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A Stable Isotope Reconstruction of Byzantine and Frankish Greek Diet in the Valley of Stymphalos

by

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Abstract

The historical sources from the Byzantine and Frankish periods provide extensive information on elite Greek diet. However, little is known about the diet of the rural Greek populations and there are a number of outstanding questions. These include the importance of millet, marine and freshwater resources and at what age weaning occurred. This research sheds light on these questions through $\delta^{13}C$ and $\delta^{15}N$ analysis of archaeological human remains.

Collagen stable isotope analyses are performed on human bone from the Early Byzantine site of Stymphalos and the Frankish site of Zaraka, located in the Peloponnese. The results do not support extensive millet, marine or freshwater resource use by either population. The diet likely included substantial amounts of grains such as wheat and animal protein, possibly in the form of dairy products and eggs. The weaning age for both populations appears to have been around 2 to 3 years of age.

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Chapter 1: Introduction

This thesis examines questions of resource use during the Early Byzantine and Frankish periods in the valley of Stymphalos using stable isotope analysis of human bone. In recent years, research into these eras has shown increasing interest in examining aspects of daily life such as diet (e.g. Bourbou and Richards, 2007; Garvie-Lok, 2001; Oikonomides, 1997; Rautman, 2006) and the research presented here on the sites of Stymphalos and Zaraka is conducted in a similar vein.

The information available on diet in Byzantine and Frankish Greece is substantial due to the numerous surviving historical texts. In general, these describe a diet largely based on Braudel's (1992) Mediterranean trinity of grain, wine and olive oil, supplemented with a large variety of other foods. While historical sources give great detail on the types of dietary items that were available, they are often weak in documenting how important those items were to the general diet and thus they are not able to answer a number of questions related to resource use during these periods.

The first question relates to what type of grain was typically consumed. Documentary evidence shows that grain was considered the main staple in everyday Greek diet and that wheat and barley were the primary grains. However, numerous historical sources mention that millet was used as a supplementary grain for animal fodder and sometimes by humans during times of famine. Further complication arises about millet's use in the general diet as some sources indicate millet played a large dietary role in some regions. Thus the historical sources tell us what was the preferred

grain for human and animal consumption but they do little to help us understand how pervasive the use of millet actually was in Byzantine and Frankish Greece.

The second uncertainty regarding diet at Stymphalos and Zaraka is the importance of marine and freshwater resources. The information from historical sources is mixed. Many sources document marine resources as a luxury item and freshwater fish being used occasionally by the peasant class; however, other sources suggest that fish and other marine and freshwater resources were important staples in Byzantine and Frankish diets, particularly during fasts. Thus, there is debate over the roles marine and freshwater resources played in the diet of the general Greek population such as those found at Stymphalos and Zaraka during the Byzantine and Frankish periods.

A final outstanding question remaining after the consultation of the historical sources is what infant feeding and weaning practices the Greek population was following. Medical texts from the Byzantine and Frankish periods indicate that physicians prescribed prolonged breastfeeding as the correct course of action, with weaning suggested around the ages of 2 to 3 years. These sources illuminate what the medical community thought but do not say whether these recommendations were the actual practice followed by the general population or if they were ignored altogether.

This thesis addresses these uncertainties in one particular area, the valley of Stymphalos, through the stable isotope analysis of human remains from two burial groups, one dating to the Byzantine period and the other to the Frankish era. Due to the patterning of carbon and nitrogen isotopes in the biosphere, the key resources and practices discussed in the questions above (grains, marine and freshwater resources, and breastfeeding) can be assessed through the stable isotope analysis of archaeological

human bone. This type of analysis allows for the relative importance of dietary resources to be assessed, something not often possible using only the historical literature. Thus an approach using both stable isotope analysis and historical sources can provide a greater understanding of past diets. This type of study has been conducted on a number of historical populations in recent years (e.g. Bourbou and Richards, 2007; Dupras et al. 2001; Garvie-Lok, 2001; Iacumin et al. 1996; Keenleyside et al. 2006) and this growing literature has shown the potential of stable isotope analysis in combination with historical sources for improving our understanding of diet and resource use in historical populations.

This study analyzes archaeological human bone collagen $\delta^{13}C$ and $\delta^{15}N$ from two sites in the valley of Stymphalos. The burials at the first site, Stymphalos, date to the Early Byzantine period (5^{th} to 6^{th} Centuries A.D.), and those at the site of Zaraka date roughly to the 14^{th} century. To place the human $\delta^{13}C$ and $\delta^{15}N$ values in context, $\delta^{13}C$ and $\delta^{15}N$ values for archaeological faunal remains are combined with literature values to create a reconstruction of $\delta^{13}C$ and $\delta^{15}N$ in food items from the Byzantine and Frankish periods to which the human bone values may be compared.

This thesis is organized as follows:

Chapter 2 will present a historical context for the study. It begins with a brief review of Greek history during the time periods of interest and then passes to a discussion of the available sources of information for Greek Byzantine and Frankish diets as well as some of their limitations. The available evidence for the use of various foodstuffs during these periods is then presented along with a description of infant feeding practices and any gender and temporal variability. The chapter concludes with a summary of Byzantine

and Frankish diet as it is currently understood along with the dietary questions that were posed for this thesis.

Chapter 3 provides the technical and theoretical background needed for this work. The majority of the chapter is devoted to a review of the general behaviour of stable isotopes of carbon and nitrogen in biological systems. The specific problems involved in tracing stable isotopes from human diet to human bone are then discussed. Finally, a brief history of stable isotope analysis in archaeological dietary reconstruction is provided.

Chapter 4 presents the sites, samples and sample quality indicators used to examine diet in the valley of Stymphalos. The sampling rationale is discussed, and the sites are outlined in terms of location, available natural resources, excavation history, and historical context along with a description of the sampling procedure. A discussion of the process of bone diagenesis follows, and finally a description of the sample processing methods and sample quality indicators chosen for this thesis is presented.

Chapter 5 discusses the samples and their quality indicators in order to assess diagenetic alteration. The values obtained for the preservation indicators are presented and their implications discussed. The chapter concludes with the presentation of the final data sets whose $\delta^{13}C$ and $\delta^{15}N$ values can be interpreted in terms of original tissue values.

Chapter 6 discusses food stable isotope values. The $\delta^{13}C$ and $\delta^{15}N$ values of the foods that historical sources documented as major dietary items during the Byzantine and Frankish periods are reconstructed. Then, the questions posed at the end of Chapter 2 are reexamined in the light of these values.

Chapter 7 presents the human $\delta^{13}C$ and $\delta^{15}N$ values obtained for Stymphalos and Zaraka. The discussion first examines the results in a general context and then presents

the sites individually. Variation within and between the sites is examined. The dietary implications of the human values follow and the sites presented in this study are compared with other agricultural groups within the Mediterranean region. This is followed by a discussion of the likely diets of the general populations of Stymphalos and Zaraka and the dietary implications of between- and within-site variability. Internal patterning is examined with the major emphasis being on $\delta^{13}C$ and $\delta^{15}N$ values and nursing in infants. The values obtained for this study are then compared to literature values for Greek communities from the Byzantine and Frankish periods as well as earlier eras. The chapter concludes with a discussion of the questions posed in Chapter 2, and the answers offered by stable isotope analysis.

Chapter 8 summarizes the important findings of this thesis and points to possible directions for continuing research.

Chapter 2: Diet in Early Byzantine and Frankish Greece

This chapter will outline the historical and archaeological background that is needed to reconstruct diet in the valley of Stymphalos in the Early Byzantine and Frankish periods. An understanding of this historical background is important for understanding past diets. Stable isotope analysis is only useful in dietary reconstruction if it can realistically examine past Greek diets. Thus, a thorough understanding of these diets through historical sources is needed in order for the stable isotope results to be placed in context. This chapter begins with a brief examination of the study periods for this thesis in order to familiarize the reader and examine some of the cultural, ethnic and religious issues that could have affected historical diets. Next is a discussion of the reconstruction of the diet through historical and archaeological sources along with the benefits and disadvantages of each. A description of the climate and topography of the Peloponnese and a synopsis of the evidence available for the use of foodstuffs will follow. After this review, the evidence for dietary variation by class and gender will follow, as well as a brief description of the weaning practices followed during the Byzantine and Frankish periods. The chapter concludes with a summary in which the use of stable isotope analysis to answer outstanding questions is assessed.

2.1. Historical Background

This brief review examines a relatively large time span beginning with unrest in the Roman Empire in the 2nd and 3rd centuries A.D. and continuing to the fall of Constantinople to the Ottoman Empire in 1453. In particular it focuses on the beginning

of the Byzantine Empire and the start of the Frankish states in the Aegean. The geographic focus is on the region within the political borders of modern Greece, due to the fact that the chosen study site falls in this region.

By the 3rd century A.D. the Roman Empire was in a state of turmoil. Civil strife and barbarian attacks eating away at the border had caused economic, political and religious instability throughout the Empire (Grant, 1998; Thorndike, 1956). Both documentary sources (Grant, 1998; Ostrogorsky, 1969; Thorndike, 1956) and data from the archaeological record (Bintliff, 1996; Garnsey, 1999; Gregory, 1982) have shown that in many areas a steep decline in rural and urban populations was occurring, suggesting increasing depopulation and instability. The division of the Empire by Diocletian in the late 3rd century attempted to stabilize an already bad situation but the Western half was so weakened that it finally collapsed in 476 (Grant, 1998). The Eastern Empire survived the instability of this era. The Byzantine Empire (what the Eastern Roman Empire will now be called) saw its start with the renaming and refortification of the city of Byzantium (renamed Constantinople) by Constantine in the 4th century. The survival of the Empire owes much to the strength of its early leaders, better fortifications, and the restructuring of social and economic structures (Ostrogorsky, 1969). The Byzantine way of life was key to this reorganization. The integration of Hellenistic culture and the Christian religion into the Roman political framework allowed the Byzantines both to connect themselves to the greatness of the Greek and Roman civilizations and to be seen as vital contributors to the new European political and economic sphere (Ostrogorsky, 1969).

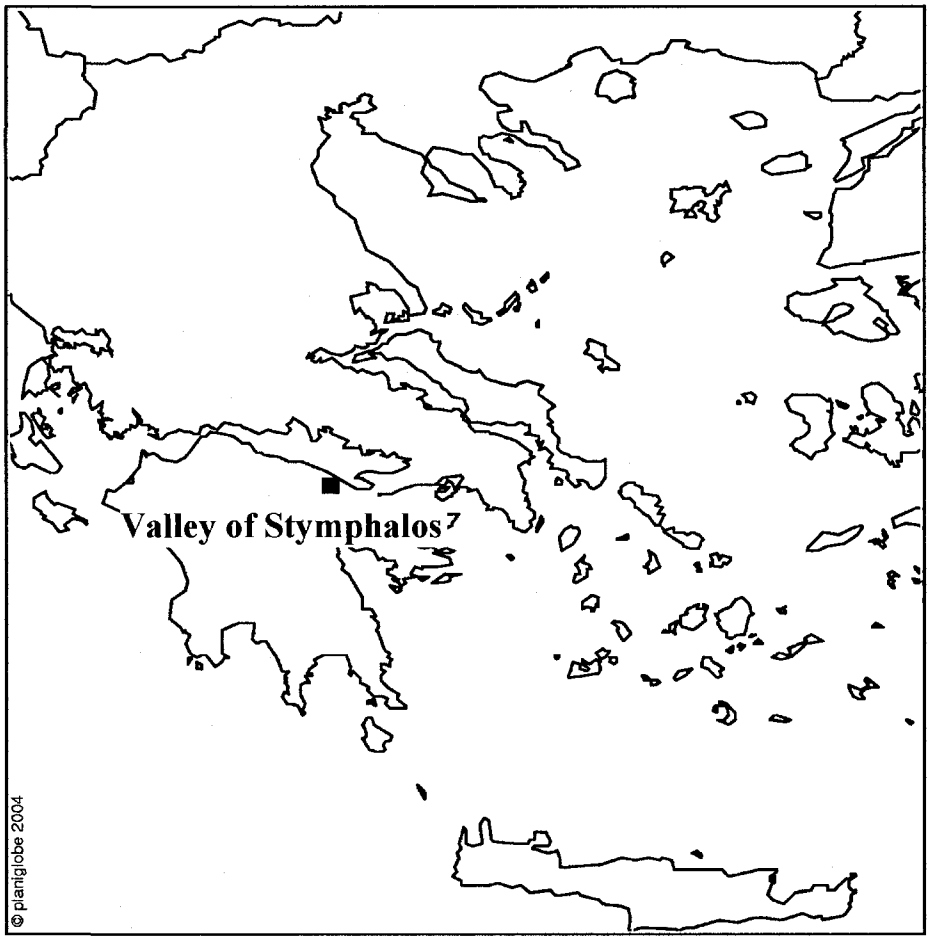
The Early Byzantine Period during the 5th and 6th centuries was relatively prosperous. In many areas within the Empire, including Greece, the Near East, and

Constantinople, there was an increase in population density and in trade (Bintliff, 1996; Foss, 1995; Thorndike, 1956). The stability and relative safety of the Empire drew large numbers of people (many fleeing Rome) into Constantinople and many of the other larger cities causing them to expand rapidly. In the rural areas, peasants forced to flee or find protection under a wealthy landlord from high taxes and barbarian invasions returned to the land in droves (Thorndike, 1956). Although the Empire was flourishing for the most part, continuing internal struggles for power and civil uprisings weakened the state substantially.

By the 6th century much of the early wealth and power held by the state was absorbed by various construction projects, tribute payments to various barbarian groups and expensive unsuccessful military campaigns. The Slavs, taking advantage of the weakness of the Empire, made repeated incursions into Greece causing considerable disruption to rural and urban life in the area (Bintliff, 1996; Gregory, 1982; Ostrogorsky, 1969; Thorndike, 1956). Some communities near the valley of Stymphalos (See Map 2.1) such as Nemea saw almost complete abandonment in the late 6th century suggesting the area was severely affected by the Slav invasions (Miller et al. 2001).

The Byzantine Empire continued to lose strength until the 8th century when it experienced a renaissance of sorts. The period saw resurgence in population density throughout the Empire attesting to the greater stability and power of the state (Bintliff, 1996; Foss, 1995). The archaeological record and documentary sources reveal an explosion in craft and trade activity largely due to the demand for Byzantine goods outside the Empire (Angold, 1997; Kazhdan and Epstein, 1985; Oikonomides, 1997; Ostrogorsky, 1969; Thorndike, 1956). The increased economic activity of the state

Figure 2.1: Valley of Stymphalos, Greece



Adapted from Paniglobe 2004

necessitated greater contact with the outside world, particularly with Western Europeans (known as Franks), and led to ethnic diversification of the population (Bass and van Doorninck, 1978; Kazhdan and Epstein, 1985). However, even with the increased outside contact, the Byzantines remained united by their Orthodox faith and Hellenic culture with the result that the introduction of foreign groups and cultures had little effect (Oikonomides, 1997; Ostrogorsky, 1969).

This prosperity and power only lasted two centuries. By the 11th century the Byzantine Empire was again in crisis. The central power of the state had weakened to the extent that many of its functions—fiscal, administrative, political, and judicial—had been assumed by various institutions and individuals (Laiou-Thomadakis, 1977).

Economically the Empire was in a difficult position. All foreign trade and even some domestic trade was in the hands of Westerners and many of the various taxes used by the state were being collected by others or abandoned completely. What few taxes still being collected were increased to such an extent that many peasants abandoned their land or sought the protection of a wealthy landowner (Angold, 1997; Kazhdan and Epstein, 1985; Laiou-Thomadakis, 1977; Ostrogorsky, 1956; Setton, 1953).

In addition, outside forces such as the Russians, the Normans and the Seljuk Turks all took advantage of the Empire's weakness to encroach on its borders. Due to its lack of military strength the Empire increasingly began to rely on military alliances with the Franks. In return the Franks used the situation to garner assistance for the Crusades. Ideologically, the Crusades were justified as a battle of Christianity against the forces of Islam. However, they were also a way to curb Muslim expansion as well as gain control of the East (including the Mediterranean) for Western expansion (Angold, 1997; Lock, 2006; Thorndike, 1956). The Byzantine Emperors, hoping to hold onto their position of power, cooperated with the Franks. Unfortunately, suspicion of Byzantium grew in the West until it culminated with the Frankish conquest of Constantinople in 1204 during the Fourth Crusade and the occupation of much of the Empire's land by the Franks (Angold, 1997; Lock, 1995; 2006; Ostrogorsky, 1969; Thorndike, 1956).

The complexities of the Frankish takeover and the subsequent organization of former Byzantine lands are detailed by Lock (1995; 2006). After the fall of Constantinople in 1204, a period of upheaval followed, with a succession of states attempting to take control of the Empire's previously held lands. When the political situation stabilized, much of the Aegean was under Western control. The Empire of Nicaea, the Greek successor state to the Byzantine Empire, retained control over parts of Anatolia and the Greek-controlled Despotate of Epiros ruled over the northern half of the Greek peninsula. The remainder was broken into a number of Frankish states, including the Principality of Achaea which included the Stymphalos region.

In the Frankish ruled areas of Greece, the 13th and 14th centuries saw a clash of cultural identities, that of Greeks (who identified themselves as Roman) versus Franks. However the depth of the division between the two groups is questionable.

The Franks had succeeded in creating a foothold for the West in the Aegean, but it was tenuous. The Franks were a small foreign minority ruling a larger Greek majority with their hold on power being tenuous at best. To help consolidate power, separation between the Franks and Greeks was necessary. However, unlike other conquered groups such as the Syrians, the Greeks were Christian and could not be marginalized and segregated in the same way. This difference helped to define the interaction between the two groups. For example, in most Frankish states, intermarriage was allowed but was generally discouraged. Surprisingly, offspring of these intermarriages often had flexibility in defining their cultural identities (Lock, 1995; 2006). The general lack of Frankish influence on Greek culture and the division between the two groups has been largely

interpreted as being due to the role of religion in defining Greek and Frankish cultural identities (Lock, 1995; Topping, 1977).

The Catholic Church was present within Greece before and during Frankish rule, but it had had little effect on the Greek populace (Lock, 1995; 2006). This was due to a number of factors. First, due to the fact that the Church was intimately involved with the planning of the Fourth Crusade, many Greeks saw it as one of the reasons they had been invaded and conquered. Secondly, in many cases, the religious orders sent by Pope Innocent III after the conquest of Constantinople were not proselytizing in nature and therefore converted few Greeks. Thirdly, Church centres were generally focused in urban areas with large populations of Latins, preventing much of the Greek population from being exposed to Roman Catholicism (the exception to this rule was the Cistercian sect which tended to build in remote areas of the Peloponnese such as Zaraka). Finally, the lack of funding, converts, and people willing to move to Greece in order to run the monasteries and nunneries caused the Catholic Church to be even more short lived than the Frankish states themselves. By the beginning of the 14th century, almost all the Catholic monasteries and nunneries in Greece had been abandoned (Panagopoulos, 1979; Lock, 1995).

At the end of the 13th century, the Frankish states were a shadow of their former selves. Limited funds and virtually no military aid from the West allowed much of their previously held lands to be taken over by the Empire of Nicaea. By 1429 the Greeks finally recaptured the Peloponnese and the Frankish states were reduced to a few islands still held by the Venetians. The Greeks did not hold onto their empire for long. The Turks

captured Constantinople in 1453 and eradicated the last remaining Latin states in Greece in 1460 (Lock, 1995; Thorndike, 1956).

The creation of the Ottoman Empire saw the end of the Byzantine and Latin empires. The dominance of the Aegean by the Turks lasted well into the 19th and even the 20th century. The introduction of Turkish rule had a great effect on the political landscape both within Greece and Europe, but daily life within the Empire continued largely as it had for centuries. Once again, the Greek people were able to stay separate from their new conquerors. Their common identity helped bind them together, keeping their culture intact (Friedman, 1992).

2.2. The Available Sources for Greek Historical Diets

In order to reconstruct diet at Stymphalos within the historical periods discussed, information was drawn both from historical documents and archaeological data. The historical sources contributed the majority of the information with archaeological data offering supplementary details.

2.2.1. Historical Sources: The historical sources consulted in this survey of Greek Byzantine and Frankish diets include historical and social commentaries, tax and food sales records, and descriptions of specific social groups. Whenever possible, primary sources in translation were consulted and secondary sources were utilized when these were unavailable. Accounts written before and after the Byzantine and Frankish periods were also consulted.

The main benefit of historical sources is they are eyewitness accounts, written by people who were present at the time and therefore able to observe the dietary choices and patterns of that society. Thus they can give great insight into what was being eaten and how. The information provided by these documents, however, varies considerably. The most common forms of documents are lists of the foods available during the Byzantine and Frankish eras. For example government taxation records and documents on regulation of food prices identify many of the foods used, in addition to supplying information on which foods were produced or imported into a region (Lowry, 1991). When these lists are unavailable, contemporary literature can often supply information on the foods consumed by a society (Dalby, 1996).

While the identification of foods available is a necessary part in reconstructing past diets it does little to help us understand how foods were actually utilized, and which were eaten in given situations. However, a small number of sources do contain more specific information about consumption patterns and nutritional importance. By examining monastic records in detail, Dembińska (1985) was able to determine the monastic dietary regimes of both Byzantine and Western religious orders. As well as describing the various foods consumed, she describes the amount of each item allowed per person. Taxation records and food prices can also indicate the dietary importance of foods. Food deemed important enough to tax likely played a greater role in everyday diet than items not taxed at all (Lock, 1995; Lowry, 1991). The pricing of food can indicate which foods were common and which were rare. More common items would have sold at a much cheaper price than items that were infrequently seen.

Contemporary sources in particular can provide great detail on the variation of nutritional practices within and between social groups. For example Niketas Choniates writing at the end of the 12th century references food a number of times in his social commentary, often noting in particular the difference between the food eaten by the poor (304, 305, 635) and that eaten by the wealthy (145, 384, 302, 441). Unfortunately these sources are often less common and less precise.

As can be seen from the description above, historical sources can be very important to the study of past diets. In many cases, these documents are the only evidence remaining for past dietary practices. Their use is not without drawbacks, however. One of the major problems faced by researchers is that food in historical documents, much as it does today, has social meaning. Its use as a social metaphor makes it much more difficult to reconstruct past diets. Additional problems include the inference of dietary information to the general from the specific and, of particular importance to this thesis, the need to place boundaries on historical analogy.

2.2.1.a. Food as a Social Metaphor: The main benefit of using historical sources is that they are eyewitness accounts. Unfortunately, this fact also creates one of the biggest challenges to researchers. Historical sources tell us what was eaten and how, but they also reveal the thoughts and opinions of their authors on what they were eating. The beliefs and opinions of a society infuse foods and the consumption of food with social meaning (Wright et al. 2001). Thus the attitudes displayed towards certain foods will affect what is written about them, potentially making these sources inaccurate reflections of the food's use in society (Counihan, 1999).

One example of the use of food as a social metaphor in historical documents is the social meaning of meat. The meanings of meat are varied and depend on the opinions of both the authors and the audience they are writing for. The excessive consumption of meat in many cases had negative connotations attached. With the introduction of Christianity into the Greek-speaking world, over-consumption of meat, and of food in general, became symbolic of sinfulness and self indulgence. The consumption of meat was seen as particularly dangerous for women because it was linked to sexual desire (Counihan, 1999). Any excess increased a woman's sexual desire, posing a moral threat both to herself and those around her (Adamson, 2004; Grimm, 1995). Researchers such as Garnsey (1999:122-125) identify sources such as Choniates (594) as using the consumption of meat to create a sense of divergence between the civilized Greeks who only ate it in moderation, and the unholy barbarians (e.g. Franks) whose unfettered enjoyment was seen as a dangerous luxury. Over-eating, the waste of food, and the consumption of luxury goods were often seen as a trope for self-indulgence and excessive luxury (Choniates, 145-146,384, 441). In this manner, authors used both specific foods and their consumption to help to define morality within society. For researchers, this can lead to difficulties when trying to determine how particular foodstuffs were used. For example, the fact that meat was seen as a dangerous luxury, particularly for women, would lead many to assume that meat was generally not consumed by women. However, without corroborating evidence from other historical sources or archaeological data, this would be a dangerous assumption to make. As can be seen through these examples, mentions of food within historical sources are often loaded with social meaning.

However, the benefits they bring to dietary reconstruction as far outweigh these disadvantages.

2.2.1.b. Understanding the General Through the Specific: An additional problem faced when using historical sources is the use of information from specific cases to draw inferences about the general population. The difficulty with this is that in many cases specific groups such as monks and nuns have distinct rules regarding the access to resources and their consumption. Due to this fact, their dietary practices are often different from that of the average person. For example, Dembińska (1985) reviewed the diets of monks and nuns from both Eastern and Western Christian orders. She found complete or near-complete exclusion of meat from the diet, and noted that even the most basic of staples were sometimes prohibited. This was due to the fact that the diets of the monks and nuns were strictly regulated by the Church. While this source provides great detail about this specific group, it translates poorly to a population that was under no obligation to follow these rules. Although the diet of the monks and nuns examined by Dembińska (1985) can be used to infer what would have been considered a minimal but nutritionally adequate diet at the time, the information is of little use when looking at the social classes who were under no unusual restrictions.

2.2.1.c. The Difficulty of Using Historical Analogy: The use of historical analogy to infer diet in Byzantine and Frankish Greece from records dating from other eras depends on a number of assumptions, chief among them being that diet remained unchanged between the periods in question. This assumption relies on a variety of factors including a short

time span separating two eras, a lack of evidence suggesting culture change, or even a limitation in dietary choices set by climatic conditions in the region. Even with the use of restrictions to temper results, analogy must be used with extreme caution in order to avoid incorrect conclusions. A more detailed discussion on the uses of analogy and problems associated with it can be found in Kelley and Hanen (1988). Analogy will be used in this thesis as a supplemental source of information, mainly to determine diet during the Early Byzantine period by examining documents dating from earlier eras. The use of these earlier documents to infer diet in the Byzantine period relies on the assumption that due to the short time span separating the two periods, dietary practices and choices could not have been affected very seriously. The restrictions in dietary choice caused by environment limitations and the influence of religious beliefs also make these assumptions plausible. The majority of the sources consulted date from the earlier Roman period and deal with agricultural practices and food usage (e.g. Cato, Columella, Galen, Pliny, Varro). The attraction of these sources is that they can provide information on the nutritional importance of foods within society. However caution has been taken as food choices and dietary practices could have changed over time due to the increasing influence of Christianity on Greek society in the Byzantine period (Macbeth and Mowatt, 2004).

2.2.2. Archaeological Sources: Unlike that provided by historical sources, the information on Greek diet in the Byzantine and Frankish periods available through the use of archaeological data is relatively limited. The sources examined in this thesis include zooarchaeological studies (e.g. Foss, 1995; Mackinnon, 2003; Mylona, 2003a,

2003b; Williams, 1996; Williams et al. 1997, 1998), palaeobotanical studies (Dar, 1995; Megaloudi, 2006) and data from land-use surveys (Bintliff, 1991, 1996; Stedman, 1996).

Although the number of archaeological sources is small, their value for dietary reconstruction cannot be underestimated. The examination of food refuse can give an unbiased look at what was actually being consumed by a society, including items often unnoticed or unrecorded by contemporary sources (Little, 2007). Land surveys help to track changes in land-use patterns over time (Alcock, 1993; Bintliff, 1991) and the discovery of extraordinary items such as shipwrecks can help to track the importance of particular foodstuffs to the economy and to society in general (Hocker, 2005; van Doorninck, 2005).

Much as with historical sources, the use of archaeological data to reconstruct diet is not without pitfalls. The main factor behind their rather limited role in this thesis is the fact that relatively little has been published on the archaeology of Byzantine and Frankish Greece. In addition, what has been published largely focuses on art and architecture (e.g. Panagopoulos, 1979) or has not been translated into English (e.g. Kroll, 1999). The focus on art has caused the archaeological data available to be biased towards monuments and public buildings, particularly churches. In addition, traditional excavations did not often include detailed examinations of middens (Bintliff, 1991). Further limiting the use of archaeological data for dietary reconstruction is the continuation of older archaeological practices. For example, the limited use of sieving (both wet and dry) in Greek archaeology has often biased data collected through archaeological excavations towards large artifacts and faunal remains. Small delicate remains such as fish or pollen samples are often lost or destroyed, leaving the archaeological record both spotty and biased

(Mylona, 2003b). Fortunately this situation is starting to change with the recent rise in interest in medieval archaeology suggesting that the archaeological record will play a greater role in future dietary reconstruction (Dar, 1995; Hocker, 2005). New questions about land use and cultural practices have led to an increase in regional surveys and in the excavation of habitation sites (Miller et al. 2001). In addition, stable isotope analysis is increasingly being used to examine questions that cannot be answered using historical sources alone (e.g. Bourbou and Richards, 2007; Garvie-Lok, 2001; Papathanasiou et al. 2000).

2.3. Environment and Topography of Greece

Throughout history the climate and topography of Greece have played a defining role in the agricultural practices and food choices of its people. Therefore a description of the physical conditions of Greece is necessary to understanding and reconstructing diet in the Byzantine and Frankish periods.

The terrain of Greece limits potential agricultural choices. The largely mountainous country, made up of the mainland, the Peloponnese peninsula and over 3000 small islands, has only 19% arable land due to the predominance of steep slopes and poor soils (rich in potash but deficient in nitrogen and phosphorous) (Higgins, 1996; Pepelasis and Thompson, 1960). This percentage of cultivable land is further limited by climatic conditions.

