DIETARY RECONSTRUCTION OF URBAN INHABITANTS OF THE 1ST CENTURY AD PETRA

By

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Petra, an ancient city located in southern Jordan, is a UNESCO World Heritage site known for its architecturally grand buildings and tombs carved into sandstone bedrock. The establishment of Petra as the capital of the Nabataean kingdom heralded the beginning of the sedentarization of the rulers of the Nabataean people. Petra rose to prominence between the 2nd century B.C. and 1st century A.D. where up to 30,000 Nabataean people may have lived. Despite decades of archaeological excavations at Petra, little is known about how these inhabitants of such a large city could have supported themselves in a semi-arid environment. This study reconstructs the diet of the non-elite Nabataeans from the 1st century A.D., whose remains were excavated from the Petra North Ridge Tombs. The residents of Petra, like many ancient cities, likely relied on the hinterland for food items and it is expected that the residents supplemented their diet by importing foods to support their large population and to provide variability to the peoples' diet. Here, we use a multidisciplinary approach to reconstruct the diet of the non-elite Nabataeans. This approach includes an analysis of carbon and nitrogen stable isotopes of human and faunal remains, combined with paleobotanical, archaeological, zooarchaeological and papyrological data. Stable isotope analysis revealed that the non-elite Nabataeans had relatively homogenous $\delta^{13}C$ and $\delta^{15}N$ bone collagen and apatite values which indicates that non-elite

Petraeans may have ate a similar diet that relied on water-intensive C_3 plants such as barley and wheat along with meat and secondary products from animals. Evidence of local agriculture production from papyrological, archaeological and paleobotanical sources indicate that C_3 plants were grown and zooarchaeological data indicates that herd animals were brought in "on the hoof" for consumption. While these data cannot directly identify reliance on imported foods within Petra, the consumption of plant types not suited for Petra's arid environment may suggest they supplemented some locally grown crops with those imported from elsewhere. Finally, through the use of a multidisciplinary approach the data produced allows a more informed interpretation for future isotope studies.

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Chapter 1: Introduction

Petra, an ancient city surrounded by towering sandstone formations, evokes wonder at the scale of its architecture and immense tombs, many of which are carved into the sandstone cliffs. This city is located in southern Jordan and was at one point the capital of the Nabataean Kingdom. The Nabataeans were once a pastoral nomadic people who built their kingdom from wealth gained through trade that began around the 4th century B.C. The capital at Petra thought to be established in the 2nd century B.C. (Wenning 2007; Zayadine 2007), acted as a hub for trade in the region. As the city grew, Petra's wealth and control of trade routes attracted the attention of Rome and by 106 A.D., the city was annexed into the Roman Empire (Fiema 2003).

Archaeologists first began excavations at Petra in 1929 (Albright 1935) and a considerable amount of information was collected on tombs, monumental architecture, gardens, and pottery in the ensuing decades. In spite of this, there is much still left to be discovered about the day-to-day lives of the Nabataean people. They left no recovered written history and what little we do know comes from outside sources. Questions have been raised about how the city fed such a large population, the Petraeans' economic relationship to their hinterland (Kouki 2013) and what the Petraeans' ate (Bedal et al. 2007, Ramsay and Bedal 2015).

In this study, I use stable isotopes of carbon and nitrogen to reconstruct the diet of 34 non-elite Nabataeans whose remains were recovered from the Petra North Ridge from three tombs dating to the 1st century A.D. (Bikai and Perry 2001; Parker and Perry in press; Perry 2002; Perry in press). These skeletal remains represent the largely ignored non-elite population of Petra. Analysis of their bone collagen and apatite along with archaeological floral and faunal remains assists in reconstructing their diet. The dietary profile illuminates aspects of the

economic relationship between urban Petra and its hinterland, and demonstrates the range of available foods accessible to Petraeans. Furthermore, diet reconstruction contributes information about the relative contribution of protein and carbohydrates, which can be used in future studies to address questions about the quality of the Petraean diet. Finally, this study provides a case study of health and diet from an ancient Old World urban center to add to the archaeological and historical information about cities in the past.

Chapter 2 provides a cultural and historical background of the Nabataeans and Petra, an explanation of diet reconstruction, basic principles of stable isotopes, and discussions of diagenesis and the burial environment and their effects on stable isotope values. These are followed by information on seminal diet reconstruction studies, problems in archaeology that stable isotopes have been able to address, and a presentation of how zooarchaeological and paleobotanical studies are utilized in diet reconstructions. Chapter 3 presents the methodology used in this project and is broken down into a discussion of how samples were selected, methods used to determine age and sex, sample preparation procedures, calculation of dietary values, methods of determining adequate collagen preservation, and information on what statistical methods were used.

Chapter 4 explains the results of the age and sex determination of sampled remains, provides a demographic breakdown, discusses the collagen preservation, presents the stable isotope data and ends with the results of the statistical analysis of the samples. Chapter 5 considers preservation of the remains at Petra, discusses the diet of the non-elite Nabataeans, inspects diet reconstruction studies from Jordan and the Mediterranean world for similarities and differences, reviews the archaeobotanical and zooarchaeological evidence available from Petra, concludes with health and paleopathological information of the skeletal population from the

Petra North Ridge and examines what information about this population's health contributes to our understanding of their diet at Petra. Chapter 6 summarizes the findings, their implications, and closes with suggestions for future research. Finally, I rely on dates for the different time periods provided by Homes-Fredericq and Hennessay (1989:10), Stager (1992:40), and Strange (1997:402-403)

Chapter 2: Background

Petra, a place that thousands of tourists visit each year, is a designated UNESCO World Heritage Site famed for its rock-carved tombs and other impressive structures. Between the winding Siq and the famous carved tomb called the Treasury, the ancient city lures people from all over the world to see the wonders built by the Nabataeans. While many archaeological excavations have been conducted at this site, most have focused on elaborate public monuments, thus there is yet much more to be discovered about day-to-day life in the city and the Nabataean people who lived there.

Culture-historical background

The death of Alexander the Great toward the end of the 4th century B.C. and the rise of the Seleucid Empire signaled a power shift in the eastern Mediterranean. At this time, several Arabian kingdoms controlled the lucrative trade routes that brought in goods from China, India, East Africa, and Arabia to Gaza and eventually to the Mediterranean world (Schmid 2008, Wenning 2007; Zayadine 2007). The Nabataeans, originally a primarily nomadic pastoral group, soon become major players in the spice trade (Wenning 2007; Zayadine 2007). They acted as intermediaries and transferred goods from Yemen and the Persian Gulf to ports at Gaza and the eastern Mediterranean. The Nabataeans competed for control of these caravan trade routes with the Ptolemies of Egypt and later the Romans as well as local Arab and Jewish groups. This competition led to Antigonos Monophthalmos of Macedonia pillaging the Nabateans and attempting a takeover of the lucrative incense trade around 312/311 B.C. (Wenning 2007).

This first recorded encounter of the Hellenistic (330-30 B.C.) world with the Nabateans was described by Hieronymus of Cardia and was included in the writings of the Greek historian

Diodorus (*Library of History* 19.94.1; 95.1-97.6). Hieronymus described a place called a "rock" where the Nabataeans stored their trade goods as a 'nomadic camp.' His description suggests that, at that point in time, the Nabateans may still have been primarily nomadic and Petra was not yet a permanently settled place. During the 4th to 1st centuries B.C. the Nabateans transitioned from a nomadic group to a sedentary population that controlled a large section of the Levant with a capital city at Petra (Figure 1) that acted as a hub for trade.

Petra was initially a place where the Nabataeans stored their trade goods (Wenning 2007). The first permanent structures at Petra were built in the 3rd through 2nd centuries B.C., as evidenced by archaeological remains (Graf 2013; Wenning 2013). The 2nd century B.C. also marks the establishment of Petra as the capital of the Nabataean state. Epigraphic evidence indicates that in 129 B.C. the city Priene in Asia Minor dispatched an ambassador to Petra (Hiller von Gaertringen 1906: 84-91, 108, 168), which suggests that Petra served as a major administrative center by that time. Around the same time Josephus refers to Petra as the residence of the Nabataean royal family and nobility, providing further evidence for Petra's central importance (Josephus *Jewish Antiquities*14, 1, 4).

Even with the establishment of Petra as a capital by the 2nd century B.C., the process of Nabatean sedentarization appears to have been a gradual one (Wenning 2007), but during the 1st century B.C., ceremonial architecture and elaborate places of burial, including façade tombs, large temples, and well-appointed dwellings, began to appear (Bedal 2001, Wadeson 2010, 2012a, 2012b). Archaeological evidence suggests that the city at its height was an eclectic mix of ceremonial structures including temples, religious monuments, sanctuaries, banqueting rooms, dwellings, pools, gardens and necropolis (Wenning 2007). By the 1st century A.D., Petra had grown into a politically and economically stable city (Schmid 2008) with an increasing

population estimated by some archaeologists at 30,000 people (Joukowsky 2001), although this number is purely speculative.

In order to support a growing population, the people of Petra may have begun to diversify their economic practices in the late 1st century B.C. (Johnson 1990). The residents appeared to be embracing their new settled lifestyle as suggested by descriptions of fruit trees and vineyards by the ancient geographer Strabo (*Geography* 16.4.21) and by evidence for conspicuous consumption of local and imported goods such as gold, silver, copper, iron, aromatics, and textiles (*Geography* 16.4.21). Additional evidence for economic diversification comes from settlement surveys in the hinterland. These suggest that the population in the hinterland, on which the city likely relied for agricultural goods and resources, expanded together with the intensification of agriculture during the 1st century A.D. (Kouki 2009, 2013) (Figures 2 and 3).

Economic activities and architectural developments at Petra were not hindered by Roman annexation of the city in A.D. 106. In fact, a number of renovations occurred shortly after this time, including a colonnaded street with thirty shops along with an upper market area (Fiema 2003; Kanellopoulos 2001). In 363 A.D. a massive earthquake seriously damaged the city, destroying many structures, some of which were never rebuilt (Russell 1980). Although three Byzantine (324-640 A.D.) ecclesiastical structures were built in Petra during the 5th and 6th centuries, the population had already begun its decline after the 363 A.D. earthquake. By the 7th and 8th centuries only relatively ephemeral occupations lived there (Beckers et al 2013; Freeman 2008, Perry and Bikai 2007; Schmid 2008).

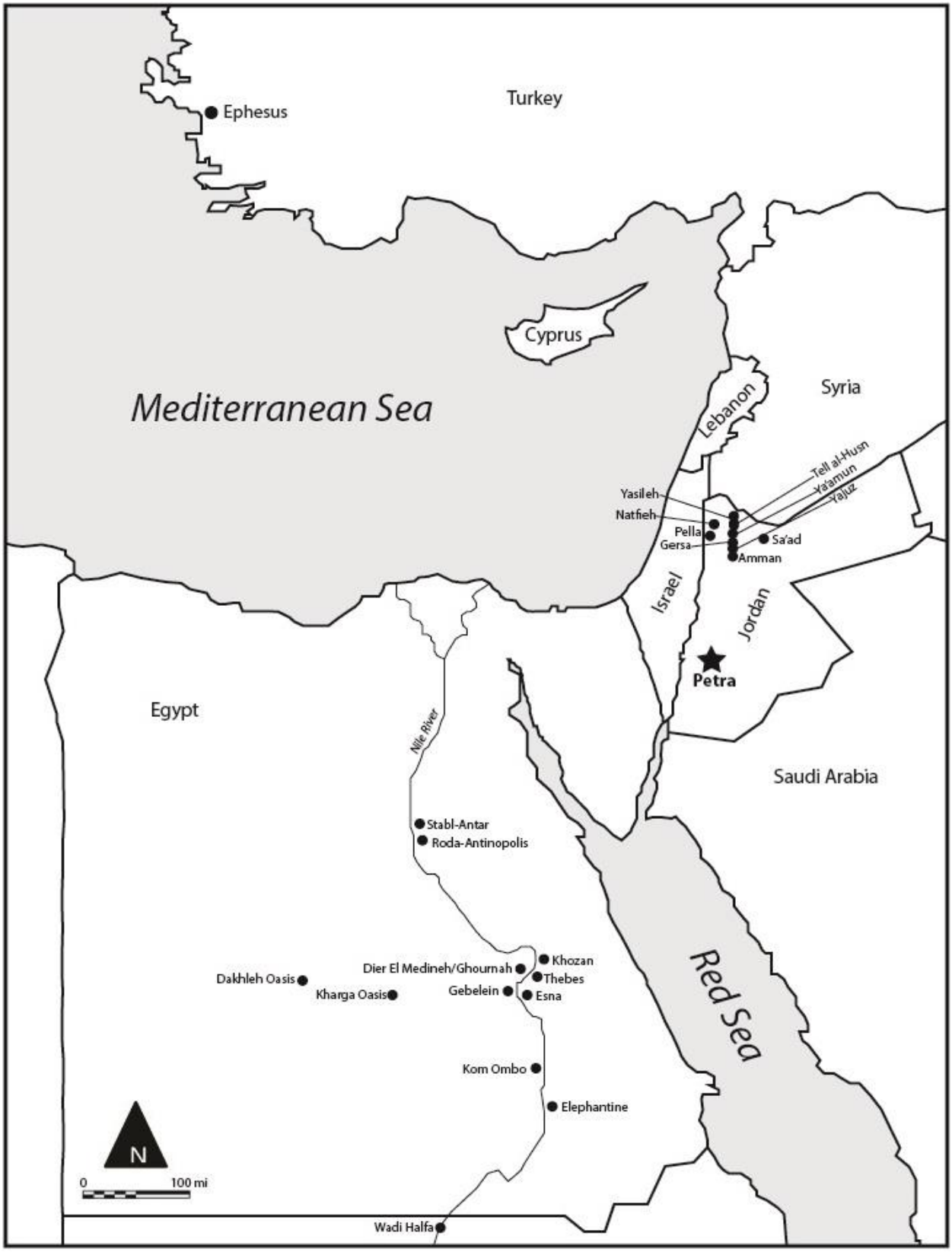

Figure 1. Location of Petra

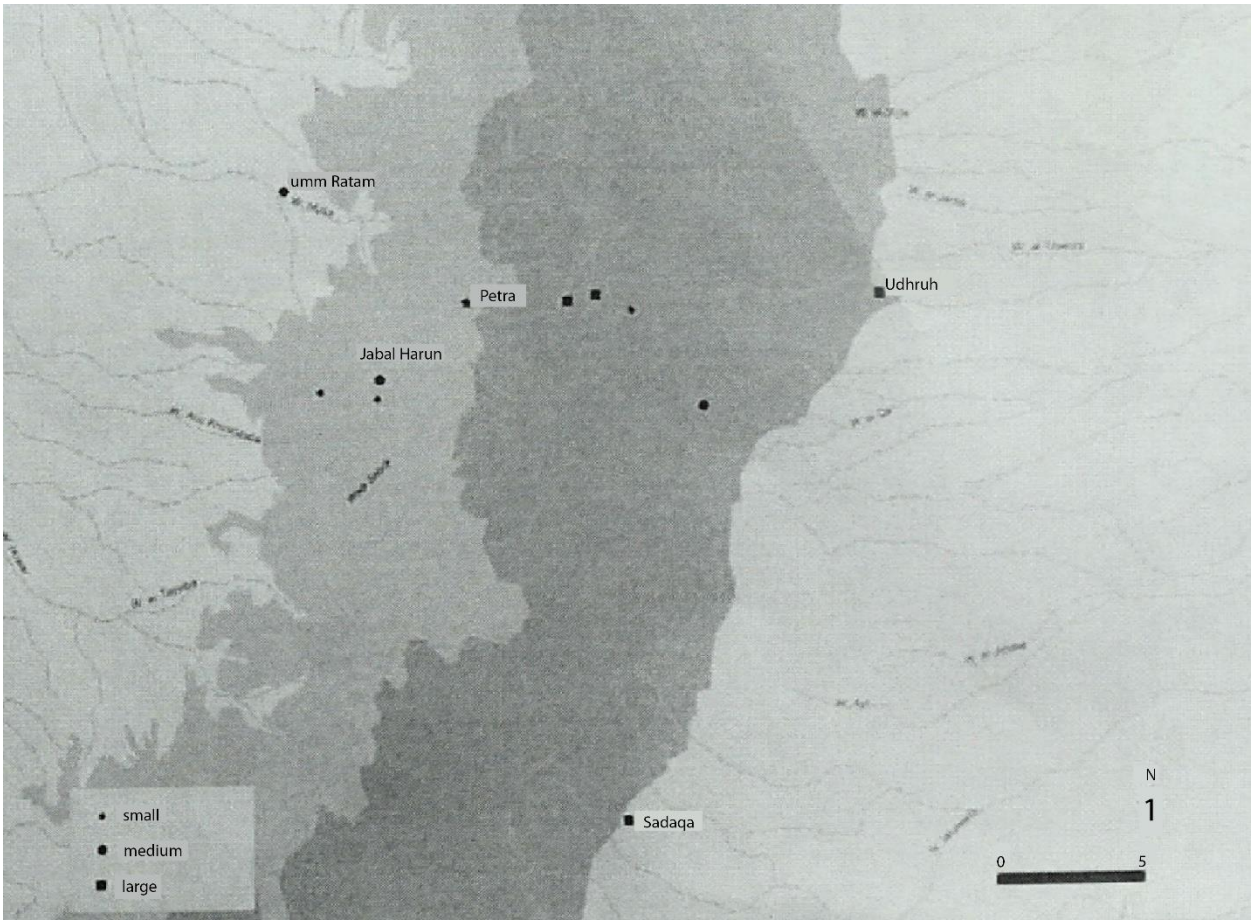

Figure 2. Kouki 2013 2nd-1st century B.C. surveyed sites

Archaeological evidence of structures, agriculture, and trade goods, along with historical documents from Greece, Rome and Egypt gives an impression of the economic and political importance of this city in antiquity. Despite this, little is known about the day-to-day lives of the Petraean Nabataeans as no historical accounts written by the Petraeans have been recovered (Schmid 2008). One way to investigate daily lives at Petra is through a reconstruction of the inhabitants' diet. People in ancient cities typically relied on the hinterland to supply food to the population (Kouki 2013); therefore, archaeologists are studying the relationship of Petra to its hinterland to investigate whether the Petraeans depended on people in the hinterland to supply food and other resources. In addition, archaeologists are looking at the Petraeans' reliance on

trade for foodstuffs, the range of plant and animal species the people used for food, and whether the inhabitants of Petra raised herds in the urban environment (Knodell and Alcock 2011; Kouki 2013; Tholbecq and al-Khraysheh 2001). This information can provide details about the supply of food to the inhabitants at Petra and about what the people may have incorporated into their diet. Literary sources, and paleobotanical and faunal information for Petra provide data on some of the common dietary items that would have been available in the Near East and the Roman sphere of influence, but the picture is incomplete without knowing the extent of agriculture and range of products available in Petra (Bedal et al. 2007). Therefore, characterizing the diet of the Petraeans through dietary reconstructions contributes data that can be used in the future to make inferences about economic practices, such as trade and agriculture, and can inform on the relationship between the hinterland and the supply to the city.

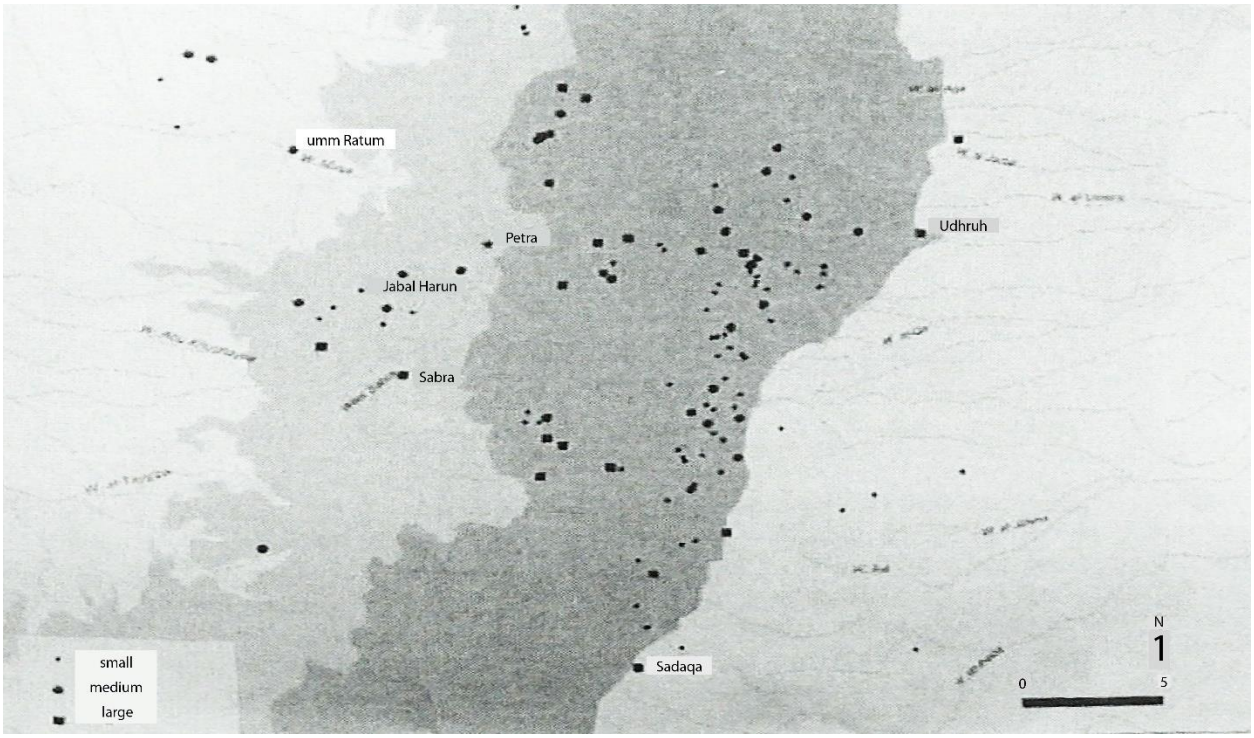

Figure 3. Kouki 2013 1st century A.D. surveyed sites

Diet reconstruction

Dietary reconstruction of ancient populations typically requires a multidisciplinary approach that includes synthesizing information on past environment, archaeological evidence of plants and animals that would have been available for consumption, and the isotopic values of individuals observed from stable isotope analysis. This multi-method approach is essential as relying on a single method to reconstruct diet provides only a partial picture of the foods that ancient people consumed. Differential preservation of plant and animal remains in the archaeological record can provide a biased picture of what existed and what was consumed at the site (Bedal et al. 2007; Katzenberg 2008; Ramsay and Smith 2013; Ramsay and Bedal 2015). In addition, plants may be grown and animals raised primarily for trade and thus not consumed by the majority of the local inhabitants. Thus, combining archaeological evidence with historical documents, along with information on the isotopic values of humans and animals, can provide knowledge about the environment, climate and agriculture, and domestic and wild plant and animal species that people could have consumed.

