and short term tissues, spanning a period of time. Each individual had a minimum of four tissues, with at least one long-term and one short-term tissue. Interesting observations were made concerning diet and trauma/disease in early life (including breastfeeding and weaning), possible migration during life, changes in diet in the months before death, seasonality of death, and changes in nitrogen pools associated with trauma/disease in the months before death. Trends noted were an inverse in $\delta^{15}N$ skin values as compared with other tissues, drastic changes in $\delta^{15}N$ values close to death, and steady $\delta^{13}C$ values as individual's approached death.

There were limitations to this study, including tenants of the "osteological paradox" and the problem of making inferences based on skeletal samples (Wood et al., 1992). That is, when

studying a cemetery population, the only irrefutable fact is that they are all dead. It is impossible to get statistics for a healthy population because the individuals have all died as the result of some infirmary. This problem can skew apparent averages, trends, and in this case values noted in a population. For example, while no differences were noted for $\delta^{15}N$ between males and females in this study, this could be the result of disease/injury at the time of death. Actual differences may occur in the healthy population. Another limitation was lack of present research regarding several tissues, like nails and skin. These tissues are not available for the majority of archaeologists; therefore, they have not been studied extensively in the human population.

## Future Considerations

The ability to analyze individuals at such an intimate level is exciting and is important for the future of stable isotope analysis because it gives researchers new tools to utilize toward the understanding of past peoples. Future studies could go even farther by incorporating more individuals in order to uncover trends and patterns not seen in this small sample. Possible research topics would include topics such as pregnancy, social status, how illness affects diet, if healthy males have higher $\delta^{15}N$ values, and the relationship between skin and other tissues. More isotopes, such as $\delta^{18}O$ and/or $\delta^{34}Sr$, could also be incorporated to help hypothesis about mobility, migration, and local verses non local patterns in diet, giving an even more detailed individual analysis. In addition, more biomedical research could be conducted and incorporated to help

researchers better understand tissues like the skin, and how the body is utilizing nitrogen in times of health and illness. If future studies endeavor to analyze individuals and present the information using the methods described above, they will be more thorough, comprehensive and more easily interpreted.

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