Greece's climate varies between and even within regions. Although defined as having a typical Mediterranean climate (i.e. winter rain and milder temperatures followed by summer heat and drought), temperature and rainfall patterns fluctuate due to Greece's

irregular terrain. In addition, the country, particularly the eastern region, is affected by high winds known as the sirocco (Pepelasis and Thompson, 1960). The result of these erratic climatic patterns is that Greece is often affected by drought, particularly in the southern and eastern regions where the valley of Stymphalos is located.[1] As much of Greece's arable land is in these regions, harvest fluctuations are regular and crop failures inevitable (Garnsey, 1988).

The high level of interannual variability seen today seems to have been a constant feature of Greece. Studies of tree-rings from classical antiquity through to the 12th century A.D. have shown similar climatic fluctuations and historical records mention numerous episodes of drought and crop failures (Garnsey, 1988; Kuniholm and Striker, 1983). This evidence, along with data from archaeological sources and information from historical documents, reveals that the prevention of food shortages due to environmental limitations played a major role in defining Greek diet (Forbes and Foxhall, 1995; Garnsey, 1988; Semple, 1921, 1922).

2.4. Preliminary Reconstruction of Byzantine and Frankish Greek Diet

The discussion turns from understanding the historical background and the theoretical limitations of historical sources and archaeological data to a general reconstruction of diet in the Byzantine and Frankish periods. This section begins with an examination of the primary staple foods making up the main nutritional component of the everyday diet (e.g. Dalby, 1996; Garnsey, 1999). This is followed by a discussion of supplementary foods whose importance to the diet is still largely uncertain. Separating the main foods from secondary food items allows the main items within each group to be

[1] Detailed information on the environment of the valley of Stymphalos can be found in Section 4.1.

identified and their nutritional importance to be detailed. Special attention will be paid to uncertainties that can be addressed through stable isotope analysis. Possible variations between different class groups and genders will be examined at the end.

2.4.1. Bread and Cereals: The base of the Greek diet from the beginning of agriculture in the region up to the present day appears to have been grain (Foxhall and Forbes, 1982). Historical sources and archaeological data indicate that for the Byzantine and Frankish periods grain was the primary staple of the diet, utilized most frequently in the form of bread.

Although a variety of cereals were known to the Greeks, the main two appear to have been wheat and barley, with wheat being the preferred grain. Evidence for this can be seen in price relationships between the two grains, with wheat selling for a higher price than barley (Teall, 1959:99-100). In addition ancient writers Columella (2.2) and Pliny (18:14-19) both make mention of the preference of wheat over barley. They describe barley as good for fodder and only consumed on its own by humans when no other options are available (Braun, 1996; Garnsey, 1988). Byzantine writer Niketas Choniates (264, 305) describes barley cakes as a basic food, used by the poor and for army rations. Although wheat was the preferred cereal during the Byzantine and Frankish periods, this does not mean that wheat or the other major grain barley were in fact the main cereals utilized by the general population.

A number of other grains were traditionally grown or used in Greece. Rye was a significant crop in the north (Galen, *On the Properties of Foodstuffs* 514) but would not have been as important in the south which suggests its importance in the valley of

Stymphalos was minor. Rye only became widely cultivated in Greece during the Late Byzantine period, a change probably related to the expansion of medieval cities (Megaloudi, 2006). Wide-scale use of rye was also partially limited by the threat of ergotism, a condition brought on by the consumption of fungus-infected grain which caused hallucinations and even death (Adamson, 2004). Oats were generally considered to be weeds by the Romans and Greeks (Faas, 2003; Zohary and Hopf, 2000) and mentioned only as animal fodder (Columella 2.10). Rice was used in a limited fashion in a few specific dishes during the Roman and Byzantine eras (Faas, 2003) but it did not become a common dietary item within Greece and Western Europe until the expansion of the Ottoman Empire (Adamson, 2004; Dalby, 1996). This suggests that rural Byzantine and Frankish Greek populations like those found in the valley of Stymphalos were unlikely to have been using rice in large amounts.

One of the other grains mentioned by both Roman and Byzantine authors is millet. Millet had been present in Greece as far back as the Early Neolithic in some areas but was not of much use until the Classical and Roman periods (Megaloudi, 2006). Roman authors such as Columella (2:17-18), Cato (1.6), and Pliny (18:24-26) mention millet, and its continued cultivation into the Byzantine period is evidenced by references to the grain in Byzantine medical texts (Teall, 1959:99). A number of scholars (e.g. Garnsey, 1988) have suggested that millet was generally considered to be of little use except as fodder or as an emergency resource. Its poor standing in the medical records and its identification by many as a barbarian food helped to reinforce this position (Adamson, 2004; Garnsey, 1999: 71). However the evidence is contradictory. In some areas of Italy and Greece, millet was a staple crop (Faas, 2003; Pliny 18.14). Columella

(2.7) identifies millet as an important grain and later states (2.9) that "millet porridge is a dish that should not be overlooked even in times of plenty." This statement is ambiguous at best. Columella could be stating that he does not find millet unpalatable or if taken in a different context he could be saying millet was normally associated with leaner times. Unfortunately this ambiguity continues into later periods. The Byzantine physician Simeon Seth considered millet to be quite unpleasant in taste and recommended that millet bread should only be eaten in times of extreme famine (Dalby, 1996:90; Teall, 1959:99). The evidence from the sources suggests that millet use varied by region and economic status but these brief descriptions do little to help evaluate millet's actual importance as a dietary staple in the Medieval Greek diet. This is one area where stable isotope analysis could provide valuable insight. As will be reviewed in Chapter 3, millet is a C4 grain and therefore is isotopically distinct from the other staples such as wheat and barley. Due to this fact, its use could be detected through $\delta^{13}C$ analysis of human remains. Investigations into millet use in Medieval Greek communities have shown that some populations were consuming at least some C4 grains (Garvie-Lok, 2001).

The nutritional importance of grain in the Greek world appears to have been considerable. Historical and archaeological sources indicate that throughout Greece's history, grain formed the cornerstone of the diet. Megaloudi's (2006) review of palaeobotanical finds from sites dating from the Neolithic to the Classical period showed that in almost every case, cereals made up the majority of the plant remains suggesting they contributed a substantial portion of the diet. The Classical and Roman Periods also showed a heavy dependence on grain. In nearly all ancient discussions of food (e.g. Columella *On Agriculture*, Galen's *On The Properties of Foodstuffs*, etc.) cereals and

their products are inevitably discussed first and are seen as having the most benefit nutritionally. In a study of Greek and Roman grain allotments Foxhall and Forbes (1982) suggest that 70% to 75% of an individual's dietary calories could come from these grain handouts. The large number of Roman recipes utilizing grains, particularly in the production of bread, also suggests their importance in the Roman world (Faas, 2003). The dependence on grain persisted into the medieval period. Byzantine writer Niketas Choniates (452, 495, 635) refers to bread as an indispensable part of the diet, particularly for the poor. Dembińska's (1985) review of monastic records (called *typika*) showed that monks and nuns typically received between 650 and 900 g. of grain per diem, or roughly 50% by weight of the total diet. Other historical records appear to back the importance of grain to the diet. Teall's (1959) survey of contemporary writers and economic records indicates that for the Byzantine populace, bread was a major dietary staple. Bread was so important to the Byzantine diet that bakers were afforded special privileges. According the *Book of the Eparch*, written ca. 895, "bakers are never liable to be called for any public service, neither themselves nor their animals, to prevent any interruption of the baking of bread..." (Dalby, 1996). This pattern continues into the Ottoman period. In a review of tax records dating from the period, Lowry (1991:287) concluded that bread made up a significant portion of the diet for the rural population. When taken altogether it is obvious that grain was the major dietary staple from the Classical Period right through the Medieval era. The bulk of the grain utilized was likely barley and wheat, with rice and rye increasing in use throughout the Byzantine and Frankish periods. The importance of millet appears to have varied by region and economic factors while oats were seen

only as animal fodder. Stable isotope analysis is potentially capable of clearing up many of the uncertainties over millet use that have not been answered by the historical sources.

2.4.2. Legumes: Legumes were also an important field crop throughout Greek history, but how important they were to the diet remains ambiguous.

In the Roman period, legumes were cultivated throughout the Mediterranean and several species including broad beans, chickpeas, lentils, vetch and lupin were noted by Roman authors as important field crops (Cato 1.34-37; Columella 2.7; Galen 524-546; Pliny 18.30-32; Varro 1.32). The fertilizing quality of leguminous plants was well known to the Romans and was utilized frequently by farmers (Columella 2.10; Pliny 18.36; Sallares, 1991). Some species such as chickpeas and lentils were consumed by humans (Pliny 18.31-33), but many species (e.g. vetch) were grown exclusively for animal fodder and soil enrichment purposes (Cato 1.37; Columella 2.7). Legumes continued to be utilized in this manner throughout the Byzantine era (Dembińska, 1985:459). It is only in the early modern era that legume consumption and utilization began to change. This has generally been seen to reflect the introduction of new foods (e.g. potatoes) to the diet which replaced legumes (Matelas, 2006).

Obviously legumes played some role in past Greek diets, but trying to determine how important they were has been problematic. Several authors such as Garnsey (1999:15), Dalby (1996:90) and Sallares (1991:300-302) have suggested that they were consumed in larger amounts than previously assumed. Support for this idea can be found in the way legumes were treated in agricultural treatises. Authors such as Columella (2.7), Pliny (18.30-32) and Varro (1.32) placed special importance on legumes, and

described them alongside grains, the dietary staple. Garnsey (1999:15,78) has theorized that legumes were of vital importance to the lower classes. He sees legumes as the "poor man's meat", a replacement for protein generally obtained through the consumption of meat. Legumes could have been particularly important to poor rural populations who generally had little access to large amounts of meat, such as the populations living in the valley of Stymphalos. Roman poetry has many examples of legumes being connected with the poor (Elliot, 2003:113-115). The fact that legumes can supply the nutrients cereals are deficient in provides added support for their dietary importance (Sallares, 1991). Although legumes were predominantly associated with the lower classes, they seem to have been enjoyed by all society. A number of Roman recipes written for the elite describe dishes based around legumes, many containing exotic spices and wild game not available to the poor (Faas, 2003). Legume consumption might have been tempered somewhat by the fact that many legumes contain toxins and antimetabolites harmful to humans and some animals. Unless proper methods of preparation are followed, the consumption of these plants often results in a variety of symptoms, or even death (Flint-Hamilton, 1999; Sallares, 1991; Zohary and Hopf, 2000). Ancient writers such as Pliny (22.142, 153) and Galen (524) were aware of the toxic effect of some legumes and recommended that care be taken in order to prevent poisoning.

Legumes' dietary role continued into the Byzantine and Frankish periods. Dembińska (1985) mentions legumes as an important base for many dishes in the diets of Byzantine monks and nuns. Consumption appeared to vary, with 55 to 210 g of dried legumes provided daily The Monastery of St. Marina on the Greek island of Andros cultivated so many legumes that they amounted to almost 1/3 of the wheat stored

(Kazhdan, 1997). Legumes were recorded frequently by Byzantine tax records as an export product (Laiou-Thomadakis, 1980). The *Farmer's Law* states that the man who enters his neighbour's furrow and injures his grain or his beans will be punished, which suggests beans and grain were of equivalent importance (Teall, 1971). In the Ottoman period legumes were important to both the Greek and the Turkish diets. Tax records from the Ottoman period suggest that for some regions, legumes were an important source of revenue (Lowry, 1999:287). Legume consumption appears to have dropped off in the 19th and 20th centuries. Matelas (2006) reports that for some rural Greek populations of those times legume consumption was infrequent.

Much as for millet, stable isotope analysis could be used to shed light on legume consumption. As will be discussed in Chapter 3, legumes have stable nitrogen isotope values distinct from those of most other foods, leading to the possibility of using bone $\delta^{15}N$ analysis to examine legume consumption levels at Stymphalos and Zaraka. While previous stable isotope analyses of Medieval Greek populations have shown little to no legume consumption (e.g. Bourbou and Richards, 2007; Garvie-Lok, 2001), if legumes did play a substantial role in the everyday diet in the valley of Stymphalos, this should have a discernible effect on bone $\delta^{15}N$ values.

2.4.3. Olives and Olive Oil: In the Classical and Roman periods olives and olive oil were a key component of agricultural practices and the diet. This can be seen in the works of Cato (1.64-69, 144-146), Columella (5.8-9), Pliny (15.3-6) and Varro (1.55) where olive cultivation and processing are discussed in great detail. Olives and olive oil were enjoyed by all classes. Almost every Roman dish used olives or olive oil in some manner (Faas,

2003) and poets mentioned olives as having a place in even the poorest individual's diet (Elliot, 2003:113-114). The importance of olives and olive oil to the Greek diet continued into the Byzantine and Frankish periods. Oil, a basic ration provided to monks and nuns, was in fact only taken away during the harshest form of fasting, called ξεροφαγια or 'dry eating'. The monastery records document that every individual received a yearly allotment of 16.4 l of oil (Dembińska, 1985). The Greeks used oil to such an extent that visitors to Byzantium often commented upon it. Liudprand, a bishop from Cremona described Byzantine upper class food at a dinner with the Emperor as "quite nasty and unspeakable, drunkenly awash with oil …"(Liudprand 11). Liudprand's description was probably influenced by the fact that by this period animal fats had replaced oil in Western European cooking (Adamson, 2004). Oil continued to be a major commodity during the Ottoman period with oil from Coron and Modon in the Peloponnese becoming a major export product (Dalby, 1996:203-204). Modern studies of post WWII rural Crete and Corfu populations document that oil continued to be of dietary importance to the Greeks (Matelas, 2006).

2.4.4. Wine: Wine, grains and olives, have often been defined as the "Mediterranean Trinity", the three crops which provided the basis of diets in the region (Braudel, 1992:176). In the Classical period, wine had become a staple within the Greek world. Wine along with meat and bread were considered by many authors to be the three constituents of a proper Greek meal (Dalby, 1996:23). All classes consumed wine in the Classical World, although the quality of wine available for each group differed considerably. Wine retained this position in the Byzantine period. Choniates saw wine as

a dietary staple and mentions that along with bread, wine was an essential part of the diet for the poor (635). Yearly, monks and nuns received on average between 213 litres and 319 litres of wine (Dembińska, 1985:459-460). Wine was so important during the medieval period that it was a major source of tax revenue for the Byzantine Empire. The Byzantine economy was so tied to wine that when the state could no longer compete with Venetian wine imports, John V forbade the import of wine into Constantinople to prevent the Greek wine industry from collapsing (Laiou-Thomadakis, 1980:215-216). Wine remained important into the Ottoman period even though a large portion of the population was forbidden to consume it since it was prohibited by Islam (Dalby, 1996). Researchers such as Matelas (2006) document that wine continued to be important to the Greek diet well into the modern era.

2.4.5. Dairy Products: Dairy products have held an important position in the Greek diet since before Classical times. Although there were cattle, sheep and goat milk appear to have been the main source of dairy products. The Roman author Columella describes both sheep (7.2) and goat (7.6) as good producers of milk which helped to feed the rural population. Varro (2.11) places sheep and goat milk as the most nourishing and Pliny (11.96) states that milk from animals with two nipples (i.e. sheep and goat) makes the best cheese. Galen (682) says that goat's milk is the best proportioned with equal parts fat and liquid. Cow's milk on the other hand was seen as extremely thick and fatty and not to be used in excess. Varro (2.10) describes the regularity of large sheep herds (some up to 1000 animals) indicating that sheep and goats were an important commodity. He goes

further by saying that milk and dairy products were a main source of profit gained from those animals.

The Greek environment in general is not suitable for large scale stock-raising; however animals such as goat and sheep are able to take advantage of the mountainous landscape and thus exploit land not suitable for other forms of agriculture (Garnsey, 1999; Semple, 1922). Archaeological land surveys have suggested that pastoralism played a significant role in Roman Greece (Lloyd, 1991; Mee et al. 1991). In addition, zooachaeological analyses have shown animal husbandry patterns that imply females were kept well into adulthood. This could be to take greater advantage of their milk and/or fleece (Leguilloux, 2003). Dairy products would have provided a cheaper and longer lasting source of protein than using the animals only for their meat.

Dairy products continued to be used throughout the Byzantine and Ottoman Empires and well into the modern period. Evidence of dairy production and consumption can be seen in an example from early 15th century Constantinople. On his travels through Constantinople, the Italian pilgrim Pietro Casola described at length the great variety and of cheeses available in the city and the sheer amount that was exported for trade (Dalby, 1996). The increase in Mediterranean trade had allowed for foreign traders to take over much of the economy, but one of the primary goods still produced and sold by Byzantines were dairy products (Laiou-Thomadakis, 1980).

The main dairy product through Greek history appears to have been cheese. Milk was consumed as a beverage but only by those who lived close to the land and thus had immediate access to it (Dalby, 1996). The lack of refrigeration forced milk to be converted to other products quickly so it would not spoil. Columella (7.8) described

cheese-making in detail and Pliny judged regional cheese varieties in his *Natural History* (Pliny 11.97). Cheese was a favorite ingredient for Roman cooks (Faas, 2003) and was frequently mentioned in Roman literature (Elliot, 2003). Byzantine sources also document the prevalence of cheese. Byzantine *typika* mention cheese as one of the few animal products regularly consumed by monks and nuns. The exact amounts that were allotted were often not recorded, but one group of nuns the documents state about 16 kg of cheese was allotted to each person per year (Dembińska, 1985). Its economic importance continued into the Frankish period, when cheese was one of the principal exports from Greece (Lock, 1995). Yoghurt became an important food product during the Ottoman period and was utilized by both Greeks and Turks (Dalby, 1996). Both milk and cheese are also mentioned as being part of the everyday diet of 19th and 20th century rural communities in Greece, although their importance declines over time (Matelas, 2006).

Dairy product consumption varied considerably over time, making it difficult to determine the importance of milk and cheese to the average Byzantine and Frankish Greek diet. One of the main variations was between urban and rural groups. Rural populations like those from Stymphalos and Zaraka who had greater access to herds would likely consume larger amounts of dairy products than those with little access (such as urban dwellers). In addition, the historical sources mentioning dairy product consumption generally concern either specialized groups (e.g. monks and nuns) or urban dwellers, making it extremely difficult to determine what the average populace was actually consuming. Although the picture is ambiguous, the available data for dairy consumption make it fairly safe to assume dairy products were an important supplementary food enjoyed by all classes.

2.4.6. Meat and Eggs: Determining the importance of meat in past diets has been a challenge due to the fact that past meat usage is often complicated by its use as a social metaphor (refer to Section 2.2.1.a.). Although this is problematic, information can still be garnered from the historical and archaeological sources. The evidence, however, must be treated with extreme caution. This section will describe the various animals available during the periods in question as well as evaluate their nutritional importance. Differences due to class and gender will be discussed in a later section.

Both historical sources and archaeological data suggest that domestic animals were an important source of meat in the Greek world. Out of all the domestic animals, the sheep, goat and pig are the three most frequently mentioned as sources of meat (Dalby, 1996). The fact that these animals are relatively economical to raise and are small enough to consume quickly and therefore avoid spoilage makes this choice reasonable. Roman sources have confirmed the use of sheep and goat for meat (Faas, 2003). There appears to have been a distinct preference for young animals (Frayn, 1995). Roman recipes left to us by Apicius only contain references to lamb and kid (Faas, 2003) and Columella (7.3, 7.6) states that most young animals are used for meat. Although goat and sheep were the main sources of meat, it appears that the pig was in fact more prized during the Roman period. The usefulness of the pig as a meat animal to the Romans is vividly portrayed by Varro (2.4) when he cites an old saying describing how pigs were given to humanity by nature to provide a banquet. Galen (661) described pork "as the most nutritious of all foods" and Pliny (8.77) mentions pig as providing more flavours than any other animal. In fact the pig enjoyed such popularity that in the recipes of Apicius the term meat was synonymous with pork (Faas, 2003:255). Compared with other domestic animals, cattle

appear to have been used rarely as a source of meat. Beef is mentioned as an ingredient in Roman dishes with immature animals and cows being the preferences (Faas, 2003). Varro (2.5) briefly mentions that cattle were bought for slaughter but he goes no further and focuses more on their use as draft animals. Columella (6.1-26) and Pliny (8.70) also focus more on their usefulness as a source of labour. The Romans used a large variety of domestic birds for both meat and eggs. The list of birds included everything from chicken, geese, ducks and pigeons to more exotic species such as peacocks and swans (Columella 8.2-15; Galen 701-703; Varro 3.3-11). Both poultry and eggs appear a number of times in Roman recipes (Faas, 2003) and were detailed as important sources of food and profit by Columella (8.4-11), Galen (706-707) and Varro (3.9). Archaeological data appear to agree with the historical sources about which animals were preferred. Faunal assemblages from excavations on the island of Delos are overwhelmingly dominated by sheep/goat and pig remains with cattle, and poultry making up a much smaller percentage (Leguilloux, 2007).

Very little change in meat usage occurred in the Byzantine period. Sheep and goat continue to dominate cattle in faunal assemblages throughout the Byzantine Empire (Dar, 1995). Historical sources indicate that sheep and goats were the main domesticated animals in the Byzantine countryside with swine taking a secondary position (Kazhdan, 1997). Poultry and eggs are also mentioned by a number of sources as having been enjoyed by all classes (Kazhdan, 1997:55-56). Eggs were particularly enjoyed by monks and nuns who were often forbidden from eating meat (Dembińska, 1985). Sheep, goats and pigs are mentioned as major domestic animals during the Frankish period as well. Pigs figured prominently on the Frankish estates of Kosmina in the Peloponnese (Lock,

1995) and faunal remains from the Frankish levels at Corinth include a number of sheep and goat with smaller frequencies of both cattle and domestic birds (Williams et al. 1997, 1998).

Although domestic animals would have been the main source of meat for most Greeks, hunted and collected meat would have also played a substantial role in the diet. Varro (3.3) mentions boar, roe deer and hare as important food sources and Galen (665) actually described hare as being healthier than even pork or beef. Roman dishes containing wild game and fowl are almost as numerous as those using domestic animals (Faas, 2003). Hunting and consuming wild game generally had upper-class connotations in both the Roman and Byzantine world (Faas, 2003; Kazhdan, 1997:55). Choniates described Byzantine Emperor Andronikos as enjoying hunting (333) and Liuprand was invited to tour the private imperial hunting park (38). The consumption of wild game by the general populace is unclear. Although wild game was generally expensive in all time periods, some animals would have been affordable to at least some of the population (Faas, 2003). Rural populations also had the option of catching their own game. In the valley of Stymphalos where there was a lake used by migrating birds, the amount of meat contributed by wild game or fowl could have been substantial (Bourne, 1982).

In addition to domestic and hunted game, collected animals were also utilized by the Greek population. In particular the snail is mentioned as a frequent food source. Galen (669) mentions that snails were a daily food for all Greeks. Varro (3.14) described how snails could either be raised or collected from the wild and snails are mentioned as an ingredient in some Roman dishes (Faas, 2003). Although small, snails could have represented a substantial amount of meat.

The nutritional importance of meat is difficult to extrapolate from the available evidence. Choniates discusses meat consumption but only in reference to the upper classes (Choniates, 594). This could be due to the fact he is using their excessive meat consumption as a criticism against their lives of lazy luxury, but also because the upper classes were actually the only ones eating substantial amounts of meat. Upper class tables during the Ottoman period also seem to have been amply supplied with meat (Dalby, 1996: 203). Determining how much meat was being consumed by the general Greek population is much more problematic. The Byzantine *typika* studies by Dembińska (1985) are of little use in this case due to the extreme religious restrictions placed on meat consumption for monks and nuns. Dalby (1996:196) argues that the regular use of meat by the general Byzantine population was unlikely and meat was only consumed on special occasions. However Kazhdan (1997: 55) argues that meat was in fact a regular foodstuff for most Byzantines citing sources that mention meat consumption by peasants during special occasions. Egg consumption is not any clearer. The nutritional importance of eggs is rarely mentioned by the historical sources. We know eggs were utilized by all classes and were generally cheap but there is no mention of how often they would have been consumed. Eggs were a supplementary food for monks and nuns in place of meat but specific allotments were not recorded (Dembińska, 1985). Although the nutritional importance of meat and eggs in the past is uncertain, stable isotope analysis provides a way to clear up some of these ambiguities and analyses of populations of this era to date suggest a fairly heavy dependence on meat, eggs or dairy.

2.4.7. Marine Resources: Much like the consumption of meat and eggs, the importance of marine resources to the Greek diet over time is uncertain. Numerous authors (e.g. Braund, 1996; Mylona, 2003b; Powell, 1996; Purcell, 1996; Wilkins, 2005) have attempted to clarify the situation but few concrete answers have been found. The modern country of Greece is home to over 15 000 km of coastline with over 72% of the country being less than 40 km from the sea (Powell, 1996). Coupled with the fact that fish have been considered desirable foodstuffs throughout history, this suggests that marine resources played a central role in the Greek diet. However this appears to not always have been the case. Much like the consumption of meat, marine resources were imbued with social meaning. Again this section will only investigate the resources utilized and try to reconstruct their importance to the Greek diet. Variations due to differences in class, gender will be examined in a later section.

The Greeks and Romans had a great love of fish and other marine animals. Not only were they exotic animals prized for their beauty, they were also valued for culinary purposes (Pliny 9.79-80). The list of marine animals known and utilized during the Roman period is extensive. Species mentioned by ancient writers include tunny, swordfish, eel, bluefish, pike, sturgeon, sea urchin, dolphin, shark, oysters, mussels, crabs, mackerel, sardine, sturgeon, squid, shrimp, octopus, red mullet, sea bream, jellyfish, lobster, cuttlefish, and tuna (Dalby, 1996: 68-74; Elliot, 2003; Faas, 2003:325-348; Galen, 709-738). An extensive list of the marine animals can be found in Book IX of Pliny's *Natural History*. Many of the species described by the Roman authors continued to be traded and eaten during the Byzantine and Ottoman periods. Both sturgeon and mackerel were mentioned during the Byzantine and Ottoman periods as regular sights in

Constantinople fish markets (Dalby, 1996). The importance of these species varied depending on how accessible they were to the public. For many marine resources, availability differed both regionally and seasonally. For example, mullet was prized during the Roman period but its wide migration patterns made it a less frequent catch and thus a more expensive food item (Faas, 2003). While larger fish had great economic importance, smaller fish such as sardines and anchovies were more commonly used due to their regular availability and cheaper price. Finally the use of shellfish and cephalopods such as octopus and squid during the Byzantine period is worth noting. The introduction of fasting days and dietary restrictions with the start of Christianity probably saw the lay population relying more on shellfish and molluscs for their dietary needs during periods when other animal products such as meat and fish were prohibited.

Marine resources were consumed in a variety of ways. In general, the Greeks preferred fresh fish and were particularly fond of those that were caught at sea (Galen, 709-711). The extensive organization and management of the fish markets in 10th century Constantinople suggest that most fish that were sold in the city were fresh (Maniatis, 2000). The excavation of a complete solitary large fish head from the Frankish levels of Corinth also implies regular fresh fish consumption as the heads of the fish would have been destroyed if salted or preserved (Williams et al. 1997). The consumption of fresh fish however was not always an option. If fresh fish were not consumed immediately, they had to be preserved in some way in order to prevent spoiling. Preserving fish became particularly important in major trade areas (e.g. Constantinople) where the supply of fresh fish always outweighed the demand (Maniatis, 2000). For many regions located

away from the coast (e.g. Stymphalos and Zaraka) preserved fish would have been the only way to obtain marine resources.

Salted and dried fish were of considerable economic importance during the Roman period. Fermented and salted fish products such as garum were produced in great quantities for transport and trade throughout the Empire (Garnsey, 1999:16; Trakadakis, 2005). Depending on the processing treatment and the size of the fish, bones would either be removed or left within the fish. These variations have implications for the use of faunal assemblages in assessing trade and dietary patterns. During the Byzantine and Ottoman empires, fish preservation was almost as important an industry as the fish markets themselves. Whatever fish were not sold at the end of a day were sent to the fish processing areas meaning production was largely continuous (Manatis, 2000). The production of caviar and botargo (cured fish roe) also became very important during the Byzantine and Ottoman periods (Dalby, 1996:189). Salted roe and botargo appear to have been regular features on Byzantine tables by the 16th century (Dalby, 1996:200).

The nutritional importance of fish in the Greek diet is hard to quantify. Some authors have seen the lack of sophisticated fishing technology and rarity of large shoals of fish as suggesting fish could only have existed as a luxury item for the rich (Garnsey, 1999: 16). Roman dishes using marine resources indicate a largely upper class consumption (i.e. along with marine foods they contain a large variety of spices and luxury products) (Faas, 2003). Varro (3.17) and Columella (8.16-17) both call fish ponds a necessary part of any farm, however, the time and money involved in creating and stocking these ponds meant that this could only be practiced by the wealthy (Pliny 9.79-80). While many of the more desired fish would have been consumed strictly by the

wealthy, that is not to say that fish did not play a large role in the diets of the general Greek population. Authors such as Wilkins (2005) and Powell (1996) have argued that fish was available for all social classes, although at differing amounts and quality. They suggest that while not a mainstay in the diet, marine resources could have been part of a mixed subsistence strategy.