Knowledge of the environment narrows down the types of animals and plants that could have been supported in the region, and is necessary for understanding how available food sources affected the dietary choices people made. The choices people make can be affected by the environment (Temple 2007), cultural food preferences, economic status (Peres 2008) and access to networks that may provide them food not available in their area (Gibbs 2005; Peres 2008). The type of food people consume is reflected in their stable isotopic signatures and therefore acknowledging the effect of choice on stable isotope signatures is a crucial consideration when reconstructing diet. In short, combining knowledge of the environment and archaeological remains of plants and animals with stable carbon and nitrogen isotopes of human

as well as faunal skeletal tissue to act as a baseline can provide a profile of the types of foods consumed at the site.

Diet reconstruction: Stable isotopes

The natural abundance of carbon and nitrogen was set during initial formation of the earth (Meier-Augenstein 2011). These elements are stored in various pools or resources, such as air, water, rocks, that are used by plants, which absorb different isotopes of the elements to properly grow. Eventually, the isotopes are integrated into human and faunal tissues through consumption of a plant or of an animal that ate a plant. Integration of isotopes into tissues produces different isotopic signatures for plants, animals and humans, which also can vary between tissue types within a single organism. Through chemical analysis, researchers are able to view these integrated isotopes (isotopic signature) and evaluate the ratios of ^{13}C to ^{12}C and ^{15}N to ^{14}N. Researchers indicate the isotope values through special notations (Fry 2007). The notation δ signifies the magnified difference between the sample taken and the reference standards and the difference is expressed by ‰ (permil) units.

There are several fundamental processes that affect how plants and animals incorporate isotopes and determine why values differ between living organisms. The natural abundance of $\delta^{13}C$ (ratio of ^{13}C and ^{12}C) in plants depends mainly on the photosynthetic pathway that is used, the absorption of atmospheric CO_2, and the season and environment in which a plant grows (Meier-Augenstein 2011; Teece and Fogel 2004). The photosynthetic pathway is closely linked with the value of nitrogen in a plant (Meier-Augenstein 2011). Plants require nitrogen for the photosynthetic process to function. The main reserve for nitrogen that can be used by plants is found in the atmosphere (N_2). The natural abundance of $\delta^{15}N$ (ratio of ^{15}N to ^{14}N) in plants

depends on the absorption of nitrogen through a either nitrogen fixation, ammonification, or nitrification (Meier-Augenstein 2011). Thus, the environment, the photosynthetic pathway and the incorporation of nitrogen into a plant play a part in the variation of isotopes that occurs within a plant.

When a plant absorbs carbon or nitrogen, fractionation— a positive increase (enrichment) in the tissues of the plant — occurs over the isotopic value of the source. This same enrichment occurs when a plant is consumed by an animal or human over the isotopic value of the consumed diet — and occurs between each increasing position in the food chain (i.e. between each trophic level) (Meier-Augenstein 2011). This fractionation affects variation in the isotopic signatures. Furthermore, a complex mix of biological, physical and chemical actions, termed secondary fractionation, results in different isotopic values between the different tissues of a fauna or human. The photosynthetic pathway, fractionation (including secondary) and biological, physical and chemical processes must be recognized for their roles in affecting isotopic signatures and should be considered during dietary analysis.

Isotope ratios of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) are the most commonly used chemical indicators of diet and can be found in faunal and human tissues including bone, teeth (Al-Shorman 2004), and hair (Macko et al. 1999a). Analysis of bone can provide information on the average diet over the last several decades prior to death (Hedges et al. 2007); hair can provide information on seasonal diet (Macko et al. 1999a) and teeth produces data in diet during adolescence (Bocherens and Drucker 2007). Researchers typically use bone collagen (organic component) and apatite of bone (inorganic portion) to extract information (Ambrose et al. 2003). Each of these tissues reflects a different aspect of the diet (Meier-Augenstein 2011). A detailed explanation of different carbon photosynthetic pathways, what carbon and nitrogen reveal about

diet, and the range of isotopic values associated with each photosynthetic pathway are included in the next few sections. This is followed by an in-depth discussion of the tissues used for dietary analysis and the fractionation that affects their values. This background will provide a basis for understanding why isotopes vary and how researchers are able to differentiate between different dietary sources.

Carbon isotopes

There are three photosynthetic pathways utilized by plants: C_3, C_4 and CAM (Crassulacean acid metabolism) (Meier-Augenstein 2011). Each of these pathways influences the amounts of ^{13}C (isotopically heavier) and ^{12}C (isotopically lighter) that are incorporated into a plant. For example, C_3 plants (^{13}C depleted) are generally located in temperate environments that include some grasses, trees, shrubs and tubers, and many domesticated crops including wheat, barley, rye, rice, oats (DeNiro 1987; Lee-Thorp et al. 1989; Sage and Zhu 2011; Sealy 2001), legumes, root crops, fiber and fruits (Sage and Zhu 2011). This pathway discriminates against the heavier (^{13}C) isotope so C_3 plants are depleted in ^{13}C in comparison to C_4 and CAM plants that utilize one of the other pathways. The second photosynthetic pathway is used by C_4 plants. These are enriched in ^{13}C in comparison to C_3 plants as this pathway, which favors hot and arid environments, discriminates less against incorporating ^{13}C. Plants that use this pathway are tropical grasses, and include maize, millet, sorghum (Sage and Zhu 2011; Van der Merwe 1982), sugar cane and fonio (Sage and Zhu 2011). CAM, the third photosynthetic pathway, includes plants such as succulents and some cacti and are generally restricted to desert environments (Van der Merwe 1982; DeNiro 1987). The $\delta^{13}C$ values of C_3 plants range from -22‰ to -33‰ with a mean value of -27.5‰ (DeNiro 1987; Sealy 2001) while C_4 plants have carbon values ranging

from -9‰ to -16‰. As previously discussed, C_4 plant values are less negative than C_3 plants due to less discrimination against ^{13}C during photosynthesis. CAM carbon values range in the middle between C_3 and C_4 plants (DeNiro 1987; Van der Merwe 1982).

In addition to identifying plants and the consumers that eat them, researchers can also look at $\delta^{13}C$ in tissue to determine if animals and humans were consuming aquatic products (DeNiro 1987). Freshwater and marine environments differ from terrestrial environments in terms of their carbon isotopic composition (Chisholm et al 1982). Marine products are enriched by ~7‰ ^{13}C in comparison to terrestrial foods. This difference is due to a divergence between seawater biocarbonate (dissolved carbon) and atmospheric CO_2 that is then used in the photosynthetic processes. CO_2 in the atmosphere has a value of -8‰, while the total dissolved carbon in seawater has a value of +1‰ and freshwater has a value of -15‰ (Meier-Augenstein 2011). These values correspond to a +9 fractionation for marine environments and a -7 ‰ fractionation for freshwater. Fractionation within the marine environment closely follows that of the terrestrial environment, which leads to a 19‰ divergence between diet and consumer of marine products (Chisholm et al 1982). Marine ($\delta^{13}C$= -17 ±4) fish in comparison to freshwater ($\delta^{13}C$ = -24 ± 4) fish are more enriched in ^{13}C (Teece and Fogel 2004) and therefore have values that are similar to C_4 plants, while freshwater fish have values that approximate C_3 plants (Chisholm et al 1982).

As mentioned above, there is both primary and secondary fractionation and these occur in terrestrial, marine and freshwater environments. The primary fractionation in carbon values is 0‰–2‰ between trophic levels, and these values will continue to fractionate 0‰–2‰ with each step up the food chain (Bocherens and Drucker 2003). For example, in a terrestrial environment plants are at the base of the food chain. If a plant is consumed by an herbivore, a fractionation of

0‰-2‰ occurs. When a carnivore consumes that herbivore then another 0‰-2‰ fractionation occurs. Likewise, a 0‰-2‰ increase occurs when a human then consumes the carnivorous animal (Bocherens and Drucker 2003).

Isotopic signatures, as previously mentioned, vary not only between different positions in the food chain but also within the tissue of a single individual animal or human (secondary fractionation). For instance, when comparing collagen to apatite, human collagen $\delta^{13}C$ values are generally 4–5‰ higher (enriched) than the consumed plant or animal (DeNiro and Epstein 1981) while carbon values in apatite range from +9‰ through +14‰ enrichment (Bocherens and Drucker 2003). This 5–9‰ difference results from the influence of dietary protein and macronutrients on the isotopic signatures. Stated another way, $\delta^{13}C$ in collagen comes mainly from the protein in a diet while carbon values in apatite reflect a combination of protein, carbohydrates and lipids, termed "total dietary values" (Krueger and Sullivan 1984; Lee-Thorp et al. 1989). This difference is called the "apatite-collagen spacing," which is not consistent between trophic levels as carbon values in tissues are influenced by different environment and biological processes (Lee-Thorp et al. 1989). In order to more fully understand why the spacing varies, researchers are examining the effects of nutrients and different biological processes on variation: 1) among tissues and 2) between different species (Teece and Fogel 2004).

Researchers can discover the potential foods that people and animals have consumed through analysis of isotope ratios within body tissues, while taking into consideration how carbon is integrated into tissues and what the isotopic signatures of carbon reflect. By examining the ratio of ^{13}C to ^{12}C in human or faunal tissues, researchers are able to differentiate between consumption of C_3 and C_4 plants and animals and may be able to discriminate between aquatic versus terrestrial foods in the diet (DeNiro & Epstein 1981; Schoeninger and DeNiro 1984).

However, an estimate of the dependence on aquatic or terrestrial food sources using $\delta^{13}C$ can only be completed if researchers ensure that the humans and animals have not consumed C_4 foods (Schoeninger and DeNiro 1984; Van der Merwe 1982; Vogel 1978). If humans and animals are consuming a mixture of C_3 and C_4 plants, then researchers will be unable to determine reliance on aquatic sources in the diet (Schoeninger and DeNiro 1984; Van der Merwe 1982; Vogel 1978).

Nitrogen isotopes

The use of nitrogen in diet reconstruction studies can provide an additional source of information on whether humans or animals were eating aquatic or terrestrially based foods and can assist in determining the human or animal's trophic level position (e.g., herbivore vs. carnivore). Nitrogen isotope analysis in diet reconstruction is based on the ratio between the stable isotopes ^{15}N and ^{14}N. Soil absorbs nitrogen through nitrogen-fixing bacteria in plants or through bacteria present in the soil (Ambrose 1991). The nitrogen values in the soil range between -10 to +20‰ (Hoefs 2009). As previously discussed, plants absorb nitrogen through the processes of either nitrogen fixation, ammonification, or nitrification leading to $\delta^{15}N$ plant values that fall in the range -10 to +10‰. (Meier-Augenstein 2011). The previously stated range for plants does not take into account processes that affect nitrogen values once nitrogen is integrated into consumer tissues. Values can fall above or below the range due to the process of fractionation in both the terrestrial and aquatic environments associated with trophic levels as well as secondary fractionation within the consumer tissues. Nitrogen isotope values have a primary fractionation factor between 3‰ and 5‰ from one trophic level to the next and a secondary fractionation factor between dietary sources and tissue collagen of 4‰–5‰ (Ambrose

1993; Bocherens and Drucker 2003; Chisholm et al 1982; DeNiro and Epstein 1981; Schoeninger and DeNiro 1984). For example, a human or animal diet consisting of mostly terrestrial food products (plants or animals that ate plants) will have $\delta^{15}N$ values ranging from +4‰ through +12‰. However, if consumers eat a mixture of a marine and freshwater diet, then the values fall between +12‰ and +22‰ (Chisholm et al. 1982; Richards and Hedges 1999, Schoeninger and DeNiro 1984). Nitrogen isotope values are higher for aquatic resources because aquatic environments have more trophic levels associated with a longer food chain than that in terrestrial environments (Meier-Augenstein 2011; Schoeninger and DeNiro 1984). Humans who consume a mixture of terrestrial and saltwater or freshwater animals and plants will have values in the middle of the two previously specified ranges (Schoeninger and DeNiro 1984). Thus, the measurement of $\delta^{15}N$ in collagen tissues reflects the relative proportions of plants, herbivores, and carnivores in a diet. In addition, the use of nitrogen isotopic analysis can detect changes in a human or animal's trophic level (Fogel et al. 1989) as well as physiological effects in animals who conserve water (Ambrose 1991). For example, a breastfeeding baby will be a trophic level higher than that of its mother. When the child is weaned, its trophic level will decrease (Fogel et al. 1989). Finally, $\delta^{15}N$ values in animals that consume little water over extended periods will increase in their tissues (Ambrose 1991).

On the surface, using nitrogen isotopes to determine aquatic or terrestrial consumption and assessing trophic levels seems a simple process as terrestrial and aquatic environments have distinct ranges with little overlap. Unfortunately, isotopic signatures in tissues are not only influenced by fractionation but also by environment (Ambrose 1991; Meier-Augenstein 2011), anthropogenic activities (Ambrose 1991), health, as well as other biological processes (Ambrose 1991; Meier-Augenstein 2011). For example, nitrogen values are higher in disturbed and/or

saline soils (Ambrose 1991; Meier-Augenstein 2011), on slopes (Mariotti et al. 1980), or in soil that is fertilized with manure (Ambrose 1991; Meier-Augenstein 2011). Values are also higher in arid (Ambrose 1991; Karamaros et al. 1981) or marine environments (Ambrose 1991) and in animals or humans that conserve water or are nutritionally deficient (Fuller et al. 2005; Meier-Augenstein 2011). These factors can confound the ability to differentiate between marine and terrestrial diets, as well as trophic level position (herbivore or carnivore) (Ambrose 1991; Ambrose and DeNiro 1986; Schoeninger and DeNiro 1984; Schoeninger 1989). Therefore, it is important to consider multiple factors that can increase or decrease nitrogen values in tissues in order to create a more accurate dietary reconstruction.

Burial environment and diagenesis

An important consideration in using stable isotope analysis to reconstruct diet is the possibility of the diagenesis of human and animal tissues post-mortem as well as contamination from the burial environment. Diagenetic activity is any post-mortem change that occurs to bone (Lee-Thorp et al. 1989). There are numerous factors that can lead to diagenetic changes and contamination of the tissues. These factors include mechanical, chemical, microbiological, and weathering processes as well as bacterial activity (Hedges 2002, Lee-Thorp 2008). Diagenetic activity begins at the time of death, where hydrolysis (separation of chemical bonds through the addition of water) of the proteins in the organic (collagen) part of the bone begins to convert to peptides and a split in the amino acids occurs (Henderson 1987). Hydrolysis of the collagen also influences the inorganic (apatite) part of the bone and causes the crystalline matrix composed of the minerals of calcium phosphate, calcium carbonate, calcium fluoride, calcium hydroxide and citrate, to reorganize. These changes lead to a diminished bond between the protein and mineral

part of the bone, making it susceptible to dissolution and other diagenetic processes. Infiltration of groundwater can speed up the hydrolysis of collagen (Ortner et.al 1972, Lambert et.al 1985), especially if the bones are porous. Furthermore, hydrolysis coupled with an environment that has periodic flooding followed by periods of drying makes the bone especially prone to poor preservation as it increases microbial activity (Maurer et.al 2014) which is correlated with loss of collagen (Hedges 2002).

A main contributor to diagenesis and contamination is the presence of hydrological activities within the burial environment (Hedges 2002; Hedges and Millard 1995; Henderson 1987). Hydrological activity can physically disturb the bones as well as introduce exogenous materials and remove endogenous materials due to any porosity in the bone (i.e., from breakage) that may have resulted from the disturbance (Hedges and Millard 1995). Soil type, temperature and climate also impact preservation of remains. For example, the aridity of an environment can simultaneously destroy the organic (collagen) part of the bone but preserve the inorganic part (Maurer et.al 2014), while burial environments with sandy soil can provide ideal conditions for periodic flooding (Hedges and Millard 1995). Water can easily move through the sandy soil allowing water to encounter a burial environment. Thus, an understanding of the burial environment and factors that can contribute to diagenesis and contamination is crucial in selecting remains for dietary studies.

In order to compensate for problems with diagenesis and contamination, methods for extracting collagen and apatite for dietary reconstruction have been fine-tuned over the years (Lee-Thorp & van der Merwe 1991). Without proper treatment, isotopic signatures will not accurately represent the signatures of the diet at time of death. Researchers now use specific cleaning methods to remove contaminants where possible. For example, Lambert et al. (1989)

advocated mechanical abrasion of the bone, which eliminates the outer surface thus reducing the possibility of surface contamination. Additional methods have used chemical cleaning such as triammonium citrate, nitric acid and acetic acid—solvents that are used to remove carbonates (Price et al. 1992; Sullivan and Krueger 1981).

Finally, there are several techniques that can be utilized to test for diagenetic changes and contamination in collagen and apatite. To check for diagenetic activity or contamination in collagen, chemical purity can be calculated by determining the weight ratio between carbon and nitrogen (C/N). A value of greater than 4.8% nitrogen, a carbon content higher than 13% (Ambrose 1990; Bocherens and Drucker 2003) in a sample and a C/N ratio outside the range of 2.9–3.6 likely reflects poor preservation (DeNiro 1985. These samples should be removed from statistical analysis (DeNiro 1985). Further, checking for collagen yield (Ambrose 1990) can be combined with the previous tests to provide a benchmark for diagenetic activity. Typically, samples are classified as having low collagen yields when they fall in the range of 3.7–5.8%. Those having less than 3.5% are classified as very low collagen yield (Dobberstein et al. 2009). The most reliable method is the first one discussed that assesses %C and %N (Ambrose 1990), followed by C/N ratio (DeNiro 1985). Collagen yield is less reliable as low collagen yield can occur in samples that have unaltered amino acid profiles (Harbeck & Grupe 2009) and thus these samples should not be excluded from statistical analysis if they pass other preservation tests. Not all researchers use these methods as not all instruments used to retrieve carbon and nitrogen produce %C and %N for individual samples and may only record C/N ratios. Therefore, researchers should take into account how their lab procedures may affect their methods.

To check for diagenetic change in apatite, researchers can use FTIR (Fourier transform infrared spectroscopy) or Raman spectroscopy to look for an unexpected amount of naturally

occurring elements. These unexpected amounts could include biogenic F, S, Fe, Zn, and Sr as these tend to increase in skeletal remains post-mortem as a result of contamination from groundwater and soil (King et.al 2011; Lee-Thorp and Sponheimer 2003, Wright and Schwarcz 1996). While many researchers use FTIR, Raman spectroscopy provides information on the preservation of the organic and inorganic part of the bone (King et al. 2011). Raman spectroscopy can look at whether the inorganic part of the bone shows a reorganization of the crystalline structure or an increase in size of crystals, which is indicative of diagenesis, and test for the presence of substitutions and secondary minerals (Al, Si, Mn and Cu) (Price et al. 1989; Reiche et.al 1999); it can also measure how much collagen is present (King et al. 2011). It is important to keep in mind, however, that even with the various methods of assessing diagenetic activity, passing one test or even several does not mean that a sample is free from contamination. Alternatively, a failure by one method does not mean that contamination has occurred. Because these methods are not failsafe, research has focused on removing contamination with mechanical and chemical cleaning rather than routinely performing expensive chemical testing for diagenetic change (Price et al. 1992).

Diet reconstruction studies

In the 1970s people from the disciplines of archaeology and geochemistry worked together to document the introduction of maize in North America using carbon isotopes (van der Merwe and Vogel 1978; Vogel and van der Merwe 1977). Since the introduction of stable isotope analysis into archaeology, dietary reconstruction has gained significant traction. This section focuses on several notable applications. The introduction of the C_4 plant maize in North America for instance marks a profound shift in the subsistence of prehistoric Native populations.

Researchers hoped to answer questions about when maize was first introduced and whether the introduction varied across different regions. A clear example of the adoption of maize (a C_4 product) is observed in Ontario, where prior to A.D. 1000, people were relying on C_3 products (Katzenberg 1993; Katzenberg et al. 1995). The analysis of $\delta^{13}C$ in both collagen and apatite revealed that people began to gradually adopt maize around 500 A.D., which eventually became a staple after 1000 A.D. (Harrison and Katzenberg 2003; Katzenberg 2006). Carbon has also been used to inspect the variation of the adoption of maize in different regions as well as to make inferences about cultural preferences or social status. For example, Cahokia and its hinterland show local differences, with Cahokia relying less on maize than the hinterland (Buikstra and Milner 1991) possibly due to social status or cultural preferences. Furthermore, the study of maize has also allowed researchers to investigate how subsistence patterns shifted over time. For example, a subsistence pattern shift occurs in the Fremont population in the eastern Great Basin region. From 400–1150 A.D., the population increasingly relied on maize but after 1150 the population switched back to foraging, likely as a result of reduced rainfall and a shorter growing period (Coltrain and Stafford 1999).

Studies in Central and South America have also looked at the introduction of maize and if there was local or regional variation in its adoption. Maize was recovered in the Tehuacan Valley in Mexico long before it was consumed in North America, possibly as early as 4000 B.C. (DeNiro and Epstein 1981). These studies have also marked increasing health problems in Mayan populations that coincide with increased maize consumption (Wright 2006; Wright and White 1996). In addition, in some Mayan populations, such as at Pacbitun, adult males during the Terminal Classic were eating higher levels of maize than females (White 1997), possibly due to the consumption of maize beer and its ritual significance (White 2005). These studies

demonstrate a number of interesting conclusions about diet that can be drawn from the use of $\delta^{13}C$ in North and South America.

In the Old World, millet, a common C_4 plant, began to appear in central Europe around the 5th millennium B.C. Millet was typically fed to domesticated animals and was not consumed by humans. One exception identified in several Iron Age skeletons from Magdalenska Gora, Slovenia has carbon isotopic values that are less negative than other non-coastal populations in Europe (Murray and Schoeninger 1988). This implies that, in relation to other groups, the Magdalenska population could have been consuming more millet and/or were eating more animals that had consumed millet (Murray and Schoeninger 1988). Researchers considered the possibility that marine products comprised a large part of the peoples' diet, as marine consumption could cause less negative carbon values than expected, but they concluded that it was an unlikely possibility due to the inland location of the site. The researchers then compared the isotopic values of the human bones with the faunal remains. The latter had more negative carbon values, thus suggesting that the animals were not likely eating millet, and therefore, that the humans appear to have been consuming millet directly (Murray and Schoeninger 1988).

Another application of $\delta^{13}C$ in studying diet is illustrated in a study from Scandinavia that pinpointed a shift in marine consumption in several populations from the Mesolithic to Neolithic (Tauber 1981, 1986). In the Neolithic, the carbon isotopic values were more negative than in the Mesolithic populations, thus indicating a shift from relying mainly on marine foods to a reliance on terrestrial foods. This shift was noticeable in both non-coastal and coastal peoples (Tauber 1981;1986).

The analysis of $\delta^{15}N$ in archaeological studies has also been useful in observing changes in diet. For example, by exploring $\delta^{15}N$ in skeletal remains at the Neolithic site at Çatal Höyük,

researchers were able to determine that over a 1400 year period, people were increasingly consuming protein. Inhabitants likely relied on wild resources but over the 1400-year period their protein intake increased with the introduction of domesticated cattle (Hillson et al. 2013). Another study demonstrated that at Eva, an Archaic period site in eastern North America, hunter gathers who were breastfeeding had infants who were a trophic level higher than their mothers. Once the infants were weaned, however, their nitrogen values dropped to mirror their mothers (Fogel et al 1989). This discovery allowed further studies to be conducted on weaning age and nitrogen levels in infants and mothers in a medieval population from Wharram Percy Site, Yorkshire, UK (Richards et al. 2002). Combining the previously mentioned studies about diet in relation to status, sex, and health, demonstrates the effectiveness of using stable isotopes to study areas of interest in archaeology. These studies indicate that carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope analysis has played an increasingly important role in archaeology.

Diet reconstruction: Zooarchaeology

In addition to the use of stable isotopes, researchers commonly utilize a multi-method approach that includes zooarchaeological and paleobotanical data from the archaeological record to provide a more complete picture of resources that could have been available for consumption at a specific site. Zooarchaeology provides evidence of specific species that existed in a region, but it also plays a significant role in diet reconstruction: the faunal assemblage can be used as an isotopic baseline for comparison with human isotopic signatures (Sealy and Makarewicz 2015; Tykot et al. 2009). In addition, zooarchaeological studies can also illuminate status-related differences, as some animals or parts of animals may only be available to certain segments of a

population (de France 2009; Killebrew et al. 2003) such as at Cahokia (Buikstra and Milner 1991) and potentially at Petra (Studer 2007).

Diet reconstruction: Paleobotany

Paleobotanicals can also supplement the zooarchaeological record and provide a fuller picture of the types of plants available for consumption by humans and animals (Bedal et al. 2007; Ramsay and Bedal 2015). While knowledge of specific plants grown and consumed, along with information on agricultural practices and trade can be gleaned from historical documents, these sources are not always available. Paleobotanical studies thus can provide information about local agricultural practices (Staller 2003) and the past climate and environment (Wolfe 1978). Finally, paleobotanicals, if isotopically tested, can complement isotopic analysis of human remains as comparisons can be made between plant isotope values and human and faunal collagen and apatite values (Meier-Augenstein 2011). Therefore, by testing local plants for their isotopic values, paleobotanicals can act as a baseline.

The study draws on a multi-disciplinary approach, combining a number of methods presented in this chapter, and permits reconstructions of the diet of the non-elite Nabataeans in Petra during the 1st century A.D. In this thesis, the isotopic signatures of non-elite Nabataeans is then interpreted within the context of agricultural, papyrological, paleobotanical and zooarchaeological remains. Stable isotope analysis enables researchers to build a profile of potential foods consumed by residents at the site and thus move beyond the inherent preservation bias encountered when relying on individual methods. The use of isotopic analysis complements these additional sources of information and hints at the dietary choices Petraeans made in order to support a large city

Chapter 3: Methods

Sample selection methods

Thirty-four human bone samples were selected for isotope analysis from the human remains excavated in the 1999 and 2012 seasons of the Petra North Ridge Project (Figure 4). During the 2012 season, thirty remains were recovered from Area B (Figure 5) and from these remains we sampled twenty-eight for isotopic analysis. From the 1999 field season, thirty-eight remains were excavated from Tomb 2. Six of the Tomb 2 remains were sampled for isotopic analysis. These remains were buried in chamber style tombs constructed in the sandstone bedrock. Tomb entrances were accessed via vertical shafts that opened up in to a chamber room (Bikai and Perry 2001). Twenty of the individuals sampled were articulated skeletons. The remaining 14 individuals were recovered from commingled contexts. In order to ensure that that individuals were not double-sampled, samples were selected from bones representative of the MNI from a particular context. For the five subadults, bones from individuals at different stages of growth were selected in order to differentiate between the individuals. In addition, five faunal bone samples— one sheep/goat, one goat, two chickens, and one pig—recovered during the 2014 season were analyzed to establish baseline data for regional dietary sources.

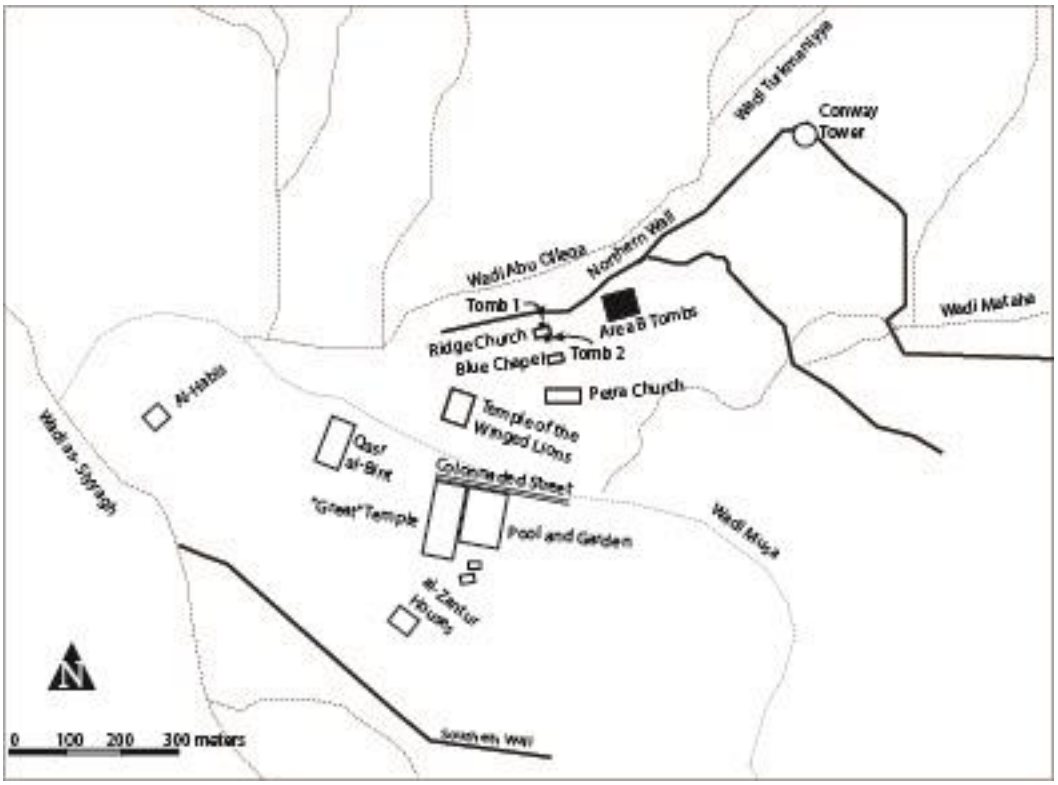

Figure 4. Petra North Ridge Map

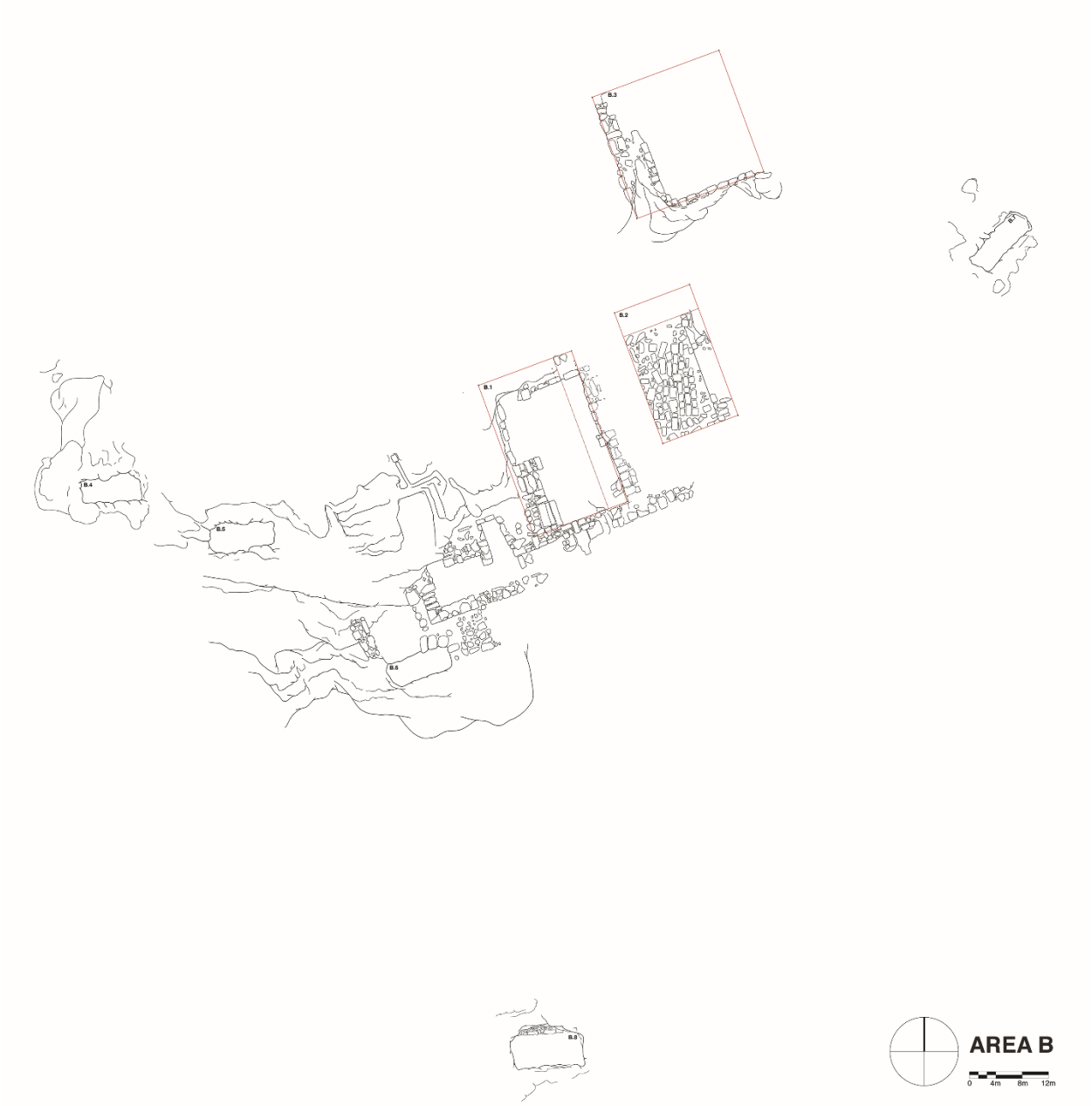

Figure 5. Area B Tomb Layouts

Age and sex determination methods

Age and sex of the individuals sampled were estimated when possible. In the case of the articulated burials, age and sex were established through standard metric and non-metric techniques. Age determination mainly relied on tooth development, epiphyseal fusion (Ubelaker 1989), skull suture closure (Buikstra and Ubelaker 1994), pubic symphysis (Brooks and Suchey 1990; Todd 1920; 1921) and the auricular surface degeneration (Lovejoy et al. 1985), while sexing methods relied on skull features and pelvic morphology (Buikstra and Ubelaker 1994). In the commingled remains, metric techniques were used to establish sex for adults when possible. Metric techniques for metatarsals (Robling and Ubelaker 1997), metacarpals (both whole and fragmentary) (Stojanowski 1999) and long bones (Spradley and Jantz 2011) were used. Reference sample populations were based on North American and, when possible, Mediterranean groups (Manolis et al. 2009; Mountrakis et al. 2010) likely genetically closer to, and with a similar pattern of sexual dimorphism as, the Nabataean population. Age determination for the commingled remains relied on tooth development (Moorrees et al. 1963) and epiphyseal fusion (Buikstra and Ubelaker 1994). For most of the adult individuals from commingled contexts, no exact age other than "adult" could be determined.

Sample preparation methods

The human and faunal bone samples were then prepared for isotope analysis at the Bioarchaeology Laboratory, East Carolina University. The outer layer of cortical bone and any internal trabecular bone, with the exception of the ribs, metatarsals, and metacarpals, was removed using a Dremel drill to reduce diagenetic and environmental contaminants (Slovak et al. 2009). The samples were subsequently crushed in a porcelain mortar using a pestle and then the

powder was separated, using sieves, into 0.25–0.50 mm and <0.25 mm fractions. Samples from the 0.25–0.50 mm fraction were used for isotope analysis of collagen, while the smaller <0.25 fraction was set aside for isotope analysis of bone apatite. Preparation for apatite analysis followed a modified Nielsen-Marsh and Hedges method (2000) which involved treatment of ~30 mg of the <0.25 mm fraction with 0.1 normal acetic acid (CH_3COOH) to remove diagenetic carbonates. Samples were left overnight then rinsed three times with distilled water and dried overnight at 50°C.

Carbon and nitrogen isotope analysis of the collagen and apatite were performed at the Environmental Isotope Laboratory of the Department of Geosciences, University of Arizona. According to David Dettman, the director of the laboratory, "the $\delta^{18}O$ and $\delta^{13}C$ of carbonates were measured using an automated carbonate preparation device (KIEL-III) coupled to a gas-ratio mass spectrometer (Finnigan MAT 252). Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70°C. The isotope ratio measurement is calibrated based on repeated measurements of NBS-19 and NBS-18 and precision is ± 0.11 ‰ for $\delta^{18}O$ and ±0.08‰ for $\delta^{13}C$ (1 sigma)." AIR (atmospheric N_2,) a reference standard based on the constant distribution of $^{15}N/^{14}N$ in the atmosphere was used as the universal standard for comparison to the results of the samples. Dettman further reported that for the collagen samples "carbonates were removed by adding sulfurous acid (H2SO3) to the sample in a silver-foil combustion capsule. Every 24 hours two drops of acid were added to the samples and then they were dried overnight at 55°C. After visible bubbles were no longer generated by the addition of acid two more drops of acid were added and the samples were dried. The foil capsule was then closed and placed in a tin capsule for combustion. $\delta^{15}N$ and $\delta^{13}C$, as well as carbon and nitrogen content were measured on a continuous-flow gas-ratio mass spectrometer (Finnigan Delta PlusXL).

Samples were combusted using an elemental analyzer (Costech) coupled to the mass spectrometer. Standardization is based on acetanilide for elemental concentration, NBS-22 and USGS-24 for $\delta^{13}C$, and IAEA-N-1 and IAEA-N-2 for $\delta^{15}N$. Precision is better than ± 0.08 for $\delta^{13}C$ and ± 0.2 for $\delta^{15}N$ (1σ), based on repeated internal standards." The lab used Vienna Pee Dee Belemnite (VPDB), a universal laboratory standard for stable carbon isotopes, for comparison to the results of the samples.

Dietary value calculations

Dietary values for carbon collagen were calculated based on a 5‰ enrichment between dietary sources and human or faunal collagen tissue (DeNiro 1985). Dietary values for the difference between diet and human or diet and faunal apatite carbon were calculated based on a 9.5‰ enrichment factor (Ambrose and Norr 1993). Nitrogen collagen values were calculated with a 3% enrichment factor (Ambrose 1993). These calculations were required to adjust for the fractionation effects that occur within a single plant and within the human or animal that consumes the plant (Bocherens and Drucker 2003).

Collagen preservation

Skeletal remains, as discussed previously, begin to deteriorate post-mortem and the environment greatly influences whether or not the deterioration leads to significant chemical or structural changes (Henderson 1987). As discussed above, these environmental changes can lead to diagenetic contamination or collagen deterioration, impacting the ability to analyze diet from poorly preserved remains. The ratio of C to N, the most commonly utilized method of identifying samples with poor collagen preservation, was used in this study to identify any postmortem

alteration of the bone collagen. An acceptable C/N ratio should range between 2.9 and 3.6 (DeNiro 1985).

Statistical methods

This study utilized a non-parametric Wilcoxon–Mann–Whitney test to analyze the data to investigate whether there were statistically significant differences between subgroups. In addition, ANOVA was used to examine any dietary variability between subgroups.

Chapter 4: Results

Carbon and nitrogen isotopes of human skeletal remains from Petra were used to investigate the diet of the city's 1st century A.D. population. This chapter presents the results of age and sex estimation, tests for sample preservation quality, stable isotope data and statistical analysis.

Age and sex determination results

The reliability of age and sex estimation of the sampled individuals varied based on the commingled or articulated nature of the individual during excavation. Associated os coxae, crania, and/or other sexually-dimorphic features of the skeleton provided the age and sex estimates of the 20 articulated burials sampled, while sexually dimorphic characteristics for a particular bone sampled, such as the maximum radial head diameter for a sampled radius, or metacarpal length for a sampled metacarpal, established age and sex for commingled remains. Appendix A provides information on how sex and/or age was determined for each sampled individual. The total sample of 34 human individuals included 8 adult females, 12 adult males, and 9 adult individuals of indeterminate sex, and 5 subadults.

Table 1. Demographic profile of the Petra sample subjected to carbon and nitrogen isotope analysis

Age	Males	Females	Indeterminate	Total
<1 year	--	--	1	1
1–4.9 years	--	--	2	2
5–9.9 years	--	--	--	--
10–19.9 years	--	1	1	2
20–34.9 years (or young adult)	1	2	--	3
35–49.9 years (or middle adult)	--	1	1	2

50+ years (or older adult)	--	1	1	2
Adult	11	3	7	21
Subadult	--	--	1	1
Total	12	8	14	34

Collagen preservation

Preservation of the Petra North Ridge skeletal remains are varied due to diverse environmental contexts that in some cases resulted in water-damage and friable bone cortices. Diagenetic activity appears to have affected the collagen preservation of a majority of the remains as evidenced by the C/N (carbon to nitrogen) ratio of the collagen. As seen in Table 2, 28 out of 39 samples have poor preservation according to DeNiro's (1985) standard of an acceptable C/N ratio range of 2.9 to 3.6. Thus, only 11 of the 39 collagen samples have been included in the statistical analysis. Those that do not meet the criteria have been indicated in Table 2 with an asterisk.

Stable isotope data

Human and faunal $\delta^{13}C$ and $\delta^{15}N$ stable isotope values for collagen and $\delta^{13}C$ for apatite raw values (not calculated for enrichment) are compiled in Table 2. Carbon and nitrogen values of collagen for human and fauna are represented in Figure 4. Figure 5 plots the $\delta^{13}C_{collagen}$ against the $\delta^{13}C_{apatite}$. The $\delta^{13}C$ isotope values for bone collagen for humans range between -17.63‰ and -19.20‰ and have an average of -18.33 ± 0.48‰, while apatite values range between -10.38‰ and -13.73‰ with an average of -12.89 ± 0.87‰. The faunal bone collagen values are -18.40‰ to -18.50‰ ($\bar{X}$ = -18.47 ± 0.06‰) and are comparable to the human values. Faunal bone apatite values of -10.34‰ to -11.62‰ ($\bar{X}$ = -11.05 ± 0.46‰) are slightly lower when compared to humans. The $\delta^{15}N$ isotope human collagen values range between 6.51‰ and 11.32‰ ($\bar{X}$ = 9.46 ±

1.55‰), which are higher on average than the primarily herbivore faunal samples that span between 7.50‰ and 9.0‰ ($\bar{X}$ = 8.4 ± 0.79‰). Based on the previously stated stable isotope values, with a calculated enrichment factor of 5.0‰ for collagen (DeNiro 1985), 9.5‰ for apatite (Ambrose and Norr 1993), and 3‰ for nitrogen (Ambrose 1991), it appears the inhabitants were acquiring protein from eating C_3 plant products and/or terrestrial animals who consumed C_3 plants. These results indicate the Petra non-elite population was eating little to no aquatic sources or C_4 foods, however several factors that affect this conclusion will be discussed below.