In general many fish and fish products were within the price range of most of the population. In particular fish products such as salt fish and garum were widely available throughout the Mediterranean. The extensive trading of both items suggests that not only the wealthy were utilizing these products (Dalby, 1996; Ejstrud, 2005; Lund and Gabrielsen, 2005; Trakadakis, 2005). Freshwater fish were readily available but were generally seen as being of poorer quality than their saltwater counterparts (Galen, 709-11). This would have led to them being both cheaper and more readily available to the general population. This pattern continued into the Byzantine period. The more desired fish were expensive and generally consumed by the higher classes while the more numerous less wanted fish were available to the general population (Maniatis, 2000). Choniates mentions marine resources only in connection to wealth and luxury living, suggesting that marine resources had an important role in upper class diets (302, 441). However for at least some of the general population, fish were regularly a part of the everyday diet. Fishing would have been a common activity for many peasants, especially those who lived on the coast or near a river, marsh or lake (Kazhdan, 1997). This is particularly true for the populations of Stymphalos and Zaraka who had access to a large lake within the valley. For Byzantine monks and nuns, marine resources were an integral part of the diet. As meat and dairy products were often prohibited due to fasting periods,

fish and shellfish were substituted. Byzantine *typika* record that monks and nuns received five weekly servings of marine resources such as fish and shellfish (Dembińska, 1985).

Unfortunately, very little else about the actual nutritional importance of marine resources in the Greek diet can be gleaned from the historical and archaeological sources. No specific records survive and even the most detailed of sources (e.g. Dembińska, 1985) still only contain rough estimates of how much of these products were used.

It is obvious that more research is needed to determine the importance of marine resources to the Roman and Byzantine Greek diet. Again stable isotope analysis has shown great use in examining marine and freshwater consumption in past populations (Bourbou and Richards, 2007; Chisholm et al. 1982; Garvie-Lok, 2001; Papathanasiou, 2003). Marine and freshwater resources have distinct nitrogen and carbon stable isotope values as compared to terrestrial resources. Therefore the consumption of marine and freshwater resources can be detected through the examination of the isotope values in human bone tissue, leading to a better understanding of marine and freshwater resource use in the past. Previous stable isotope analyses on populations from this era suggests that for most Greeks, particularly those located inland, marine and freshwater resources made up only a small portion of the everyday diet.

2.4.8. Fruits and Vegetables: The domestication of fruit trees and vegetables in the Mediterranean was late compared to the cereals and olives but by the Classical and Roman periods, fruit orchards and gardens were regular features of Greek farms (Megaloudi, 2005; Zohary and Hopf, 2000). Garden and orchard cultivation was considered extremely important by the Romans and a great deal of attention is given to

the proper methods of caring for fruits and vegetables by Roman authors (Columella 10; Pliny 15.9-40, 19.19-62). Vegetables formed a vital part of the main meal. For the Romans, vegetables were not side dishes but main courses (Faas, 2003:209). Fruits were appetizers, often eaten before and after a meal along with wine and nuts (Dalby, 1996:77). Fruits in particular became a common element in Byzantine and later Ottoman cuisine. They were so sought after that fruit and sweets were an important trading commodity in the empire and throughout Western Europe (Laiou-Thomadakis, 1980). Vegetables continued to be a mainstay for every class. Liuprand (20, 32) mentions onions, garlic and leeks in his descriptions of upper class Byzantine cuisine and Byzantine *typika* record that fruits and vegetables were part of the everyday diet for monks and nuns Dembińska (1985).

Determining how important fruits and vegetables were nutritionally is difficult. Very few sources record actual amounts that were eaten. While the *typika* reviewed by Dembińska (1985) record that fruits and vegetables were eaten frequently by the monks and nuns, they do not record the actual daily allotments.

2.4.9. Honey and Sugar: The Romans had a great love of honey and other sweetening agents such as dried fruits and syrups (Faas, 2003). The practice of apiculture was discussed in length by a number of authors including Columella (9.2-16), Pliny (11.5-15) and Varro (3.16). Archaeological excavations at Isthmia uncovered a number of ceramic beehives suggesting that the practice of apiculture was fairly sophisticated from quite early on (Anderson-Stojanovic and Jones, 2002). By the Roman period, sugar was known to the Greeks but it was seen as having a medicinal purpose rather than a dietary one

(Pliny 12.17). The preference for sweetened foods and drinks continued into the Byzantine and Ottoman periods. Sweets were a standard gift offered to guests and honey (and later with more regularity sugar) was utilized in a vast number of dishes (Dalby, 1996:192, 203). Honey's medicinal importance also increased consumption. Honey was often prescribed by Byzantine physicians as the best food for a newborn and for infants being weaned (Lascaratos and Poulakou-Rebelakou, 2003). While stable isotope analysis can do little to determine the amount of honey consumed, it could be possible to discern whether cane sugar was being consumed. As will be discussed in a later chapter, cane sugar is a C4 plant and thus could be differentiated from the C3 plants that made up the bulk of the diet. Cane sugar consumption could be detected through the analysis of stable isotopes in human bone tissue, allowing for a greater understanding of the spread of cane sugar through Greece and possibly how important it was to the diet.

2.5. Variation by Class and Gender

As this preliminary reconstruction of the Greek diet shows, consumption patterns were extremely variable. The next section will elaborate on some of the variation patterns seen with certain foods, particularly those caused by class and gender differences.

2.5.1. Variation by Class: As the historical sources and archaeological data have shown, the upper classes had access to a great variety of foodstuffs, much greater than the average Greek citizen. The most obvious difference appears to be the consumption of meat and seafood. The consumption of meat and seafood has often been linked with the wealthy upper classes while the lower classes have often been theorized as consuming

more legumes. During the Byzantine period access to fresh meat and fish was the surest sign of rank (Rautman, 2006:95). In Choniates' *Historia* meat was associated with emperors and conquerors - those in positions of power and wealth. However in many of these cases, meat consumption was used symbolically and therefore some caution must be taken when attempting to discern meat's importance to the upper classes. Despite this it does appear that the upper classes consumed substantial amounts of meat. Preferential access to other animal products such as dairy products and eggs could also have been affected by class variation. Unusual cheeses and exotic birds' eggs prized by the upper classes would have been out of the reach of many of the lower classes forcing them to rely on more common and therefore cheaper forms of dairy products. While these variations are clearly seen in urban areas such as Constantinople, differences would have been seen regionally. In the case of Stymphalos and Zaraka, the populations were of rural lower class and would have ready access to both domestic and wild animals. This could have led to greater consumption of meat and most assuredly greater consumption of dairy products and eggs. In addition, their close association to a lake located on bird migratory routes could mean substantial amounts of fish and wild game were also consumed. If this was true, it would cause any class variation to disappear.

Consumption patterns of millet could also suggest class variation. As discussed in the previous section, millet was seen as an inferior grain only utilized by the very poor and as animal fodder. If this was true then the lower classes would have depended more heavily on the grain than the upper classes that had access to more valued grains (e.g. wheat).

Finally, if monks and nuns are defined as a separate class their diet was considerably different from the rest of society. Unlike the general population, the diet of monks and nuns was strictly regulated due to religious reasons. Meat was generally forbidden and the consumption of other foods such as fish and dairy products was dependent on specific religious observances.

The extent of these dietary patterns in the past is still uncertain. However, stable isotope analysis has been shown to be valuable in assessing these questions. As mentioned above, legume and meat consumption can be detected through stable nitrogen isotope analysis and the consumption of marine resources has been studied through carbon and nitrogen analysis (e.g. Bourbou and Richards, 2007; Garvie-Lok, 2001; Katzenberg and Weber, 1999; Keenleyside et al. 2006). The consumption of millet has also been detected through stable carbon isotope analysis (Copley et al. 2004; Garvie-Lok, 2001; Thompson et al. 2008). Thus stable isotope analysis of human bone tissue can clarify dietary patterns and identify any variations between classes which might not otherwise be seen through historical sources or archaeological data.

2.5.2. Gender Variation: Some gender variation in diet appears to have been present in medieval Greece. Such variation had been present in Greece for some time. The 4th century physician Oribasius referenced earlier medical treatises describing the strict regulation and moderation of food intake for females. In these treatises meat was forbidden and it was recommended that the consumption of some other foods should be strictly controlled (Lascaratos and Poulakou-Rebelakou, 2003). With the introduction of Christianity, these food restrictions for women were further enforced (Grimm, 1995).

How pervasive these restrictions were in practice has been difficult to determine. Again stable isotope analysis has been used to great effect to shed light on gender variation in past diets (Müldner and Richards, 2007; Richards et al. 2006). Differences in stable isotope values between the males and females of a population can reveal gender variation that is largely unmentioned in the historical sources.

2.6. Breastfeeding and Weaning Practices

Greek dietary practices would also have varied by age group. Newborns and young children generally have diets that are significantly different from that of the general population. As few of the sources in the previous sections mention the foods generally consumed by this portion of the population, they will be discussed here. Both Roman and Byzantine medical writers expressed great interest in perinatal nutrition and health. Roman authors Soranus (2.17-18) and Galen both recommend limited feeding for the first few days with only honey given to soothe the child when it become irritated (Fildes, 1986:60). Breastfeeding was considered the best option for the child after these first few days but if the mother was unable to breastfeed and a wet nurse was not available, animal milk could be used as a substitute. Soranus (2.46) suggests the first solid foods introduced to the diet should be cereal based (e.g. softened bread and porridge) which should be eaten in connection to continued breastfeeding. Galen also recommends some consumption of vegetables and meat in addition to cereals (Fildes, 1986:60). The age at which weaning should occur depended largely on which author was consulted. Soranus recommended 18 to 24 months while Galen suggested the infant should be at least 3 years of age before weaning (Fildes, 1986:60). Byzantine and

Western European medical experts were primarily influenced by earlier medical writers and so few changes were made in breastfeeding and weaning practices (Fildes, 1988). The 4th century physician Oribasius generally follows the teachings of Soranus and Galen (Lascaratos and Poulakou-Rebelakou, 2003). Honey continued to be the first food recommended for newborns followed by breastmilk and cereals with weaning occurring around two years of age. Although the historical sources give an idea of what the medical opinions were, they give no indication of whether these practices were followed. The available historical sources and archaeological data provide little information on whether Greek women actually followed these recommendations. Stable isotope analysis has provided a way to shed light on this question (Bourbou and Garvie-Lok, in press; Dupras et al. 2001; Richards et al. 2002; Garvie-Lok, 2001).

2.7. Summary

Through an examination of the historical sources and archaeological data, a general picture of the Greek diet from the Byzantine and Frankish periods can be constructed. The detail available on what foods were available and cultural opinions about these foods is extensive. These records make it clear that the Byzantine and Frankish Greek diet relied upon cereals, oil and wine as main dietary staples. This has been corroborated by stable isotope analysis. While wheat was the more preferred grain, barley most likely made a considerable contribution to the diet, particularly after the loss of the major wheat producing areas. The consumption of millet is unclear but its importance probably varied depending on economics and the local environment. Stable isotope analysis has suggested that millet did not play a large role in the diet of many

Medieval Greek populations. Legumes were enjoyed by all levels of society but were most likely relied on more heavily by the poorer classes who had limited access to other sources of protein; this has yet to be proven with any certainty. The availability and consumption of dairy products and eggs makes legume consumption even more uncertain. While the wealthy had access to better quality and more costly varieties, dairy products and eggs were widely available to the general population. This was particularly true in the rural areas where there was direct access to animals and fowl. Stable isotope analyses to date suggest that dairy products and eggs were in fact a major component of everyday diet and legumes played only a small role. The consumption of meat during the Byzantine and Frankish periods is also difficult to determine. Domestic animals such as goat, sheep, pig and chicken were important sources of meat but wild foods such as birds and snails could also have made significant contributions to the diet. Beef was consumed but on a much more limited scale to sheep, goats and pigs. The importance of meat to the general diet is unclear at present. The upper classes appeared to have depended heavily on meat but it is not known how much meat was consumed by the lower classes. While meat consumption depended largely on economics it also depended on what the local environment could provide which could have enabled meat to make a much more significant contribution to the diet for some lower class populations. Stable isotope analyses have suggested that meat could have been a much more substantial part of the diet than the historical sources indicate. While it appears that the historical sources have underestimated the importance of meat to the everyday diet, stable isotope analyses have suggested that they have overestimated the importance of marine resources. Historical documents suggest marine resources were heavily utilized by all levels of society in a

variety of forms. While some forms (e.g. fresh fish) were generally consumed by the upper classes, enough less expensive forms such as fish sauce and salted fish were available for marine resources to have made a large contribution to the diet of the lower classes. The observance of fasting periods by the population would also have increased marine resource consumption in all levels of society. While marine resources were utilized, their actual nutritional importance to the diet is less definitive. Records show that fish were an important part of the economy and were consumed by the population, but the actual amount is not known and previous stable isotope analyses on Greek populations have shown little evidence of marine resource consumption. Class variation in meat and fish consumption does appear to have been present but how pervasive this was throughout the empire is unclear. Gender variation appears to be intimately linked with meat and fish consumption but again how true this was for all society is difficult to discern. Fruits and vegetables and honey were utilized by all levels of society and while not dietary staples these foods were consumed on a regular basis.

Byzantine infant feeding and weaning practices were heavily influenced by Roman medical opinions. Honey was recommended as the first food with breastmilk utilized after the first few days. Much like the general diet, weaning foods were heavily cereal based with the introduction of other products such as vegetables and meat occurring after weaning was finished. Whether these recommendations were actually followed by Greek women remains unclear. Stable isotope results to date suggest a late weaning age for infants but more work is needed to see if this was true for all Greek populations.

Obviously much is known about the Medieval Greek diet in general, but uncertainties remain regarding more detailed questions about the consumption of millet, legumes, meat, and fish. What infant feeding and weaning practices were undertaken by the population is also unknown. Stable isotope analysis could provide direct evidence for consumption patterns unavailable in historical sources. This thesis will focus on the dietary questions posed within this section that can be examined using stable isotope analysis of bone collagen. They will include:

1) *How significant was millet use in the valley of Stymphalos? Did it vary over time?* The information regarding millet consumption suggests that its use was variable depending on the local environment and economic level. In the drier South where the rural populations of Stymphalos and Zaraka are located, millet's ability to thrive in environments unsuitable for other grains could have made millet an important cereal for both humans and domestic animals. If there was any significant increase in millet's use over time between Stymphalos and Zaraka it could be seen as an indicator of economic stress affecting the population.

2) *How important were marine resources to the diet? Were freshwater fish consumed with any regularity?* Marine resources clearly were an important part of the Byzantine economy, although how important they were for rural poor populations is still uncertain. Both Stymphalos and Zaraka are located far enough from the coast that transportation of goods would be difficult. It is likely that preserved fish would have been the only way to receive marine resources with any regularity and even then the cost of transport could

have reduced the importance of marine resources. In addition to these problems, marine resources could have been supplanted by the use of freshwater resources. The location of a large lake nearby suggests that fresh fish were readily available to the populations of Stymphalos and Zaraka but how important the lake's resources were to the local diet still needs to be ascertained.

3) *When did weaning typically occur?* This question is extremely difficult to divine from the available historical sources and archaeological data. In general this topic was of little interest to Byzantine physicians and even if it was, these sources were inherently biased as they were written only by men. It is not known what practices women were actually following, or if they were even following a standard procedure. If the women of Stymphalos and Zaraka were following the medical suggestions of the day, weaning would be occurring late in childhood.

This thesis will now turn to answering these questions using stable isotope analysis of human remains.

Chapter 3: Stable Isotopes – Theoretical and Technical Background

The purpose of this chapter is to provide a theoretical and technical background for the stable isotope analysis described later in this thesis. It will begin with a brief description of stable isotopes in general as well as their measurement. This study will use two isotopes, carbon and nitrogen, and thus a discussion on their behaviour in biological systems will be included in this chapter. This information is necessary in order to illustrate the principles of $\delta^{13}C$ and $\delta^{15}N$ variation in foodwebs. This helps to create the background needed to understand assumptions about variation in foodstuff $\delta^{13}C$ and $\delta^{15}N$ values and its expected impact on $\delta^{13}C$ and $\delta^{15}N$ in human tissues. The chapter concludes with a review of the specific problems and concerns involved in tracing stable isotopes from human diet to human bone which is important in tracing the history of the use of stable isotopes in archaeology which will be presented at the end of the chapter.

3.1. Stable Isotopes

The following brief background section provides fundamental information on isotopes, including their measurement and notation as well as fractionation. For more detail, readers may consult a source such as Hoefs (2004). Isotopes of an element are atoms that have the same number of protons in their nuclei but a different number of neutrons. Protons and neutrons are of similar mass, but while protons possess positive electrostatic charge, neutrons do not. The charge of the nucleus determines the number of electrons that an atom possesses and thus its chemical properties. Nuclei containing the

same number of protons will thus have the same general chemical traits, regardless of the number of neutrons that are present.

There are two forms of isotopes: stable and radioactive. Stable isotopes stay constant over time and maintain their original number of neutrons and protons. Excluding any change by chemical reactions or alteration by physical processes, stable isotopes do not change in abundance through time. Radioactive isotopes, on the other hand, are unstable and will decay and change in abundance over time.

3.1.1. Measurement: Isotope abundances within a given substance are typically measured using a gas inlet mass spectrometer. Mass spectrometers separate charged atoms of different isotopes on the basis of their mass differences (Hoefs, 2004). In order for a sample to be analyzed by a gas-inlet mass spectrometer, it must first be converted into a gas (e.g. carbon is converted into CO_2). Once the sample is converted to gas, it is ionized by a beam of electrons emitted from a heated filament. These ions then pass between a series of charged plates which cause the ions to accelerate and create an ion beam. This ion beam then enters a magnetic field. Due to the differences in their masses, the lighter and heavier ions are deflected to different degrees. The separated streams of ions then pass through collector slits to impact on collector cups. The ion impacts of each collector cup are converted to electrical impulses which are amplified and converted to signals. The ratio of the frequencies of the signals put out by the different collector cups allows the abundance of the tested isotopes present in the sample to be determined.

3.1.2. Notation: Differences in isotope abundances in a given substance are usually very small, making it difficult to assess the absolute abundance of each isotope. The conventional way of expressing the isotope content of a substance is using differential notation:

$$\delta X_{std} = ((R_{sample}/R_{standard}) - 1) \times 1000$$

R_{sample} and $R_{standard}$ are the ratios of isotope abundance of a sample of the substance and of a standard, respectively. Generally they are calculated with the heavier isotope being the numerator (e.g. $^{13}C/^{12}C$). The final expression δX_{std}, uses the delta (δ) notation in parts per thousand (‰) or per mil to give the departure of the isotope content of the sample from the standard. The delta value is expressed in terms of the heavier isotope; for example, the delta value of carbon is written $\delta^{13}C$. For each element, there is a standard which is a closely measured isotopic composition whose δ value is zero by definition. This standard is defined internationally in order to ensure consistency in notation and reported δ-values.

3.1.3. Fractionation: The extra neutrons present in heavier isotopes largely do not affect the chemical characteristics of the atom, but they do add mass. The difference in mass will cause the isotopes of an element to behave differently in chemical reactions. This can result in fractionation, a shift in isotope proportions occurring during chemical reactions or physical processes.

For example, during the evaporation of water, molecules that contain the lighter ^{16}O will evaporate more readily than those containing the heavier ^{18}O. Thus, the vapor phase will contain more ^{16}O while the heavier ^{18}O tends to remain in the water phase.

Another cause of fractionation is the preferential participation of a given isotope in a reaction. In some situations, the lighter isotope of a given element is more likely to enter into a reaction, and will constitute a greater proportion of that element in the final product of the reaction than it did in the initial reactant. This is not always the case. In some reactions there is no isotopic discrimination and in other reactions, the heavier isotope is favoured over the lighter one. Because of this, experimentation must be done in order to establish the fractionation resulting from a reaction or series of reactions. Understanding fractionation is an important aspect in understanding isotopic behaviour within biological systems.

3.1.4. Stable Isotope Analysis and Ecology: For decades stable isotope analysis has been utilized by geochemists to understand global elemental cycles. Stable isotope variation within biological systems was first reported in the 1930s. Substantial field studies during the 1950s through the 1970s documented the variation seen in plants and animals (e.g. Bender, 1968; Craig, 1953; Smith and Epstein, 1971). This has allowed the development of stable isotope applications in ecology and archaeology (Peterson and Fry, 1987; Tieszen, 1991).

3.2. Carbon: Characteristics and Measurements

Carbon has two stable isotopes ^{12}C, with six neutrons, and ^{13}C, with seven. ^{12}C is by far the most common, making up 98.89% of modern atmospheric carbon with ^{13}C constituting 1.11%.[2] This ratio has not stayed constant over time. A decrease in atmospheric $\delta^{13}C$ in the atmosphere began around the nineteenth century and continues to the present day. The main cause is likely the burning of fossil fuels and forests, both of which are depleted in ^{13}C relative to the atmosphere (Marino and McElroy, 1991). In order to assess the isotopic composition of carbon in a substance, stable carbon isotope ratios are compared to the standard Peedee belemnite (PDB), a marine limestone from the Cretaceous Peedee formation of North Carolina. The form to show this is:

$$\delta^{13}C‰ = \{(^{13}C/^{12}C_{sample} - {}^{13}C/^{12}C_{standard}) \div {}^{13}C/^{12}C_{standard}\} \times 1000$$

A negative $\delta^{13}C$ value indicates depletion in ^{13}C in relation to PDB and a positive value indicates enrichment. Due to the fact that PDB is enriched relative to most living things in ^{13}C, the $\delta^{13}C$ values of organic matter are usually negative (e.g. Bender, 1971; Craig, 1953).

3.3. Carbon in Plants

In order for carbon atoms to enter the biosphere, the activity of photosynthetic organisms is needed. Photosynthetic organisms convert light energy into chemical energy through the incorporation of atmospheric carbon dioxide into their chemical pathways.

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[2] ^{14}C, the most common unstable carbon isotope, is also present in the atmosphere but in extremely small trace amounts (Clark, 1979).

This can only be done by certain organisms which include some bacteria, the algae, and the higher plants.

The stable carbon isotope variation seen in foodwebs begins with these photosynthetic organisms. The two main factors determining the $\delta^{13}C$ values in autotrophs are their habitat and the photosynthetic pathway used. The important causes of variation and the $\delta^{13}C$ values that result will be briefly summarized here; those interested in more detailed examinations should refer to studies such as O'Leary (1981) and Tieszen (1991).

3.3.1. Photosynthesis: In terms of photosynthesis there are three groups of autotrophs. The majority of autotrophs fix carbon through the Calvin-Benson cycle. Smaller in number are plants that fix carbon through the Hatch-Slack cycle or a combination of the two.

3.3.1.a. The Calvin Cycle: This most commonly used pathway sees the initial fixation of atmospheric CO_2 by the carboxylation of ribulose biphosphate (RuDP) (Calvin and Benson, 1948). The products of this reaction are then used in succeeding reactions to form carbohydrates and other components needed by the plant. Due to the fact that the initial product of this type of fixation is a three-carbon molecule (phosphoglyceric acid), plants using this pathway are known as C3 plants. Most of the crops harvested by humans, such as wheat and barley, are of the C3 variety.

C3 plants have been reported to have $\delta^{13}C$ values distributed in the -35‰ to -20‰ range (Bender, 1968, 1971; Craig, 1953; Smith and Epstein, 1971; Tieszen and Boutton,

1989). An extensive review conducted by Deines (1980) combined data from a number of studies and resulted in a range of -33‰ to -23‰ with an average value of -26‰.

3.3.1.b. The Hatch-Slack Cycle: The Hatch-Slack pathway sees the fixation of CO_2 by the carboxylation of phosphoenolpyruvate (PEP) (Hatch and Slack, 1970). The products of this initial reaction are transferred from the outer part of the leaf to the inner bundle-sheath cells. Here the CO_2 is released to be refixed to ribulose biphosphate as in the first step of the Calvin cycle (Björkman and Berry, 1972; Hatch-Slack, 1970; O'Leary, 1981). These types of plants are referred to as C4 plants as the first product of this fixation forms a four carbon molecule (oxaloacetic acid). All C4 plants are grasses; examples of C4 plants are millet and cane sugar.

C4 plants are better adapted to hot, arid environments. However, as conditions grow cooler and sunny periods decline, the C4 system is at a disadvantage and C3 plants increase in predominance. C4 plants exhibit far different $\delta^{13}C$ values, largely due to the fact that C4 plants discriminate against ^{13}C far less than C3 plants (Björkman and Berry, 1972). Smith and Epstein (1971) obtained a range of -18.6‰ to -11.5‰ for C4 plants while a survey by Bender (1971) yielded a $\delta^{13}C$ range of -19.5‰ to -11.4‰ with an average of -13.5‰. Deines (1980) reported a general range of -16‰ to -9‰ for C4 plant $\delta^{13}C$ values with an average of -13‰.

3.3.1.c. Crassulacean Acid Metabolism: The last group of plants has the ability to fix carbon using the C3 pathway or the C4 pathway. The amount of time each pathway is used largely depends on environmental factors such as temperature, availability of water

and hours of sunlight. Although these plants are relatively rare compared to C3 and C4 plants, they include succulents and cacti as well as pineapple (Ting, 1985). As there were very few CAM plants available in Byzantine and Frankish Greece it is doubtful that they made any significant contribution to human diet.

The $\delta^{13}C$ values of CAM plants generally fall between the ranges of C3 and C4 plants. The $\delta^{13}C$ values largely depend on the plants' growth conditions, which determine the photosynthetic pathway utilized to fix carbon within their tissues (Bender, 1973). The values for CAM plants ranged from -34‰ to -11‰ in Deines' (1980) survey. This range spans both the C3 and C4 observed ranges.

3.3.1.d. $\delta^{13}C$ Variation Within Plant Groups: The values of terrestrial C3 and C4 plants fall into two distinct ranges, with the $\delta^{13}C$ values of CAM plants spanning the gap between them. The variation in CAM plants can largely be explained as being the result of varying use of the two different pathways. The reasons behind the variation seen in C3 and C4 plants are less understood. Possible reasons behind this variation include interspecies metabolic differences, the effects of environmental factors (e.g. salinity, temperature, CO_2 concentration, and light intensity), the influence of artificial fertilizer, and varying nutritional status in plants (Dercon et. al., 2006; O'Leary, 1981). Despite these variations and differences in the internal $\delta^{13}C$ values of plants, there is still a clear pattern of $\delta^{13}C$ values in terrestrial plants based on photosynthetic pathways (O'Leary, 1981).

3.3.1.e. Marine and Freshwater Environments: The $\delta^{13}C$ values of photosynthetic organisms are also affected by differences between marine (and, to a lesser extent, freshwater) and terrestrial environments. This variation is largely a factor of different initial inorganic carbon sources. The initial inorganic carbon source for terrestrial environments is air; but in aquatic environments, inorganic carbon is brought into the biosphere through dissolved carbon compounds including CO_2 and carbonates. In the oceans, this carbon has a $\delta^{13}C$ value around 0‰ (Kroopnick, 1985). Atmospheric CO_2, on the other hand, has an average $\delta^{13}C$ value of around -7‰ (Craig, 1957; Hoefs, 2004). Thus the base source of carbon in marine environments is elevated by about 7‰ over the base source in terrestrial environments (Chisholm et al., 1982). The $\delta^{13}C$ values of dissolved inorganic carbon vary much more in freshwater bodies. A study by Parker (1964) found that the dissolved inorganic carbon $\delta^{13}C$ value ranged from -10‰ to -4‰ for lake and river water. Thus, depending on the body of water, the range of inorganic carbon $\delta^{13}C$ could vary from a value close to that of atmospheric CO_2 to something significantly different.

Although many studies have suggested that aquatic plants follow a C3 photosynthetic pathway, variations in dissolved inorganic carbon values, responses to growing conditions and other factors cause aquatic plants to display a wide range of $\delta^{13}C$ values (Andrews and Abel, 1979; Craig, 1953; Vizzini and Mazzola, 2003). Algae studied by Craig (1953) showed a $\delta^{13}C$ range from -8.1‰ to -17.0‰. Seagrasses are consistently enriched in ^{13}C due to the fact they fix carbon using a closed system, which causes them to have values close to that of terrestrial C4 plants (Andrews and Abel, 1979; Benedict et al., 1980). Emergent marine plants on the other hand show wide variation in

$\delta^{13}C$ values due to the fact they are able to use atmospheric CO_2, falling between the ranges of C3 and C4 plants (Smith and Epstein, 1970). Freshwater plants show wide variation but tend to have lower $\delta^{13}C$ values compared to marine plants. A survey by Deines (1980) reports a range of -30‰ to -7‰ with most values being below -17‰.

Phytoplankton, one of the major constituents of the freshwater and marine food chains, show wide variation in $\delta^{13}C$ values. Plankton from one bay showed $\delta^{13}C$ values ranging from -14.8‰ to -10.8‰ (Parker, 1964). Much like the freshwater higher plants, freshwater plankton show lower $\delta^{13}C$ values as compared to marine values.