Table 2. Results of carbon and nitrogen isotope analysis of bone collagen and apatite of human and faunal samples from Petra

Context	Element	Sex	Age	Sample #[1]	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	C/N
HUMAN							
Tomb 2							
Tomb 2 burial 1	Unsided femur fragment	Female	20–24 years	Petraco25	-20.29	4.93	5.5*
				Petraap25	-13.18	--	--
Tomb 2 burial 2	Unsided long bone fragment	Indeterminate	45–49 years	Petraco26	-17.87	10.07	3.3
				Petraap26	-10.85	--	--
Tomb 2 burial 4	Unsided femur fragment	Male	25–29 years	Petraco27	-17.87	12.04	4.7*
				Petraap27	-11.09	--	--
Tomb 2 burial 5	Unsided femur fragment	Female	50–59 years	Petraco28	-18.48	6.51	3.5
				Petraap28	-11.06	--	--
Tomb 2 burial 6	Unsided femur fragment	Female	35–39 years	Petraco29	-17.22	7.65	4.4*
				Petraap29	-10.38	--	--
Tomb 2		Female	18–20 years	Petraco30	-18.62	8.83	3.4

[1] Collagen samples are denoted as "Petraco#" and apatite samples as "Petraap#"
* Denotes that C/N ratio does not meet collagen preservation criteria (DeNiro 1985)

Context	Element	Sex	Age	Sample #[1]	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	C/N
burial 8	Unsided femur fragment			Petraap30	-12.65	--	--
Tomb B.4							
B.4:10 #1	R humerus	Indeterminate	Adult	Petraco12	-20.34	14.56	9.0*
				Petraap12	-12.85	--	--
B.4:10 #2	R humerus	Female	Adult	Petraco13	-18.66	14.47	12.2*
				Petraap13	-13.56	--	--
B.4:10 #3	R. humerus	Indeterminate	Adult	Petraco14	-20.72	13.39	8.1*
				Petraap14	-13.33	--	--
B.4:13 subadult	R ilium	Indeterminate	36–37 weeks	Petraco32	-17.63	11.32	3.4
				Petraap32	-11.96	--	--
B.4:17	R MT4	Male	Adult	Petraco6	-22.57	19.52	10.3*
				Petraap6	-13.14	--	--
B.4:17/22 subadult	Cervical 1-7	Indeterminate	3–4 years	Petraco34	-19.20	8.10	3.2
				Petraap34	-12.68	--	--
B.4:18 subadult	R tibia	Indeterminate	Subadult	Petraco11	-19.04	10.21	4.1*
				Petraap11	-13.52	--	--
B.4:18 adult	L MT3	Indeterminate	Adult	Petraco5	-21.64	15.38	13.0
				Petraap5	-13.57	--	--
B.4:22	R MC3	Male	Adult	Petraco7	-18.13	10.43	3.4
				Petraap7	-13.53	--	--
B.4:23 subadult	L clavicle	Indeterminate	16–22 years	Petraco33	-20.68	12.75	6.4*
				Petraap33	-12.77	--	--
B.4:23 individual 1	L MT3	Male	Adult	Petraco8	-18.39	10.25	3.3
				Petraap8	-12.48	--	--
B.4:23 individual 2	L MT3	Male	Adult	Petraco9	-18.29	10.18	3.4
				Petraap9	-13.04	--	--
B.4:23 individual 3	R MC5	Indeterminate	Adult	Petraco10	-21.92	18.05	9.1*
				Petraap10	-13.22	--	--
Tomb B.5							
B.5:9 skull 11	Unsided parietal fragment	Male?	Adult	Petraco23	-20.63	9.30	8.0*
				Petraap23	-13.67	--	--
B.5:9 individual 1	R ribs	Female	Adult	Petraco3	-22.37	18.14	10.1*
				Petraap3	-13.14	--	--
B.5:12	Unsided rib fragments	Male	Adult	Petraco4	-20.24	14.49	8.6*
				Petraap4	-13.70	--	--
B.5:15 commingled subadult	L femur	Indeterminate	2–3 years	Petraco31	-20.71	10.32	7.9*
				Petraap31	-12.66	--	--
		Male	Adult	Petraco24	-20.71	7.87	8.0*

Context	Element	Sex	Age	Sample #[1]	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	C/N
B.5:15 skeleton 1	Unsided rib fragments			Petraap24	-13.22	--	--
B.5:15 skull 1	Unsided cranial fragment	Indeterminate	Old Adult	Petraco15	-20.01	17.01	12.4*
				Petraap15	-13.52		
B.5:15 skull 2	Unsided parietal fragment	Male	Adult	Petraco16	-20.40	17.74	15.7*
				Petraap16	-13.61		
B.5:15 skull 4	Unsided parietal fragment	Male?	Adult	Petraco17	-20.81	18.55	13.7*
				Petraap17	-13.22		
B.5:15 skull 5	Unsided skull fragment	Indeterminate	Adult	Petraco18	-19.53	18.72	16.1*
				Petraap18	-13.98		
B.5:15 skull 6	Unsided skull fragment	Male?	Adult	Petraco19	-20.92	18.87	12.9*
				Petraap19	-13.35	--	--
B.5:15 skull 7	Unsided skull fragment	Female?	Adult	Petraco20	-20.15	13.22	11.3*
				Petraap20	-12.73	--	--
B.5:15 skull 9	Unsided parietal fragment	Indeterminate	Adult	Petraco21	-19.92	9.54	8.2*
				Petraap21	-13.10	--	--
B.5:15 skull 10	Unsided skull fragment	Male?	Adult	Petraco22	-20.19	11.34	7.9*
				Petraap22	-12.92	--	--
B.5:17	R humerus	Female	Young Adult	Petraco2	-17.65	14.72	13.9*
				Petraap2	-12.66	--	--
B.5:31	Unsided long bone fragment	Indeterminate	Adult	Petraco1	-19.12	11.30	5.6*
				Petraap1	-13.73	--	--
FAUNAL							
B.6:24	Sheep/Goat unsided scapula fragment	Indeterminate	--	Petraco39	-18.50	7.50	3.1
				Petraap39	-10.34	--	--
B.6:28	Goat unsided scapula fragment	Indeterminate	--	Petraco35	-19.70	7.10	8.4*
				Petraap35	-11.62	--	--
B.6:28	Chicken unsided femur	Indeterminate	--	Petraco37	-21.00	8.00	6.8*
				Petraap37	-11.20	--	--

Context	Element	Sex	Age	Sample #[1]	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	C/N
B.7:33	Chicken unsided tibia	Indeterminate	--	Petraco38	-18.50	9.00	3.4
				Petraap38	-11.05	--	--
B.8:5	Pig intermediate phalange	Indeterminate	--	Petraco36	-18.40	8.70	2.9
				Petraap36	-11.05	--	--

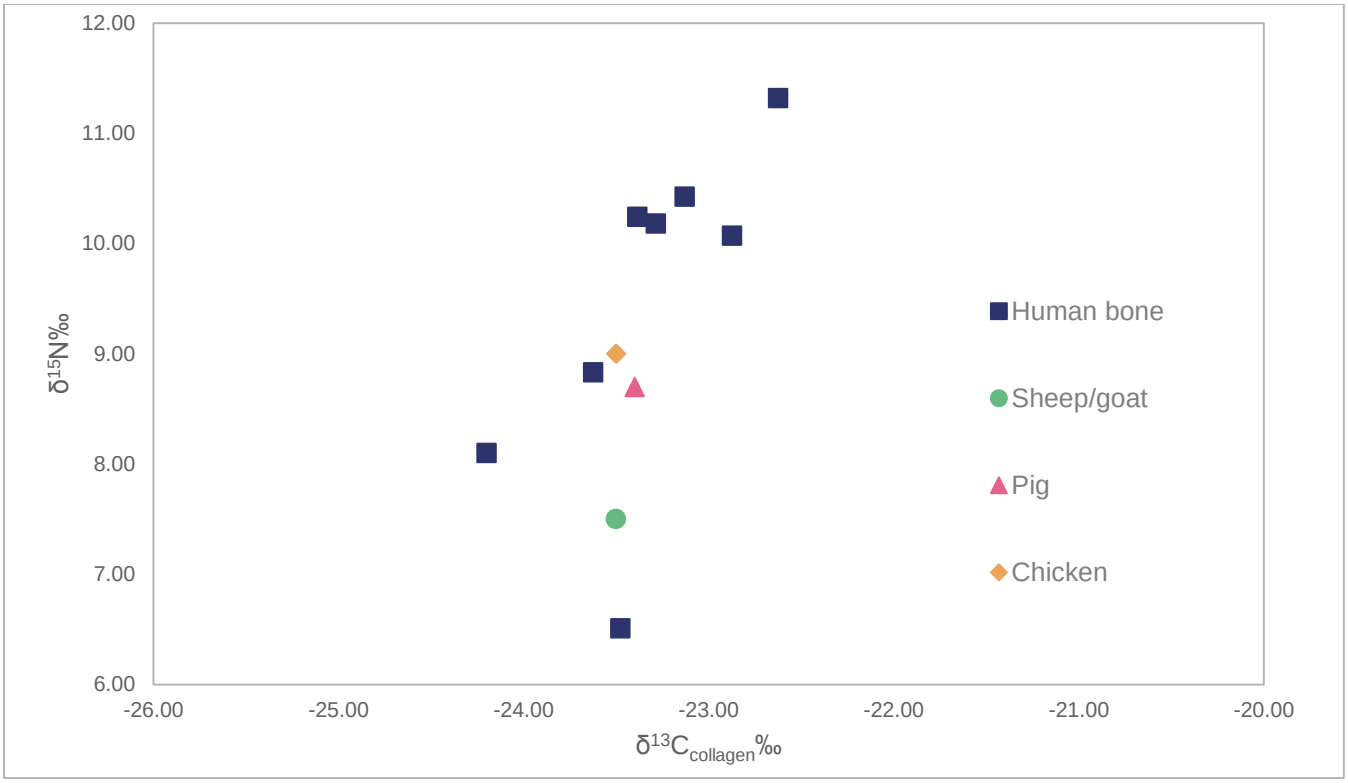

Figure 6. Dietary $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values of Petra humans and fauna

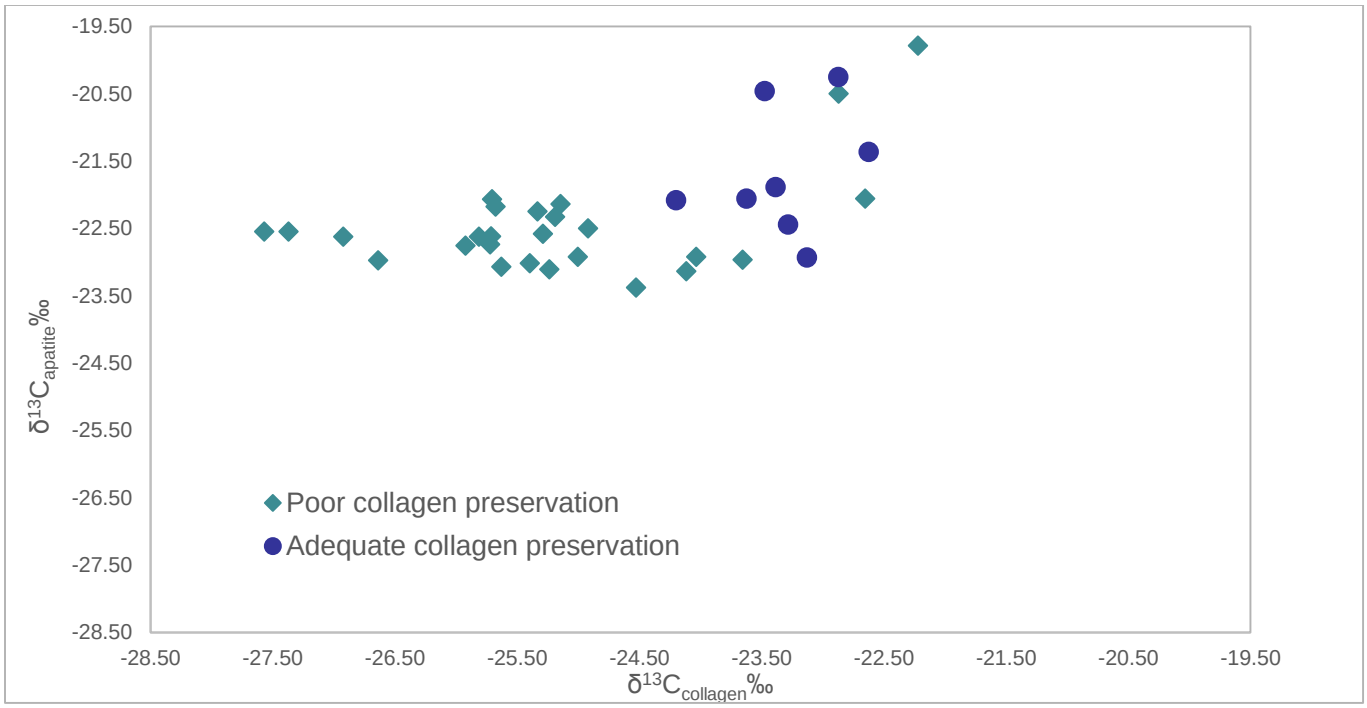

Figure 7. Dietary $\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$ values of Petra humans

Statistical analysis

The results are organized based on comparisons of the following four subgroups: male to female, adult to subadult, between the three tombs, and faunal to human. The statistical results of these comparisons are grouped by $\delta^{13}C_{collagen}$, $\delta^{13}C_{apatite}$, and $\delta\ ^{15}N_{collagen}$ and are detailed in Table 3. Statistically significant differences in $\delta^{13}C$ apatite values were observed between different tombs, notably tomb B.4 and Tomb 2 and between tomb B.5 and Tomb 2. In addition, humans had a significantly higher $\delta^{13}C$ apatite than sampled fauna at the site.

It is possible that the different subgroups at Petra had different levels of dietary variation, with some relying on more diverse dietary sources than others. An ANOVA of the significantly different comparisons was used to identify subgroups with different levels of dietary diversity. In this case, Tomb 2 had more variation than either Tomb B.4 or B.5, and humans had more diversity than fauna.

Table 3. Analysis of isotope data from Petra by sex, tomb, age, and human/fauna[2]

	N	Mean	SD	Wilcoxon results	ANOVA results
$\delta^{13}C_{collagen\ diet}$					
Male	3	-23.270	0.131149	Z=-1.443, p=0.1489	F=6.3855, p=0.0857
Female	2	-23.550	0.098995		
Subadult	2	-23.415	1.11016	Z=0.000, p=1.000	F=0.0793, p=0.7877
Adult	6	-23.297	0.26711		
Tomb B.4	5	-23.328	0.568348	Z=-0.2981, p=0.7656	F=0.0002, p=0.9906
Tomb B.5	0	--	--		
Tomb 2	3	-23.323	0.398790		
Human	8	-18.326	0.18566	Z=-0.9207, p=0.3572	F=0.2395, p=0.6363
Fauna	3	-18.326	0.479611		
$\delta^{13}C_{apatite\ diet}$					
Male	12	-22.482	0.71748	Z=1.7359, p=0.0826	F=2.6452, p=0.1212
Female	8	-21.821	1.10979		
Subadult	5	-22.119	-.553481	Z=1.2157, p=0.2241	F=0.2072, p=0.6521
Adult	29	-22.314	0.920720		
Tomb B.4	13	-22.451	0.48946	B.4 vs. B.5: Z=-1.1056, p=0.2689 B.4 vs. Tomb 2: Z=2.5873, **p=0.0097** B.5 vs. Tomb 2: Z=2.9972, **p=0.0027**	F=18.4115, **p=<0.0001**
Tomb B.5	15	-22.681	0.41797		
Tomb 2	6	-20.935	1.11018		
Human	34	-22.285	0.872531	Z=3.0456, **p=0.0023**	F=20.8668, **p<0.0001**
Fauna	5	-20.452	0.462144		
$\delta\ ^{15}N$					
Male	3	7.28667	0.128970	Z=-1.443, p=0.1489	F=9.0473, p=0.0573
Female	2	4.67000	1.64049		
Subadult	2	6.71000	2.27688	Z=0.1667, p=0.8676	F=0.0593, p=0.8157
Adult	6	6.37833	1.51756		
Tomb B.4	5	7.05600	1.18496	Z=-1.4907, p=0.1360	F=2.3295, p=0.1778
Tomb B.5	0	--	--		
Tomb 2	3	5.74700	1.80710		
Human	8	9.46125	1.55215	Z=-1.1227, p=0.2616	F=1.2202, p=0.2980
Fauna	3	8.4000	0.79373		

* Bolded items indicate significant results

[2] human carbon and nitrogen values converted to reflect dietary values except for the human/faunal comparison

Chapter 5: Discussion

The stable isotope data from Petra outlined in the previous section is one part of the multi-method approach taken in this research project. These data are interpreted within the context of information on the environment, and agricultural history, as well as zooarchaeological and paleobotanical data published from excavations at other sites in Petra, along with evidence of trade provided by historical documents. This section also includes a discussion on the preservation of the remains at Petra in context of the burial environment, which ultimately influenced stable isotope data at Petra. In addition these data are discussed within the framework of available isotopic data from studies in northern Jordan (Al-Bashaireh and Al-Muheisen 2011; Al-Shorman 2004; King 2001; Sandias 2011), Egypt (Aufderheide et al. 2003; Touzeau et al. 2014; White et al. 1999), Turkey (Lösch et al. 2014) and Sudan (White and Armelagos 1997). Paleopathology data on health, disease, and malnutrition of the Petra sample (Canipe 2014), also informs the interpretations.

As discussed in the previous chapter, preservation of the skeletal remains from Petra was variable and only 11 out of 39 remains had sufficient collagen preservation for isotopic analysis (DeNiro 1985). The truncated collagen sample therefore did not produce significant subpopulation differences as the apatite data did. The $\delta^{13}C_{apatite}$ data revealed statistically significant results between tomb subgroups, with Tombs B.4 and B.5 having higher values than Tomb 2. In addition, humans had higher $\delta^{13}C_{apatite}$ values than fauna recovered from the site.

The main factors that likely affected preservation of collagen at Petra are temperature, soil type, hydrological activity and disturbance by humans or animals (Henderson 1987). These factors can work independently as well as dependently and include intrinsic as well as extrinsic mechanisms. Collagen, the organic portion of the bone, can survive for long periods with

minimal bacterial damage but in arid environments, collagen can rapidly degrade (Maurer et.al 2014). This would suggest that remains at Petra would have poor collagen preservation. However, aridity was not the only factor in operation. A combination of temperature and soil type has contributed to Petra's poor bone and collagen preservation that has been further amplified by hydrological activity.

Petra's climate is typically hot during the summer months (Cordova 2007) with average historic temperatures between 25-30°C (The Weather Channel LLC n.d). High temperatures can lead to rapid loss of collagen (Saliège et al. 1995). Petra's tombs, however, remain relatively cool in comparison to the outside temperature as personally observed in 2014. These cooler temperatures may have provided some protection against collagen loss.

The soil composition and its potential salinity also contribute to poor collagen preservation at Petra. Petra's soil is composed of weathered limestone (Parr 2003) and sandstone (Cordova 2007), aeolian sand, and loess (Foss et. al. 2005). Limestone, an alkaline sedimentary rock composed of calcium carbonate and sand or clay, is particularly susceptible to diagenesis from groundwater (Nesse 2011; Stow 2005). When limestone weathers, it produces an increase in the alkalinity of the resulting soil (Rudakova and Zaikov 1987). Sandstone, a porous sedimentary rock, is more resistant to environmental processes but when it weathers its produces an acidic soil (Jackson 1997). The acidity and alkalinity of soil can affect diagenetic activity in bones (Henderson 1987). In addition to the composition of the soil, its salinity can also influence bone preservation (Henderson 1987). Petra's soil may be somewhat saline due to its semi-arid environment. Anthropogenic activities, e.g. irrigation, can also contribute to soil salinity (Cordova 2007; Raheja 1966). Moreover, bones that are buried in sandy deposits generally are

more porous and friable and are therefore particularly susceptible to hydrological effects (Hedges 2002).

While Petra is semi-arid, it does experience flash flooding in the winter months (Beckers et al. 2013). These floodwaters can infiltrate the tombs and promote disintegration of the remains. As noted earlier, the North Ridge tombs are accessed via a vertical shaft that opens up into a larger chamber (Bikai and Perry 2001). Water from above can percolate down through the soil that filled up the vertical shaft and enter the chambers. This process is clearly seen in the water-borne silt that fills the chamber and shaft. Sitting water has already been implicated in the disarticulation of the remains (Bikai and Perry 2001; Perry 2002). It would also contribute to diagenetic breakdown and bone porosity (Goffer 1980).

Disturbance by humans through looting activities (Bikai & Perry 2001; Perry 2002) is a final factor that likely contributes to poor bone preservation. Disturbance can cause breakage, which can make the bone more susceptible to hydrological activities due to porosity and cavities where water can infiltrate (Hedges et al. 1995), thus speeding up the process of collagen hydrolysis (see background for discussion of hydrolysis) (Lambert et.al 1985; Ortner et.al 1972). Thus, the environment within Petra's rock-cut chamber tombs is particularly poor for bone collagen preservation. A review of other Jordanian sites also reveal that when the researchers attempted to use bone collagen for dietary reconstructions, they also ran into poor collagen preservation for a number of their samples probably due to similar conditions (Diaz et al. 2012; Sandias 2011).

Subgroup variation at Petra

Despite the poor preservation of the collagen in the samples from Petra, statistical analysis of the carbon values from the apatite revealed significant differences between faunal and human remains. The $\delta^{13}C$ apatite from the humans in tombs B.4 and B.5 were significantly different from Tomb 2 but ANOVA revealed that the humans in B.4 and B.5 had less variation than Tomb 2. Tombs B.4, B.5 and 2 are located in different sectors of the North Ridge: Tomb 2 is positioned at the western end, and Tombs B.4 and B.5 are ca. 125 m further along the ridge to the northeast of Tomb 2 (see Figure 4). As archaeologists believe that each tomb held extended family members (Perry in press; Schmid 2012; Wadeson 2012a, 2012b), the statistically significant differences between the tombs may be based on food preferences of extended families buried in each tomb or there might have been socially restricted access to specific foods (e.g., Ambrose et al. 2003) in Petra. Additionally, while the tested sample size from Tomb 2 was half that from Tombs B.4 and B.5, Tomb 2 had significantly greater variance, which may indicate that the entombed family in Tomb 2 relied on a wider variety of food sources. Breaking down the individuals buried in Tomb 2 illustrates that two individuals (burials 1 and 8) have values similar to the Tombs B.4 and B.5 samples, while the other four had less negative carbon values possibly indicative of minor consumption of C_4 plants or animals that ate C_4 plants. Furthermore, while all tombs were in use during the 1st century A.D., more detailed dating analysis might demonstrate temporal differences between the two parts of the North Ridge cemetery and may explain the observed variation between the tombs. In addition, humans had more negative (-22.29‰) $\delta^{13}C$ apatite values than fauna (-20.45‰) recovered from the site. The statistically significant differences between human and sheep/goats, chickens, and pigs could result from fauna consuming local C_4 plants or fauna may have been supplemented with C_4 foods, most

likely millet. The difference between human and fauna values could also result from humans' higher trophic position in the food web compared to herbivores. There is frequently a 0‰–2‰ difference between each trophic level (Bocherens and Drucker 2003). Alternatively, variation in the consumers' tissues may differ slightly in their carbon value from their diet due to metabolic processes (DeNiro and Epstein 1981).

No parallel differences were found in the $\delta^{15}N$ values from Petra, which likely indicates that these individuals at Petra had similar access to, and preference for, meat or secondary products (eggs, yogurt, milk) from animals. However, as previously discussed, physiology and an arid environment, as well as local agricultural practices such as manure fertilizing and soil disruption can all contribute to increased nitrogen values in consumers' tissues (Ambrose 1991). Higher temperatures combined with other diagenetic factors can also decrease the post-mortem nitrogen values in collagen (Ortner et. al 1972). Thus, the nitrogen values from the Petra North Ridge sample may not accurately reflect meat or potential marine consumption. Additional tests are required to determine relative meat consumption.

Water management and agriculture at Petra

Petra is located in the Eastern Highlands in southern Jordan, a semi-arid environment. Rainfall differs between the valleys and the higher elevations (Beckers et al. 2013; Schmid 2008; Tholbecq 2013). In present day, little to no rain falls during the summer months, while dangerous flash flooding occurs in the winter months, as mentioned above. Due to this uneven rainfall pattern, vegetation varies greatly across the landscape (Jacquat and Martinoli 1999). For example, the slopes of Jabal ash-Sharā (Figure 8) receives 300mm annually, while some portions of the hinterland receive less than 200mm per annum (Lavento et al. 2007; Van der Veen et al.

1996), and other parts of the landscape receive only 200mm of rain annually, the minimum requirement for dry farming (Beckers et al. 2013). Storing enough water resources to sustain a large population, herds and agriculture in an area with variable rainfall required advanced water catchment techniques.

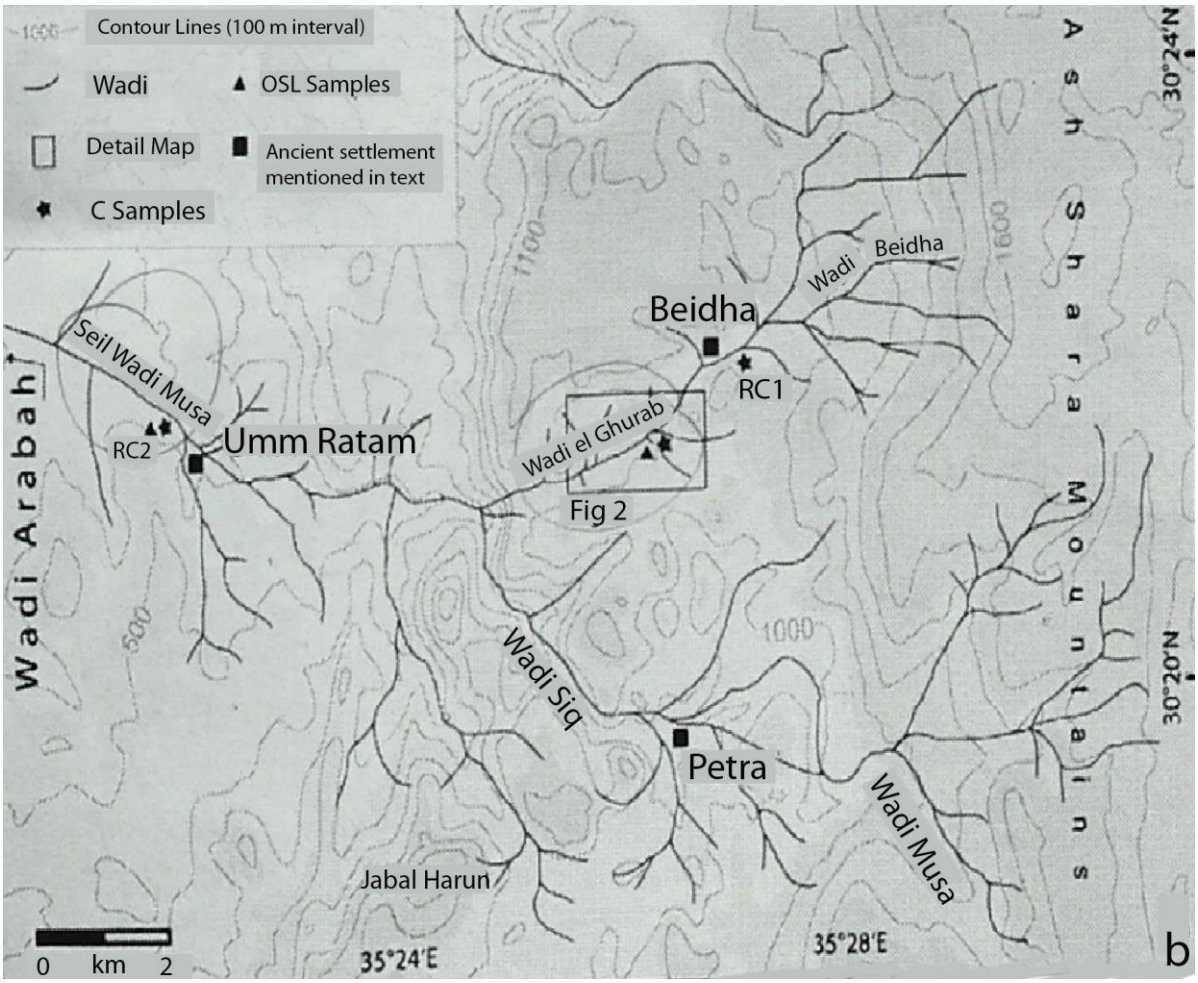

Figure 8. Beckers et al. 2013 Location of Ash-Sharā Mountains

As the population of Petra grew, this put additional pressure on the demand for water, thus necessitating extensive water management systems. The Nabataeans used their engineering skills and knowledge of the desert environment to bring in water from various sources, enough to support a large urban population and animal herds (Schmid 2008; Tholbecq 2013). The success

in this endeavor is suggested by sufficient surplus water to support ceremonial architecture within the city, such as pools and gardens (Bedal 2001).

The Nabataeans constructed three types of drainage systems to provide water to the city. First was a local drainage system that tapped into two springs located within the city (Nehmé 2003). Another drainage system included the construction of rock-carved channels to bring water from three springs outside the city: Ain Musa, Ain Brāq and Ain Dibdibeh (Al-Muheisen and Tarrier 2002). The last drainage system included creating numerous cisterns that varied in size to collect rainwater run off (Nehmé 2003).

The Nabataeans appear to have used their skill in managing water to support agriculture. Archaeological surveys indicate that run-off terrace systems were constructed in the hinterland of Petra probably for agricultural purposes (Beckers et al. 2013; Haiman 2012; Kouki 2009; Oleson 2007; Ramsay & Smith 2013; Tholbecq 2013). Some of these terrace systems in the northern and western hinterlands (Wadi el Ghurab, Seil Wadi Musa) of Petra have been dated to the 1st century A.D. using OSL (optically stimulated luminescence), radiocarbon, and archaeological methods (Beckers et al 2013; Kouki 2009, 2013). Their construction at this time supports the theory that there was an expansion and intensification of agriculture at this time (Beckers et al. 2013; Kouki 2009, 2013; Ramsay & Smith 2013). The archaeological data supporting agriculture production in the hinterlands of Petra, combined with archaeobotanical and zooarchaeological data, provides support to build a potential profile of foods the Nabataeans could have consumed. Isotopic data can then be interpreted within the context of this information and is able to provide some possible explanations for the observed isotopic signatures.

Paleobotanical data

The recovery of paleobotanical materials can provide information for what was available for consumption to the inhabitants in Jordan, but people also make choices as to what to cultivate and to gather that are, in part, influenced by variables such as environment and climate. It is necessary, then, to look at the archaeological data from Petra for what has been recovered in order to provide site-specific plant information. Historical documents about Petra provide an additional source of information pertaining to whether the consumed plants were locally grown or imported.

There have only been a few archaeobotanical studies in Jordan and these have focused on the Neolithic through Iron Age periods (Engel 1993; Flanagan & McCreery 1990; Helback 1974; Neef 1989, 1990, 1998; Richardson & McCreery 1976) but a few have studied the Nabataean and Roman (Bedal et al. 2007; Jacquat and Martinoli 1999; Karg 1996; Ramsay and Bedal 2015; Ramsay 2013; Ramsay and Smith 2013; Stucky et al. 1995; Tholbecq et al. 2008), as well as the Late Roman/Byzantine (Crawford 2006; Ramsay 2013). Findings from these studies are included in Appendix B. The paleobotanicals found specifically at Petra are presented in Table 4. Cereals that are commonly recovered in the archaeological record of the Near East include einkorn, emmer, and barley (Zohary and Hopf 1973).

Three sites from Petra, the domestic complexes of Ez-Zantur, the Obodas Chapel Complex, and the Petra Pool and Garden Complex along with the nearby site of Bir Madkhur, provide most of the paleobotanical information that has been published to date about Petra and its hinterland. These previously stated sites have been placed into Table 4 and will be discussed in detail below.

Table 4. Paleobotanicals Petra: Nabataean through Byzantine Periods

Cereal	C_3	*Triticum L. Sp* (wheat)	Bedal et al. 2007; Ramsay and Bedal 2015; Ramsay and Smith 2013
Cereal	C_3	*L Hordeum vulgare* (barley)	Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995; Tholbecq et al. 2008
Cereal	C_4	*Setaria sp. or Panicum sp.* (millet)	Ramsay and Smith 2013
Legume	C_3	*Lathyrus sativus* (vetch/pea)	Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995
Legume	C_3	*Lens culnarius medik* (lentil)	Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995
Legume	C_3	*Pisum sativum L.* (pea)	Stucky et al. 1995; Tholbecq et al. 2008
Legume	C_3	*Vicia ervilia L.*(bitter vetch)	Bedal et al. 2007; Ramsay and Bedal 2015; Ramsay and Smith 2013
Legume	C_3	*Vicia fava* (fava bean)	Ramsay and Smith 2013
Legume	C_3	*Vicia sativa L*. (common vetch)	Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995
Fruit	C_3	*Cucurbitaceae* (gourd)	Ramsay and Smith 2013
Fruit	C_3	*Ficus carica L.* (common fig)	Bedal et al. 2007; Jacquat and Martinoli 1999; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995); Tholbecq et al. 2008
Fruit	C_3	*Olea europaea L.* (olive)	Bedal et al. 2007; Jacquat and Martinoli 1999; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995),
Fruit	C_3	*Phoenix dactylifera L.* (date palm)	Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995
Fruit	C_3	*Prunus* (plum or peach)	Ramsay and Smith 2013
Fruit	C_3	*Vitis vinifera* (wild or cultivated grapes)	Jacquat and Martinoli 1999; Karg 1996; Ramsay and Smith 2013; Stucky et al. 1995; Tholbecq et al. 2008
Fruit	C_3	*Ziziphus sp.*	Tholbecq et al. 2008
Nut	C_3	*Juglans regia L.* (walnut)	Bedal et al. 2007; Ramsay and Bedal 2015

Vegetable	C_3	*B. vulgaris* (beetroot)	Ramsay and Smith 2013

During excavations at Petra, archaeologists have recovered barley more often than wheat, while only one poorly preserved specimen of millet was recovered from the Late Roman/Early Byzantine period in the hinterland at Bir Madkhur (Ramsay and Smith 2013). Barley, a more drought tolerant species than other grains (Ramsay and Smith 2013), is an ideal crop for the Petra environment. The predominance of barley in the paleobotanical record may be due to several factors. Wheat matures more slowly than barley and therefore may be more affected by drought conditions (Aguilera et al. 2008) making it a less ideal crop to cultivate in the Petra hinterland. Alternatively, the prevalence of barley may be explained by the practice of feeding barley to animals and using their dung for fuel, leading to carbonization of the plant remains in the dung (Crawford 2006). The Petra Pool and Garden Project also recovered some unidentified grains, suggesting that species of grains other than wheat and barley may have been grown at Petra (Bedal et al. 2007). While C_4 crops including millet (a grain) were grown in Jordan and are ideal for the environment (Neef 1989) they have yet to be recovered within the city of Petra. The presence of millet in the hinterland of Petra in the Late Roman/Early Byzantine suggests that it may have been available to the city. As millet was commonly fed to animals in Europe (Murray and Schoeninger 1988), the plant may be found in animal dung at Petra in the future. If millet or other C_4 plants were consumed, it was likely as a byproduct through eating animals grazing in the local environment or whose feed may have been supplemented with millet. For example, C_4 plant families including Chenopodiaceae and Polygonaceae (flowering plants) have been found in modern day Jordan (Al-Eisawi 1996). Even if a small amount of millet or local C_4 vegetation were consumed, however, it does not appear to have affected the non-elite Petraeans' stable isotope values.

Several of the species listed in Table 4, including cereal crops and fruit trees, may initially seem surprising considering the low amount of rainfall that Petra receives annually but with a sufficient supply of water, likely through irrigation, these types of plants could have been cultivated (Bedal et al. 2007). For example, olive trees, which favor rocky and dry conditions, could have been grown in Petra (Bedal et al. 2007), but would have required irrigation (Ramsay and Smith 2013). Remains of grapes, date palms, and figs were found at the previously mentioned sites in Petra and in the hinterland (Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995; Tholbecq et al. 2008). In addition, remains from a gourd (fruit) and a peach or plum have only been recovered at Bir Madkhur (Ramsay and Smith 2013). The presence of these fruits in Petra and the hinterland may suggest that the fruits had been grown locally, (Ramsay and Smith 2013). Evidence of continued growth of some of these species (barley, wheat and olives) in the region today comes from personal observations during the 2014 field season, which attests to the capability of the people to mitigate environmental factors in order to cultivate these species. In addition to cereal crops and fruit trees, crop by-products and a number of wild species that are opportunistic growers in tilled fields were recovered. Their discovery supports the existence of cultivated plants in Petra and its hinterland (Bedal et al. 2007; Ramsay and Bedal 2015; Ramsay and Smith 2013). Finally, the Petra Papyri, a cache of personal documents that date to the Byzantine period, indicate that wheat and orchard crops were cultivated in the hinterland of Petra, indicating a continuity over a 500 year period (Frosen et al. 2002).

While Petraeans likely grew and consumed vegetables, few remains of these plants have been recovered, possibly due to preservation bias (Ramsay and Smith 2013). The remains of beetroots have only been recovered in the hinterland (Ramsay and Smith 2013; Stucky et al.

1995; Tholbecq et al. 2008). On the other hand, legumes like lentils and vetch/pea were recovered at both Ez-Zantur and the Petra Pool and Garden Complex while fava bean, lentil, bitter vetch, and vetch/pea were found in the hinterland (Bedal et al. 2007; Karg 1996; Ramsay and Bedal 2015; Ramsay and Smith 2013; Stucky et al. 1995). Once again, these were recovered in small quantities, potentially indicating that they did not survive in the archaeological record or that they may have been imported (Bedal et al. 2007). According to Bedal (Bedal et al. 2007), legumes like lentils, peas and vetch, were typically consumed by humans and animals, lending additional support to the idea that animal husbandry was taking place in Petra. Finally, only one nut species (walnut) has been found at Petra (Bedal et al. 2007; Ramsay and Bedal 2015). The same explanations offered for the few remains of wheat and legumes is likely applicable to the scant evidence of walnuts.

The inhabitants of Petra likely took advantage of the extensive trade networks in the Near East to bring in food that could not be grown in the regional environment (Bedal et al. 2007). Foods such as wheat, legumes and nuts may have been imported potentially explaining their scant evidence in the archaeological record. As more paleobotanical evidence is recovered, information about wild and domestically available plants in Petra and the hinterland should provide a better idea of available plant foods and what the Nabataeans grew during the 2nd century B.C through the 4th century A.D. (Bedal et al. 2007).

Zooarchaeological data

The Petra North Ridge Project (PNRP) site has produced an assemblage of faunal bones that are associated with the non-elite tombs and domestic areas. The recovery of 1st century A.D. faunal remains that could reflect the diet of the individuals buried in the North Ridge tombs

during the 1st century A.D. provided valuable contributions to the reconstruction of the Petraean diet. First, the faunal isotopic values were tested in order to act as a baseline for comparison with the human remains and, as previously discussed, comparison of their values with the non-elite humans revealed values that were less negative than humans were and also indicated that animals were consuming a C_3 diet. Second, the assemblage collected in previous field seasons provides information about the animals potentially consumed by the city's inhabitants. The bulk of the faunal remains from the 2014 season were sheep and goat bones (ovicaprines) with lesser representation of chicken, equids, camels, and other non-domestic taxa. According to Lowrey (2014), sheep, goat, and chicken probably provided the bulk of animal protein and secondary products for the inhabitants of the North Ridge domestic structures. Small numbers of equid and camel bones with evidence of bone modification suggests that equids and camels were occasionally consumed. Horses and camels probably served as pack animals rather than being utilized as a significant source of meat. Finally, cattle and pig bones were recovered in small numbers and likely contributed little to the diet at this site.

Excavations at Ez-Zantur, a series of elite domestic complexes on a slope to the south of Petra's city center, began in 1988 with Jacqueline Studer joining the sixth campaign in 1994 (Jacquat and Martinoli 1999). During excavations, archaeologists unearthed a domestic complex with three separate terraces dating from the Nabataean through Roman (63 B.C.-324 A.D) periods. On EZ I (terrace one) a large house was excavated that was founded in the 1st century B.C., while EZ III contained domestic structures and at EZ IV a mansion was uncovered (Studer 2007). Archaeologists recovered over 10,000 animal remains. Similar to the North Ridge, the majority of the faunal remains recovered were ovicaprines, the bulk of which were identified as sheep. The inhabitants on all three terraces appear to have had access to whole carcasses of sheep

and goat, butchered on-site, as elements from all portions of the skeletons were recovered. Based on the sheep and goat age profiles, most animals were adults when killed, indicating that they were likely raised primarily for their secondary products (yogurt, milk, eggs) and eventually killed for meat (Studer 2007). Pigs were killed as juveniles and piglets rather than adults suggesting that the pigs were raised for their meat.

The assemblage at Ez-Zantur also contained remains from fish, molluscs, birds (chicken, partridge, goose, ostrich) and wild animals (gazelle, wild boar, possibly ibex). Studer (2002; 2007) suggests that fish and molluscs were likely trade items brought from the Red Sea, the Mediterranean and freshwater sources. Marine fish species included tuna, mackerel, emperors, groupers, parrotfish, snappers, barracudas, seabreams, trevallies, and possibly grunts (Desse-Berset and Studer 1996). Catfish, the only identified freshwater fish species, was likely brought in via trade from a riverine environment (Studer 2002; 2007). In addition, over 400 pieces of marine molluscs sourced from the Mediterranean and Red Seas (including wedge clams and the top shell) were recovered. Finally, some unidentified freshwater bivalves were discovered (Studer 2002; 2007).

Two of the terraces of the Ez Zantur complex (EZ I and EZ IV) provide some interesting within-group comparisons that researchers suggest may be linked to social status (Studer 2002; 2007). There were clear differences in the faunal assemblages between the terraces. The assemblages discussed here show evidence of butchery indicating consumption by humans. On EZ IV, remains of domesticated birds (domestic chickens, and goose, along with game birds such as Chukar partridge and *Rallidae*) were recovered in much larger amounts than those in EZ I. Gazelles were also recovered more on EZ IV than by EZ I but less frequently than birds. Studer (2002, 2007) related these intra-assemblage differences to the differences in architecture

in the two areas and suggested that these differences reflected social class. Thus, if EZ IV reflects a higher social status, poultry and game birds plus gazelle may have been considered luxury items. The elite domestic complex on EZ IV may then provide a comparative profile to the non-elite contexts of the Petra North Ridge.

Overall, more zooarchaeological studies need to be conducted at Petra to provide a clearer picture of the range of animals available for consumption and the frequency for which each species were consumed (Studer 2007). Despite the small number of studies, the data provides valuable information about the economy and potentially highlights different consumption patterns based on social status (Studer 2002; 2007). In addition, by raising animals like pig, sheep and cattle which require large amounts of water (Horwitz and Studer 2005), the possibility exists that the Nabataeans had the ability to provide enough water for water intensive species in a semi-arid environment (Horwitz and Studer 2005).

Health and paleopathology at Petra

Malnutrition and poor health are closely intertwined. It is generally thought that crowding and social stratification in ancient cities led to disease and poor nutrition (Marshall 2002). It has been suggested that the average urban, sedentary population suffers from increased disease and malnutrition in comparison to non-sedentary populations (Larsen 1997). Crowding and social stratification were further compounded by the movement of people in and out of cities as well as poor sanitation in the cities, which would have created an ideal environment for infection to spread (Marshall 2002). As a city, Petra would have had to deal with similar issues. In fact, assessment of 29 individuals from Tombs B.4 and B.5 on the Petra North Ridge found that the people suffered from low levels of chronic diseases and malnutrition (Canipe 2014). Canipe

(2014) found that only 9% of the urban Petra sample showed signs of periostitis, a condition potentially caused by infection or malnutrition, compared to 13% from a sample of rural or nomadic groups. In addition, only 18% of the sampled population had indications of dental enamel hypoplasias, which are commonly associated with periods of stress during childhood, compared to 27% from sampled rural/nomadic populations. Lower than expected percentages of porotic hyperostosis/cribra orbitalia, a condition associated with megaloblastic anemia or parasitic infections (Larsen 1997; Walker et al. 2009), also occurred: 0% compared with 24% from rural/nomadic populations (Canipe 2014). The majority of bone pathologies seen were degenerative disorders, specifically osteoarthritis and vertebral osteophytosis—pathologies not associated with malnutrition or infectious disease (Canipe 2014).

The PNRP paleopathological results, while surprising in comparison to assumptions about population health in ancient city life, can still provide information that is relevant to diet reconstruction and the interpretation of stable isotopes. Petraeans had low levels of chronic infection and malnutrition, suggesting that the urban inhabitants had access to clean water resources and an adequate combination of protein, carbohydrates and fat resources (Canipe 2014). As previously reviewed, poor nutrition might affect the way the body metabolizes nutrients, thereby influencing isotopic ratios (Fuller et al. 2005; Meier-Augenstein 2011). Canipe's (2014) conclusion that the inhabitants suffered from low levels of malnutrition is supported by the stable isotope data. The non-elite Petraeans sampled for this study do not show evidence of high nitrogen levels that would potentially indicate nutritional stress (Fuller et al. 2005). Finally, the stable isotope data reveals that the Petraeans' nitrogen levels indicate that the non-elite Petraean diet likely contained meat, secondary products (milk, yogurt, eggs), legumes or grains, which provided adequate amounts of protein and fats.

The combination of stable isotopic analysis and paleopathology studies at this site provide us with a clearer picture of nutrition and health for the inhabitants of the Petra North Ridge. The non-elites' stable isotope values combined with the paleobotanical and zooarchaeological record all support that the Petra North Ridge people had access to a variety of foods that included adequate protein, fats and carbohydrates. In addition, the archaeological evidence for agriculture indicates that Petraeans may have received crops and other plants from the hinterland, while Petraeans may have cared for animals locally as the Ez-Zantur provides evidence of access to whole carcasses and the butchering of young pigs (Studer 2007).