3.4. Carbon in Heterotrophs

As heterotrophs consume autotrophs, carbon present in the plants moves into their consumers. These organisms are in turn consumed by other heterotrophs allowing carbon to pass further into the foodweb. Heterotrophs derive all their carbon from their diet, which causes their tissue $\delta^{13}C$ values to reflect the $\delta^{13}C$ composition of their food. Whole-body $\delta^{13}C$ values of heterotrophs have been demonstrated through controlled feeding experiments to be close to the $\delta^{13}C$ values of their food (DeNiro and Epstein, 1978a; DeNiro and Schoeninger, 1983). $\delta^{13}C$ variation in response to dietary $\delta^{13}C$ values has been shown for large free-ranging animals (Vogel, 1978) as well as humans (e.g. Ambrose and Krigbaum, 2003; Fogel et al., 1997). Heterotroph $\delta^{13}C$ values reflect both their habitats and the photosynthetic pathways of their food sources in predictable ways. While fractionation occurs within the plant itself, it also takes place during the incorporation of plant carbon into an animal's tissues. The reason behind this is that carbon must first go through various chemical processes in order to be integrated into the

animal's tissues. A study by DeNiro and Epstein (1978a) on a number of different species determined that for most of the species studied, whole-animal $\delta^{13}C$ values were slightly enriched in ^{13}C over that of the diet. A much more complex pattern comes to light when animals' individual tissues are examined. While some tissues are depleted in ^{13}C relative to the diet, others are enriched. Studies by both DeNiro and Epstein (1978a) and Tieszen et al. (1983) showed that rodent tissues varied significantly in $\delta^{13}C$, with hair and brain enriched and muscle, liver and fat depleted. Vogel (1978) obtained similar results for large African wild herbivores, with skin collagen, bone collagen, muscle tissue and fat showing successively lower $\delta^{13}C$ values. In addition to tissue $\delta^{13}C$ variations, different fractionation values are seen in the various metabolites. Lipids in particular are consistently depleted in ^{13}C in relation to whole-body value (DeNiro and Epstein, 1978a; Tieszen et al. 1983; Tieszen and Fagre, 1993; Vogel 1978). Specific amino acids' $\delta^{13}C$ values can also differ within a single organism (Hare et al. 1991). Thus, while it is true that the whole-body $\delta^{13}C$ of an animal may be predicted to be similar to the total $\delta^{13}C$ of its diet, some of its tissues and metabolites can be quite far from this value. One implication of this fact is when animal $\delta^{13}C$ is studied comparatively care must be taken to compare the same tissues or metabolic fractions from the animals in question.

3.4.1. Terrestrial Heterotrophs: The $\delta^{13}C$ values of land animals largely reflect the proportion of C3 to C4 plants or C3- to C4-eating animals being consumed (Tieszen et al., 1983). The wide range of $\delta^{13}C$ values seen in photosynthetic organisms is reflected in heterotrophs. A study by Schoeninger and DeNiro (1984) examining bone collagen of a number of different terrestrial mammals and birds yielded $\delta^{13}C$ values ranging from

-22.5‰ to -11.9‰. Surveys of other terrestrial animals found $\delta^{13}C$ values even outside of this range (Vogel, 1978). Theoretically, terrestrial animals consuming only terrestrial organisms should show $\delta^{13}C$ values that are within the values recorded for terrestrial plants.

The variation of terrestrial animal $\delta^{13}C$ values due to diet has been extensively studied. A number of surveys have found a difference between $\delta^{13}C$ values of browsing and grazing animals. Vogel (1978) showed a distinct separation between South African browsers and grazers, reflecting the fact that many grasses and no trees or shrubs utilize a C4 pathway, which caused grazers to show higher $\delta^{13}C$ values than those consuming trees or shrubs (Ambrose and DeNiro, 1986; Tieszen et al., 1979; Vogel, 1978). The $\delta^{13}C$ values of terrestrial grazers reflect the proportion of C3 to C4 grasses in the ground cover. In more northern areas, and during cooler and wetter climatic intervals, C3 plants predominate and terrestrial grazers have lower $\delta^{13}C$ values (Minson et al., 1975).

A further source of variation in terrestrial animal $\delta^{13}C$ values is the trophic level effect that results from the fact that an animal's whole body $\delta^{13}C$ value is slightly higher than its dietary $\delta^{13}C$ value. Studies such as Estep and Vigg (1985) and Schoeninger (1985) have documented this effect, and found a separation of roughly 1‰ between the herbivores and carnivores of single ecosystems. However, this small difference disappears once organisms from different ecosystems are grouped (Schoeninger and DeNiro, 1984).

This trophic level effect is also seen in nursing infants. Studies of modern infant-mother pairs have shown that breastfed infants are 1‰ higher than their mothers consuming pure C3 diets (Fuller et al. 2006a). Once the infants begin consuming solid

foods however, this trophic level difference disappears quickly. This trophic level effect and the complications with examining it in archaeological populations is examined in more detail in Section 7.7.

The consumption of marine organisms is an additional source of variation. The consumption of marine resources can cause variations in $\delta^{13}C$ values in terrestrial animals. Those consuming marine resources will have higher $\delta^{13}C$ values compared to terrestrial-based feeders (Szepanski et al., 1999).

3.4.2. Marine Heterotrophs: The $\delta^{13}C$ values of marine animals are often high compared to terrestrial animals. This partially reflects the difference in the initial inorganic carbon sources for both environments (Kroopnick 1985). Schoeninger and DeNiro (1984) sampled bone collagen from a number of marine mammals from along the North American west coast and found $\delta^{13}C$ values of -16.4‰ to -9.6‰. In addition, $\delta^{13}C$ values of marine animals can be affected by variations in temperature and depth. Studies conducted by Burton et al. (2001; 2002) on pinniped species along the North American west coast determined that $\delta^{13}C$ values varied depending on whether the animal was utilizing nearshore resources or offshore resources as well as what latitude the animal inhabited. Lower $\delta^{13}C$ values were seen for offshore and higher latitude feeders, but $\delta^{13}C$ values also varied seasonally due to increases in temperature. Thus migration between areas with different baseline $\delta^{13}C$ values caused variation in heterotroph $\delta^{13}C$ values (Burton and Koch, 1999; Burton et al., 2001; 2002; Hobson and Schell, 1998; Schell et al. 1989; Vizzini and Mazzola 2003). Like terrestrial heterotrophs, marine animal $\delta^{13}C$ values vary by trophic level. Consumers higher up the food chain have higher $\delta^{13}C$ values

than those lower down (Rau et al., 1983). As this brief survey suggests, marine animal $\delta^{13}C$ values vary due to a number of factors and often overlap the $\delta^{13}C$ ranges of terrestrial animals to a considerable extent. However, when terrestrial and marine animals are examined in a specific region, their $\delta^{13}C$ values are usually distinct enough for both groups to be distinguished from one another (Chisholm et al., 1982; Schoeninger and DeNiro, 1984).

3.4.3. Freshwater Heterotrophs: The $\delta^{13}C$ values of freshwater animals also vary due to differences in initial inorganic carbon sources (Parker, 1964). Freshwater animals often have lower $\delta^{13}C$ values than do marine animals (Schoeninger and DeNiro, 1984). A study by Katzenberg and Weber (1999) on Lake Baikal documented freshwater fish with $\delta^{13}C$ values ranging from -24.6‰ to -12.9‰. While freshwater animal $\delta^{13}C$ values do vary, in general they tend to have stable carbon isotope values similar to those of terrestrial C3 plant consumers.

3.5. Nitrogen: Characteristics and Measurements

Nitrogen possesses two stable isotopes: ^{14}N, which contributes about 99.63% of terrestrial nitrogen, and ^{15}N, making up the remaining 0.37%. Unlike atmospheric $\delta^{13}C$, atmospheric $\delta^{15}N$ has stayed relatively constant over time (DeNiro, 1987). Stable nitrogen isotope ratios are expressed in relation to atmospheric nitrogen (AIR). The expression for this is:

$$\delta^{15}N‰ = \{(^{15}N/^{14}N_{sample} - {}^{15}N/^{14}N_{standard}) \div {}^{15}N/^{14}N_{standard}\} \times 1000$$

Most $\delta^{15}N$ values of organic matter are positive (Mariotti, 1983).

3.6. Stable Nitrogen Isotopes in Ecosystems

Atmospheric N_2 is the ultimate source of the nitrogen present in organic compounds. However, as most organisms cannot assimilate nitrogen directly, they obtain it through various nitrogenous compounds (nitrate, nitrite, and ammonium) that are present in soil and water. These compounds are produced by diazotrophs as well as decomposition within the ecosystem. The resulting products form the base pool of biologically available nitrogen for use by autotrophs and heterotrophs (Létolle, 1980).

3.6.1. Nitrogen in Diazotrophs, Soil and Water: The compounds through which most organisms assimilate nitrogen are the products of either N_2 fixation by bacteria known as diazotrophs or the recycling of detritus nitrogen by decomposers present in the soil and water.

In diazotrophs, N_2 is fixed and then reduced to ammonia (NH_3) through a reaction catalyzed by the enzyme nitrogenase. The ammonia produced through this fixation is then utilized in further chemical reactions by the organism to synthesize a number of biomolecules, including amino acids and nucleic acids (Burns and Hardy, 1975; Postgate, 1998).

Diazotrophs can be organized into free-living and symbiotic organisms. Free living diazotrophs are those that live independently in the soil, water, or marine sediments, and symbiotic diazotrophs are those which have formed symbiotic relationships with plants (e.g. legumes). Free-living diazotrophs fix only enough nitrogen

to use for their internal processes, but diazotrophs in symbiotic relationships fix nitrogen in order for ammonia to be available to the host plant (Postgate, 1998). These nitrogen compounds, in addition to biomolecules taken from dead bacteria, allow the host plants to become less dependent on the nitrogen compounds found in the soil (Burns and Hardy, 1975).

The nitrogen compounds of diazotrophs pass to the wider environment through the death and decay of these organisms. During the decay process, microorganisms break down the nitrogen-bearing biomolecules in organic matter (e.g. dead organisms, animal waste, etc.) and release the excess nitrogen in the form of ammonia. This ammonia is then utilized by nitrifying bacteria which produces nitrate as a waste product. This nitrate in turn can either be used by denitrifying bacteria to create nitrite or reduced back to N_2 by yet other forms of bacteria. This N_2 then returns to the atmosphere or is contributed to local pools of dissolved N_2. Thus the results of the decay process are the nitrogen compounds, ammonia, nitrate, and nitrite, which form a pool of inorganic nitrogen available to the majority of plants (Postgate, 1998).

The nitrogen fixation reaction appears to show little fractionation (Delwiche and Steyn, 1970; Hoering and Ford, 1960; Kohl and Shearer, 1980). This causes the $\delta^{15}N$ values of diazotrophs to be close to atmospheric N_2 (Shoeninger and DeNiro, 1984; Wada and Hattori, 1976). However, unlike the $\delta^{15}N$ values of diazotrophs, the $\delta^{15}N$ values of the inorganic nitrogen in soils and water can vary substantially. Soil $\delta^{15}N$ values are generally higher than both the $\delta^{15}N$ values of air and those of diazotrophs and vary by locale, soil depth, soil type, and even season (Cheng et al., 1964; Delwiche et al. 1979; Rennie et al. 1976; Shearer et al. 1978). Much like soil, the $\delta^{15}N$ values of oceanic

dissolved inorganic nitrogen are usually higher than that of atmospheric nitrogen (Wada and Hattori, 1976). The range of variation within oceanic $\delta^{15}N$ values is considerable and values as high as 24‰ have been reported (Cifuentes et al. 1989). Ocean values vary due to a number of factors including geographic location, depth, and season, as well as the specific inorganic nitrogen compound tested (Cifuentes et al. 1989; Horrigan et al. 1990). These factors also affect the $\delta^{15}N$ values of freshwater systems (Cifuentes et al. 1989; Mariotti et al. 1984). The variability of soil and water $\delta^{15}N$ values and their tendency to be above 0‰ are generally due to a number of factors, including fractionation during denitrification.

Changes in soil and water ^{15}N can also be caused by the introduction of anthropogenic factors such as sewage and fertilizers into an ecosystem. These substances often have $\delta^{15}N$ values differing substantially from those typical of pristine soil and water samples. $\delta^{15}N$ values of these pollutants can vary. For example, fertilizer nitrites have generally low $\delta^{15}N$ values while the nitrates of sewage and domestic animal waste generally have higher values. This is due to the denitrification and volatization of ^{14}N-rich ammonium that occurs during the early stages of decay (Boyer et al. 2002; Mariotti et al. 1988; McClleland et al. 1997). These pollutants can have dramatic effects as they cause $\delta^{15}N$ values to shift throughout the biosphere (Galloway, 1998; Jordan and Weller, 1996; Kohl et al. 1971; Kreitler, 1979). Understanding these effects is crucial for studying diet in archaeological agricultural communities. Unlike modern fertilizers which have low $\delta^{15}N$ values, preindustrial fertilization practices (e.g. the use of human and animal waste on fields) create high $\delta^{15}N$ values. These higher values cause soil $\delta^{15}N$ values to increase, and consequently, plants grown in these manured fields have high

$\delta^{15}N$ values. Some researchers have suggested that high $\delta^{15}N$ values in archaeological plant remains could be due to this fertilizer effect (Ambrose, 1991:297; Bogaard et al. 2006; Schwarcz et al. 1999). Interestingly, there is evidence indicating that soil and water $\delta^{15}N$ values were less variable before they were affected by anthropogenic pollutants (Krietler, 1979).

3.6.2. Nitrogen in Plants: Most plants are dependent solely on the nitrogen present in soil and water. However, some plants acquire at least some of their nitrogen though a symbiotic relationship with other autotrophs. This can cause differences in the $\delta^{15}N$ values between the two groups.

3.6.2.a. Nitrogen in Non-Symbiotic Plants: The tissue $\delta^{15}N$ values of most plants are largely determined by the $\delta^{15}N$ value of the specific nitrogen pool that they utilize.

Fractionation during nitrogen uptake by terrestrial plants is generally minor and is related to nitrogen availability in the soils. In areas with high nitrogen abundances, fractionation effects as much as -5‰ can be seen (Kohl and Shearer, 1980). As the nitrogen abundance decreases, so does the fractionation effect. Plants in areas with a barely adequate supply of nitrogen show little to no fractionation effect (Kohl and Shearer, 1980; Mariotti et al. 1982). Because variation due to fractionation is quite minor, the $\delta^{15}N$ of non-symbiotic terrestrial plants is largely dependent on soil $\delta^{15}N$ (Delwiche et al. 1979; Shearer et al. 1983; Virginia and Delwiche, 1982). The end result is that as regional soil $\delta^{15}N$ vary, terrestrial plant $\delta^{15}N$ values vary accordingly.

One interesting general pattern is that higher $\delta^{15}N$ values are typically seen in non-symbiotic plants from hot, dry environments. Studies by Heaton (1987) and Ambrose (1991) observed a negative association between non-symbiotic plant $\delta^{15}N$ values and rainfall, with higher plant $\delta^{15}N$ values being seen in more arid conditions. Schwarcz and colleagues (1999) theorize that this relationship between aridity and higher plant $\delta^{15}N$ values is due to a link between climatic dryness and soil $\delta^{15}N$. They suggest that the greater the aridity, the greater the evaporation of ^{15}N-depleted ammonia from the soil, which leads to an overall ^{15}N enrichment of the soil nitrogen pool.

The fractionation associated with nitrogen uptake in marine plants is highly variable and generally responds to the concentration of nitrogen compounds found within the water (Cifuentes et al. 1989; Pennock et al. 1996; Wada et al. 1975; Wada and Hattori, 1976; Yoshioka et al. 1994). Because of this variable fractionation, determining the response of marine autotroph $\delta^{15}N$ to the local nitrogen pool $\delta^{15}N$ is more difficult than it is for terrestrial autotrophs. Some studies have shown a good relationship between marine autotroph $\delta^{15}N$ and local water $\delta^{15}N$, but others have demonstrated that marine autotroph $\delta^{15}N$ respond more strongly to local and seasonal variation in nitrogen availability than local $\delta^{15}N$ (Yoshioka et al. 1994; Pennock et al. 1996).

3.6.2.b. Nitrogen in Symbiotic Plants: A minority of plants can acquire nitrogen both from soil and water and through a symbiotic relationship with diazotrophs. In this symbiotic relationship, the diazotroph is maintained within the autotroph and the nitrogen fixed by the diazotroph is absorbed directly by its partner, reducing the plant's reliance on inorganic nitrogen compounds within the soil and water. Symbioses with diazotrophs are

seen in a variety of organisms from terrestrial, marine and freshwater environments, but the major group of interest for this study is the legumes. The legumes, which include plants such as clover, alfalfa, peas and beans, have traditionally been important agricultural crops and are important to understand for palaeodietary reconstruction.

In symbiotic plants, fractionation during nitrogen assimilation is relatively small (Kohl and Shearer, 1980). Additionally, the nitrogen compounds fixed by the symbiotic diazotrophs and then passed onto the host plant generally have $\delta^{15}N$ values close to that of air. The result is that generally, legumes and other symbiotic plants show lower $\delta^{15}N$ values than those of non-symbiotic plants grown in the same soil (e.g. Delwiche and Steyn, 1970; Delwiche et al. 1979; Shearer and Kohl, 1978; Shearer et al. 1983; Virginia and Delwiche, 1982; Virginia et al. 1989). However, the extent of the host plant's dependence on symbiotically fixed N_2 varies according to local conditions. If there is adequate inorganic fixed nitrogen available in the soil, N-fixing plants will utilize it, allowing the plant to decrease the amount needed from diazotrophs and spare the energy involved in the fixation of N_2 (Postgate, 1998). Under these conditions, the plants will have $\delta^{15}N$ values similar to that of other plants grown on the same soil (Kohl et al. 1980; Postgate, 1998). If little soil nitrogen is available and the plant is completely relying on nitrogen from the symbiont, it will have $\delta^{15}N$ values close to 0‰ (Kohl et al. 1980).

3.6.3. $\delta^{15}N$ Values in Terrestrial Environments: Within the literature there is a broad range of values reported for terrestrial plants in various ecosystems. This is the result of differences in local soil $\delta^{15}N$ and other factors affecting terrestrial plant $\delta^{15}N$ variation. A review by Schoeninger and DeNiro (1984) included terrestrial plant $\delta^{15}N$ values from a

number of studies. They ranged from -7.8‰ to +17.5‰ with a mean of about +3‰ for non-symbiotic plants, and -6.5‰ to +6.5‰ with a mean of +1‰ for symbiotic plants. Ambrose (1991) documented mean plant community $\delta^{15}N$ values ranging from -1.3‰ to 3.9‰ in a number of East African locales. Clearly, when a number of studies from a variety of ecosystems are combined, plant $\delta^{15}N$ values can vary widely. The fact that $\delta^{15}N$ values of non-symbiotic plants and symbiotic plants will often overlap completely when multiple studies are examined also complicates matters. While the N-fixers will show a lower mean and smaller range than those of non-N-fixers, the difference is often negligible in comparison to the overall range being reported.

Studies examining terrestrial plant $\delta^{15}N$ values on a more local level will see the ranges of $\delta^{15}N$ narrow, and the distinction between N-fixers and non-N-fixers become clearer. For example, Virginia and Delwiche (1982) reported that the ranges of N-fixing and non-N-fixing plants at individual collection sites in Northern California were smaller than the overall range for all the sites. The distinction between N-fixing and non-N-fixing plant $\delta^{15}N$ values improved as well. This pattern has also been seen in other studies (e.g. Ambrose, 1990; Shearer et al. 1983). Obviously while an overall range of terrestrial plant $\delta^{15}N$ values can be determined through general studies, the values of plants from specific localities must be established in order to correctly identify typical plant $\delta^{15}N$ values.

3.6.4. $\delta^{15}N$ Values in Marine Environments: Studies on the $\delta^{15}N$ values of nonsymbiotic marine autotrophs have shown regional variability reflecting the differences in $\delta^{15}N$ values between local nitrogen pools. A broad review by Schoeninger and DeNiro (1984) cited a range of around +2‰ to +16‰ for non-symbiotic autotrophs while more

restricted studies such as Wada and Hattori (1976) on a number of North Pacific locales found values ranging from +3.2‰ to +9.7‰ for marine autotrophs. A similar study conducted by Keegan and DeNiro (1988) on nonsymbiotic algae from the Bahamas cited a range of +1.7‰ to +6.2‰ in a locale where the local nitrogen pools have been substantially affected by nitrogen-fixing organisms. In contrast to the wide variability seen in nonsymbiotic marine autotrophs, the $\delta^{15}N$ values seen in symbiotic marine algae and plants are much less variable and are generally close to that of the atmosphere, ranging from around -2‰ to +2‰ (Keegan and DeNiro, 1988; Wada and Hattori, 1976; Wada et al. 1975).

3.6.5. $\delta^{15}N$ in Freshwater Environments: Like terrestrial and marine autotrophs, the $\delta^{15}N$ values of freshwater autotrophs can be affected by a number of factors including the activity of N-fixing organisms, runoff from natural and anthropogenic terrestrial sources, and the recycling of organic detritus within the local system. Due to these factors the $\delta^{15}N$ values of freshwater autotrophs can vary from freshwater system to freshwater system (Estep and Vigg, 1985). For example, a study by Estep and Vigg (1985) reported $\delta^{15}N$ values that ranged from +4.2‰ to +6‰ for green algae in a Nevada Lake system.

3.7. Nitrogen in the Heterotrophs

As heterotrophs cannot fix nitrogen for themselves, they are dependent on the nitrogen assimilated by autotrophs. Nitrogen from the diet is the only source of nitrogen for heterotrophs; thus, heterotroph tissue $\delta^{15}N$ might be expected to reflect dietary $\delta^{15}N$. However the $\delta^{15}N$ pattern is not so simple. While heterotroph tissue $\delta^{15}N$ does reflect

dietary $\delta^{15}N$, a trophic level $\delta^{15}N$ enrichment is also seen. In addition there is considerable variability between ecosystems, species, individuals, and tissues, but only some of this variability is currently understood. While these variables affect $\delta^{15}N$ values, heterotroph $\delta^{15}N$ values reflect both their habitats and the $\delta^{15}N$ values of their diet in relatively predictable ways.

3.7.1. The Trophic Level Effect and Other Variations: Early research into heterotroph $\delta^{15}N$ values in the wild revealed a ^{15}N enrichment in heterotroph tissues over that of their dietary $\delta^{15}N$ values (Wada et al. 1975). This separation between the $\delta\ ^{15}N$ value of an animal's diet and the $\delta\ ^{15}N$ value of its tissues, calculated as $\Delta^{15}N$, however was not constant. Studies conducted on different East African locales obtained a number of values including +4.3‰ found by Shoeninger (1985), +5.7‰ obtained by Ambrose and DeNiro (1986), +3.9‰ found by Sealy et al. (1987), and a range of +3.5‰ to +5.4‰ found by Ambrose (1991). A recent review by Bocherens and Drucker (2003) on the $\Delta^{15}N$ values in the Bialowieza forest in Poland found $\Delta^{15}N$ values of +3.6‰ and +4.0‰ for wolf and lynx respectively. $\Delta^{15}N$ values obtained through studies of marine and freshwater foodwebs have also shown this tight grouping, with $\Delta^{15}N$ values ranging from +2‰ to +5‰ and the majority falling between +3‰ and +4‰ (Estep and Vigg, 1985; Hobson and Welch, 1992; Sholto-Douglas et al. 1991; Wada et al. 1987; Yoshioka et al. 1994). When examined altogether the total range of the field-determined values for $\Delta^{15}N$ cited above is +2.0‰ to +5.7‰, suggesting that $\Delta^{15}N$ values of heterotrophs in natural ecosystems should fall around an average of +4‰. Recently however, there have been questions as to the usefulness of an average $\Delta^{15}N$ value. Bocherens and Drucker (2003)

suggest that using a range of values (they suggest +3‰ to +5‰ for terrestrial ecosystems) might help to better understand the variations in enrichment between predators and their prey.

In terms of an organism's overall mass balance the trophic level $\delta^{15}N$ effect seems to be caused by the excretion of wastes depleted in ^{15}N relative to the diet. This was first noticed by Steele and Daniel (1978) in the course of their research on nitrogen isotope fractionation in steers. Through their controlled feeding study of cattle they determined that urine $\delta^{15}N$ was lower than dietary $\delta^{15}N$ by an average of -1.5‰. Mammals excrete most nitrogen through their urine and this pattern results in a net excretion of ^{15}N-depleted nitrogen. This in turn requires the nitrogen retained in the animal's tissues be enriched in ^{15}N relative to the diet. Further studies such as those reviewed by Hare et al. (1991) suggest that the excretion of ^{15}N-depleted nitrogen is general in heterotrophs. Various authors (e.g. Ambrose and DeNiro, 1986; Minagawa and Wada, 1984) have suggested that this apparent generality is the cause behind trophic level ^{15}N enrichment.

3.7.2. Other Factors Determining Heterotroph $\delta^{15}N$: Dietary $\delta^{15}N$ and trophic level discrimination are the main determinants of $\delta^{15}N$ in heterotrophs; however, a number of other variables also influence $\delta^{15}N$ values.

3.7.2.a. The Arid Environment Effect: One of the largest departures from predicted heterotroph $\delta^{15}N$ values based on diet and trophic level is the appearance of systematically higher $\delta^{15}N$ values in terrestrial animals from dry environments (Ambrose, 1991; Ambrose and DeNiro, 1986; Heaton et al. 1986; Schoeninger and DeNiro, 1984;

Schwarcz et al. 1999; Sealy et al. 1987; Thackery et al. 1996). As discussed above, soil and plants in arid environments have higher $\delta^{15}N$ values than soils and plants in more humid environments (Ambrose, 1991; Heaton, 1987). However, heterotroph $\delta^{15}N$ values from these areas show even higher levels of enrichment than would be expected based on the high plant values. Why this occurs has been the focus of a number of studies. The cause behind this pattern has generally been thought to be related to water conservation and urea excretion. One possible reason for this pattern is that animals conserving water excrete urine with increased amounts of urea. During urea production, ^{15}N is discriminated against. The production of more concentrated urine containing greater amounts of urea high in ^{14}N by water-stressed animals should cause their tissues to become enriched in ^{15}N as compared to their diet (Ambrose, 1991; Ambrose and DeNiro, 1986). An alternative explanation has been put forward by Sealy et al. (1987). This study proposes that the high herbivore $\delta^{15}N$ values in arid environments are due to increased urea recycling by ruminants consuming dry-climate plants low in protein. While the urea recycling mechanism would explain the high $\delta^{15}N$ values seen in ruminants, it does not explain the equally high values seen in non-ruminants in arid environments (Schwarcz et al. 1999). In addition, the urea recycling theory is based on the assumption that herbivores in arid environments show high $\delta^{15}N$ values due to protein-poor diets. However, many studies have found high $\delta^{15}N$ values in herbivores from hot, arid areas where the plants are not poor in protein (Ambrose, 1991; Ambrose and DeNiro, 1986; Schwarcz et al. 1999). While the existence of this pattern has been clearly shown, there are still unanswered irregularities.

3.7.2.b. Effects of Nursing and Nutritional Stress: Another pattern in $\delta^{15}N$ variation is the considerable increase in tissue $\delta^{15}N$ values seen in nursing young relative to their mothers. This difference is particularly valuable in dietary analyses. Mammalian milk $\delta^{15}N$ values are similar to those of blood and other tissues meaning that offspring consuming this milk are essentially consuming the mother's tissues (Jenkins et al. 2001; Steele and Daniel, 1978). The result is that the young should be positioned one trophic level above the mother and should show higher $\delta^{15}N$ values. This pattern has been documented in a number of mammals including humans. However, care must be taken as some species do not show consistent shifts (Jenkins et al. 2001). Studies such as Fuller et al. (2006a) confirm that increased $\delta^{15}N$ values are seen in nursing human infants relative to the mother. In Fuller et al. (2006a), fingernail and hair samples taken from 8 mother-infant pairs during various times between birth and one year of age showed that the $\delta^{15}N$ values of the infants gradually increased as tissue formed in utero was replaced by tissue formed after birth. The $\delta^{15}N$ values peaked at about one trophic level above the mother's $\delta^{15}N$ values and then gradually decreased towards the mother's level when the infants' diets began to be supplemented with other foods. This phenomenon is particularly important to keep in mind when examining mammalian $\delta^{15}N$ values within one population and during examination of animals from different environments.

This elevation of $\delta^{15}N$ values, however, can be complicated by the effects of nutritional stress. Studies on mammals and birds have shown that during times of nutritional stress (due for example to poor diets or pregnancy) the $\delta^{15}N$ values can increase due to the movement of proteins from one tissue in the body to another (Fuller et al. 2004; Hobson and Clark, 1992; Hobson et al. 1993). This movement could cause

additional fractionation favouring the heavier isotope, leading to higher $\delta^{15}N$ values. Thus it must be kept in mind that infants being fed a nutritionally deficient diet (which might not include breastmilk) could still show elevated $\delta^{15}N$ values due to the recycling of protein from other tissues.

3.7.3. Literature Values for Heterotrophs: From the brief review above, it is obvious that heterotroph $\delta^{15}N$ values can vary substantially between different environments and by trophic level. When these effects are taken into consideration, however, heterotroph $\delta^{15}N$ values reflect both their habitats and the $\delta^{15}N$ values of their food sources in relatively predictable ways.

3.7.3.a. Terrestrial Heterotrophs: Literature values for terrestrial heterotrophs show clear trophic level separation when local values are examined. Herbivores are elevated a trophic level above their plant diet and carnivores further elevated above them. Depending on their diet omnivores can assume values similar to herbivores or carnivores or have values falling between the two groups. A large study by Ambrose and DeNiro (1986) examining bone collagen samples from a variety of East African mammals found that herbivores fell between a range of +4.3‰ to +10.6‰ with an average of +7.1‰ and carnivore values ranged between +9.8‰ to +17.2‰ and had an average of +11.9‰. Similar results were obtained by Schoeninger (1985) from Kenyan animals. Katzenberg (1989), who looked at archaeological bone collagen from southern Ontario, found that herbivorous beaver and deer ranged from +4.0‰ to +6.7‰ while omnivores varied significantly. Dog and raccoon values ranged from +9.3‰ to +11.9‰ while bear values

were about a trophic level lower and fell in the range of herbivores at +4.8‰ to +5.2‰. Herbivore values were also seen to vary depending on legume consumption. If an animal is consuming large amounts of legumes, it will show lower tissue $\delta^{15}N$ values than other herbivores in the area. Bone collagen $\delta^{15}N$ values of +1.1‰ to +3.7‰ were reported by Katzenberg (1989) for two woodchucks, which consume substantial amounts of legumes. These values were much lower than other local herbivore values.