Northern Jordan and Mediterranean world dietary reconstructions

In addition to Petra, diet reconstruction studies have been completed in the Near East and Eastern Mediterranean region from 5500 B.P. through the Byzantine (324-640 A.D.) period in Egypt and Sudan (Aufderheide et al. 2003; Touzeau et al. 2014; White and Armelagos 1997; White et al. 1999), the Bronze Age (3500 B.C.-1050 B.C) through the Byzantine periods in Jordan (Al-Bashaireh and Al-Muheisen 2011; Al-Shorman 2004; King 2001; Sandias 2011) and the Roman period in Turkey (Lösch et al. 2014) (Figure 9). The studies discussed in this section, are not comprehensive. A review of the data from these studies potentially indicates that C_3 consumption may have been common in these regions. Caution must be exercised, as the number of samples taken are small and the number of sites that have been reconstructed are few, while several of these sites date to an earlier period than Petra's, therefore greater variability in diet may have occurred. Results from the northern Jordan sites of Gersa , Natfieh, Pella, Tell al-Husn, Yajūz, Yaʿmūn and Yasileh dating from the Early Bronze through Byzantine periods along with the Egyptian sites of Kellis, Kharga Oasis and multiple sites in the Nile Valley dating from 5500

B.P. to 700 A.D. indicate that people were consuming a diet consisting of C_3 resources similar to Petra (Al-Bashaireh and Al-Muheisen 2011; Al-Shorman 2004; Aufderheide et al. 2003; King 2001; Sandias 2011; Touzeau et al. 2014; White et al. 1999). In contrast, results from the sites of Saʿad (northern Jordan), Wadi Halfa (Sudan) and Ephesus Turkey dating from 2nd through 6th centuries A.D. indicate that people were consuming a mixed diet of C_3 and C_4 products (Lösch, et al. 2014; Sandias 2011; White and Armelagos 1997). Figure 9 compares those sites in Jordan for which data was included in publications (See Appendix C for data) and shows that Petra has a stronger C_3 signal than the other northern Jordan sites.

Together, these studies from northern Jordan, Egypt, and Turkey demonstrate that people from these sites were consuming C_3 products while people from one site in northern Jordan, Turkey and Sudan ate a mix of C_3 and C_4 products. The bulk of the sites in arid environments (Egypt and northern Jordan) show little consumption of C_4 products. This is surprising considering that C_4 plants are more suited to arid environments than the C_3 plants (Touzeau et al. 2013). Explanations for the preference of C_3 plant consumption in Petra, northern Jordan, and Egypt likely rest on a combination of environmental, cultural, and economic reasons.

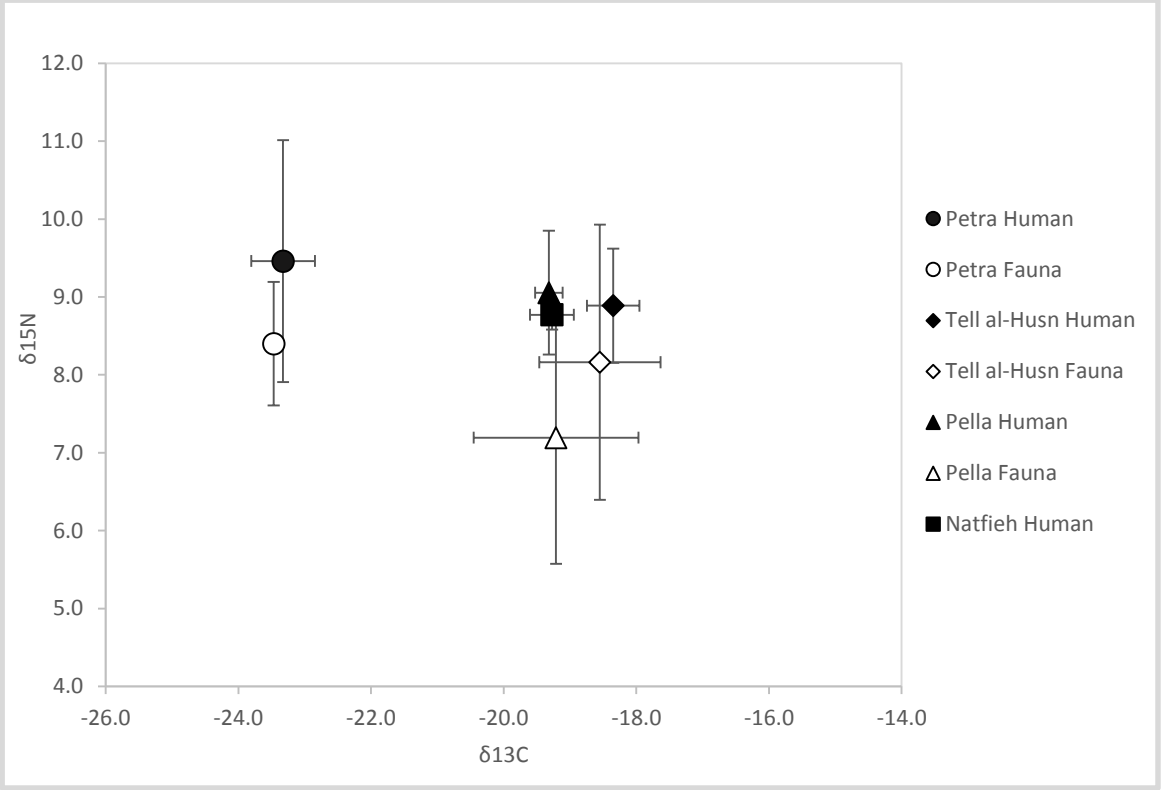

Figure 9. Comparing Petra, Tell al-Husn, Natfieh and Pella Stable Isotope Values

The diet of Petra non-elites

Despite the subgroup differences between the tombs outlined above, the $\delta^{13}C$ and $\delta^{15}N$ bone collagen values (N=11) and apatite values (N=34) suggest that people buried on the North Ridge had relatively homogeneous diets. The archaeological evidence for agriculture, the paleobotanical remains, trade information and zooarchaeological data suggest that the non-elite Petraean diet consisted of C_3 plants and animals that ate C_3 foods. A profile of the potential foods the people consumed likely included barley, some wheat, legumes, nuts, fruits and vegetables as well as fish, pigs, chickens and goats along with their secondary products, with lesser amounts of other domestic and wild animals. Finally, the people may have consumed beer from the malted

barley (Bedal et al. 2007) and evidence of winepresses show that they were likely drinking wine as well (Jacquat and Martinoli 1999).

Chapter 6: Conclusion

The non-elite Nabataean people from the Petra North Ridge tombs appear to have consumed a diet that may have been typical for the period. When viewed together with the data from sites in northern Jordan, Predynastic Egypt, and Roman Turkey, data shows these people were consuming mainly C_3 resources from 5000 B.P through the Byzantine period while a small number were eating a mixed diet of C_3 and C_4 resources in northern Jordan, Sudan and in Roman-period Turkey. The sites discussed here with diet reconstructions are few in number; therefore, they may not be representative of the region. Regardless, it is surprising that the tested remains from Egypt and from northern Jordan demonstrated that these people were consuming mainly C_3 food sources as the environment in Jordan and Egypt was more favorable for the growth of C_4 foods, rather than C_3 (Touzeau et al. 2013). Despite the lack of isotopic evidence for people consuming millet at Petra, this product has been recovered in the paleobotanical record in Jordan (Neef 1989). With future studies at Petra, evidence for consumption of C_4 products may be revealed.

The paleopathological data on the non-elite population from the Petra North Ridge revealed that, despite living in a city, few people suffered from chronic infection or malnutrition (Canipe 2014). Combining this information with the stable isotope results supports the perspective that the people were eating a diet that provided adequate proportions of proteins, carbohydrates, and fats. The paleobotanical, papyrological, and zooarchaeological evidence all suggest that a typical non-elite Petraean diet likely consisted of C_3 plants, comprised of local and imported grains, as local production could not have supported the urban population supplemented by animal sources. Inhabitants of the Petra North Ridge likely ate a combination of C_3 plants including cereals, fruits, legumes, and vegetables along with meat from chicken,

sheep, and goat, with occasional consumption of pigs and cattle. In addition, it is expected humans ate secondary products produced by chicken, sheep, or goat (yogurt, eggs, milk), likely consumed some wild animals and would have occasionally consumed marine and freshwater fish and molluscs brought in by trade (Bedal et al. 2007; Lowrey 2014; Studer 2002; 2007).

A number of biological, environmental and bone preservation factors were considered in this study that may have affected isotopic values in the samples. For example, while Petra North Ridge inhabitants may have had access to C_4 products like millet, the isotopic signal would be masked at very small levels of consumption. In addition, while the zooarchaeological assemblages suggest that the inhabitants had access to aquatic products; these may have been eaten mainly by elite individuals (Studer 2007), or consumed in such small quantities that the terrestrial land based protein sources dominate the isotopic ratio. The effect of the semi-arid environment on nitrogen isotope values was also considered as the aridity can obscure the presence of aquatic consumption in tissues and influence the ability of researchers to differentiate between trophic levels of aquatic and terrestrial or herbivore and carnivore (Ambrose 1991). Finally, as collagen preservation in the sample population was poor, most likely due to the burial environment, a larger sample size is needed to test for collagen quality and to determine if the majority of people from the Petra North Ridge consumed meat or secondary products.

Further research and considerations

The goal of this project was to test whether a multi-method approach to diet reconstruction that included stable isotope analysis was applicable to the Petra North Ridge inhabitants. Through physical observations and chemical testing, it was discovered that collagen preservation at the site was poor. Poor collagen preservation seems typical for a number of

Jordanian sites (Al-Bashaireh et al. 2010; Diaz et al. 2012; Sandias 2011). Poor preservation was most likely due to high temperatures and hydrological activity within the tombs.

While the use of apatite for carbon was successful, future research on diet reconstruction at Petra would benefit from several improvements to the methodology. First researchers should test for diagenetic activity utilizing FTIR (Fourier transform infrared spectroscopy), a tool commonly used by archaeologists (Lee-Thorp and Sponhemier 2003, Wright and Schwarcz 1996), or Raman spectroscopy combined with La-Icp-Ms (Laser Ablation Inductively Coupled Mass Spectrometry) prior to running samples in order to choose the best preserved samples for testing (King et.al 2011). Therefore, it is recommended that future research at Petra on dietary reconstruction should use FTIR, Raman, or other acceptable techniques depending on goals and budgetary concerns to determine preservation levels for both the organic and inorganic parts of the skeletal remains.

The use of a mixing model was considered for the sample on the Petra North Ridge, but several limitations discussed below negated the use of one at this time. Some prominent researchers have used mixing models in their dietary reconstructions (Bocherens et.al 2005; Kellner and Schoeninger 2007; Newsome et.al 2004). Mixing models can be used to provide a more precise determination of proportions of the diet (i.e. proportion of protein, fats or carbohydrates). A mixing model is not warranted in this study, as the models require a larger number of human samples, a representative sample of faunal remains as well as contemporaneous botanical isotopic values (Makarewicz and Sealy 2015). Perhaps in the future it would be possible to incorporate a mixing model to provide a more precise determination of the proportions of proteins, fats and carbohydrates Petraeans may have consumed.

In order to clarify the subgroup differences between humans and potentially determine a cause, a larger sample size and finer chronology based on pottery is required. These may help determine if the differences between the tombs are due to temporal differences (i.e. dietary change over time) or based on extended family dietary preferences. During stable isotope analysis, it was determined that a number of confounding factors influenced the ability to determine consumption of aquatic resources. Therefore, I suggest that future researchers should monitor developments in dietary research. A promising research area involving amino acids and their $\delta^{15}N$ values (Styring et.al 2010) may prove useful in determining aquatic resource consumption. The difference between the non-essential amino acid glutamate and essential amino acid phenylalanine is greater in aquatic organisms than terrestrial ones and this difference is passed on to the consumers' tissues. Therefore, researchers are able to estimate aquatic consumption without the problems encountered in measuring aquatic protein consumption from collagen tissues (Styring et.al 2010). Alternatively, researchers could use $\delta^{34}S$ (sulfur) values in collagen which can provide insights into aquatic consumption (Privat et al. 2007). Sulfur analysis is particularly useful as it can differentiate between freshwater (Privat et al. 2007) and marine sources (Macko et al. 1999b) and no fractionation of the sulfur isotopes occurs between the diet and the consumer (Peterson and Fry 1987) unlike that with carbon and nitrogen. Finally, to provide a more comprehensive sample, human remains and faunal remains from multiple areas of Petra, from different social groups, and from inhabitants of the hinterland should be tested.

The results of this project indicate that inhabitants were able to support an increasing urban population through relying on a combination of imported foodstuffs, local agriculture and animal husbandry. Stable isotope analysis also revealed differences between faunal and human diet and dietary differences between tombs. Explanations for these differences should be further

explored to understand aspects of animal foddering, human food preferences and levels of access to foods. Knowledge of these factors, along with a greater understanding of trade and locally available plants and animals would help inform our understanding of the quality of diet in an urban environment. Future studies that take into account the discussed modifications on methodology and which collect larger comparative samples would provide a clearer picture of diet across Petra in a range of social classes and environments, and would complement studies of health allowing for more informed interpretations of future isotopic studies.

References Cited

Aguilera, Monica, Luis Araus, José, Voltas, Jordi, Oliva Rodríguez-Ariza, Maria , Molina, Fernando, Rovira, Nuria, Buxo, Ramon, and Juan Pedro Ferrio
2008 Stable Carbon and Nitrogen Isotopes and Quality Traits of Fossil Cereal Grains Provide Clues on Sustainability at the Beginnings of Mediterranean Agriculture. Rapid Communications in Mass Spectrometry 22(11):1653-1663.

Al-Bashaireh, Khaled, Al-Shorman, Abdullah, Rose, Jerome Rose, Jull, A.J. Timothy, and Gregory Hodgins
2010 Paleodiet Reconstruction of Human Remains from the Archaeological Site of Natfieh, Northern Jordan. Radiocarbon 52(2): 645-652.

Al-Bashaireh, Khaled, and Zeidoun Al-Muheisen
2011 Subsistence Strategies and Palaeodiet of Tell al-Husn, Northern Jordan: Nitrogen and Carbon Stable Isotope Evidence and Radiocarbon Dates. Journal of Archaeological Science 38(1):2606-2612.

Albright, W. F.
1935 The Excavation of the Conway High Place at Petra. Bulletin of the American Schools of Oriental Research 57(1):18-26.

Al-Eisawi, D.M.
1996 Vegetation of Jordan. Cairo: UNESCO Regional Office for Science and Technology for the Arab States.

Al-Muheisen, Zeidoun, and Dominique Tarrier
2002 Water in the Nabataean Period. ARAM Periodical 13(1):515-524.

Al-Shorman, Abdulla
2004 Stable Carbon Isotope Analysis of Human Tooth Enamel from the Bronze Age Cemetery of Ya'amoun in Northern Jordan. Journal of Archaeological Science 31(1):1693-1698.

Ambrose, Stanley H., and Michael J. DeNiro
1986 Reconstruction of African Human Diet using Bone Collagen Carbon and Nitrogen Isotope Ratios. Nature 319(1):321-324.

Ambrose, Stanley H.
1990 Preparation and Characterization of Bone and Tooth Collagen for Isotopic Analysis. Journal of Archaeological Science 17(1):431-451.

Ambrose, Stanley H.
1991 Effects of Diet, Climate and Physiology on Nitrogen Isotope Abundances in Terrestrial Foodwebs. Journal of Archaeological Science 18(3): 293-317.

Ambrose, Stanley H.
1993 Isotopic Analysis of Paleodiets: Methodological and Interpretive Considerations. *In* Investigations of Ancient Human Tissue: Chemical Analysis in Anthropology. M. K Sandford, ed. Pp. 59-129. Langhorne: Gordon and Breach Science Publishers.

Ambrose, Stanley H., and Lynette Norr
1993 Experimental Evidence for the Relationship of the Carbon Isotope Ratios of Whole Diet and Dietary Protein to those of Bone Collagen and Carbonate. Prehistoric Human Bone. Berlin: Springer.

Ambrose, Stanley H., Buikstra, Jane, and Harold W. Krueger
2003 Status and Gender Differences in Diet at Mound 72, Cahokia, Revealed by Isotopic Analysis of Bone. Journal of Anthropological Archaeology 22(3):217-226.

Aufderheide, A. C., Cartmell, L., Zlonis, M., and P. Horne
2003 Chemical dietary reconstruction of Greco-Roman mummies at Egypt's Dakhleh oasis. Journal of the Society for the Study of Egyptian Antiquities, 30(1):1-8.

Beckers, Brian, Brigitta Schütt, Sumiko Tsukamoto, and Manfred Frechen
2013 Age Determination of Petra's Engineered Landscape-Optically Stimulated Luminescence (OSL) and Radiocarbon Ages of Runoff Terrace Systems in the Eastern Highlands of Jordan. Journal of Archaeological Science 40(1):333-348.

Bedal, Leigh-Ann
2001 A Pool Complex in Petra's City Center. Bulletin of the American Schools of Oriental Research 324 (1):23-41.

Bedal, Leigh-Ann, K. L. Cleason, and James G. Schryver.
2007 The Petra Garden and Pool Complex, 2003–2005. Annual of the Department of Antiquities of Jordan 51(1):151-76.

Bikai, Patricia Maynor, and Megan A. Perry
2001 Petra North Ridge Tombs 1 and 2: Preliminary Report. Bulletin of the American Schools of Oriental Research 324(1):59-78.

Bocherens, Hervé, and Dorothée Drucker
2003 Trophic Level Isotopic Enrichment of Carbon and Nitrogen in Bone Collagen: Case Studies from Recent and Ancient Terrestrial Ecosystems. International Journal of Osteoarchaeology 13(1-2): 46-53.

Bocherens, H., Drucker, D. G., Billiou, D., Patou-Mathis, M., and B. Vandermeersch
2005 Isotopic Evidence for Diet and Subsistence Pattern of the Saint-Césaire I Neanderthal: Review and Use of a Multi-Source Mixing Model. Journal of Human Evolution 49(1)L71-87.

Bocherens, H., and D. G. Drucker
2007 Carbonate stable isotopes/terrestrial teeth and bones. Encyclopedia of Quaternary Sciences. Pp. 309-316. New York-Elsevier.

Brooks, Sheilagh, and Judy M. Suchey
1990 Skeletal Age Determination Based on the Os Pubis: A Comparison of the Acsádi-Nemeskéri and Suchey-Brooks Methods. Human Evolution 5(3): 227-238.

Buikstra, J. E., and G.R. Milner
1991 Isotopic and Archaeological Interpretations of Diet in the Central Mississippi Valley. Journal of Archaeological Science 18(3):319-329.

Buikstra, J. E., and D.H. Ubelaker
1994 Standards for Data Collection from Human Skeletal Remains. Arkansas Archeological Survey Research Series 44.

Canipe, Courtney
2014 Exploring Quality of Life at Petra through Paleopathology. Unpublished MA, Department of Anthropology, East Carolina University.

Chisholm, Brian S., D. Erle Nelson, and Henry P. Schwarcz
1982 Stable-Carbon Isotope Ratios as a Measure of Marine versus Terrestrial Protein in Ancient Diets. Science 216(4550):1131-1132.

Coltrain, J. B., and T.W. Stafford Jr.
1999 Stable Carbon Isotopes and Salt Lake Wetlands Diet: Towards an Understanding of the Great Basin Formative. *In* Prehistoric Lifeways in the Great Basin Wetlands: Bioarchaeological Reconstruction and Interpretation. Salt Lake City-University of Utah Press.

Cordova, C. E.
2007 Millennial Landscape Change in Jordan: Geoarchaeology and Cultural Ecology. Tucson: University of Arizona Press.

Crawford, Patricia
2006 The Roman Frontier in Central Jordan: Final Report on the Limes Arabicus Project, 1980–1989 volume II. S. Thomas Parker, ed. Washington D.C.-Dumbarton Oaks.

de France, Susan D.
2009 Zooarchaeology in Complex Societies: Political Economy, Status, and Ideology. Journal of Archaeological Research 17(1):105-168.

DeNiro, Michael J., and Samuel Epstein
1981 Influence of Diet on the Distribution of Nitrogen Isotopes in Animals. Geochimica et Cosmochimica Acta 45(3): 341-351.

DeNiro, Michael J.
1985 Postmortem Preservation and Alteration of In Vivo Bone Collagen Isotope Ratios in Relation to Palaeodietary Reconstruction. Nature 317(1):806-809.

DeNiro, M. J.
1987 Stable Isotopy and Archaeology. American Scientist 75(2):182-191.

Desse-Berset, N., and J. Studer
1996 Fish Remains from ez Zantur (Petra, Jordan). Petra, Ez Zantur I: Ergebnisse der Schweizerisch-Leichtensteinischen Ausgrabungen 1988–1992 Pp. 381-87.

Diaz, A. L., O'Connell, T. C., Maher, L. A.,and J.T. Stock
2012 Subsistence and Mobility Strategies in the Epipalaeolithic: A Stable Isotope Analysis of Human and Faunal Remains at 'Uyun al-Hammam, Northern Jordan. Journal of Archaeological Science 39(7):1984-1992.

Dobberstein, R. C., Collins, M. J., Craig, O. E., Taylor, G., Penkman, K. E. H., and S. Ritz-Timme
2009 Archaeological Collagen: Why Worry about Collagen Diagenesis? Archaeological and Anthropological Sciences 1(1):31-42.

Engel, Thomas
1993 Charcoal Remains from an Iron Age Copper Smelting Slag Heap at Feinan, Wadi Arabah (Jordan). Vegetation History and Archaeobotany 2(4): 205-211.

Fiema, Zbigniew T.
2003 Roman Petra (A.D 106-363): A Neglected Subject. Zeitschrift des Deutschen Palästina-Vereins 119(1) :38-58.

Flanagan, James W., and David W. McCreery
1990 First Preliminary Report of the 1989 Tell Nimrin Project. Annual of the Department of Antiquities of Jordan 34(1):131-152.

Fogel, Marilyn L., Noreen Tuross, and Douglas W. Owsley
1989 Nitrogen Isotope Tracers of Human Lactation in Modern and Archaeological Populations. Annual Report of the Director, Geophysical Laboratory, Carnegie Institution of Washington 1988–1989. Pp.111-117. Washington, DC: Carnegie Institution of Washington.

Foss, John E., Essington, Mike, Gartley, Karen, and Leigh-Ann Bedal
2005 Soils of the Garden and Pool Complex Archaeological Site in Petra, Jordan. Poster presented at the ASA-CSSA-SSSA International Annual Meetings, Salt Lake City, November 8.

Freeman, Philip
2008 The Roman Period. *In* Jordan an Archaeological Reader. Russell B. Adams, ed. Pp. 414-441. London: Equinox.

Frosén, J., Arjava, A., and M. Lehtinen, eds
2002 The Petra Papyri I (Vol. 1). Amman: American Center of Oriental Research.

Fry, Brian
2007 Stable isotope ecology. New York: Springer Science & Business Media.

Fuller, B. T., Fuller, J. L., Sage, N. E., Harris, D. A., O'Connell, T. C., and R.E. Hedges
2005 Nitrogen Balance and δ15N: Why you're not What you Eat During Nutritional Stress. Rapid Communications in Mass Spectrometry 19(18):2497-2506.

Gibbs, Martin
2005 The archaeology of subsistence on the maritime frontier: faunal analysis of the Cheyne Beach Whaling Station 1845-1877. Australasian Historical Archaeology 23(1): 115-122.

Graf, David F.
2013 Petra and the Nabataeans in the Early Hellenistic Period: The Literary and Archaeological Evidence. *In* Men on the Rocks: The Formation of Nabataean Petra. M. Mouton and S. G Schmid, eds. Pp. 35-56. Berlin: DFG ANR.

Goffer, Z.
1980 Archaeological Chemistry. New York:Wiley-Interscience.

Haiman, M.
2012 Dating the Agricultural Terraces in the Southern Levantine Deserts – The Spatial-Contextual Argument. Journal of Arid Environments 86(1):43-49.

Harbeck, M., and G. Grupe
2009 Experimental Chemical Degradation Compared to Natural Diagenetic Alteration of Collagen: Implications for Collagen Quality Indicators for Stable Isotope Analysis. Archaeological and Anthropological Sciences 1(1):43-57.

Harrison, R. G., and M.A. Katzenberg
2003 Paleodiet Studies using Stable Carbon Isotopes from Bone Apatite and Collagen: Examples from Southern Ontario and San Nicolas Island, California. Journal of Anthropological Archaeology 22(3):227-244.

Hedges, R. E. and A.R. Millard
1995 Bones and Groundwater: Towards the Modelling of Diagenetic Processes. Journal of Archaeological Science 22(2):155-164.

Hedges, Robert E. M.
2002 Bone Diagenesis: An Overview of Processes. Archaeometry 44(3):319-328.

Hedges, R. E., Clement, J. G., Thomas, C. D. L., and T.C. O'Connell
2007 Collagen turnover in the adult femoral mid-shaft: Modeled from anthropogenic radiocarbon tracer measurements. American Journal of Physical Anthropology 133(2): 808-816.

Helback, Hans
1974 Grain from the Tell Siran Bronze Bottle: Department of Antiquities Jordan 19(1): 167-168.

Henderson, J.
1987 Factors Determining the State of Preservation of Human Remains. *In* Death, Decay and Reconstruction: Approaches to Archaeology and Forensic Science. A. Boddington, A. N. Garland, and R.C. Janaway, eds. Pp. 43-54. Manchester:Manchester University Press.

Hillson, S.W., Larsen, C.S., Boz, B., Pilloud, M.A., Sadvari, J.W., Agarwal, S.C., Glencross, B., Beauchesne, P., Pearson, J., Ruff, C.B., Garofalo, E.M., Hager, L.D., and S.D. Haddow
2013 The Human Remains : Interpreting Community Structure, Health, and Diet in Neolithic Çatalhöyük. *In* Humans and Landscapes of Çatalhöyük: Reports from the 2000-2008 Seasons, Ian Hodder, ed. Los Angeles- Monographs of the Cotsen Institute of Archaeology.

Hoefs, Jochen.
2009 Isotope fractionation processes of selected elements. Stable Isotope Geochemistry. Pp. 35-92. Berlin:Springer-Verlag Berlin Heidelberg.

Homès-Fredericq, D., and J. B. Hennessy
1989 Archaeology of Jordan II: Field Reports. *In* Surveys and Sites. Akkadica Supplementum 7/8.

Horwitz, Liora Kolska and Jacqueline Studer
2005 Pig production and Exploitation during the Classical Periods in the Southern Levant. *In* Archaeozoology of the Near East VI. H. Buitenhuis, A.M. Choyke, L. Martin, L. Bartosiewicz and M. Mashkour, eds. Pp. 222-Groningen: ARC Publication 123.

Jackson, J. A.
1997 Glossary of Geology, 4th Edition. American Geological Institute. New York-Springer.

Jacquat, Christiane, and Danièle Martinoli
1999 Vitis Vinifera L: Wild or Cultivated? Study of the Grape Pips Found at Petra, Jordan; 150 B.C.-A.D. 40. Vegetation History and Archaeobotany 8(1):25-30.

Johnson, David J.
1990 Nabataean Piriform Unguentaria. Aram Periodical 2(1-2):235-248.

Josephus, Flavius
1980[1737] The Works of Josephus: Complete and Unabridged. Antiquities of the Jews. 14, 1,4. William Whiston, trans. Massachusetts: Hendrickson Publishers.

Joukowsky, Martha Sharp
2001 Nabataean Petra. Bulletin of the American Schools of Oriental Research 324 (1):1-4.

Kanellopoulos, Chrysanthos
2001 The Architecture of the Shops and Colonnaded Street in Petra. Bulletin of the American Schools of Oriental Research 324(1):9-22.

Karamanos, R. E., Voroney, R. P. and D.A. Rennie
1981 Variation in Natural N-15 Abundance of Central Saskatchewans Oils. Soils Science Society of America Journal 45(1): 826-828.

Karg, S.
1996 Pflanzenreste aus den nabatäischen und spätrömischen Schichten. In Petra ez Zantur I. Ergebnisse der Schweizerisch-Liechtensteinischen Ausgrabungen 1988-1992. Kolb B, S. Schmid, R Stucky, eds. Pp. 355-357. Copenhagen-Terra Archaeologoca 2.

Katzenberg, M. A.
1993 Applications of Elemental and Isotopic Analysis to Problems in Ontario Prehistory. In Investigations of Ancient Human Tissue: Chemical Analyses in Anthropology. M.K. Sandford, ed. Langhorne, PA: Gordon and Breach Scientific Publishers.

Katzenberg, M. Anne, Henry P. Schwarcz, Martin Knyf, and F, Jerome Melbye
1995 Stable Isotope Evidence for Maize Horticulture and Paleodiet in Southern Ontario, Canada. American Antiquity 60(2):335-350.

Katzenberg, M. A.
2006 Prehistoric Maize in Southern Ontario. *In* Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize. J.J. Staller, R. Staller, R. Tykot, eds. Amsterdam: Elsevier.

Katzenberg, M. Anne
2008 Stable Isotope Analysis: A Tool For Studying Past Diet, Demography, And Life History. *In* Biological Anthropology of the Human Skeleton. M. Anne Katzenberg and Shelley R. Saunders, eds. Pp. 413-441. Hoboken: John Wiley and Sons, Inc.

Kellner, C. M., and M.J. Schoeninger
2007 A Simple Carbon Isotope Model for Reconstructing Prehistoric Human Diet. American Journal of Physical Anthropology 133(4):1112-1127.

Killebrew, Ann E., Grantham, Billy J. and Steven Fine.
2003 A" Talmudic" House at Qasrin. Near Eastern Archaeology 66 (1-2): 59-72.

King, M.J.
2001 Analysis of diet in Byzantine Jordan: isotopic evidence in human dentine [unpublished Master's thesis]. Anthropology Department, University of Arkansas, Fayetteville, Arkansas, USA.

King, S. W., French, M., Bielefeld, J., and W.A. Lanford
2011 Fourier Transform Infrared Spectroscopy Investigation of Chemical Bonding in Low-k a-SiC: H Thin Films. Journal of Non-Crystalline Solids 357(15):2970-2983.

Knodell, A.R., and S.E. Alcock.
2011 Brown University Petra Archaeological Project: The 2010 Petra Area and Wadi Silaysil Survey. Annual of the Department of Antiquities of Jordan 55 (1):489-508.

Kouki, Paula
2009 Archaeological Evidence of Land Tenure in the Petra Region, Jordan: Nabataean-Early Roman to Late Byzantine. Journal of Mediterranean Archaeology 22(1):29-56.

Kouki, Paula
2013 The Intensification of Nabataean Agriculture in the Petra Region. *In* Men on the Rocks: The Formation of Nabataean Petra. M. Mouton and S. G Schmid, eds. Pp. 323-333. Berlin: DFG ANR.

Krueger, Harold W., and Charles H. Sullivan.
1984 Models for Carbon Isotope Fractionation between Diet and Bone. *In* Stable Isotopes in Nutrition ACS Symposium Series 258. J. Turnlund and P.E. Johnson, eds. Pp. 205-222. Washington: American Chemical Society.

Lambert, J. B., Vlasak, S., Szpunar, C. B.,and J.E. Buikstra
1985 Bone Diagenesis and Dietary Analysis. Journal of Human Evolution 14(5):477-482.

Lambert, J.B., Xue, L., J.E. Buikstra
1989 Physical Removal of Contaminative Inorganic Material from Buried Human Bone. Journal of Archaeological Science 16(1):427–436.

Larsen, Clark Spencer
1997 Bioarchaeology: Interpreting Behavior from the Human Skeleton. Cambridge-Cambridge University Press

Lavento, Mika, Paula Kouki, Sarianna Silvonen, Heini Ynnilä, and Mika Huotari
2007 Terrace Cultivation in the Jabal Hārūn Area and its Relationship to the City of Petra in Southern Jordan. Studies in the History and Archaeology of Jordan 9(1):145-156.

Lee-Thorp, Julia A., Judith C. Sealy and Nikolaas J. van der Merwe
1989 Stable Carbon Isotope Ratio Differences between Bone Collagen and Bone Apatite, and their Relationship to Diet. Journal of Archaeological Science 16(1):585-599.

Lee-Thorp, Julia A. and Nikolaas J. van der Merwe
1991 Aspects of the Chemistry of Modern and Fossil Biological Apatites. Journal of Archaeological Science 18(1):343-354.

Lee-Thorp, J., and M. Sponheimer
2003 Three Case Studies Used to Reassess the Reliability of Fossil Bone and Enamel Isotope Signals for Paleodietary Studies. Journal of Anthropological Archaeology 22(3):208-216.

Lee-Thorp, Julia A.
2008 On Isotopes and Old Bones. Archaeometry 50(6): 925-950.

Lösch, S., Moghaddam, N., Grossschmidt, K., Risser, D. U.,and F. Kanz
2014 Stable isotope and trace element studies on gladiators and contemporary Romans from Ephesus (Turkey, 2nd and 3rd Ct. AD)-Implications for differences in diet. PLOS ONE 9(10): 1-17.

Lovejoy, C. O., Meindl, R. S., Pryzbeck, T. R., and R.P. Mensforth
1985 Chronological Metamorphosis of the Auricular Surface of the Ilium: A New Method for the Determination of Adult Skeletal Age at Death. American Journal of Physical Anthropology 68(1):15-28.

Lowrey, Daniel
2014 Faunal Summary Report. Unpublished Report to Directors. Petra North Ridge Project. Megan A. Perry and S. Thomas Parker.

Macko, S.A., Lubec G., Teschler-Nicola M., Andrusevich, V., and M.H. Engel
1999a The Ice Man's Diet as Reflected by the Stable Nitrogen and Carbon Isotopic Composition of his Hair. The Federation of American Societies for Experimental Biology Journal 13(3):559-562.

Macko, S.A., Engel, M.H., Andrusevich, V., Lubec, G., O'Connell, T.C. and R.E.M. Hedges
1999b Documenting the Diet in Ancient Human Populations through Stable Isotope Analysis of Hair. Philosophical Transactions of the Royal Society B: Biological Sciences 354(1379): 65-76.

Makarewicz, C. A., and J. Sealy
2015 Dietary Reconstruction, Mobility, and the Analysis of Ancient Skeletal Tissues: Expanding the Prospects of Stable Isotope Research in Archaeology. Journal of Archaeological Science 56(1):146-158.

Manolis, S. K., Eliopoulos, C., Koilias, C. G., and S.C. Fox
2009 Sex Determination Using Metacarpal Biometric Data from the Athens Collection. Forensic Science International, 193(1), 130.e1–130.e6.

Mariotti, A., Pierre, D., Vedy, J. C., Bruckert, S., and J. Guillemot
1980 The Abundance of Natural Nitrogen 15 in the Organic Matter of Soils along an Altitudinal Gradient (Chablais, Haute Savoie, France). Catena 7(1):293-300.

Marshall, Eireann
2002 Death and disease in Cyrene. *In* Death and Disease in the Ancient City. Valerie Hope and Eireann Marshall, eds. Pp. 8-23. London: Routledge.

Maurer, A. F., Person, A., Tütken, T., Amblard-Pison, S., and L. Ségalen
2014 Bone Diagenesis in Arid Environments: An Intra-Skeletal Approach. Palaeogeography, Palaeoclimatology, Palaeoecology 416 (1):17-29.

Meier-Augenstein, Wolfram.
2011 Stable Isotope Forensics: An Introduction to the Forensic Application of Stable Isotope Analysis, Vol. 3. NJ: John Wiley & Sons.

Moorrees, Coenraad FA, Elizabeth A. Fanning, and Edward E. Hunt Jr.
1963 Age variation of formation stages for ten permanent teeth. Journal of Dental Research 42 (6): 1490-1502.

Mountrakis, C., Eliopoulos, C., Koilias, C. G., and S.K. Manolis
2010 Sex Determination Using Metatarsal Osteometrics from the Athens Collection. Forensic Science International 200(1), 178-e1- 178.e7.

Murray, Matthew L. and Margaret J. Schoeninger
1988 Diet, status, and complex social structure in Iron Age Central Europe: Some contributions of bone chemistry. *In* Tribe and polity in late prehistoric Europe. Pp. 155-176. United States: Springer.

Neef, R.
1989 Plants. *In* Picking up the Threads. A Continuing Review of Excavations at Deir Alla, Jordan. G. van de Kooij G. and M.M. Ibrahim, eds. Pp. 30-37. University of London-Archaeological Centre.

Neef, R.
1990 Introduction, Development, and Environmental Implications of Olive Culture: The Evidence from Jordan. *In* Man's Role in the Shaping of the Eastern Mediterranean Landscape. S. Bottema, G. Entjes-Nieborg, and W. van Zeist, eds. Proceedings of the INQUA/BAI Symposium on the Impact of Ancient Man on the Landscape of the Eastern Mediterranean Region and the Near East, Groningen, Netherlands, 6-9 March 1989. Pp. 295-306. Balkema, Rotterdam.

Neef, R
1998 Status and Perspectives of Archaeo-botanical Research in Jordan. *In* The Prehistory of Jordan, 2, Perspectives from 1998. H.G.K Gebel, Z. Kafafi Z, G.O. Rollefson, eds, Pp.601-609. Berlin- Stud Early Near Eastern Product Subsistence Environment 4.

Nehmé, Laïla.
2003 The Petra Survey Project. *In* Petra Rediscovered. Lost City of the Nabataeans. Glenn Markoe, ed. Pp. 145-163. Cincinnati: Harry N. Abrams, Inc.

Nesse, William D.
2011 Introduction to Mineralogy, 2nd Edition. Oxford-Oxford University Press.

Newsome, S. D., Phillips, D. L., Culleton, B. J., Guilderson, T. P., and P.L. Koch
2004 Dietary Reconstruction of an Early to Middle Holocene Human Population from the Central California Coast: Insights from Advanced Stable Isotope Mixing Models. Journal of Archaeological Science 31(8):1101-1115.

Oleson, John Peter
2007 Nabataean Water Supply, Irrigation, and Agriculture: An Overview. *In* The World of the Nabataeans. Konstantinos D. Politis, ed. Pp. 217-249. Stuttgart: Franz Steiner Verlag.

Ortner, Donald J., vonEndt, David W., and Mary S. Robinson
1972 The Effect of Temperature on Protein Decay in Bone: Its Significance in Nitrogen Dating of Archaeological Specimens. American Antiquity 37(4):514-520.

Parker, S. Thomas and Megan A. Perry
N.d. Petra North Ridge Project: The 2012 Season. In press. Annual of the Department of Antiquities of Jordan.

Parr, Peter J.
2003 The Origins and Emergence of the Nabataeans. *In* Petra Lost City of the Nabataeans. G. Markoe, ed. Pp. 26-36. Cincinnati: The Cincinnati Art Museum.

Peres, T. M.
2008 Foodways, economic status, and the antebellum Upland South in central Kentucky. Historical Archaeology 42(4): 88-104.

Perry, Megan A.
2002 Life and Death in Nabataea: The North Ridge Tombs and Nabataean Burial Practices. Near Eastern Archaeology 65(4):265-270.

Perry, Megan A., and Patricia Maynor Bikai.
2007 Petra's Churches. Crossing Jordan: North American Contributions to the Archaeology of Jordan. T. Levy, P.M. Michèle Daviau, R.W. Younker, and M. Shaer, eds. Pp. 435-443. London: Equinox.

Perry, Megan
2015 New Light on Nabataean Mortuary Rituals in Petra . Studies in the History and Archaeology of Jordan XII", in press.

Peterson, B.J. and B. Fry
1987 Stable Isotopes in Ecosystem Studies. Annual Review of Ecology Systematics 18(1):293-320.

Price, T.D., Armelagos, G.J., Buikstra, J.E., Bumsted, M. P., Chisholm, B.S., Ericson, J.E., Lambert, J.B., van der Merwe, N.J., Schoeninger, M. J., and A. Sillen
1989 The Chemistry of Prehistoric Human Bone: Recommendations and Directions for Future Study. *In* The Chemistry of Prehistoric Human Bone. T.D. Price, ed. Pp. 245-252. Cambridge-Cambridge University Press.

Price, T. D., Blitz, J., Burton, J., and J.A. Ezzo
1992 Diagenesis in Prehistoric Bone: Problems and Solutions. Journal of Archaeological Science 19(5):513-529.

Privat, K.L., O'Connel, T.C., and R.E.M. Hedges
2007 The Distinction between Freshwater and Terrestrial-Based Diet: Methodological Concerns and Archaeological Applications of Sulphur Stable Isotope Analysis. Journal of Archaeological Science 34(1):1197-1204.

Raheja, P. C.
1966 Aridity and Salinity. *In* Salinity and Aridity. Netherlands-Springer Netherlands.

Ramsay, J.H.
2013. Plant Remains. *In* Humayma Excavation Project, 2. :J.P. Oleson, ed. American Schools of Oriental Research e353-e360.

Ramsay, Jennifer, and Andrew M. Smith II
2013 Desert Agriculture at Bir Madhkur: The First Archaeobotanical Evidence to Support the Timing and Scale of Agriculture during the Late Roman/Byzantine Period in the Hinterland of Petra. Journal of Arid Environments 99(1):51-63.

Ramsay, J., and L.A. Bedal
2015 Garden Variety Seeds? Botanical Remains from the Petra Garden and Pool Complex. Vegetation History and Archaeobotany, Pp.1-14 doi 10.1007/s00334-015-0520-4

Reiche, I., Favre-Quattropani, L., Calligaro, T., Salomon, J., Bocherens, H., Charlet, L., and M. Menu
1999 Trace Element Composition of Archaeological Bones and Post-mortem Alteration in the Burial Environment. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 150(1):656-662.

Richards, M. P., and Hedges, R. E.
1999 Stable Isotope Evidence for Similarities in the Types of Marine Foods used by Late Mesolithic Humans at Sites along the Atlantic Coast of Europe. Journal of Archaeological Science 26(6):717-722.

Richards, Michael P., Simon Mays, and Benjamin T. Fuller
2002 Stable Carbon and Nitrogen Isotope Values of Bone and Teeth Reflect Weaning Age at the Medieval Wharram Percy site, Yorkshire, UK. American Journal of Physical Anthropology 119(3) (2002): 205-210.

Richardson III, J.B. and D. McCreery
1976 Preliminary Analysis of the Plant Remains from Bâb edh- Dhrâ, 1975. Annual American Schools of Oriental Research 43(1):55-56.

Robling, A. G., and D.H. Ubelaker
1997 Sex Estimation from the Metatarsals. Journal of Forensic Sciences 42(6):1062-1069.

Rudakova, T. E. and G.E. Zaikov
1987 Degradation of Collagen and its Possible Applications in Medicine. Polymer Degradation and Stability 18(4):271-291.

Russell, K.W.
1980 The Earthquake of May, 19, A.D. 363. Bulletin of the American Schools of Oriental Research 238(1):47-64.

Sage, R. F., and X.G. Zhu
2011 Exploiting the Engine of C_4 Photosynthesis. Journal of Experimental Botany 62(9):2989-3000.

Saliège, J. F., Pearson, A., and F. Paris
1995 Preservation of 13 C/12 C Original Ratio and 14 C Dating of the Mineral Fraction of Human Bones from Saharan Tombs, Niger. Journal of Archaeological Science 22(2):301-312.

Sandias, Michela
2011 The Reconstruction of Diet and Environment in Ancient Jordan by Carbon and Nitrogen Stable Isotope Analysis of Human and Animal Remains. *In* Water, Life and Civilisation: Climate, Environment and Society in the Jordan Valley. Steven Mithen and Emily Black, eds. Pp. 337-346. Cambridge: Cambridge University Press.

Schmid, Stephan G.
2008 The Hellenistic Period and the Nabataeans. *In* Jordan an Archaeological Reader. Russell B. Adams, ed. Pp. 353-411. London: Equinox.

Schmid, S.G.
2012 Foucault and the Nabataeans – or What Space has to Do With It. *In* Men on the Rocks: The Formation of Nabataean Petra. M. Mouton and S.G. Schmid, eds. Pp. 251-270. Berlin: DFG ANR.

Schoeninger, Margaret J., and Michael J. DeNiro
1984 Nitrogen and Carbon Isotopic Composition of Bone Collagen from Marine and Terrestrial animals. Geochimica et Cosmochimica Acta 48(1):625-639.

Schoeninger, M. J.
1989 Reconstructing Prehistoric Human Diet. *In* The Chemistry of Prehistoric Human Bone. T. D. Price, ed. Pp. 38-67.Cambridge-Cambridge University Press.

Sealy, J.
2001 Body Tissue Chemistry and Paleodiet. *In* Handbook of Archaeological Sciences. D.R. Brothwell, and A.M. Pollard, eds. Pp. 269-279. New Jersey: John Wiley & Sons Inc.

Siculus, Diodorus
1935 Library of History: Loeb Classical Library. C.H. Oldfather, trans. Cambridge: Harvard University Press.

Slovak, NM, A. Paytan A, B.A. Wiegand
2009 Reconstructing Middle Horizon Mobility Patterns on the Coast of Peru through Strontium Isotope Analysis. Journal of Archaeological Science 36:157–165.