While trophic level $\delta^{15}N$ patterning is visible on a local level, when terrestrial heterotrophs are examined on a broader geographical scale the pattern is erased. For example, a study by Schoeninger and DeNiro (1984) surveying bone collagen $\delta^{15}N$ values from a variety of terrestrial herbivores and carnivores from around the world found significant overlap in the $\delta^{15}N$ values of herbivores (+1.9‰ to +9.2‰) and carnivores (+5.9‰ to +10‰). Other surveys such as Thackeray et al. (1996), Sealy et al. (1987) and Heaton et al. (1986) examining southern African terrestrial animals also documented an erasure of trophic level $\delta^{15}N$ patterning generally resulting from differences in plant species consumed and in local baseline $\delta^{15}N$.

3.7.3.b. Marine Heterotrophs: Much like terrestrial heterotrophs, marine heterotrophs show good trophic level separation. However, the $\delta^{15}N$ values of marine heterotrophs are generally higher than those of terrestrial herbivores. To some extent, this is due to the higher $\delta^{15}N$ values of the nitrogen compounds typically available in marine environments. The fact that marine ecosystems generally exhibit longer food chains than those seen in terrestrial environments is also a factor. Zooplankton with their relatively low $\delta^{15}N$ values are the beginning of marine heterotroph food chains and a number of

studies have focused on determining their values. Studies from various locales have reported values ranging from +2‰ to +14‰, with the majority falling between +5‰ and +7‰ (Jennings et al. 1997; Minagawa and Wada, 1984; Schoeninger and DeNiro, 1984; Wada and Hattori, 1976). Filter feeders directly consuming zooplankton will have $\delta^{15}N$ values that fall just above them. The filter feeders will then by followed by primary and then secondary carnivores. Large marine heterotrophs generally show higher $\delta^{15}N$ values reflecting their higher position in the food chain. For example, Hobson and Welch (1992) documented the trophic level enrichment through a marine food chain in the Canadian Arctic. The study documented the progression from bivalves with species $\delta^{15}N$ values ranging from +7.9‰ to +10.8‰ through fish $\delta^{15}N$ means at +11.1‰ to +16.2‰ and finally through to marine mammals such as seals and polar bears that had values of +17.3‰ and +21.1‰ respectively. Studies such as Jennings et al. (1997) and Vizzini and Mazzola (2003) which both focused on Mediterranean marine food chains also documented this trophic level $\delta^{15}N$ enrichment.

The $\delta^{15}N$ values of marine heterotrophs in the upper trophic levels are generally higher than those of terrestrial organisms on nearby land. A study by Ambrose et al. (1997) is a good example of this. The survey found that while terrestrial heterotrophs in the Marinas Islands had $\delta^{15}N$ values averaging around +6.3‰, the $\delta^{15}N$ values of marine heterotrophs immediately offshore had a mean value of around +8.8‰, and that large deep-water marine heterotrophs further up the food chain were higher still with an average at +12.4‰. This contrast between marine and terrestrial $\delta^{15}N$ tends to be greatest in wet, cool terrestrial environments (e.g. Hilderbrand et al. 1999). In hot, arid

environments by contrast, the marine-terrestrial $\delta^{15}N$ difference may disappear entirely, as was seen by Sealy et al. (1987) for arid African biomes.

3.7.3.c. Freshwater Heterotrophs: Much like the $\delta^{15}N$ values of marine heterotrophs, the $\delta^{15}N$ values of freshwater heterotrophs vary by trophic level but will vary also by water body. For example, Minagawa and Wada (1984) found that for one Japanese lake the zooplankton had values of +6.8‰ and +9.0‰ and fish averaged around +10.7‰ to +11.6‰. In contrast, a second Japanese lake surveyed by Yoshioka et al. (1994) produced zooplankton $\delta^{15}N$ as high as +16‰. Freshwater heterotrophs also typically show higher $\delta^{15}N$ than their nearby counterparts on land. For example, Katzenberg and Weber (1999) reported the $\delta^{15}N$ values of aquatic and terrestrial heterotrophs in and around Lake Baikal. While the terrestrial herbivore $\delta^{15}N$ values ranged from +4.1‰ to +5.4‰, the $\delta^{15}N$ values of the Lake Baikal fish ranged from +7.3‰ to +13.7‰ with a seal, a top consumer in this lacustrine food chain, having a value of +14.0‰.

3.8. Stable Isotopes from Diet to Bone

From the discussion above, it is clear that much of the variation seen in animal $\delta^{13}C$ and $\delta^{15}N$ is due to patterns caused by diet and habitat. However internal variation in $\delta^{13}C$ and $\delta^{15}N$ can also have a large effect. In order to understand past diet in archaeological populations, it is vital to understand how these patterns affect human $\delta^{13}C$ and $\delta^{15}N$ values. This section deals with the factors involved in moving from $\delta^{13}C$ and $\delta^{15}N$ values in the diet to $\delta^{13}C$ and $\delta^{15}N$ in the body's tissues, in particular bone and some of the variations that can occur.

3.8.1. Fractionation Values: The topic of $\delta^{15}N$ separation between dietary protein and collagen was effectively discussed in Section 3.8.1 due to the fact that many of the observations used to establish a general $\delta^{15}N$ value for heterotrophs were made using bone collagen. Thus, the value used for $\delta^{15}N$ separation between bone collagen and dietary protein should be the same as that established for $\Delta^{15}N$ in general: around 3‰ to 5‰. However, determining the $\delta^{13}C$ separation between the carbon in mammalian bone collagen and the diet is more difficult.

During the 1970s and 1980s, the relationship between the $\delta^{13}C$ values of collagen and carbonate fractions of bone and the $\delta^{13}C$ value of the bulk diet and its components became the topic of much research (DeNiro and Epstein, 1978b; Land et al. 1980; Sullivan and Krueger, 1981). Two models were put forward to explain how carbon from the diet is incorporated into bone. The first model suggested that both collagen and apatite were synthesized from a single general pool of nutrient carbon which has a uniform $\delta^{13}C$ value (Schoeninger 1989; Schwarcz et al. 1985, Spielmann et al. 1990). Thus the $\delta^{13}C$ value of bone collagen should reflect a mass balance of the $\delta^{13}C$ values of nutrients consumed, weighted by the amount of carbon contributed by each. However, this model did little to explain the wide variations that were being seen in studies of collagen-apatite spacing. The second model, which is the model followed today, proposed that while bone carbonate is synthesized from a general pool of dietary carbon, bone collagen is basically derived from proteins in the diet (Chisholm et al. 1982; Krueger and Sullivan, 1984; Lee-Thorp et al. 1989). According to this model, the $\delta^{13}C$

value of an animal's bone collagen should primarily reflect the $\delta^{13}C$ values of proteins consumed, while the $\delta^{13}C$ of its bone carbonate reflects the $\delta^{13}C$ of its whole diet.

Research done since the models were proposed indicates that bone collagen shows a relatively poor correlation with bulk diet. Laboratory studies such as Ambrose and Norr (1993) and Tieszen and Fagre (1993) found $\delta^{13}C$ separations between collagen and bulk diet ranging from -2.2‰ to +10.0‰. This wide range of values does not support a link between bulk diet and collagen, but instead a model in which dietary protein is the major source of collagen carbon. Studies of both large and small animals support this, showing good correlations between collagen $\delta^{13}C$ and dietary protein $\delta^{13}C$ (Ambrose and Norr, 1993; Hare et al. 1991; Tieszen and Fagre, 1993). While dietary protein appears to be the main source of collagen carbon, non-protein dietary carbon is also used. Feeding studies using different proportions of C3/C4 and varying protein contents show that the incorporation of non-protein carbon into collagen $\delta^{13}C$ varied depending on the amount of protein in the diet, rising when diets poor in protein are eaten (Ambrose and Norr, 1993; Tieszen and Fagre, 1993). Thus, tissue $\delta^{13}C$ values can be affected by both the composition of the diet but also its quality.

Studies of diets based purely on C3 or C4 resources and possessing adequate protein have shown relatively consistent values for the separation between dietary protein and bone collagen. Tieszen and Fagre (1993) reported $\delta^{13}C$ separations between dietary protein and collagen of +3.7‰ and +3.8‰ for pure C3 and C4 diets, suggesting that if non-protein carbon is incorporated into collagen under a pure C3 or C4 diet, little effect is seen. In general it appears that if dietary protein and other nutrients are coming from

similar sources (for example, all C3 or all C4), the $\delta^{13}C$ separation between dietary protein and bone collagen does not vary significantly with dietary protein content.

The laboratory results discussed above are supported by studies on free-ranging large mammals. A number of different studies have shown a consistent separation between animal bone collagen and diet, with the bone collagen of large animals being about +5‰ more positive than diet (e.g. Ambrose, 1993; Tieszen and Boutton, 1989; Vogel, 1978). Archaeological human populations whose diets were shown to contain no C4 or marine components (therefore theoretically showing only a C3 component) have shown diet-to-bone fractionation values of about 5‰ for humans (Chisholm et al. 1982; van der Merwe and Vogel 1978). Further studies of human $\delta^{13}C$ have shown almost no effect on $\delta^{13}C$ due to sex or age (Katzenberg et al. 1993; Lovell et al. 1986; Schwarcz et al. 1985).While most $\delta^{13}C$ variability seen in a human group can be related to differences in diet, factors such as individual health and nutritional status and variations in metabolism can affect $\delta^{13}C$, and account for some of the variability in the $\delta^{13}C$ values of a population (Ambrose, 1993; Ambrose and Norr, 1993; Katzenberg and Lovell, 1999; Katzenberg and Weber, 1999). From the above discussion it is obvious that the relationship between bone collagen and dietary protein is complex. However, even with this complexity, the separation between collagen $\delta^{13}C$ and dietary protein $\delta^{13}C$ appears to stay around +5‰.

3.8.2. Tissue Turnover: $\delta^{13}C$ and $\delta^{15}N$ values also vary within individuals due to tissue turnover. Turnover, the process by which tissues are continually renewed with new structural elements secreted and new cells created to replace the old, can often have a

large impact on $\delta^{13}C$ and $\delta^{15}N$ values. As the turnover rate, the speed at which this occurs for a given tissue, can cause variations to be seen within tissues as well as between different types.

During turnover, newly synthesized tissues show carbon values reflecting that of the current diet. However, if the diet of an animal changes at any time, its isotopic composition may change, causing the isotopic composition of the newly synthesized tissues to shift to the new value (Hare et al. 1991; Metges et al. 1990; Tieszen et al. 1983). This shift is not instantaneous and until all of the older tissue has been replaced by new tissue with the new isotopic values, the isotopic composition of the tissues will be somewhere between those of the old and new diets. This results in the values in fact representing an artifact of the dietary change and not a diet ever eaten by the animal (Hare et al. 1991; Tieszen et al. 1983). Sequential examination of hair has been able to show this transition from old to new diet isotopic values quite well (White, 1993). However this does not happen at the same speed for all tissues. Depending on the turnover rate for each individual tissue, the $\delta^{13}C$ and $\delta^{15}N$ values of the body's tissues will vary for a certain period of time after a dietary shift has occurred until such time that all the older tissues have been replaced.

Studies such as Libby et al. (1964) have demonstrated substantial variation in turnover rate by tissue and age of the individual. Other studies have also shown that turnover rate varies due to differences in activity, health, and even stress (e.g. Katzenberg and Lovell, 1999). In some body products, the response to change in dietary stable isotope values is very rapid; these include respired CO_2 and in some cases milk (Metges et al. 1990). Bone turnover appears to be the slowest by far. Although the skeleton is a

single organ system, turnover rates can vary significantly between and within bones (Babraj et al. 2005). Long bone cortical bone turns over slowly while cancellous bone does so much more quickly (Gerhardsson et al. 1993). Thus, skeletal $\delta^{13}C$ and $\delta^{15}N$ can vary internally in any individual who has undergone a substantial dietary change in his or her lifetime. This internal variability is further added to by the fact that dental enamel and most dentine do not turn over at all. The result is that teeth reflect the stable isotope values of the diet consumed during the time of their formation (Sealy et al. 1995).

3.9. $\delta^{13}C$ and $\delta^{15}N$ Analysis in Archaeology

Attempts to apply $\delta^{13}C$ analysis to archaeological populations began as a result of research into photosynthetic pathways in plants. Archaeologists' initial interest stemmed largely from the need to understand carbon isotope fractionation in order to effectively calibrate radiocarbon dates. As the initial fractionation effect during incorporation of ^{14}C into living tissues would affect any dates estimated from the ^{14}C content of these tissues, the effects of fractionation had to be taken into account and the dates adjusted to compensate (Vogel and van der Merwe, 1977). Around the same time researchers began systematic work on the $\delta^{13}C$ values of plants and animals. With the revelation that an animal's tissues could show the $\delta^{13}C$ values of its diet, the $\delta^{13}C$ values of human remains became a potential source of information about the diets of past populations. The first applications of stable carbon to archaeological dietary analysis focused on areas where researchers had access to materials and a clear problem to solve. They included areas where maize, a C4 crop, was introduced into C3 environments (e.g. van der Merwe et al 1981; van der Merwe and Vogel, 1978; Vogel and van der Merwe, 1977) and where

human populations were consuming a mixture of terrestrial C3 and marine foods (e.g. Tauber, 1981; Chisholm et al. 1982). These initial applications of $\delta^{13}C$ analysis of archaeological remains had impressive results and led to other research applications.

Applications of $\delta^{15}N$ work to archaeological dietary analysis were not far behind that of $\delta^{13}C$. As with $\delta^{13}C$ work the first application of $\delta^{15}N$ analysis in archaeological research occurred not long after the early systematic work on plants and animals. The first study, conducted by DeNiro and Epstein (1981), attempted to look at the introduction of legumes and increased dependence on them in past diets. While $\delta^{15}N$ analysis did show some potential for archaeological purposes during this early period the use of $\delta^{15}N$ in this capacity was limited by the uncertainties of the behaviour of stable isotopes in living ecosystems.

A major theme of the stable isotope ecological research conducted in the late seventies and continuing into the nineties was trying to reduce some of the uncertainties surrounding stable isotopes in living organisms. For stable isotopes to be of any use for ecological and archaeological research, the factors causing variations in isotopic compositions had to be understood. Critical factors examined included the typical fractionation values between diet and tissue, the typical relationship between values of certain tissues, and the variation that might be expected in a population consuming a uniform diet (e.g. Ambrose, 1991; Bender, 1968; Craig, 1953; DeNiro and Epstein, 1978a; Hare et al. 1991; Schoeninger and DeNiro 1982, 1984; Smith and Epstein, 1971; Tieszen et al. 1983).

3.9.1. Applications: Applications of stable isotope analysis to archaeological questions have been diverse and have included the assessment of palaeoenvironmental changes (e.g. Iacumin et al. 1996; 2004; Zazzo et al. 2000), examining the migration of peoples and the geographical origins of individuals (Dupras and Schwarcz, 2001; Prowse et al. 2007) and dietary reconstruction, which accounts for a large amount of work conducted. In this section some of the recent trends in archaeological stable isotope studies are discussed with particular attention paid to those that are of interest to the problem of this thesis.

While some of the current trends have already been discussed (e.g. $\delta^{15}N$ patterning in arid environments), these are but a few of the areas investigated by archaeologists using stable isotopes. In recent years, research has moved toward examining more detailed dietary information. One avenue of investigation that has seen an increase in use is the study of an individual over his/her life span through the analysis of different tissues, or of different portions of the same tissue laid down at different times. In the 1990s, studies such as Sealy et al. (1995) revealed that change in diet and residence over the lifetime of an individual could be detected by comparing $\delta^{13}C$ and $\delta^{15}N$ values between teeth, bones showing slow turnover, and those bone experiencing more rapid turnover rates. Wright and Schwarcz (1998, 1999) demonstrated the potential of this concept by using comparisons of enamel carbonate $\delta^{18}O$ and dentine $\delta^{13}C$ and $\delta^{15}N$ in teeth formed at different points in infancy to reconstruct the timing and nature of the weaning process in populations from Kaminaljuyú, Guatemala. Comparisons of different portions of the same tissue were also seen to hold great potential to look at dietary changes over a long period of time (Fuller et al. 2003). Connected to these ongoing trends

is the recent exploration of analytic alternatives to human bone carbonate and collagen. Research on hair (Macko et al. 1999; White, 1993) and other soft tissues (White and Schwarcz, 1994; O'Connell et al. 1999; 2001) have shown that these, when available, can be used in a similar way to bone carbonate and collagen. Hair, when available, is particularly useful as isotopic changes along its length can be used to track dietary fluctuations over a short period of time (Macko et al. 1999; White, 1993). In addition, the comparison of tissues laid down during times of good health to tissues laid down during times of illness and stress has also been investigated as having the potential to provide information about the health and diet of past populations (Katzenberg and Lovell, 1999). Another development is the creation of methods using stable isotope values of domesticated animals as a comparison to or even as a substitute for the information gathered on human remains. These studies have great potential in understanding diet in areas with few available human remains or poor preservation. For example, Cannon et al. (1999) demonstrated that collagen $\delta^{13}C$ and $\delta^{15}N$ of dogs from pre-contact sites in British Columbia can be used to document changes in resource use over time. As domestic dogs ate many of the same foods as humans – either intentionally being fed these foods or scavenging from refuse piles – their collagen values could track changes in resource use from these sites in much the same way human collagen values are used. Domestic animal collagen $\delta^{13}C$ and $\delta^{15}N$ values have also been used as evidence of the introduction of new foodstuffs to an area. Studies in the Americas have shown their potential in tracking the introduction of maize agriculture (Burleigh and Brothwell, 1978; Finucane et al. 2006). In a somewhat different application, domestic animal bones can also be used to reconstruct animal husbandry practices, providing more detailed information on subsistence practices

(Copley et al. 2004; Lösch et al. 2006; Makarewicz and Tuross, 2006; Pechenkina et al. 2005).

A final trend appearing in recent years is the expansion into areas and cultures previously underrepresented in archaeological stable isotope work. Much of the work done in the 1980s focused on questions that could be clearly answered using stable isotopes (e.g. maize consumption, marine resource use) and thus tended to have a heavy emphasis on the New World. The last decade has seen a considerable branching out of research into other areas of the world including Asia (e.g. Katzenberg and Weber, 1999; Makarewicz and Tuross, 2006; Pechenkina et al. 2005; Yoneda et al. 2004), the Pacific (Ambrose et al. 1997; McGovern-Wilson and Quinn, 1996), Egypt and North Africa (e.g. Copley et al. 2004; Dupras and Schwarcz 2001; Dupras et al. 2001; Iacumin et al. 1996, 1998; Schwarcz et al. 1999) and particularly Europe (e.g. Arneborg et al. 1999; Honch et al. 2006; Lillie and Richards, 2000; Müldner and Richards, 2005; Polet and Katzenberg, 2003; Privat et al. 2002; Richards et al. 2000, 2006), which is where the focus of this review will now turn.

Although work had been conducted in Europe before the 1990s (e.g. Tauber, 1981), the lower isotopic variability seen among many European foods caused many researchers to focus on areas where isotopic variability was extensive enough for clear unambiguous results to be found (van Klinken et al. 2000). However, new developments within the field have allowed past diets to be investigated in greater detail and caused research in Europe to expand. In addition to work conducted on prehistoric populations (e.g. Honch et al. 2006; Lillie and Richards, 2000; Lubell et al. 1994; Papathanasiou, 2003; Richards and Hedges, 1999; Richards et al. 2000; Schulting and Richards, 2001),

archaeological stable isotope work in Europe has increasingly focused on historical peoples (e.g. Bourbou and Richards, 2007; Garvie-Lok, 2001; Iacumin et al. 1996; Mays, 1997; Müldner and Richards, 2005; O'Connell and Hedges, 1999; Polet and Katzenberg, 2003; Privat et al. 2002; Richards et al. 2006; Schutkowski et al. 1999). Of particular interest to this thesis is the work that has been conducted on the role of marine and freshwater resources and C4 grain use.

Historical sources on diet describe marine and freshwater fish as being major foods for the elite but are largely silent on if these foods were utilized with any regularity of the general population. Stable isotope analyses have shown that in many areas of Europe, marine and freshwater resources made up a minor, or in some cases, a substantial part of the diet for many populations (Arnesborg et al. 1999; Mays, 1997; Müldner and Richards, 2005; Polet and Katzenberg, 2003; Richards et al. 2006). Stable isotope analysis in Greece seems to indicate that while many populations had access to either marine or freshwater resources, few took advantage of them. However, more work needs to be conducted to ascertain if this was true for all groups and all historical time periods (Bourbou and Richards, 2007; Garvie-Lok, 2001). The use of C4 plants such as millet in Europe and specifically Greece is documented throughout history but how important they were has been vague (Teall, 1959). Stable isotopic work has confirmed that millet use varied environmentally and economically but showed that millet also varied by time period, as with the increase in use during the Ottoman period in Greece (Bourbou and Richards, 2007; Garvie-Lok, 2001). In addition to these dietary questions, interest about the weaning customs of historical populations and their change over time has significantly contributed to the research conducted in Europe (Bourbou and Richards,

2007; Fuller et al. 2003, 2006b; Mays et al. 2002; Richards et al. 2002, 2006). This research on historical cultures has shown the great potential stable isotope analysis has to add significantly to documentary sources of diet and resource use. In the future, the integration of documentary sources and stable isotope analysis to study past cultures will most likely become increasingly common once its potential is more widely known.

3.10. Summary

Isotopes, both stable and radioactive, occur in differing proportions within any element of a substance. While the radioactive isotope content of an element will change over time, the amount of the stable isotope should remain constant excluding any change by chemical reactions or physical processes. Although isotopes behave similarly in chemical reactions, their differences in weight may lead to differences in the isotopic composition of the substances involved in a chemical reaction. The discovery that there are natural variations in stable isotope abundances in ecological systems has led to the use of stable isotopes to study biological systems.

Variation in $\delta^{13}C$ values in the biosphere can ultimately be attributed to the different types of photosynthesis used by plants and differences in the $\delta^{13}C$ values of carbon available to plants in different environments. The distinctive $\delta^{13}C$ patterning of plants in marine and terrestrial environments is passed onto the heterotrophs consuming them. C3 plants in terrestrial environments have $\delta^{13}C$ values ranging from -35‰ to -20‰ with an average of -26‰, while C4 plants show $\delta^{13}C$ values between -20‰ and -10‰ with an average of -13‰. Recorded values for CAM plants, at -34‰ to -11‰, span both the C3 and C4 ranges. Terrestrial heterotrophs consuming these plants will have whole

body values slightly higher than the overall value of their diet. Consumers of C3 or C4 organisms will have whole-body values distributed around the means of the two plant types, with mixed feeders spanning the gap between them. Marine environments often have higher $\delta^{13}C$ values for both autotrophs and heterotrophs than terrestrial ecosystems. Although freshwater heterotrophs $\delta^{13}C$ values do vary, they often show values similar to those of terrestrial C3 plant consumers. This distinctive patterning can be used to detect distinctions in heterotroph feeding habits (C3 based as opposed to C4 or marine based) using tissue $\delta^{13}C$ values.

$\delta^{15}N$ values in the biosphere differ largely due to variations in autotroph $\delta^{15}N$ values which cause baseline $\delta^{15}N$ values to vary between regions. Autotroph $\delta^{15}N$ values show a general separation between symbiotic and non-symbiotic species within a given local region, with the former usually showing $\delta^{15}N$ values closer to that of the atmosphere and the latter exhibiting $\delta^{15}N$ values similar to those of the available fixed nitrogen compounds present in the soil or water. As heterotrophs consume the autotrophs and are consumed in turn, tissue $\delta^{15}N$ values increase. This trophic level effect varies but generally appears to range from 3‰ to 5‰. Ecosystem $\delta^{15}N$ values vary due to differences in baseline $\delta^{15}N$ causing heterotroph $\delta^{15}N$ values to differ substantially between regions. Terrestrial heterotroph $\delta^{15}N$ values vary widely between regions but within any given locale this range will narrow. Marine and freshwater heterotrophs also show a wide range of $\delta^{15}N$ values which the $\delta^{15}N$ values of top consumers in marine and freshwater ecosystems being higher than terrestrial ones. This is due to a combination of differences in baseline $\delta^{15}N$ and the fact that marine and freshwater environments exhibit longer food chains than terrestrial ones. As with $\delta^{13}C$ values, this distinctive patterning

can be used to detect distinctions in heterotroph feeding habits and environments using $\delta^{15}N$ values.

Field and archaeological studies have shown that animal $\delta^{13}C$ and $\delta^{15}N$ values can vary due to a number of factors including tissue turnover and fractionation. These studies reveal that bone collagen $\delta^{13}C$ and $\delta^{15}N$ values reflect those of proteins in the diet and the generally consistent separation values between bone collagen and dietary protein $\delta^{13}C$ and $\delta^{15}N$ (around 5‰ and 3‰ to 5‰ respectively) show bone collagen can be used to study the diet of past societies.

The use of stable isotope analysis to examine diet in archaeological populations increased in scope and breadth once the uncertainties regarding the streaming of $\delta^{13}C$ and $\delta^{15}N$ to human bone were better understood. The methods utilized today not only allow the use of foods in the past to be examined but also shed light on short– and long–term dietary changes, and even nursing and weaning patterns.

Based on the review above, it is clear that $\delta^{13}C$ and $\delta^{15}N$ analysis of archaeological bone collagen can help to resolve the questions put forward in Chapter 2. Previous work on other archaeological populations both from Greece and other regions has addressed similar questions successfully. Within a given ecosystem, plant and animal products, and terrestrial, marine and freshwater resources should differ clearly in their $\delta^{13}C$ and $\delta^{15}N$ values and thus the analysis of the remains of humans in this area should provide information on how these resources were being used.

Chapter 4: Sites, Samples, and Methods

The dietary questions discussed in Chapter 2 – use of millet in the diet, consumption of marine versus terrestrial resources, use of legumes versus animal protein – have been posed before for a number of different cultures and successfully examined using stable isotope analysis. In order to assess resource use at Stymphalos and Zaraka using stable isotope analysis, a sample set of human remains from each site is necessary. To provide an idea of the $\delta^{13}C$ and $\delta^{15}N$ values of some of the foods available in the region during the Early Byzantine and Frankish periods, a comparative faunal sample is also necessary. This chapter discusses the sites and samples examined in this thesis along with the methods used in their analysis. It begins with an explanation of the sites studied including their location, the natural resources available both at present and in the past, a brief historical sketch and information garnered from past excavations. This is followed by a description of the samples (both human and faunal) utilized for this study. The rest of the chapter deals with the complications associated with diagenesis and the analytical techniques undertaken in this study to assess sample quality.

4.1. Sites

The two sites chosen were the Early Byzantine community of Stymphalos and the Zarakan monastery, both situated in the valley of Stymphalos near the modern village of Stymphalia. The valley, which lies 600 m above sea level, is located in the northwest region in the Peloponnese. It is surrounded by mountains including the 2400 m Mount Kyllene which overlooks the valley from the north east. The eastern end of the valley is

dominated by Lake Stymphalia (Williams, 1983). The lake which is fed by underground streams, is home to a number of freshwater species (both native and introduced) and is one of the main waterfowl habitats in south east Europe (Bourne, 1982; Economidis et al. 2000; Vassilakis et al. 1994). During the dry summer season the lake often recedes, allowing farmers to take advantage of the rich alluvial silt found along the lake bed. In recent years the lake has been threatened by siltation causing it to expand further into the valley. The leaching of fertilizer into the water due to an intensification of agriculture has also caused the lake to become choked with reeds (Vassilakis et al. 1994). The rest of the valley is a mixture of scrub and agricultural areas. The generally moderate temperatures of the valley allow for a wide variety of products to be produced locally including fruit, nuts, honey, cheese, and grain. Stock-raising and recreational hunting and fishing are also conducted by the valley's population. It is not hard to see why this valley has been repeatedly occupied throughout the centuries.

4.1.1. Stymphalos: The ancient city of Stymphalos is located just south of the modern village of Stymphalia. The site extends for over a kilometre, stretching from the northern shore of the lake almost to the foot of the valley's surrounding ring of mountains. Unfortunately due to the expansion of the lake in recent decades much of the southern portion of the city has been flooded (Williams, 1983).

Unlike other Greek cities that are well known through historical and literary sources, Stymphalos is rarely mentioned by ancient writers. The main source of the site's fame comes from the Stymphalian birds said to have occupied the lake, whose destruction comprised one of Herakles' mythical labours. One of the few ancient sources

confirming the existence of the ancient city of Stymphalos was the fifth century B.C. lyrical poet Pindar who wrote of Hagesias, an Olympic winner, who was from Stymphalos (Olympic Ode 6). By the second century A.D. when the Roman writer Pausanias visited Stymphalos, he wrote only of a still functioning Temple of Artemis and indicated that the city was largely abandoned (8.22). The city was essentially forgotten until the nineteenth century when travelers in the area reaffirmed its existence and described the city as a collection of generally unimpressive ruins. Scholars agreed with this assessment and the site was left largely unexplored until the twentieth century (Williams et al. 1998). Beginning in 1924 and continuing until 1930 Anastasios Orlandos conducted a number of excavations in the valley. Unfortunately much of the information was lost in the following decades. It was not until the 1980s that the site was examined in any detail. The Canadian Archaeological Institute at Athens and the University of British Columbia initially surveyed the site in 1982. Continuing until 2001, researchers under Dr. Hector Williams conducted excavations as well as detailed geophysical and resistivity surveys at Stymphalos, Zaraka and the surrounding valley (Williams et al. 2002). These excavations suggest that the present city was founded about 350 B.C., but the site did see earlier occupation. Scattered artifacts dating from the Late Archaic to the Early Classical periods indicate the site was utilized prior to the fourth century B.C.; however, the exact location of the earlier settlement is still unknown. The late Classical Stymphalos was an orthogonally planned city surrounded by a roughly triangular wall built of stone and mud brick. The wall was interspersed with a number of gatehouses and artillery towers and enclosed an area about 800 m by 800 m. A variety of buildings have been identified included houses, a theatre, a palaestra, a fountain house, several temples, a sanctuary, and

a large artillery bastion. A large amount of pottery was uncovered during the course of the excavations. Both fine and coarse wares were identified by John Hayes and later by Peter Stone. The majority of the fine wares seemed to be imported to the area and the coarse wares generally made locally (Stone, 2007; Williams et al. 1997). Interestingly most of the transport and storage vessels also appear to have been made locally, indicating the possibility that the people of ancient Stymphalos were quite independent agriculturally from other areas (Williams et al. 1997). Analysis of the faunal remains found at the site was conducted by Deborah Ruscillo, who identified over 20 species. With the identification of both domestic and wild animals, some of which show signs of butchering, it appears that the inhabitants of Stymphalos were eating both domesticated animals and game (Williams, 1996).