Spradley, M. K., and R.L. Jantz
2011 Sex Estimation in Forensic Anthropology: Skull Versus Postcranial Elements. Journal of Forensic Sciences 56(2):289-296.

Stager, L. E.
1992 The periodization of Palestine from Neolithic through Early Bronze times. Chronologies in Old World Archaeology 1: 22-41.

Staller, John E.
2003 An Examination of the Palaeobotanical and Chronological Evidence for an Early Introduction of Maize (Zea mays L.) into South America: A Response to Pearsall. Journal of Archaeological Science 30(3):373-380.

Stojanowski, Christopher M.
1999 Sexing Potential of Fragmentary and Pathological Metacarpals. American Journal of Physical Anthropology 109(2): 245-252.

Stow, D.A.V.
2005 Sedimentary Rocks in the Field: A Color Guide. Massachusetts-Academic Press.

Strabo
1924 The Geography of Strabo. H.L. Jones, trans. Cambridge: Harvard University Press.

Strange, J.
1997 Tall al-Fukhar 1990-1991: A preliminary report. Studies in the History and Archaeology of Jordan 6: 399-406.

Stucky, R.A., Kolb, B., Schmid, S.G., Gerber, Y., Bellwald, U., and C. Jacquat
1995 Swiss- Liechtenstein Excavations at az-Zantur in Petra 1994. The Sixth Campaign. Annual Department Antiquities Jordan 39(1):297-315.

Studer, Jacqueline
2002 Dietary Differences at Ez Zantur Petra, Jordan (1st century BC – AD 5th century). *In* Archaeozoology of the Near East V. H. Buitenhuis, A.M. Choyke, M. Mashkour and A.H. Al-Shiyab, eds. Pp. 273-281. Groningen: ARC: Publication 62.

Studer, J.
2007 Animal Exploitation in the Nabataean world. *In* The World of the Nabataeans. Konstantinos D. Politis, ed. Pp. 251-272. Stuttgart: Franz Steiner Verlag.

Styring, Amy K., Judith C. Sealy, and Richard P. Evershed
2010 Resolving the Bulk $\delta^{15}N$ Values of Ancient Human and Animal Bone Collagen Via Compound-specific Nitrogen Isotope Analysis of Constituent Amino Acids. Geochimica et Cosmochimica Acta 74(1):241–251.

Sullivan and Krueger
1981 Carbon Isotope Analysis of Separate Chemical Phases in Modern and Fossil Bone. Nature 292(1):333-335.

Tauber, H.
1981 ^{13}C evidence for dietary habits of prehistoric man in Denmark. Nature 292(1): 332-333.

Tauber, H.
1986 Analysis of stable isotopes in prehistoric populations. In Innovative trends in prehistoric archaeology. B. Hermann, ed. Pp. 31-38. Berlin: Mitteilungen der Berliner Gesellschaft für Anthropologie, Ethnologie und Urgeschichte.

Teece, Mark A. and Marilyn L. Fogel
2004 Preparation of Ecological and Biochemical Samples for Isotope Analysis. Handbook of Stable Isotope Analytical Techniques. Vol. 1. De Groot, Pier A., ed. Amsterdam: Elsevier.

Temple, Daniel H.
2007 Dietary variation and stress among prehistoric Jomon foragers from Japan. American Journal of Physical Anthropology 133(4): 1035-1046.

The Weather Channel LLC
N.d. Weather Underground History. http://www.wunderground.com/history/, accessed May 1, 2015.

Tholbecq, L.,and F. al-Khraysheh
2001 The Hinterland of Petra from the Edomite to the Islamic Period: The Jabal ash-Shara Survey (1996-1997). Studies in the History and Archaeology of Jordan, vol. 7. Pp. 399-405.

Tholbecq, L., C. Durand, and C. Bouchaud
2008 A Nabataean Rock-Sanctuary in Petra. Annual Department of Antiquities Jordan 52(1):248-252.

Tholbecq, Laurent
2013 The Hinterland of Petra (Jordan) and the Jabal Shara During the Nabataean, Roman and Byzantine periods. *In* Men on the Rocks: the Formation of Nabataean Petra. M. Mouton and S. G Schmid, eds. Pp. 295-311. Berlin: DFG ANR.

Todd, T. W.
1920 Age Changes in the Pubic Bone. I. The Male White Pubis. American Journal of Physical Anthropology 3(3):285-334.

Todd, T. W.
1921 Age Changes in the Pubic Bone. American Journal of Physical Anthropology 4(1):1-70.

Touzeau, Alexandra, Blichert-Toft, Janne , Amiot, Romain , Fourel, François, Martineau, François, Cockitt, Jenefer, Hall, Keith , Flandrois, Jean-Pierre and Christophe Lécuyer
2013 Egyptian Mummies Record Increasing Aridity in the Nile Valley from 5500 to 1500yr before Present. Earth and Planetary Science Letters 375(1):92-100.

Touzeau, Alexandra, Amiot, Romain, Blichert-Toft, Janne , Flandrois, Jean-Pierre, Fourel, François, Grossi, Vincent, Martineau, François, Richardin, Pascale and Christophe Lécuyer
2014 Diet of Ancient Egyptians Inferred from Stable Isotope Systematics. Journal of Archaeological Science 46(1):114-124.

Tykot, R. H., Falabella, F., Planella, M. T., Aspillaga, E., Sanhueza, L., and C. Becker
2009 Stable Isotopes and Archaeology in Central Chile: Methodological Insights and Interpretative Problems for Dietary Reconstruction. International Journal of Osteoarchaeology 19(2):156-170.

Ubelaker, D. H.
1989 Human Skeletal Remains: Excavation, Analysis, Interpretation. Washington, DC: Taraxacum.

Van der Merwe, Nikolaas J., and John C. Vogel
1978 ^{13}C Content of Human Collagen as a Measure of Prehistoric Diet in Woodland North America. Nature 276(1): 815-816.

Van der Merwe, Nikolaas J.
1982 Carbon Isotopes, Photosynthesis and Archaeology. American Scientist 70(1): 596-606.

Van der Veen, Marijke, Annie Grant, and Graeme Barker
1996 Romano-Libyan Agriculture: Crops and Animals. *In* Farming the Desert: the UNESCO Libyan Valleys Archaeological Survey Vol. 1. Graeme Barker, David Gilbertson, Barri Jones

and David Mattingly, eds. Pp. 227-263. Tripoli: UNESCO, the Department of Antiquities, Tripoli, and the Society for Libyan Studies.

Vogel, J. C., and Van der Merwe, N. J.
1977 Isotopic Evidence for Early Maize Cultivation in New York State. American Antiquity 42(2): 238-242.

Vogel. J. C.
1978 Isotopic Assessment of the Dietary Habits of Ungulates. South African Journal of Science 74(1):298-30.

von Gaertringen, Hiller
1906 Inschriften von Priene 84–91, 108, 168. Berlin:Georg Reimer.

Wadeson, Lucy
2010 The Chronology of the Façade Tombs at Petra: A Structural and Metrical Analysis. Levant 42(1):48-69.

Wadeson, Lucy
2012a Excavations at Petra: The International Al-Khubtha Tombs Project (IKTP). Palestine Exploration Quarterly 144(3):208-218.

Wadeson, Lucy
2012b The Funerary Landscape of Petra: Results from a New Study. Supplements to Proceedings of the Seminar for Arabian Studies 42(1):99-126.

Wenning, Robert
2007 The Nabataeans in History. *In* The World of the Nabataeans. Konstantinos D. Politis, ed. Pp. 25-44. Stuttgart: Franz Steiner Verlag.

Wenning, Robert
2013 Towards "Early Petra": An Overview of the Early History of the Nabataeans in its Context. *In* Men on the Rocks: the formation of Nabataean Petra. M. Mouton and S. G Schmid, eds. Pp. 7-22. Berlin: DFG ANR.

White, C.D.
1997 Diet at Lamanai and Pacbitun: Implications for the Ecological Model of Maya Collapse. *In* Bones of the Maya: Studies of Ancient Skeletons. S.L. Whittington and D. Reed, eds. Pp. 171-181. D.C.: Smithsonian Institution Press.

White, C. D., and G.J. Armelagos
1997 Osteopenia and stable isotope ratios in bone collagen of Nubian female mummies. American Journal of Physical Anthropology 103(2):185-199.

White, C. D., Longstaffe, F. J., and K.R. Law
1999 Seasonal stability and variation in diet as reflected in human mummy tissues from the Kharga Oasis and the Nile Valley. Palaeogeography, Palaeoclimatology, Palaeoecology 147(3): 209-222.

White, C. D.
2005 Gendered Food Behaviour among the Maya Time, Place, Status and Ritual. Journal of Social Archaeology 5(3):356-382.

Wolfe, Jack A.
1978 A Paleobotanical Interpretation of Tertiary Climates in the Northern Hemisphere: Data from Fossil Plants Make it Possible to Reconstruct Tertiary Climatic Changes, Which May be Correlated with Changes in the Inclination of the Earth's Rotational Axis. American Scientist 66(6):694-703.

Wright, L.E., and H.P. Schwarcz
1996 Infrared and Isotopic Evidence for Diagenesis of Bone Apatite at Dos Pilas, Guatemala: Palaeodietary Implications. Journal of Archaeological Science 23(6):933-944.

Wright, L. E., and C.D. White, C. D.
1996 Human Biology in the Classic Maya Collapse: Evidence from Paleopathology and Paleodiet. Journal of World Prehistory 10(2):147-198.

Wright, L.E.
2006 Diet, Health, and Status among the Pasión Maya: A Reappraisal of the Collapse. Nashville: Vanderbilt University Press vol 2.

Zayadine, Fawzi
2007 The Spice Trade from South Arabia and India to Nabataea and Palestine. *In* The World of the Nabataeans. Konstantinos D. Politis, ed. Pp. 201-215. Stuttgart: Franz Steiner Verlag.

Zohary, Daniel, and Maria Hopf
1973 Domestication of Pulses in the Old World Legumes were Companions of Wheat and Barley when Agriculture Began in the Near East. Science 182(4115):887-894.

Appendix A: Age and sex estimation methods

Context	Disposition	Element sampled	Age	Observer	Sex	Observer
B.5:31	Articulated	Unsided long bone fragment	Tooth development[i]	KAP, CC	Skull features[ii]	AGP, LA
B.5:17	Commingled	R. humerus	Tooth development[i]	MAP	Skull features[ii]	MAP
B.5:9 individual 1	Articulated	R. ribs	Tooth development[i]	AGP, KAP, CW	-RMC4[iii] -Radius transverse diameter MS[iv] -Radius transverse diameter MS[iv] -Skull features[ii]	LA LA LA AGP
B.5:12	Articulated	Unsided rib fragments	Epiphyseal fusion[ii]	AGP, LA, CW, KAP	-Humerus minimum midshaft diameter[iv] -Femur circumference midshaft[iv]	LA LA
B.4:18 Adult	Commingled	L MT3	Epiphyseal fusion[ii]	MAP	--	--
B.4:17	Commingled	R MT4	Epiphyseal fusion[ii]	CC, MAP, KAP, CW, AGP	RMC5[iii]	LA
B.4:22	Articulated	R MC3	Epiphyseal fusion[ii]	MAP, CC, AGP CW	-RMC3[iii,v] -RMC1[iii]	LA LA
B.4:23 individual 1	Commingled	L MT3	Epiphyseal fusion[ii]	CC	LMC5[iii, iv]	LA
B.4:23 individual 2	Commingled	L MT3	-Epiphyseal fusion[ii] -Tooth Development[i]	MAP, CC MAP, CC	-LMT3[vi,vii] -LMT4[vi,vii]	LA LA
B.4:23 individual 3	Commingled	R MC5	Epiphyseal fusion[ii]	MAP, CC	-RMC1[iii] -Radius sagittal diameter MS[iv]	LA LA
B.4:18 Subadult	Commingled	R. tibia	Epiphyseal fusion[ii]	MAP	--	--
B.4:10 #1	Commingled	R. humerus	Epiphyseal fusion[ii]	MAP	--	--
B:4:10 #2	Commingled	R. humerus	Epiphyseal fusion[ii]	MAP	-Epicondylar breadth[iv] -Minimum midshaft[iv]	LA LA

B:4:10 #3	Commingled	R. humerus	Epiphyseal fusion[ii]	MAP	--	--
B.5:15 skull 1	Articulated	Unsided cranial fragment	Skull suture closure[ii]	MAP	Skull features[ii]	MAP
B.5:15 skull 2	Articulated	Unsided parietal fragment	Tooth development[i]	MAP	Skull features[ii]	MAP
B.5:15 skull 4	Commingled	Unsided parietal fragment	Tooth development[i]	KAP	Skull features[ii]	KAP
B.5:15 skull 5	Articulated	Unsided skull fragment	Skull suture closure[ii]	AGP, KAP	Skull features[ii]	KP, AGP
B.5:15 skull 6	Articulated	Unsided skull fragment	Skull suture closure[ii]	MAP	Skull features[ii]	MAP
B.5:15 skull 7	Articulated	Unsided skull fragment	Skull suture closure[ii]	AGP, KAP	Skull features[ii]	AGP, KAP
B.5:15 skull 9	Articulated	Unsided parietal fragment	Skull suture closure[ii]	AGP, KAP	--	--
B.5:15 skull 10	Articulated	Unsided skull fragment	Tooth development[i]	AGP, KAP	Skull features[ii]	AGP, KAP
B.5:9 skull 11	Articulated	Unsided parietal fragment	Skull suture closure[ii]	MAP	Skull features[ii]	MAP
B.5:15 skeleton 1	Articulated	Unsided rib fragments	Pubic Symphysis[viii]	AGP	-LMC2[iii] -Radius sagittal diameter MS[iv]	LA
Tomb 2 burial 1	Articulated	Unsided femur fragment	Auricular surface[x]	MAP	Pelvic morphology[ii]	MAP
Tomb 2 burial 2	Articulated	Unsided long bone fragment	-Pubic symphysis[viii, ix] -Auricular surface[x]	MAP MAP	-Pelvic morphology[ii] -Skull features[ii]	MAP MAP
Tomb 2 burial 4	Articulated	Unsided femur fragment	- Pubic symphysis[ix] -Auricular surface[x]	MAP MAP	-Pelvic morphology[ii] -Skull features[ii]	MAP MAP
Tomb 2 burial 5	Articulated	Unsided femur fragment	Auricular surface[x]	MAP	Pelvic morphology[ii]	MAP
Tomb 2 burial 6	Articulated	Unsided femur fragment	-Pubic symphysis[viii, ix] -Auricular surface[x]	MAP MAP	-Pelvic morphology[ii] -Skull features[ii]	MAP MAP
Tomb 2 burial 8	Articulated	Unsided femur fragment	Epiphyseal fusion[ii]	MAP	Skull features[ii]	MAP

B.5:15 commingled subadult	Commingled	L. femur	Epiphyseal fusion[ii]	AGP, KAP, CC	--	--
B.4:13 subadult	Articulated	R. Ilium	Epiphyseal fusion[ii]	MAP, KR, KD	--	--
B.4:23 subadult	Commingled	L. clavicle	Fusion vertebras & clavicle[ii]	MAP, CC	--	--
B.4:17/22 subadult	Commingled	Cervical 1-7	Fusion of body & neural arch[ii]	CC	--	--

[i] Ubelaker 1989
[ii] Buikstra & Ubelaker 1994
[iii] Stojanowski 1999
[iv] Spradley & Jantz 2011
[v] Manolis et al. 2009
[vi] Mountrakis et al. 2010
[vii] Robling & Ubelaker 1997
[viii] Todd 1920, 1921
[ix] Brooks & Suchey (1990)
[x] Lovejoy et al. 1985

Appendix B: Neolithic through Byzantine paleobotanicals in Jordan (Excluding Petra)

Plant type	Plant	Source
Cereal	*Hordeum vulgare L.* (barley)	Crawford 2006; Flanagan & McCreery 1990; Helback 1974; Neef 1989; Richardson & Mccreery 1976
Cereal	*Linum usitatissimum L*. (flax)	Flanagan & McCreery 1990; Neef 1989
Cereal	*Panicum miliaceum L.* (millet)	Neef 1989
Cereal	*Triticum aestivum L*. (include T. compactum host) (wheat)	Crawford 2006; Flanagan & McCreery 1990; Helback 1974; Neef 1989; Richardson & McCreery 1976
Cereal	*Triticum dicoccum schrank* (emmer)	Flanagan & Mccreery 1990; Helback 1974; Neef 1989; Richardson & McCreery 1976
Cereal	*Triticum durum desf* (durum wheat)	Neef 1989
Herbs	*Coriandrum sativum L*. (coriander)	Neef 1989
Herb	*Cuminum cyminum L.* (cumin)	Neef 1989
Herb	*Lepidium sativum L*. (garden cress)	Neef 1989
Herb	*Nigella sativa L.* (fennel flower)	Neef 1989
Herb	*Ocimum basilicum L.* (basil)	Neef 1989
Herb	*Trigonella foenum-graecum L*. (Fenugreek)	Neef 1989
Fruit	*Ficus carica L.* (common fig)	Crawford 2006; Neef 1989
Fruit	Ficus syocomorous L.	Neef 1989
Fruit	*Olea europaea L.* (olive)	Crawford 2006; Flanagan & McCreery1990; Neef 1989, 1990; Richardson & McCreery 1976
Fruit	*Phoenix dactylifera L.* (date palm)	Crawford 2006; Engel 1993; Neef 1989; Richardson & McCreery 1976
Fruit	*Prunus persica* (peach)	Crawford 2006
Fruit	*Punica granatum L*. (pomegranate)	Neef 1989
Fruit	*Vitis vinifera* (grape)	Crawford 2006; Flanagan & McCreery 1990; Neef 1989; Richardson & McCreery 1976
Nut	*Amygdalus communis L*. (almond)	Neef 1998
Nut	*Pistacia sp*. (cashew)	Neef 1998
Legume	*Cicer arietinum L.* (chickpea)	Neef 1989
Legume	*Lathyrus sativus L*. (grass pea)	Neef 1989
Legume	*Lens culnarius medik* (lentil)	Crawford 2006; Flanagan & McCreery 1990; Neef 1989
Legume	*Vicia ervilia L.*(bitter vetch)	Flanagan & McCreery 1990; Neef 1989
Legume	*Vicia faba L.* (broad bean)	Flanagan & McCreery 1990; Neef 1989
Legume	*Vicia sativa L*. (common vetch)	Crawford 2006; Neef 1989
Vegetable	*Pisum sativum L.* (pea)	Crawford 2006; Flanagan & McCreery 1990; Neef 1989

Appendix C: Data for statistical comparison of northern Jordan sites

Site	δ13C collagen	δ15N collagen	Average δ13C collagen	Standard Deviation δ13C collagen	Average δ15N collagen	Standard Deviation δ15N collagen	Species	Time period
Site 1 Petra								
	-23.1	10.4					Human	Nab
	-23.4	10.2					Human	Nab
	-23.3	10.2					Human	Nab
	-22.9	10.1					Human	Nab
	-23.5	6.5					Human	Nab
	-23.6	8.8					Human	Nab
	-22.6	11.3					Human	Nab
	-24.2	8.1	-23.3	0.5	9.5	1.6	Human	Nab
	-23.4	8.7					Sus	Nab
	-23.5	9.0					Chicken	Nab
	-23.5	7.5	-23.5	0.1	8.4	0.8	Ovis/Capra	Nab
Site 2 Tell al-Husn								
	-18.8	8.5					Human	EB
	-18.9	8.9					Human	EB
	-18.3	8.1					Human	EB
	-18.5	8.4					Human	EB
	-18.0	10.4					Human	EB
	-17.8	8.4					Human	EB
	-18.0	9.3					Human	EB
	-18.5	9.1	-18.4	0.4	8.9	0.7	Human	EB
	-19.0	7.2					Ovis/Capra	EB
	-18.7	9.0					Horse	EB
	-19.6	6.3					Ovis/Capra	EB
	-19.2	5.9					Ovis/Capra	EB
	-17.3	10.8					Ovis/Capra	EB
	-17.6	10.2					Ovis/Capra	EB
	-17.6	8.4					Ovis/Capra	EB
	-19.4	7.5	-18.6	0.9	8.2	1.8	Ovis/Capra	EB
Site 3 Pella								
	-19.4	9.5					Human	MB/LB
	-19.3	9.6					Human	MB/LB
	-19.7	7.1					Human	III-IV A.D.
	-19.3	8.8					Human	III-IV A.D.
	-18.9	9.0					Human	III-IV A.D.
	-19.4	8.5					Human	III-IV A.D.
	-19.2	9.4					Human	III-IV A.D.
	-19.3	8.7					Human	III-IV A.D.

	-19.5	9.7					Human	III-IV A.D.
	-19.1	9.3					Human	III-IV A.D.
	-19.4	10.0	-19.3	0.2	9.1	0.8	Human	III-IV A.D.
	-19.4	6.8					Sus	EB
	-19.0	7.3					Ovis/Capra	LMB
	-20.4	5.7					Ovis/Capra	LMB
	-18.4	8.2					Ovis/Capra	LMB
	-19.1	7.1					Ovis/Capra	LMB
	-15.3	10.7					Ovis/Capra	LMB
	-19.2	9.5					Canis	LMB
	-19.8	6.3					Bos	LMB
	-19.3	6.8					Ovis/Capra	Hell
	-18.7	8.2					Bos	LR
	-18.0	7.3					Bos	LR/Byz
	-19.6	3.5					Ovis/Capra	LR/Byz
	-20.3	5.2					Ovis/Capra	LR/Byz
	-18.3	6.2					Ovis/Capra	LR/Byz
	-20.0	7.0					Sus	LR/Byz
	-20.1	7.1					Sus	LR/Byz
	-20.6	8.8					Su	LR/Byz
	-20.3	7.8	-19.2	1.2	7.2	1.6	Sus	LR/Byz
Site 4 Natfieh								
	-19.6	9.0					Human	ER
	-19.7	8.6					Human	ER
	-18.7	8.7					Human	ER
	-19.3	9.0					Human	ER
	-19.3	8.8					Human	ER
	-19.1	8.8					Human	ER
	-19.2	8.5	-19.3	0.3	8.8	0.2	Human	ER

EB: Early Bronze
LMB:Late Middle Bronze Age
MB/LB: Middle Bronze/Late Bronze Age
Hell: Hellenistic
ER: Early Roman
Nab: Nabataean
III-IV A.D.: Third through 4th centuries A.D.
LR/Byz: Late Roman/Byzantine