By the late third and early second centuries B.C. signs of possible problems begin to be seen in the city. Road intrusions and large debris layers found in the streets and houses suggest that many of the inhabitants had left the city. Projectile points were uncovered in this debris level throughout the site, possibly indicating the city had seen fighting at some point. However, the city appears to have remained in use, although somewhat reduced, until the mid second century B.C. Its partial destruction and abandonment at this time coincides with an increase in Roman military activity in the area and the destruction of Corinth by Mummius in 146 B.C, possibly indicating the two events could be connected (Williams et al. 2002).

The site saw some resettlement during the Roman period. The extent of this occupation is unknown due to differential preservation preventing a complete survey of the area (Williams et al. 1997, 1998). The discovery of a number of early Christian

cemeteries built in and among the earlier structures indicates that small scale resettlement continued sporadically at Stymphalos until at least the sixth century A.D. The number of graves uncovered suggests the existence of a thriving fifth or sixth century A.D. community but its exact location has yet to be determined (Williams et al. 2002). The burials were found in and among the remains of the city of Stymphalos and near the modern village. Many of the bodies are oriented east-west with very few grave goods accompanying them. This orientation and the general absence of grave goods suggest the burials were early Christian. The few grave goods present indicate that the burials date roughly to the Late Roman/Early Byzantine Periods (4th to 6th centuries A.D.). The burial types range from simple, shallow primary interments to substantial tile or stone-covered multi-use burials. There is some evidence of reburial (for example, several skulls were found in one pit) indicating that primary burial places were being reused by the population (Williams et al. 2002). The remains were in varied states of preservation due to the different conditions present at the site. On the whole, however, the bones were in poor condition.

4.1.2. Zaraka: The Cistercian monastery of Zaraka, located just west of the modern village of Stymphalia, is the best preserved Frankish monastic site in Greece (Panagopoulos, 1979). Its location in a relatively remote valley and lack of large scale settlement in the area enabled Zaraka to survive better than its monastic counterparts located in more urban areas (Campbell, 1997). The founding of the Zarakan monastery and the other Latin monastic sites are all the direct result of the Fourth Crusade and the conquest of Greece by the Franks in the 13th century.

As discussed in chapter 2, the Fourth Crusade was originally created to rout the Muslims from the Holy Land and free Jerusalem from their control. When the goal of the crusade turned instead to the conquering of Constantinople and the Aegean, the Pope saw an opportunity to try to regain religious control of an area long held by the Eastern Orthodox Church. To facilitate this he dispatched a number of religious orders to Greece to build monasteries from which monks and nuns could proselytize to the Greek population (Lock, 1995).

The Cistercians were one of the first orders to establish itself in the Aegean.[3] Their intimate involvement with the preparation and prosecution of the Fourth Crusade and the fact that they were the favoured order for many of the crusaders allowed the Cistercians to spread rapidly in the new Frankish states. During the first half of the thirteenth century they founded twelve monasteries in Greece, one of which was the monastery of Zaraka or Saracez as it was known at the time.

In 1210 Geoffrey of Villehardouin asked Pope Innocent III to send monks from the monastery of Haute-Combe to Patras where he was planning on building a daughter house for the monks. This did not appear to have occurred as in 1225 Geoffrey asked the Chapter General (an assembly of abbots) for a group of monks to be sent for a monastery he intended to build in Achaia. This most likely resulted in the founding of the monastery of Saracez in the diocese of Corinth. Although the exact date the monastery was started is unknown, historical documents do show that by 1236 the monastery was flourishing.

Numerous historical sources dating from the 13th century attest to the fact that the monastery of Saracez was often called upon to assist in various church matters in Greece. Its importance, however, does not appear to have been long lived. The final mention of

[3] All historical information in this section is taken from Brown (1958) unless otherwise stated.

the monastery appears in 1260 when the Chapter General ordered the abbot of Daphni (a Cistercian monastery located near Athens) and the abbot of Rufinianai to inspect the location where the abbot of Saracez intended to transfer his house. No records remain as to whether this transfer ever took place; however it is likely that the monastery was abandoned around this date.

The power of the Cistercians in the Aegean did not last much past 1260. As the power of the Franks waned in Greece, the power and scope of the monastic orders also began to decline and by the late 13th century only Daphni and one or two monasteries on Crete survived.

The site of Zaraka went unexamined by researchers until the 20th century. During his survey of the nearby ancient city of Stymphalos in the 1920s Anastasios Orlandos conducted a preliminary investigation of the monastery. It was not until the 1980s that the site received a more detailed examination. In connection with their surveys of nearby Stymphalos, the University of British Columbia undertook a number of geophysical investigations of Zaraka under the direction of Dr. Hector Williams. However, detailed excavations at the site were only undertaken when the Pontifical Institute of Medieval Studies took over the site in 1993 and continued until 1997 (Campbell, 1997).

Subsequent excavations revealed a number of buildings including the ruins of a rectangular church, a gate tower and part of a fortification wall. Many of the blocks utilized in the construction of the monastery appear to have been plundered from the remains of ancient Stymphalos, located only a few hundred metres to the south.

The church, oriented southwest to northwest, measures roughly 34 m by 16 m and was constructed of walls consisting of large outer blocks enclosing a rubble core. Due to

the ruined condition of the church it is impossible to calculate the exact height of its ceiling. The church plan shows a rectangular protruding apse, single side aisles, evidence of rib vaulting and the complete absence of a transept. The lack of window architecture suggests that the church had few sources of outside light. There is very little sculptural ornamentation and what is present is very simple (Panagopoulos, 1979).

The plan of the church and its decoration help to identify the monastery as Cistercian. The design is purely Western with many elements bearing striking similarities to other Cistercian buildings located in Western Europe (Campbell, 1997). The Cistercians were well known for the uniformity of their buildings, whose architectural style was defined by a focus on simplicity of design and the utility of its elements. Thus their churches were often extremely simple, with few windows and almost no sculptural decoration (Panagopoulos, 1979).

Although the church is Western in design and decoration, the construction appears to be Greek in technique. This agrees with historical Cistercian practices. Cistercian monks generally built their own abbeys with the help of both labourers from the local population and a master builder following the plan of a mother house. The fact that Cistercians preferred to build in valleys away from urban areas is also consistent with the situation at Zaraka (Panagopoulos, 1979).

The excavations revealed little information about the date the monastery was founded. The earliest date for the site comes from a coin of St. Martin of Tours minted sometime in the early 1200s (Campbell, 1997). This date corresponds with architectural evidence which suggests the site could not have been constructed any earlier than the 1220s (Panagopoulos, 1979).

A bell tower and living quarters were also discovered connected to the church. Little evidence remains as to whether the lay brothers were in fact Greek converts but given the animosity between the Latin Church and the Greek Orthodox population, this seems unlikely. The bell tower was an intriguing find given the fact that the Cistercians very seldom constructed them in connection to their monasteries and only did so when monasteries were restricted in location and the monks might have had difficulties hearing the call to services. As the only obstacle to the monks' hearing in the 13th century valley of Stymphalos would have been wind it seems plausible that the area under cultivation by the monks might have been fairly extensive, thus causing the monks to travel out of shouting distance in order to work in the fields (Campbell, 1997; Panagopoulos, 1979). The additional discovery of irrigation channels built of rough stone suggests that the monks were utilizing the surrounding land quite effectively.

Zaraka contained few artifacts dating from the period when the monks would have been occupying the site. Campbell (1997) suggested that the large amount of ash present could be due to the monks practicing metalworking. As the Cistercians were well known for their skills in this medium, it seems plausible this might have been occurring at Zaraka (Biek, 1993).

No evidence remains as to when the monastery was abandoned by the monks but the site does appear to have been resettled. The discovery of a number of Venetian coins dating from the 14th century, bone, and pottery also dating from this period suggests an unknown group was occupying the monastery around this time. The small number of animal remains uncovered at the site enabled the identification of three different types of deer as well as wild boar. Several human skeletons were also found in a number of

locations within the church. The lack of a cohesive burial pattern and the fact that these burials includes male and female adults as well as children seems to suggest they do not date from the time the monastery was functioning. If the monastery had still been functioning when these burials took place, only males would have been present and likely all buried within a specific area of the church.

4.2. Samples

4.2.1. Human: Human bone samples were collected from the burials at Stymphalos and Zaraka during the summer of 2007 by Dr. Sandra Garvie-Lok from in-site storage facilities in Stymphalia. The minimum number of individuals recovered from Stymphalos was 30, and 7 individuals were excavated from Zaraka. In order to assess diet, it was critical to obtain a wide variety of age ranges and both sexes. This proved difficult for Stymphalos as some individuals could not be reliably identified due to poor preservation and commingling in multiple-use burials. In order to reduce the chance of sampling one individual twice, only individuals that could be identified with certainty were sampled. The Stymphalos sample included 26 individuals from the five Late Roman/Early Byzantine cemeteries (see Table 4.1). The Zaraka sample set consisted of all 7 individuals recovered at the site (see Table 4.2).

4.2.2. Faunal: A number of faunal samples were collected from Stymphalos and Zaraka in order to ascertain the stable isotope values of resources available to past peoples inhabiting the valley. Unfortunately faunal samples contemporary to the Early

Table 4.1. Stymphalos Individuals by Age and Sex

Sample	Age	Sex
CST-01	Juvenile	ND
CST-02	Neonate	ND
CST-03	Adult	ND
CST-04	Juvenile (9-10yrs)	ND
CST-05	Juvenile (4-6yrs)	ND
CST-06	Juvenile (6-8yrs)	ND
CST-07	Infant (6-12mo)	ND
CST-08	Juvenile (10-12yrs)	ND
CST-09	Juvenile (7-11yrs)	ND
CST-10	Adult (30-39yrs)	M
CST-11	Adult (>40yrs)	F
CST-12	Juvenile (10-12yrs)	ND
CST-13	Adult	M
CST-14	Adult	F
CST-15	Adult (45-49yrs)	M
CST-16	Adult	F
CST-17	Adult (>35yrs)	M
CST-19	Adult	F
CST-21	Juvenile (2-4yrs)	ND
CST-22	Adult	M
CST-23	Young adult	M
CST-24	Juvenile (ca.10yrs)	ND
CST-25	Young adult	M
CST-26	Adult	F

*ND represents samples either too young or too damaged to be sexed accurately

Table 4.2. Zaraka Individuals by Age and Sex

Sample	Age	Sex
CZA-01	Adult	F
CZA-02	Young adult	ND
CZA-03	Adult (45-49yrs)	M
CZA-04	Infant (0-6mo)	ND
CZA-05	Juvenile ca. 3yrs	ND
CZA-06	Infant (6-9mo)	ND
CZA-07	Infant (12-18mo)	ND

*ND represents samples too young or too damaged to sex accurately

Byzantine burials were not available and thus samples were collected from material dating roughly to the Early Roman Period (Williams, 1996). The reasoning behind this was that animals present during the 2nd century B.C. probably continued to be present into the 4th century A.D. Therefore they would have been available to the population occupying the valley.

The samples were collected by Dr. Garvie-Lok from material stored at Stymphalia during the summer of 2007. In total 21 samples were taken, 6 from Stymphalos and 15 from Zaraka (Tables 4.3 and 4.4). Emphasis was placed on choosing as wide a variety of different fauna as possible. The identified fauna sampled include cow, sheep, goat, pig, chicken, and grouse. A number of fish species were also represented including both freshwater (chub) and marine species (sea bream and tuna). Together these will provide an idea of the stable isotope values of resources available in the valley of Stymphalos.

4.3. Methods

In order to prepare archaeological bone collagen for stable isotope analysis, the mineral phase of the bone must first be removed and the collagen freed of as many contaminants as possible. The prepared sample is then assessed for signs of diagenetic alteration to validate its applicability for analysis. This final section deals with the methods chosen for collagen preparation and to evaluate diagenetic alteration in this study.

4.3.1. Collagen Preparation: A number of methods have been developed over the years in order to isolate collagen from archaeological bone for stable isotope analysis. A survey

Table 4.3 Stymphalos Faunal Samples

Sample	Species
CST-01f	Cow
CST-02f	Pig
CST-03f	Goat
CST-04f	Sheep
CST-05f	Goat
CST-06f	Cow

Table 4.4 Zaraka Faunal Samples

Sample	Species
CZA-02f	Pig
CZA-03f	Chicken
CZA-04f	Chub
CZA-05f	Cow
CZA-06f	Sheep
CZA-07f	Chub
CZA-08f	Chub
CZA-09f	Goat
CZA-10f	Goat
CZA-11f	Cow
CZA-12f	Tuna
CZA-14f	Sea Bream
CZA-15f	Cow

of the recent literature on bone collagen extraction, however, reveals that the majority use either techniques in which whole bone chunks are slowly demineralized in dilute HCl or a modified version of the Longin treatment. For this study, the demineralization of whole bone chunks in a dilute HCl solution was used and thus will be focused on here.

The whole-chunk method begins with the cutting of small bone chunks from the larger bone samples. Any surface contaminants are then largely removed through various

cleaning procedures. The samples are slowly demineralized by soaking in a dilute 1% to 3% HCl solution (Sealy, 1986). The time required for complete mineralization varies depending on the sample size and on whether the sample contained mainly compact or cancellous bone. The length of this process can range from a week to almost a month. The HCl solution is changed regularly until the reaction has ceased and the mineral component of the bone is gone. The goal is an intact chunk of demineralized material known as a collagen model. Often poorly preserved material fails to produce a model, leading to no sample being obtained. In some cases, the demineralized samples are treated with a 0.125M solution of NaOH to remove any humic contaminants. The whole-chunk method or a variation of it have been used by a number of researchers to study palaeodiet, including Corr et al. (2005), Garvie-Lok (2001), Harrison and Katzenberg (2003), Lee-Thorp et al. (1989), and Richards and Hedges (1999). Between researchers there is some methodological variability, generally in the form of omission of humate removal using NaOH.

When studying well-preserved material both the Longin method and those using whole bone chunks of bone show good results (Ambrose, 1990; DeNiro and Weiner, 1988; Tuross et al. 1988). However evidence suggests that for poorly preserved bones, the demineralizing of whole bone chunks is often more dependable than the Longin method. In a study conducted by Schoeninger et al. (1989) comparing both treatments, the Longin method (which uses bone powder instead of whole bone chunks) yielded material with a large portion of non-collagenous material. While the HCl-based method sometimes failed to produce any product, when material was produced it showed a more collagen-like profile. Thus the soaking of whole bone chunks (when successful) had a

greater chance of producing viable samples than the Longin method. Other studies such as Tuross et al. (1988), Schurr (1992) and Pfeiffer and Varney (2000) have all found evidence that samples treated with the Longin method often contain large amounts of non-collagenous material whereas HCl-based samples which form a collagen model do not. The reason behind this discrepancy could be the fact that samples which fail to hold together when soaked in HCl are generally discarded, resulting in the elimination of many of the non-collagenous contaminants which are retained in the Longin treated samples.

NaOH treatment of the collagen has been omitted in a number of studies. Researchers such as Bocherens et al. (1999) and Chisholm (1989) have cited sample loss as a reason to avoid using NaOH during collagen extraction. Some loss of sample during the NaOH treatments has been documented (e.g. Bocherens et al. 1999; Katzenberg, 1989; Stafford et al. 1988) but the use of short treatment times (on average less than 20h) generally assures that the loss is minimal. The inclusion of the NaOH treatment seems particularly prudent when one considers that some of the humic contaminants removed by NaOH have $\delta^{13}C$ values distinct from those found in collagen and if left in the sample could distort its $\delta^{13}C$ value (Katzenberg, 1989).

4.3.2. Diagenesis: For stable isotope analysis to be of any use in examining the past, the archaeological materials it is applied to must retain the isotopic values they had in life. If these values were altered significantly while the objects were buried, all results obtained from their study using isotopic analysis would be questionable. In general archaeological isotopic analysis is conducted on ancient human or animal bone, except in those rare

cases where other tissues such as hair or mummified tissues are present. As this study examines bone collagen, only the effects of diagenesis on bone collagen will be reviewed.

Initial studies on archaeological bone collagen seemed to indicate that intact collagen $\delta^{13}C$ and $\delta^{15}N$ values could be and were being recovered (Bender et al. 1981; Chisholm et al. 1982; DeNiro and Epstein, 1981; Schoeninger et al. 1983; van der Merwe et al. 1981; van der Merwe and Vogel, 1978; Vogel and van der Merwe, 1977). However, cautions soon arose regarding the chemical integrity of archaeological bone samples. Studies such as DeNiro (1985) showed that some preserved animal bones yielded collagen $\delta^{13}C$ values which did not reflect the animals' known feeding habits, demonstrating that diagenesis could affect archaeological bone collagen samples. Concerns about contaminants from the burial environment affecting archaeological bone collagen $\delta^{13}C$ and $\delta^{15}N$ values prompted further studies (Ambrose, 1990; Masters, 1987; Nielson-Marsh and Hedges, 2000a, 2000b; Schoeninger, 1989; Stafford et al. 1988; van Klinken, 1999; van Klinken and Hedges, 1995). In order to try to identify bone collagen samples whose stable isotope values have been altered by diagenesis, these studies developed a number of quality control indicators. The preservation indicators used in this study will be briefly reviewed in the sections below.

4.3.2.a. Collagen Yield: The collagen yield of a sample is defined as the final dry weight of the extracted collagen as a proportion of the initial dry weight of the sample prior to treatment. The rationale behind using collagen yield as an indicator of diagenesis is that if most of the collagen in the sample has vanished, it stands to reason that the integrity of what is left could be compromised. In general, the stable isotope literature regarding

collagen yield agrees that very low yields should be considered suspect (Ambrose, 1990, 1993; DeNiro and Weiner, 1988; Tuross et al. 1988; Schoeninger et al. 1989; van Klinken, 1999; White et al. 1993). However determining the point at which samples should be rejected has varied. Schoeninger and DeNiro (1982) and Tuross et al (1988) suggested that samples with collagen yields below 5% to 6% should be rejected. White and Schwarcz (1989) and White et al (1993) have suggested that anything higher than 1% is acceptable for stable isotope analysis. The acceptance of such a low value is in agreement with research by DeNiro and Weiner (1988) which indicated that sample quality only dropped sharply between 1% and 2% collagen yield and anything higher than 2% was acceptable. Several recent studies (e.g. Honch et al. 2006; Le Huray and Schutkowski, 2005; Mays, 1997; White et al. 2001) have used cut-off points in the 1% to 2% range. However determining specific cut-off ranges is purely arbitrary and thus the range of acceptable collagen yields generally varies depending on the conditions found at each site. Some authors (e.g. Ambrose, 1990; Bocherens et al. 1999; White et al. 2001) have also recommended checking for statistically significant relationships between collagen yields and collagen $\delta^{13}C$ and $\delta^{15}N$ and in cases where these relationships appeared rejecting those samples with low yields.

4.3.2.b. Collagen Model Quality: As stated above, the goal of using dilute HCl to demineralize whole chunks of bone is to produce an intact collagen model. The reason for this is that the appearance of the model reflects the amount of intact collagen molecules in the sample and thus can be used to determine if the sample has been altered in any way by diagenesis (Hare, 1980). Studies by Schoeninger et al. (1989) and Tuross et al. (1988)

documented that well-preserved bone tended to produce intact collagen models which served as a good indicator of the sample's collagen quality. These findings have led many authors to recommend the successful formation of a collagen model as an indicator of good collagen quality (e.g Aufderheide et al. 1994; Katzenberg and Weber, 1999; Tuross et al. 1988; Schoeninger et al. 1989; Ubelaker and Owsley, 2003).

Although many authors utilize the whole-chunk method and thus create collagen models, many fail to mention model formation as an indicator for diagenesis. This is largely the result of the fact that researchers automatically check for intact samples and reject those that fail to form a model, thus eliminating any mention of the indicator in their studies (e.g. Iacumin et al. 1998; Nicholson, 1998). The unfortunate consequence of this is there is often no mention of what exactly constitutes an intact model. Samples do not either successfully create a model or fail completely. Due to varying preservation of the bone, collagen models can range from solid through to fragmentary and soft and finally failing to form anything. Thus like collagen yield, the rejection of a sample due to the quality of its collagen model largely depends on the researcher, the conditions found at the site and other preservation indicators.

4.3.2.c. C/N Ratio: Atomic C/N ratio is one of the most frequently used indicators of diagenesis in archaeological stable isotope analysis. Recent studies such as Bourbou and Richards (2007), Clayton et al. (2006), Finucane et al. (2006), Honch et al. (2006), Papathanasiou (2003), and Pechenkina et al. (2005) have all used it to determine collagen quality. C/N ratio is measured using an elemental analyzer (Ambrose, 1993). C/N ratios are useful as indicators of diagenesis for several reasons. Evidence suggests that as the

collagen in a sample starts to break down and be lost, the carbon or nitrogen within it can be preferentially lost as well. When this occurs, it causes the C/N ratio of the sample to shift thus indicating that the collagen has been altered by diagenesis (Ambrose, 1990; Schoeninger et al. 1989). Shifts in C/N ratios can also be seen if carbon rich contaminants (such as lipids) are not eliminated from the sample. In a study of intact modern bone collagen, the C/N ratios ranged from 2.9 to 3.6 (DeNiro, 1985). Further studies using archaeological bone collagen samples revealed that bone samples with C/N ratios within the 2.9 to 3.6 range typically retained collagen-like amino acid compositions and had $\delta^{13}C$ and $\delta^{15}N$ values consistent with the animals' known diet and habitat (Ambrose, 1990; DeNiro, 1985; Masters, 1987). In contrast, the studies showed that bone collagen samples with C/N ratios falling outside of the 2.9-3.6 range showed aberrant amino acid compositions and shifted $\delta^{13}C$ and $\delta^{15}N$ values. The studies also revealed that there was a correlation between the apparent physical preservation of a bone collagen sample and its C/N ratio. While well preserved samples had C/N ratios that generally fell within the 2.9-3.6 range, the C/N ratios of poorly preserved samples were much more erratic and were often outside the accepted range.

Although the correlation between preservation level and C/N ratio is clear, it does not mean that bone collagen samples showing good C/N ratios have not been affected by diagenesis (DeNiro, 1985). Studies such as Ambrose (1990), and van Klinken and Hedges (1995) have confirmed that in some cases, bone collagen samples with acceptable C/N ratios also exhibited significant diagenetic changes. Thus there is always the chance that samples with C/N ratios within the 2.9-3.6 range have in fact been contaminated. Therefore, in order to reduce possible misinterpretations of a collagen sample's C/N

value, many authors combine the measuring of C/N ratios with other diagenetic indicators such as C and N content and collagen yield (Ambrose, 1990; Finucane et al. 2006; Honch et al. 2006; Polet and Katzenberg, 2003).

4.3.2.d. C and N Content: The final indicators of collagen diagenetic alteration used by this study are C and N content (%C and %N). The %C and %N of a collagen sample expresses the concentration of the two elements within the sample. Like C/N ratio, the %C and %N measurements are calculated by putting the sample through an elemental analyzer. A study examining modern mammalian collagen suggested that for modern collagen samples %C typically ranges from 15% to 47% and %N values are generally within the 5% to 17% range (Ambrose, 1990). In the same study Ambrose (1990) also measured archaeological bone collagen %C and %N content. The results suggested that when the archaeological collagen had low %C and %N contents the collagen had been altered in some way. Bone collagen samples showing %C and %N values below the modern ranges had low yields and C/N ratios outside the accepted 2.9-3.6 range. Thus it appeared that %C and %N could be useful in determining whether collagen had been affected by diagenesis. Unfortunately, the consistency of this method is questionable

A number of studies examining the usefulness of %C and %N values have suggested that the measurement is best used in combination with other diagenetic indicators such as C/N ratio. Studies have shown that samples can show poor %C and %N but show good quality but can still have intact collagen (Iacumin et al. 1998; Pfeiffer and Varney, 2000). Researchers who have utilized %C and %N along with other indicators such as C/N ratio and collagen yield to determine diagenetic alteration include

Finucane et al. (2006), Keenleyside et al. (2006), Polet and Katzenberg (2003), Pearson et al. (2007), Schulting et al. (2008) and Schutkowski et al. (1999).

4.3.3. Bone Collagen Preparation and Preservation Assessment: For this study, collagen samples were prepared by slowly dissolving whole bone chunks in a dilute HCl solution which was then followed by a NaOH treatment. The exact procedure is outlined here. Small chunks of bone were first broken off from the sample. The inner and outer surfaces were cleaned with a Dremel tool to remove any surface contaminants and the sample was then cleaned thoroughly with distilled water and a toothbrush to remove any remaining dirt and rootlets. The chunks were then placed in beakers partially filled with distilled water and cleaned in an ultrasonic cleaner with the water being changed periodically until it stayed clear. The samples were given a final rinse in distilled water and then left to air-dry for at least 12 hours. Once the samples were dry, they were weighed and placed into a beaker with ca. 100ml of 1% HCl solution. The samples were left to sit, with the HCl solution being changed every two days until the bone was completely demineralized. The signs of this, according to Schoeninger et al. (1989), are the cessation of bubbles (which are caused by the reaction of the acid and the bone mineral), softening of the sample and a translucent appearance. The samples were left in the HCl solution at least a day after this stage had been reached in order to assure that all bone mineral had completely dissolved. Once the sample was completely demineralized it was rinsed to neutrality by rinsing and soaking the sample in distilled water for about 2 days. The samples were then soaked in ca. 100ml of 0.125M NaOH solution for 20 hours. The extreme fragility of some of the samples (e.g. CST-08, CZA-02f), however, led to this step being modified

for these samples. In order to preserve as much of the sample as possible, they received a shorter NaOH treatment of about 4 hours. After the NaOH soak, the samples were again rinsed to neutrality through rinsing and a 24 hour soak in distilled water. Once neutral, the samples were placed in weighed scintillation vials, frozen, and freeze-dried. Finally the samples were reweighed and were then ready for analysis. Prepared samples were analyzed at the Biogeochemical Analytical Laboratory of the University of Alberta Department of Biological Sciences, using a continuous flow stable isotope ratio mass spectrometer (CF-IRMS) coupled to a Eurovector 3000 high temperature elemental analyzer (EA). The measurement accuracy was 0.1‰ for $\delta^{13}C$ and 0.2‰ for $\delta^{15}N$.

During preparation, collagen model quality was noted for each sample. As stated in Section 4.3.2.b., depending on the preservation of the bone, collagen models can range from solid through to fragmentary and soft and finally failing to form anything. Thus samples that fail to create a completely solid model could in fact still have viable collagen. Due to this, a set of quality categories created and used by Garvie-Lok (1993; 2001) was adapted to assess the quality of the collagen model. The use of these categories by Garvie-Lok (1993, 2001) to assess a large number of bone collagen samples from a variety of regions confirmed their value in determining collagen model quality. These were as follows:

Fail: no visible material recovered
Bad: no model present, only feathery bits recovered
Poor: soft, deformable partial model with some feathery bits
Fair: soft deformable intact model
Good: intact model, somewhat soft but not deformable
Excellent: firm intact model, retains shape and look of original bone sample

This categorization of the samples was done in order to assess collagen model quality in connection with the other diagenesis indicators and thus identify samples which appeared

to be of dubious quality. Samples with collagen yields below 2% were seen as suspect; however, in cases where all other preservation indicators were acceptable the samples were included in the study. C/N and %C and %N were measured on the Eurovector elemental analyzer. C/N was calculated for all samples, with the acceptable range of 2.9-3.6 recommended by DeNiro (1985) being used. The acceptable limits for %C (15-47%) and %N (5-17%) defined by Ambrose (1990) were also used here to assess sample preservation.

4.4. Summary

The two sites chosen for study were the Late Roman/Early Byzantine site of Stymphalos and the Zaraka Monastery, both located in the valley of Stymphalos. The temperate nature of the valley and the presence of Lake Stymphalia along the eastern end enable the inhabitants to grow a number of foods locally and for the surrounding area to be utilized for game and fish. 30 individuals were sampled from Stymphalos and date roughly from the Late Roman/Early Byzantine resettlement of the area. 7 individuals from Zaraka dating after the 13th century abandonment of the Cistercian monastery were also sampled. In order to ascertain the stable isotope values of resources available to past peoples inhabiting the valley 21 faunal samples were taken: 6 from Stymphalos and 15 from Zaraka. The samples were prepared by demineralizing whole bone chunks in an HCl solution followed by a NaOH treatment in order to remove humates. They were then analyzed using a continuous flow stable isotope ratio mass spectrometer. While archaeological bone collagen does contain stable isotope values that can be studied the values can be altered through diagenesis. In order to assess if the samples retained the

stable isotope values they had in life a number of preservation indicators were utilized including collagen yield (the amount of collagen still present), collagen model quality (how intact the sample is), C/N ratio (amount of carbon to nitrogen in the sample) and C and N content (the percentage of carbon and nitrogen in the sample).

Chapter 5: Results and Assessment of Sample Preservation

This chapter presents the results of the stable isotope analysis and evaluates the evidence for diagenetic alteration of collagen in the bone samples analyzed. The quality of the samples is assessed for each preservation indicator and the results are presented and then discussed. Sample preservation did vary slightly, but in general the collagen samples were of good quality, and very few samples had to be discarded outright. However there were some samples that showed contradictions in their indicators of diagenesis. The reasoning behind their inclusion into the study will therefore be discussed in detail.

5.1. Bone Collagen Preservation

The bone collagen samples were checked for quality using the criteria set forward in Chapter 4. The preservation appeared to be good for both Stymphalos (Table 5.1) and Zaraka (Table 5.2) and collagen $\delta^{13}C$, $\delta^{15}N$, and C/N data were obtained for all samples. Quality controls were assessed individually and then compared to each other to determine which samples to keep, which had to be rejected and which showed borderline acceptability. All samples were first assigned a category based on the quality of their collagen models. Most samples created excellent-to-fair collagen models with none failing to produce any material at all. The poorest collagen models were associated with the Stymphalos faunal material (CST-01f to CST-06f). The difference between these samples and the others from Stymphalos could stem from the fact that many of the faunal samples show evidence of burning and were excavated from areas of the site known to

Table 5.1: Stymphalos Human and Faunal Samples

Sample	Collagen Data						
	Yield (%)	$\delta^{15}N$ (‰AIR)	$\delta^{13}C$ (‰PDB)	C/N	%N	%C	Model
Stymphalos Human							
CST-01	5.5	12.53	-15.55	3.2	16.64	45.94	excellent
CST-02	6.0	9.74	-13.04	3.2	15.95	44.24	excellent
CST-03	10.8	9.25	-18.46	3.2	17.18	46.73	excellent
CST-04	8.3	8.33	-18.45	3.2	16.84	46.28	excellent
CST-05	5.7	9.07	-18.35	3.3	16.11	45.90	excellent
CST-06	2.5	8.42	-18.50	3.4	15.16	44.25	good
CST-07	7.9	11.29	-17.77	3.3	15.73	44.90	good
CST-08	4.5	8.33	-19.63	3.2	16.37	45.58	poor
CST-09	2.6	8.41	-19.49	3.2	16.40	45.08	poor
CST-10	8.6	9.33	-19.29	3.2	16.86	46.39	excellent
CST-11	11.3	8.68	-19.73	3.2	17.00	46.41	excellent
CST-12	13.6	7.33	-19.55	3.2	16.76	45.91	excellent
CST-13	11.6	8.77	-19.55	3.2	16.63	45.66	excellent
CST-14	13.9	9.22	-19.41	3.2	16.78	45.91	excellent
CST-15	12.7	8.89	-19.87	3.2	16.79	45.89	excellent
CST-16	11.5	8.80	-19.44	3.2	16.16	44.47	poor
CST-17	2.0	8.20	-19.54	3.3	15.81	44.08	bad
CST-18	1.6	8.11	-20.21	3.5	12.98	39.39	bad
CST-19	8.4	8.42	-19.44	3.2	16.68	45.77	excellent
CST-20	0.7	11.01	-19.67	4.6	7.16	28.10	bad
CST-21	10.1	8.08	-18.60	3.2	17.77	48.27	excellent
CST-22	6.4	7.66	-19.50	3.2	16.27	44.48	excellent
CST-23	10.4	9.29	-19.14	3.2	16.72	46.05	excellent
CST-24	2.9	8.87	-18.77	3.3	15.94	45.31	excellent
CST-25	2.3	9.29	-18.99	3.3	16.22	46.09	excellent
CST-26	10.1	9.01	-18.62	3.2	16.53	45.25	excellent
Stymphalos Faunal							
CST-01f	7.7	4.04	-21.51	3.2	14.58	40.07	bad
CST-02f	2.5	3.44	-21.43	3.3	13.87	39.06	bad
CST-03f	8.9	5.15	-20.00	3.2	12.47	34.69	bad
CST-04f	5.3	4.61	-21.09	3.3	12.56	35.24	bad
CST-05f	6.6	4.37	-20.76	3.2	13.95	38.14	bad
CST-06f	2.9	4.12	-20.71	3.2	16.08	44.59	bad

Table 5.2: Zaraka Human and Faunal Samples

Sample	Collagen Data						
	Yield (%)	$\delta^{15}N$ (‰AIR)	$\delta^{13}C$ (‰PDB)	C/N	%N	%C	Model
Zaraka Human							
CZA-01	10.3	8.50	-16.88	3.2	17.57	47.83	excellent
CZA-02	8.7	10.77	-17.25	3.2	16.90	46.88	good
CZA-03	11.0	8.51	-18.22	3.2	16.78	46.24	fair
CZA-04	8.9	12.99	-16.95	3.4	14.44	41.81	excellent
CZA-05	4.9	10.82	-17.81	3.2	16.37	45.23	excellent
CZA-06	10.6	11.22	-16.36	3.2	16.48	45.18	excellent
CZA-07	3.4	12.26	-13.08	3.2	16.83	46.38	excellent
Zaraka Faunal							
CZA-01f	0.3	9.57	-19.01	3.7	7.29	22.84	good
CZA-02f	2.4	5.37	-19.86	3.4	13.25	38.99	bad
CZA-03f	2.1	4.56	-21.07	3.4	15.39	44.50	excellent
CZA-04f	1.3	9.84	-26.88	3.3	17.00	48.56	good
CZA-05f	5.0	4.42	-20.69	3.3	15.26	43.09	good
CZA-06f	2.9	5.20	-19.75	3.4	13.78	40.36	fair
CZA-07f	3.1	9.82	-27.46	3.1	16.42	43.17	good
CZA-08f	4.6	8.71	-24.42	3.2	15.96	43.27	good
CZA-09f	8.7	4.63	-20.80	3.2	15.96	44.05	good
CZA-10f	10.5	4.96	-20.48	3.3	15.63	44.20	excellent
CZA-11f	3.8	5.13	-20.99	3.2	17.45	48.63	fair
CZA-12f	7.4	9.59	-10.40	3.2	15.81	43.79	excellent
CZA-13f	11.6	10.35	-25.16	3.2	18.30	50.80	excellent
CZA-14f	4.4	7.45	-12.07	3.2	10.18	28.05	poor
CZA-15f	5.0	4.76	-21.26	3.1	15.33	40.58	excellent

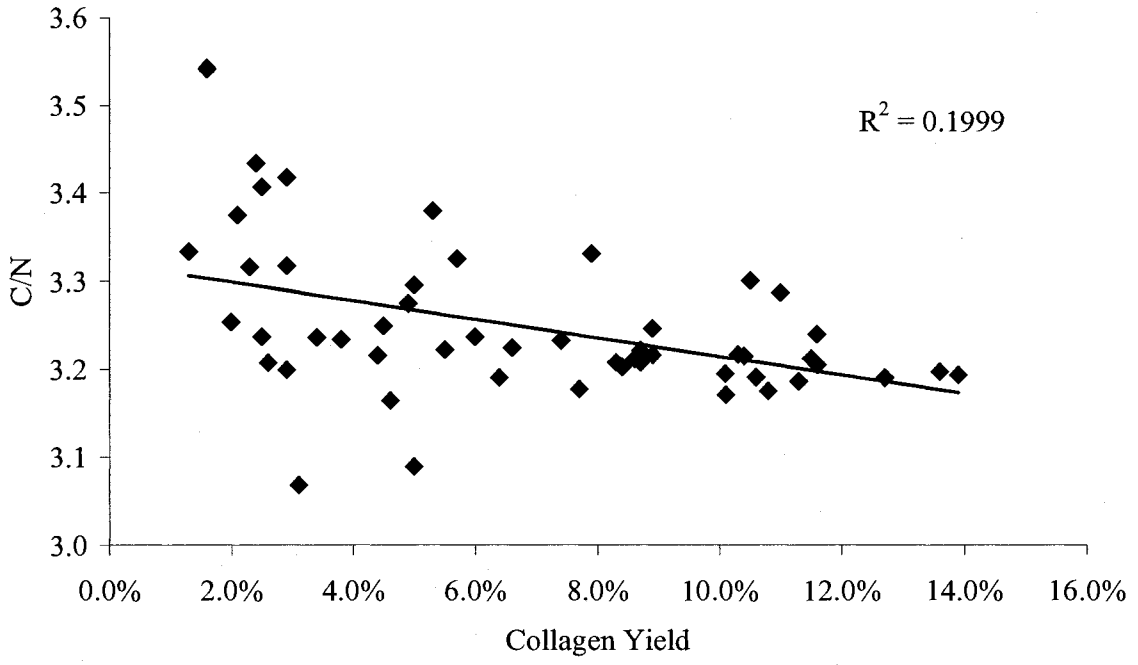
flood periodically (Garvie-Lok, Williams per comm.). This could have affected the bone enough to lead to poorer collagen models. While the Stymphalos faunal collagen models were of bad apparent quality, the samples showed acceptable C/N ratios, %C and %N values within the ranges set by Ambrose (1990) and good yields, and thus they were included within the study. Other bone samples showing poor to bad collagen models (CST-08, CST-09, CST-16, CST-17, CZA-02f, CZA-14f) also showed poor apparent

physical preservation, with the majority showing staining and a chalky appearance. However, like the Stymphalos faunal material, the other preservation indicators suggested the remaining collagen was still usable and they were kept. These results emphasize the difficulty in using model appearance as a quality indicator as many samples that show poor preservation have other preservation indicators suggesting the collagen is intact. Out of all the samples only two (CST-18, CST-20) had other preservation indicators suggesting the collagen might not show intact $\delta^{13}C$ and $\delta^{15}N$ values.

Collagen yield was relatively low for all samples and ranged from 0.3% to 13.9%, with a mean of 6.6%. All samples below the 2% cutoff were seen as suspect. Generally these four samples also showed other indications of contamination. However one sample (CZA-04f) with a yield below 2% did have a good collagen model, an acceptable C/N ratio and %C and %N within the ranges set for the study and was kept in the study.

C/N ratios of all samples ranged from 3.1 to 4.6 with a mean of 3.3. Only two samples had C/N ratios falling outside the range set by DeNiro (1985) and thus were omitted from the sample set. Once these samples were omitted, the sample set was tested to see if a relationship could be seen between C/N and collagen yield (Figure 5.1). As collagen yield decreases, C/N increases ($F = 12.49$, $p < 0.05$). For the samples with collagen yields above 3% C/N remains within the 3.1 to 3.4 range, close to that of modern collagen. Below this point, C/N ratios above the 3.4 range begin to appear, and it is only after collagen yields are below 2% that C/N begins to fluctuate beyond the 3.6 range accepted as the upper boundary of good C/N values. While it is clear that sample quality is poorer at lower yields, most of the samples still appear usable and thus are kept.

Figure 5.1: C/N vs. Collagen Yield, Omitting Outliers



%C and %N values generally stayed within the boundaries set by Ambrose (1990). %C ranged from 22.8% to 50.8% with the majority falling around 43% and %N ranged from 7.2% to 18.3% with an average of around 15%. Only 3 samples (CST-21, CZA-01f, CZA-13f) had both %C and %N falling outside the upper boundaries suggested by Ambrose (1990). While few fell outside of the accepted range, %C and %N values that differed substantially from the majority were also examined carefully for contamination. As the sample %C and %N values generally clustered closely together, the departure of these few values from the cluster was seen as suspicious. However, if the other preservation indicators showed good collagen was present, the samples were conditionally kept. When collagen C/N is compared to %C and %N (Figures 5.2 and 5.3), it is seen that sample C/N shows no relationship to %C ($F = 1.83$, $p > 0.05$). However the relationship between %N and C/N is significant with %N decreasing as C/N increases (F

= 11.14, $p < 0.05$). This patterning seems to suggest that a degradation of collagen in this sample set involves the presence of contaminants of low N content increasingly accounting for more of the sample weight as collagen yields decrease.

In total, only four samples were completely rejected from the study. These reasons behind their rejection are outlined in Table 5.3 (below). Many more samples

Table 5.3: Samples Rejected From Study

Sample	Collagen Data					
	Yield	**C/N**	**%N**	**%C**	**Model**	**Reason**
CST-18	1.6%	3.5	13.0	39.4	bad	yield, model quality, C/N
CST-20	0.7%	4.6	7.2	28.1	bad	yield, model quality, C/N
CZA-01f	0.3%	3.7	7.3	22.8	good	yield, C/N, %C, %N
CZA-13f	11.6%	3.2	18.3	50.8	excellent	%C, %N

(CST-01f, CST-02f, CST-03f, CST-04f, CST-05f, CST-06f, CZA-02f, CZA-11f) seemed to lie along the borderline of acceptance and rejection. These samples, which all happened to be faunal, had at least one preservation indicator suggesting the sample be rejected, but in all cases, the samples showed good C/N ratios and good collagen yields. In addition, their $\delta^{13}C$ and $\delta^{15}N$ values were largely unremarkable as each fell within the average isotope values of its specific species and all corresponded well with known faunal stable isotope values from nearby locations (Garvie-Lok, 2001).

Once the rejected samples were eliminated from the data set, the preservation indicators were compared to each other and then to the samples' $\delta^{13}C$ and $\delta^{15}N$ values. C/N and yield (Figure 5.4) again showed a significant relationship but no significant correlation appeared between $\delta^{13}C$ and yield ($F = 0.74$, $p > 0.05$), C/N ($F = 0.18$, $p >$

Figure 5.2: Collagen %C vs. C/N, Omitting Outliers

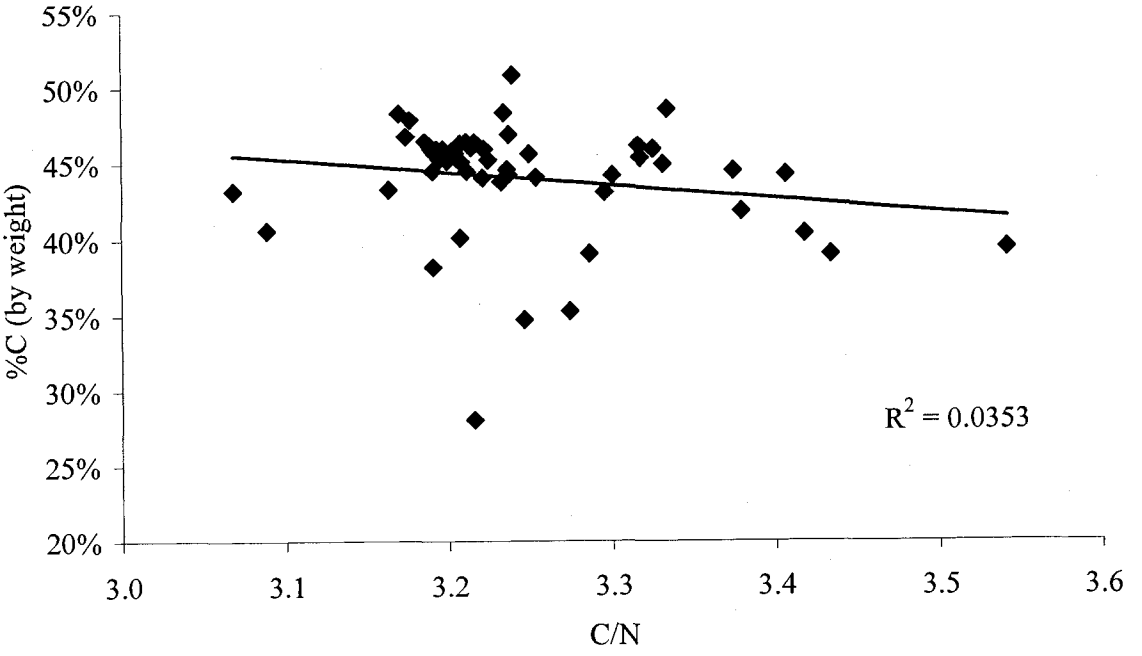


Figure 5.3: Collagen %N vs. C/N, Omitting Outliers

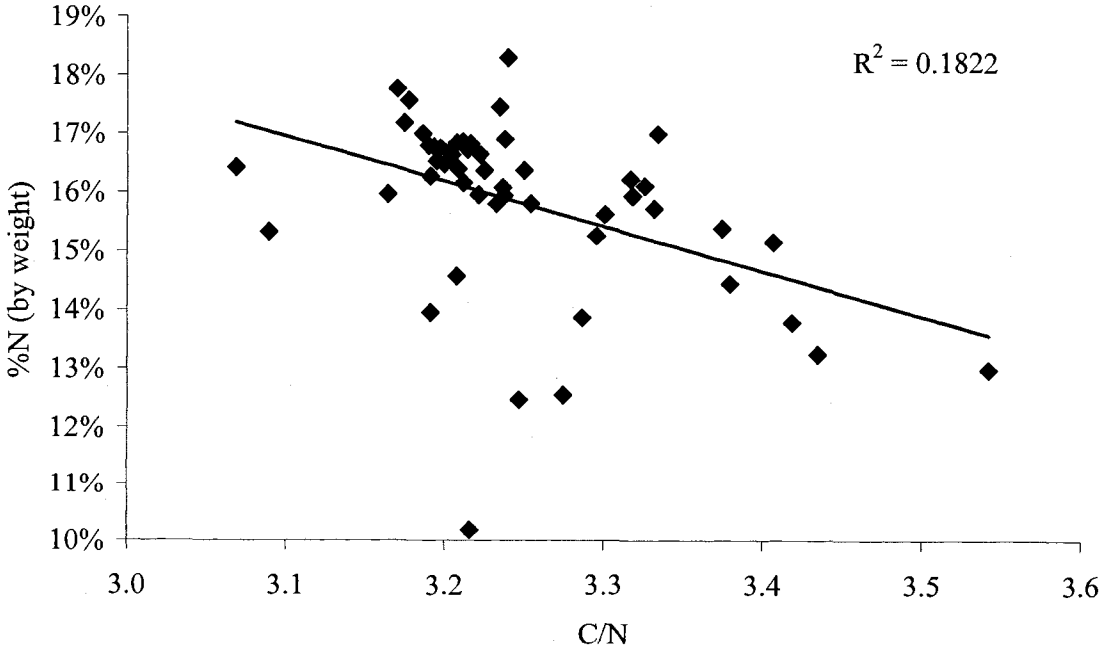


Figure 5.4: Collagen C/N vs. Yield, Final Data Set

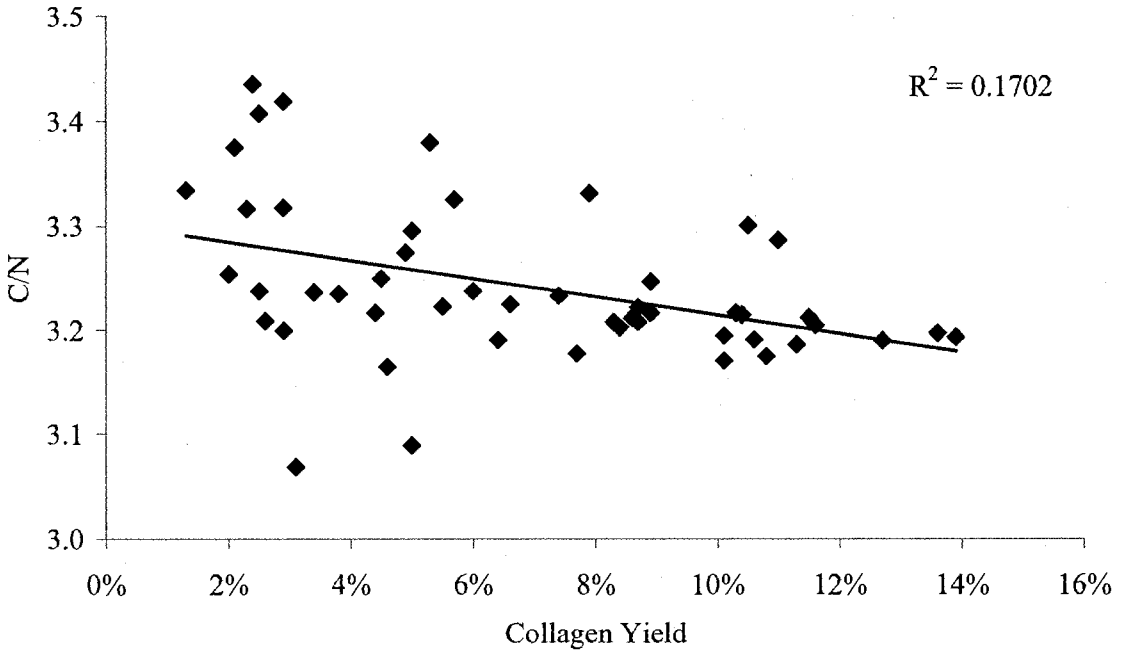


Figure 5.5: Collagen $\delta^{13}C$ vs. Yield, Final Data Set

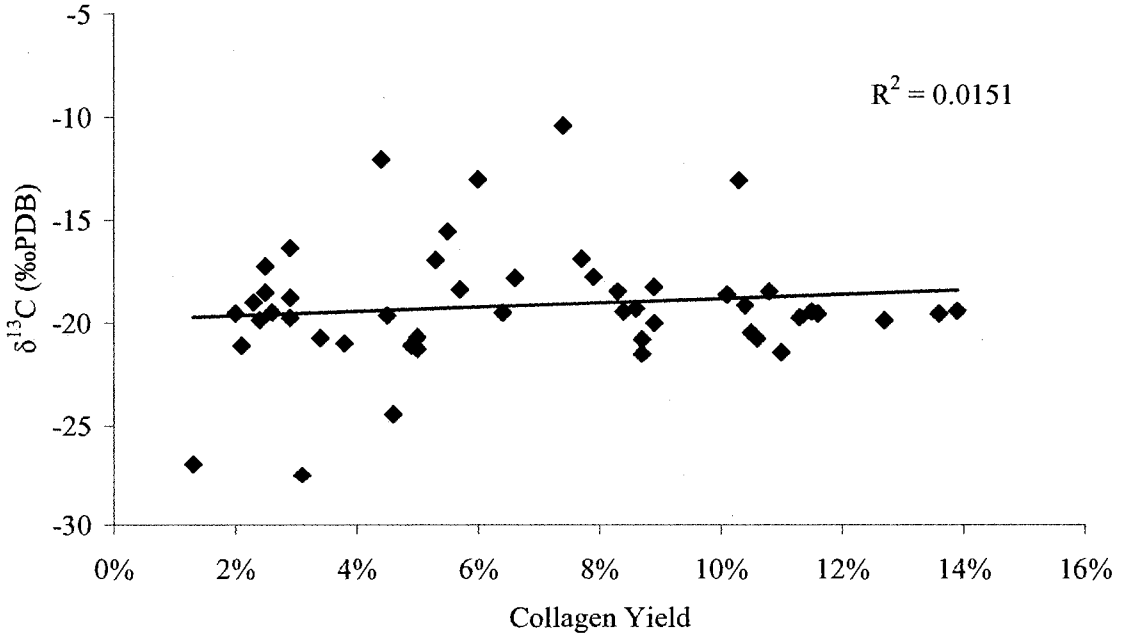


Figure 5.6: Collagen $\delta^{13}C$ vs. C/N, Final Data Set

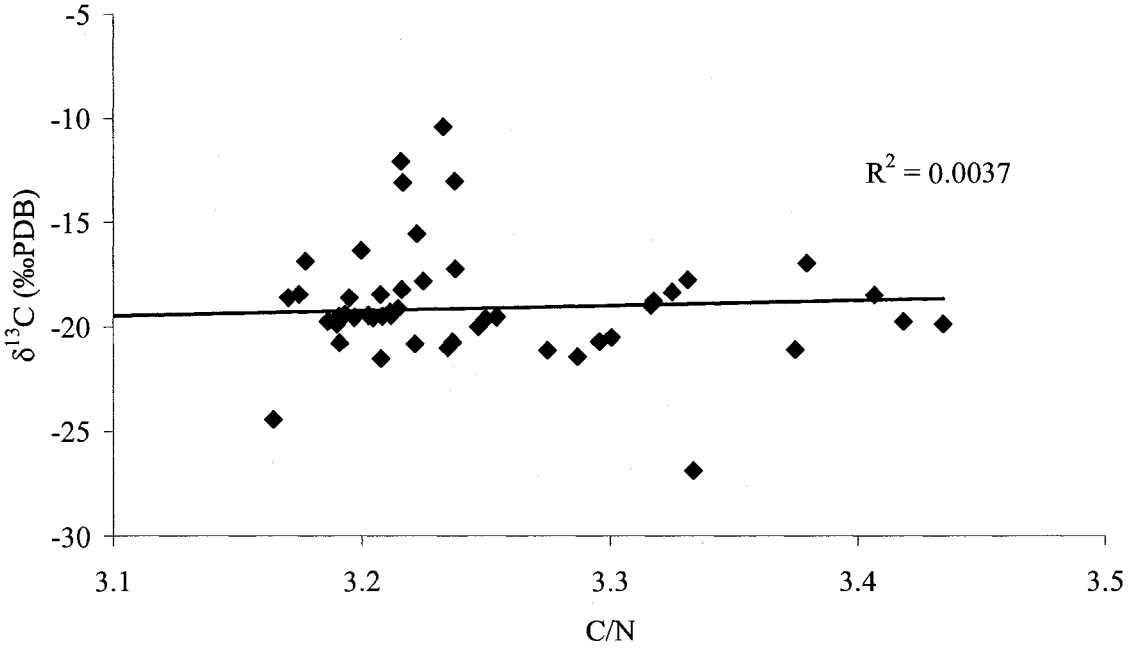


Figure 5.7: Collagen $\delta^{13}C$ vs. %C, Final Data Set

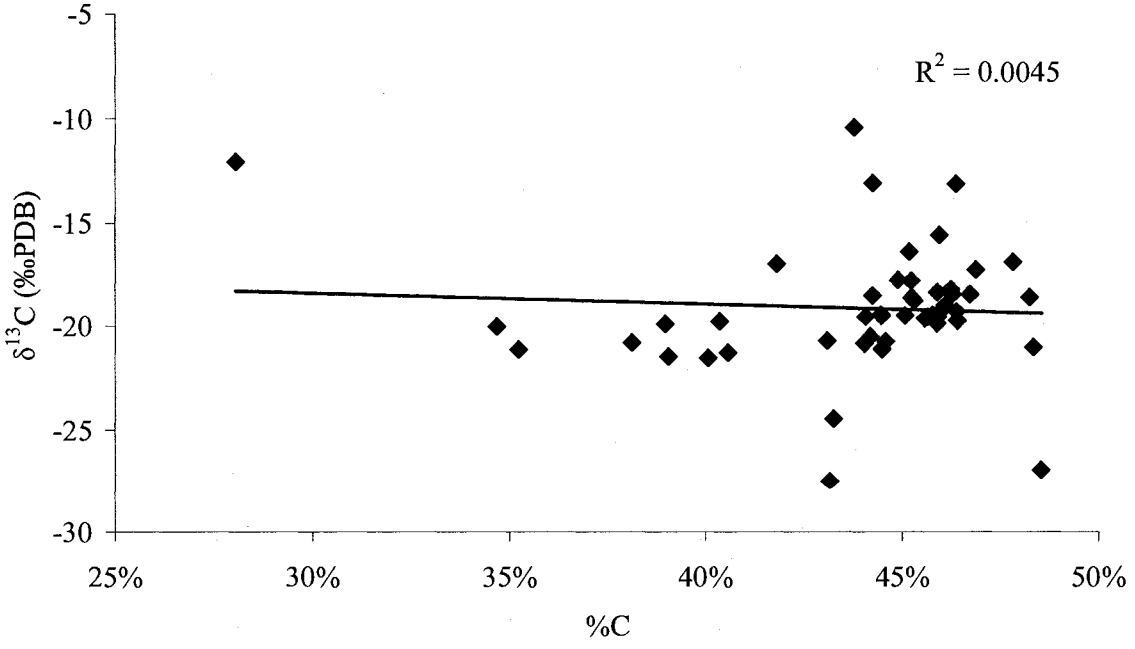


Figure 5.8: Collagen $\delta^{15}N$ vs. C/N, Final Data Set

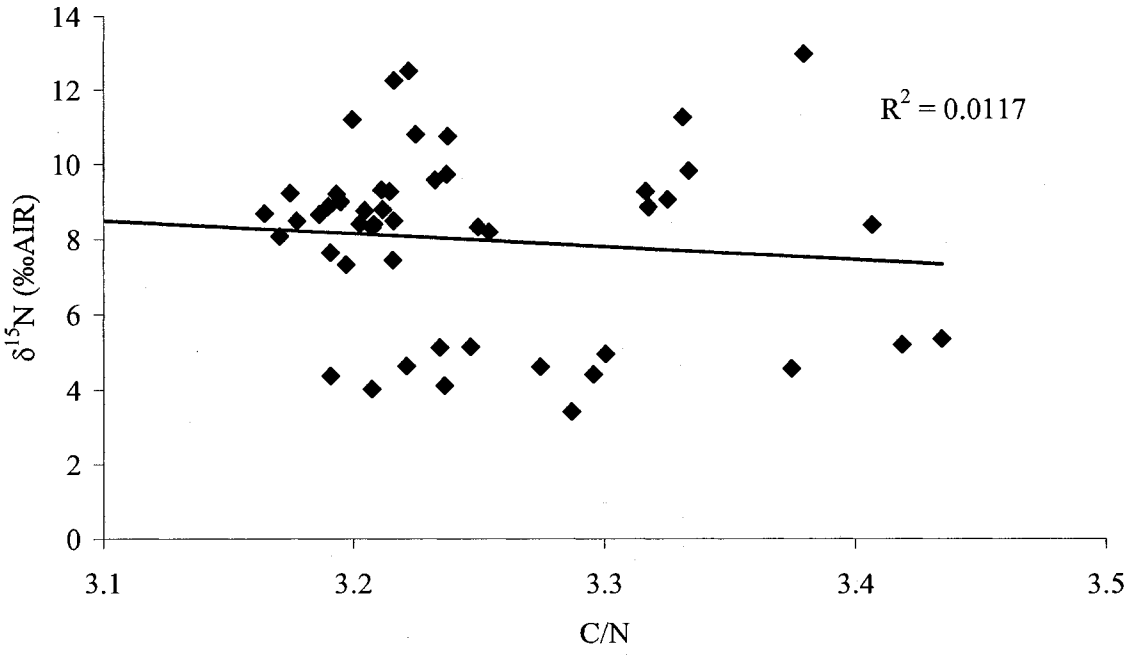


Figure 5.9: Collagen $\delta^{15}N$ vs. Yield, Final Data Set

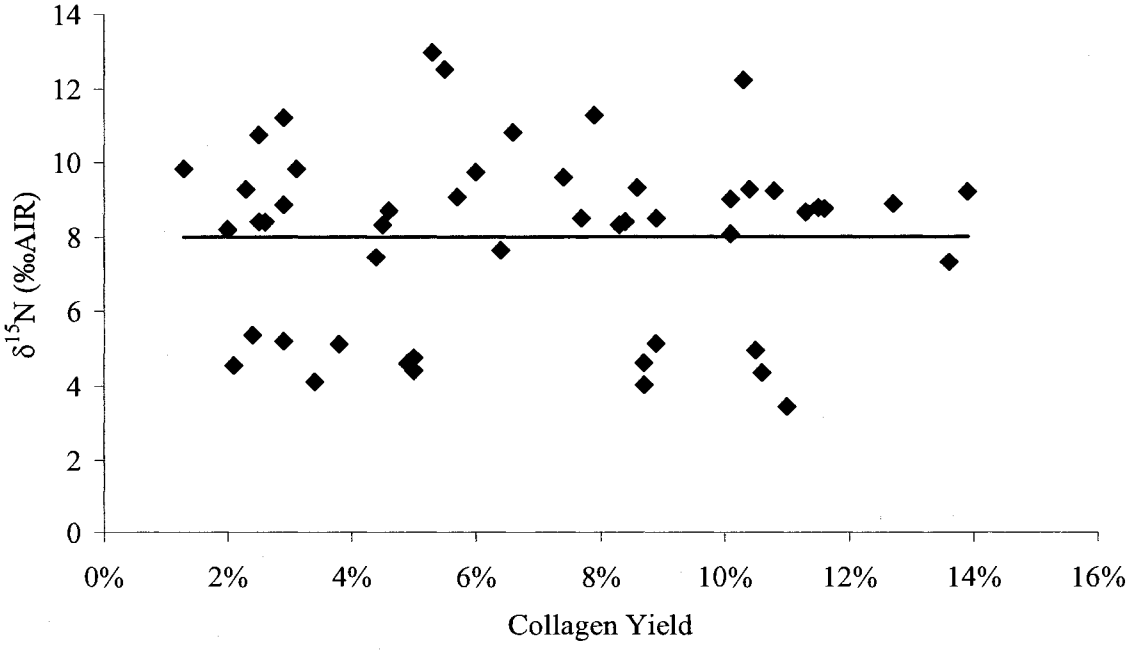
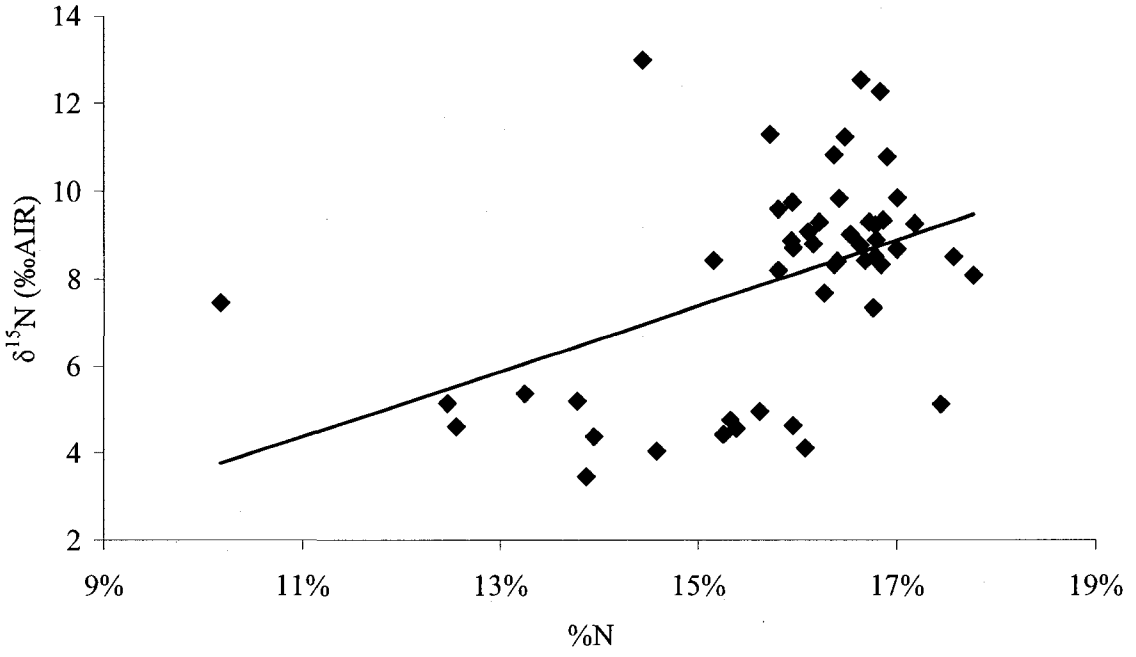


Figure 5.10: Collagen $\delta^{15}N$ vs. %N, Final Data Set

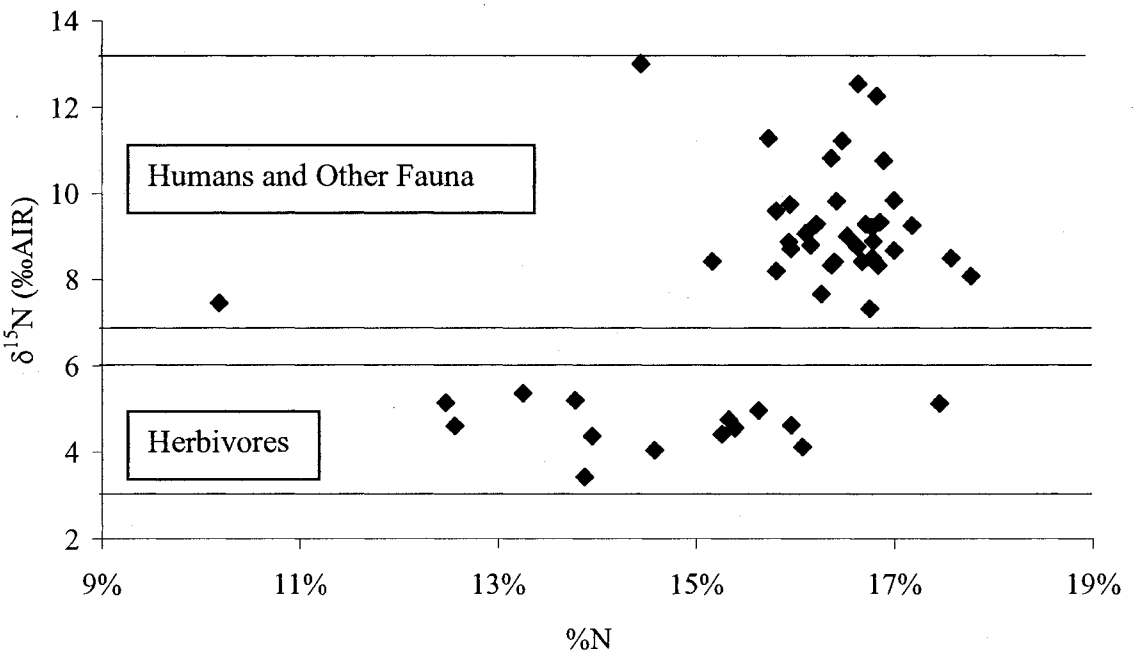


0.05) or %C ($F = 0.22$, $p > 0.05$) (Figures 5.5, 5.6, and 5.7). The lack of any relationship shows that although higher C/N values are seen as collagen yields decrease, sample preservation is not affecting the stable isotope values. This was also true for $\delta^{15}N$ values and C/N ($F = 0.57$, $p > 0.05$) (Figure 5.8) and yield ($F = 3.26E\text{-}05$, $p > 0.05$) (Figure 5.9). There does appear to be a significant relationship between $\delta^{15}N$ and %N ($F = 12.18$, $p <$ 0.05) (Figure 5.10). However this is somewhat misleading. Due to their lower $\delta^{15}N$ values, the herbivores were separated from the other fauna and the humans by almost 2‰. Because a number of the herbivores were poorly preserved and show low %N values, this creates an apparent relationship between $\delta^{15}N$ and %N (See Figure 5.11). Incidentally, this pattern is helpful as it shows that herbivores in the valley of Stymphalos are a trophic level below omnivores, further evidence that the collagen values are not altered.

5.2. Summary

All samples were checked using the quality controls outlined in Chapter 4 to determine if their stable isotope values had been altered by diagenesis. The samples were examined altogether to examine each preservation indicator and to determine if any patterning was present between these controls. The collagen model quality varied between and within the two sites and collagen yield was generally low with a mean of 6.6%. Most samples were also within the acceptable range for C/N ratios and for %C and %N. Only C/N vs. collagen yield (Figure 5.1) and %N vs. $\delta^{15}N$ (Figure 5.10) showed significant relationships. However, the patterning between %N and $\delta^{15}N$ was due to the separation of the herbivores from the rest of the samples and thus was not considered relevant for issues of sample quality. In total only 4 samples (CST-18, CST-20, CZA-01f, CZA-13f) were rejected from the study. In total, 31 human and 19 faunal samples appeared of good quality and their collagen $\delta^{13}C$ and $\delta^{15}N$ values were accepted for analysis.

Figure 5.11: Collagen $\delta^{15}N$ vs. %N, Final Data Set



Chapter 6: Determining Diet at Stymphalos and Zaraka Through Food $\delta^{13}C$ and $\delta^{15}N$ Values

The chapter will focus on the initial steps of reconstructing Early Byzantine and Frankish Greek diets. In order to reconstruct past diets from human $\delta^{13}C$ and $\delta^{15}N$ values, it is first necessary to reconstruct the likely $\delta^{13}C$ and $\delta^{15}N$ values of the foods available during the time period in question. Unfortunately this is not always easy. As shown in Chapter 3, the $\delta^{13}C$ and $\delta^{15}N$ of many foods can vary dramatically between and even within different areas. To try to reduce this problem, this study utilizes food $\delta^{13}C$ and $\delta^{15}N$ values particular to Greece.

The first section of this chapter focuses on the reconstruction of food $\delta^{13}C$ and $\delta^{15}N$ values. Food values were reconstructed using values available in the literature. These values were examined in conjunction with the historical evidence to check for disparities between the two. Afterwards, the questions posed at the end of Chapter 2 are revisited. The main focus of this part of the chapter is to examine how these dietary differences can be investigated by looking for the $\delta^{13}C$ and $\delta^{15}N$ differences they would be expected to cause in human remains.

6.1. Reconstructed Stable Isotope Food Values

This section focuses on reconstructing the local $\delta^{13}C$ and $\delta^{15}N$ food values for the valley of Stymphalos during the Late Roman/Early Byzantine and Frankish periods. This will be done by examining $\delta^{13}C$ and $\delta^{15}N$ values from this study in connection with $\delta^{13}C$ and $\delta^{15}N$ values from similar time periods and regions available in the literature. By

doing so, $\delta^{13}C$ and $\delta^{15}N$ values for some important dietary items (grains, meat, dairy products, marine resources and legumes) can be proposed.

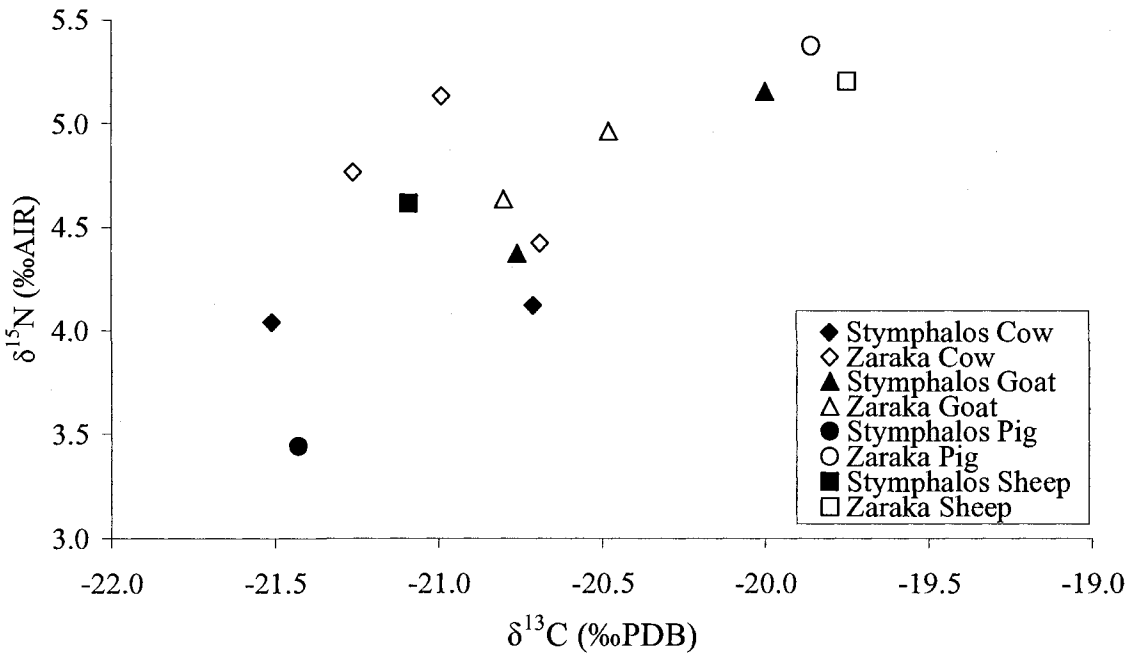
6.1.1. Meat: Meat $\delta^{13}C$ and $\delta^{15}N$ values were reconstructed using the archaeological faunal bone samples collected from Stymphalos and Zaraka and comparing them to the $\delta^{13}C$ and $\delta^{15}N$ values found at other temporally similar sites in the region. The collagen $\delta^{13}C$ and $\delta^{15}N$ data for the faunal samples are presented in Table 6.1.

The faunal $\delta^{13}C$ and $\delta^{15}N$ values found at Stymphalos and Zaraka are extremely close which is expected as they both come from the same valley. Because they are so similar to each other there is little chance the differences between them are enough to affect attempts at dietary reconstruction and thus, the fauna from Stymphalos and Zaraka will be amalgamated and discussed together (see Figure 6.1). The values for the valley of Stymphalos appear to be consistent with other faunal $\delta^{13}C$ and $\delta^{15}N$ values from other contemporaneous sites in Greece. Garvie-Lok (2001) examined faunal remains from medieval Athens, Corinth and Mitilini. Sheep/goat values in her study ranged from -19.6‰ in Athens and Corinth to -21.5‰ at Mitilini. Sheep and goat combined values from the valley of Stymphalos had an average of -20.5‰, falling between the values found by Garvie-Lok (2001). The low $\delta^{13}C$ value found in meat and dairying animals at Stymphalos and Zaraka suggest that these animals were not consuming C4 plants with any regularity. Dietary $\delta^{13}C$ values for these animals were calculated using the value of +5.0‰ for spacing between bulk diet and collagen $\delta^{13}C$ that has been documented for herbivores (see Chapter 3). The average $\delta^{13}C$ value for goats and sheep from the valley of

Table 6.1: Faunal $\delta^{13}C$ and $\delta^{15}N$ Values

Animal	$\delta^{15}N$	$\delta^{13}C$
Cow	4.0	-21.5
	4.1	-20.7
	4.4	-20.7
	5.1	-21.0
	4.8	-21.3
Mean	**4.5**	**-21.0**
s.d.	**0.4**	**0.3**
Goat	5.2	-20.0
	4.4	-20.8
	4.6	-20.8
	5.0	-20.5
Mean	**4.8**	**-20.5**
s.d.	**0.3**	**0.3**
Pig	3.4	-21.4
	5.4	-19.9
Mean	**4.4**	**-20.6**
s.d.	**1.0**	**0.8**
Sheep	4.6	-21.1
	5.2	-19.8
Mean	**4.9**	**-20.4**
s.d.	**0.3**	**0.7**
Chicken	4.6	-21.1
Chub	9.8	-26.9
	9.8	-27.5
	8.7	-24.4
Mean	**9.5**	**-26.3**
s.d.	**0.5**	**1.3**
Sea Bream	7.5	-12.1
Tuna	9.6	-10.4

Figure 6.1: Faunal $\delta^{13}C$ and $\delta^{15}N$, Stymphalos and Zaraka



Stymphalos gave diet $\delta^{13}C$ values of -25.5‰ and -24.5‰ respectively. These values suggest the herbivores in the valley of Stymphalos had a diet predominantly based on C3 plants and C4 plants such as millet were rarely if ever used as fodder.

Faunal $\delta^{15}N$ values also showed little variability. Goat $\delta^{15}N$ values ranged from 4.4‰ to 5.2‰. These values are similar to those found at Corinth where the average value for sheep and goat was 4.0‰ (Garvie-Lok, 2001). The small difference seen between the values from the valley of Stymphalos and those from Corinth could reflect a difference in the local baseline $\delta^{15}N$.

To estimate beef, mutton, pork and goat $\delta^{13}C$ and $\delta^{15}N$ values, the general isotopic separation of meat from bone collagen was used to create estimated meat values for each species. In general, mammalian bone collagen $\delta^{13}C$ values are higher than those of muscle tissues. A number of studies (e.g. Hare et al. 1991; Tieszen and Fagre, 1993;

Vogel 1978) have suggested separations of 1‰ to 2‰. This study uses a separation value of 1.5‰. Mammalian muscle $\delta^{15}N$ values have been documented as being close to those of collagen $\delta^{15}N$ (e.g. DeNiro and Epstein, 1981), and so the estimated meat $\delta^{15}N$ values here will use the values of bone collagen $\delta^{15}N$.

The resulting reconstructed meat values are summarized in Table 6.2. Reconstructed meat $\delta^{13}C$ values ranged from -21.9‰ (mutton) to -22.5‰ (beef). Using this approach, the mean reconstructed meat $\delta^{13}C$ and $\delta^{15}N$ values are -22.1 ± 0.5‰ and 4.7 ± 0.5‰ respectively.

Table 6.2: Meat $\delta^{13}C$ and $\delta^{15}N$ Based on Archaeological Faunal Values

Meat	Number	$\delta^{13}C$ (‰)		$\delta^{15}N$ (‰)	
		Mean	**s.d.**	**Mean**	**s.d.**
Beef	5	-22.5	0.3	4.5	0.4
Goat	4	-22.0	0.3	4.8	0.3
Pork	2	-22.1	0.8	4.4	1.0
Mutton	2	-21.9	0.7	4.9	0.3
Meat mean		**-22.1**	**0.5**	**4.7**	**0.5**

6.1.2. Dairy Products and $\delta^{13}C$ and $\delta^{15}N$ Values: Dairy foods were also an important dietary source and thus it is important to reconstruct their expected $\delta^{13}C$ and $\delta^{15}N$ values, specifically those of goat and sheep as there is much evidence that these animals were the primary sources of dairy products in Byzantine and Frankish Greece (see Chapter 2). In particular, this study is interested in the use of dairy as a source of protein and reconstructing dairy protein $\delta^{13}C$ and $\delta^{15}N$ will be the focus of this section.

The $\delta^{13}C$ patterning of milk varies due to a number of factors including which milk component is studied and what the animal's bulk diet is. Studies by Minson et al. (1975) and Metges et al. (1990) determined that animals fed on a C3 diet tended to have whole-milk $\delta^{13}C$ values about +2.0‰ higher than the bulk diet $\delta^{13}C$ values. When only the dairy protein is taken into consideration, the separation between dairy protein $\delta^{13}C$ values and bulk diet $\delta^{13}C$ values is higher, around +3.0‰ (Kornexl et al. 1997). Reported milk $\delta^{15}N$ values are generally similar to the animal's other tissues (e.g. blood) and thus should be similar to collagen $\delta^{15}N$ (Kornexl et al. 1997; Steele and Daniel, 1978).

Other dairy products such as cheese and yoghurt have been documented as having similar protein $\delta^{13}C$ and $\delta^{15}N$ values to fresh milk. Research by Garvie-Lok (2001) on locally produced modern dairy products from the valley of Stymphalos showed fresh defatted milk to have a $\delta^{13}C$ value of -24.0‰ and a $\delta^{15}N$ value of 4.7‰. The $\delta^{13}C$ and $\delta^{15}N$ values of the defatted processed dairy foods fell close to this ($\delta^{13}C$: -25.5‰ to -23.9‰, $\delta^{15}N$: 4.3‰ to 5.6‰), suggesting that dairy products should have protein values similar to milk.

Using the separations established in the literature, estimated protein $\delta^{13}C$ and $\delta^{15}N$ values of dairy foods for Stymphalos and Zaraka were calculated from the mean $\delta^{13}C$ and $\delta^{15}N$ of goat and sheep collagen. The results can be seen in Table 6.3. These values agree well with the modern $\delta^{13}C$ and $\delta^{15}N$ values for dairy products from the valley of Stymphalos.

6.1.3. Birds: Unfortunately only one bird had good collagen values and thus was available for study. The bird, identified as a chicken, had $\delta^{13}C$ and $\delta^{15}N$ values of -21.1‰

Table 6.3: Dairy $\delta^{13}C$ and $\delta^{15}N$ Based on Archaeological Faunal Values

Animal	Number	Protein $\delta^{13}C$ Mean	$\delta^{13}C$ s.d.	Protein $\delta^{15}N$ Mean	$\delta^{15}N$ s.d.
Goat	4	-22.5	0.3	4.8	0.3
Sheep	2	-22.4	0.7	4.9	0.3
All Mean		**-22.5**	0.5	**4.8**	**0.3**

and 4.6‰ respectively. Although some studies have suggested higher $\delta^{15}N$ values should be seen in chickens due to the higher tropic level protein obtained from consuming insects, this does not seem to be the case here and the chicken appears to have values similar to the other fauna (Schwarcz et al. 1999).

6.1.4. Marine and Freshwater Resources: Both marine and freshwater fish remains were available for study. The marine samples consisted of a species of tuna with a $\delta^{13}C$ value of -10.4‰ and a $\delta^{15}N$ value of 9.6‰ and a gilt head sea bream (*Sparus aurata*) with $\delta^{13}C$ at -12.1‰ and $\delta^{15}N$ at 7.5‰. These values match well with published values for modern Mediterranean fish $\delta^{13}C$ and $\delta^{15}N$ values which range between -19.6‰ and -16.1‰ for $\delta^{13}C$ and between 4.6‰ and 13.8‰ for $\delta^{15}N$ (Jennings et al. 1997; Pinnegar and Polunin, 2000). Garvie-Lok (2001) also assessed fish from the Mediterranean and found that low-trophic fish had $\delta^{13}C$ values ranging from -16.4‰ to -17.5‰ and $\delta^{15}N$ values of 6.3‰ to 6.7‰ whereas fish from higher trophic levels had $\delta^{13}C$ values ranging from -12.1‰ to -18.3‰ and $\delta^{15}N$ values from 8.1‰ to 17.9‰. A study by Rojas et al. (2007) on wild and farmed gilt head sea breams from a variety of locations in the Mediterranean

reported $\delta^{13}C$ values ranging from -23.3‰ to -14.6‰ and $\delta^{15}N$ values from 7.5‰ to 16.3‰: the gilt head $\delta^{13}C$ and $\delta^{15}N$ values found in this study fall just outside this range. The ranges of $\delta^{13}C$ and $\delta^{15}N$ found in by Rojas et al. (2007) show how much variety can be seen between different habitats.

The three freshwater samples available for this study were from one species *Leuciscus leuciscus*, a form of chub. The $\delta^{13}C$ values ranged from -27.5‰ to -24.4‰ and $\delta^{15}N$ from 8.7‰ to 9.8‰. The freshwater fish $\delta^{13}C$ and $\delta^{15}N$ values agree with the general pattern of lower $\delta^{13}C$ than marine fish and higher $\delta^{15}N$ than local terrestrial herbivores which is often seen with freshwater animals (see Chapter 3).

Literature values for the $\delta^{13}C$ and $\delta^{15}N$ separation between fish bone and flesh are often contradictory with flesh $\delta^{13}C$ and $\delta^{15}N$ reported as both higher and lower than bone collagen $\delta^{13}C$ and $\delta^{15}N$ (Keegan and DeNiro 1988; Sholto-Douglas et al. 1991). Thus the decision was made to assume that the fish flesh $\delta^{13}C$ and $\delta^{15}N$ values were comparable to those of fish collagen. The results are seen in Table 6.4.

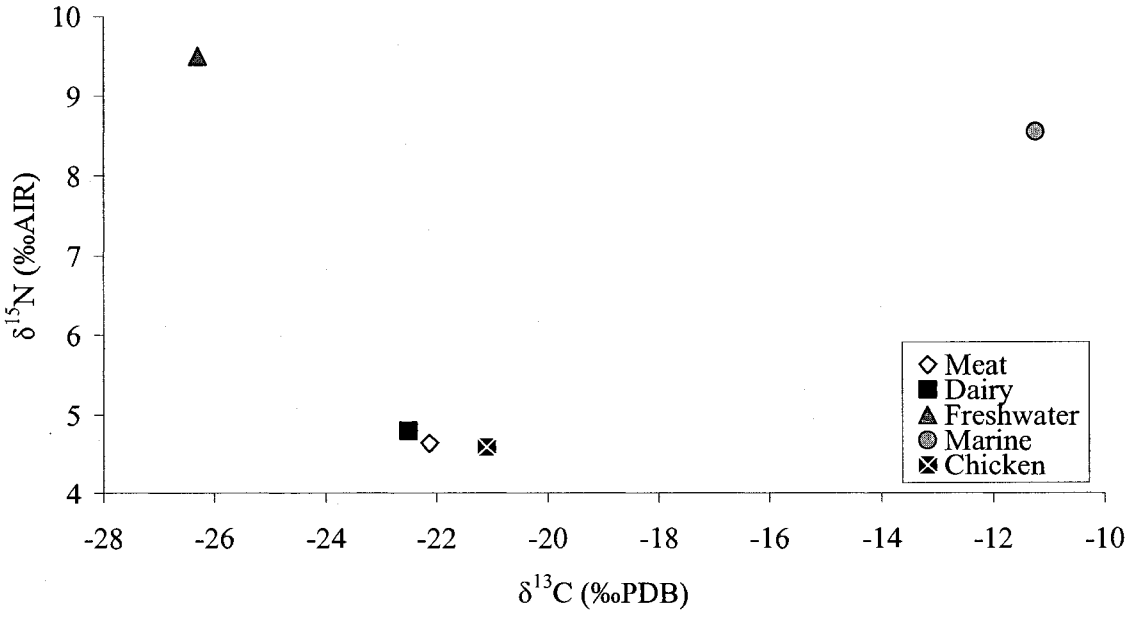
Table 6.4: Flesh $\delta^{13}C$ and $\delta^{15}N$ Based on Archaeological Fish Values

Species	N	Environment	$\delta^{13}C$	s.d.	$\delta^{15}N$	s.d.
Chub	3	Freshwater	-26.3	1.3	9.5	0.5
Tuna	1	Marine	-10.4	----	9.6	----
Sea Bream	1	Marine	-12.1	----	7.5	----

6.2. Reconstructed Animal Product Values Summary

By plotting all the reconstructed animal product values together a picture of the hypothetical $\delta^{13}C$ and $\delta^{15}N$ values of animal products available to the Stymphalos and

Figure 6.2: Reconstructed $\delta^{13}C$ and $\delta^{15}N$ Values of Animal Products



Zaraka populations are revealed (Figure 6.2). Meat and dairy products have similar $\delta^{13}C$ and $\delta^{15}N$ values typical of terrestrial organisms. The chicken value also falls around the range of terrestrial organisms. This result has implications for dietary reconstruction in the valley of Stymphalos. These values help to rule out milk, dairy and chickens as sources of elevated $\delta^{13}C$ signals in human diets. If the animals were consuming high amounts of C4 plants and passing those values onto humans, the human $\delta^{13}C$ values would be considerably higher than those expected for a C3 terrestrial-based diet. Secondly, the low $\delta^{13}C$ and $\delta^{15}N$ values of the terrestrial animal products are separated clearly from the freshwater and marine $\delta^{13}C$ and $\delta^{15}N$ values. Thus, there should be little confusion occurring in determining terrestrial protein from freshwater and marine sources.

6.3. Plant Products

The stable isotope values of key plant resources were estimated from known $\delta^{13}C$ values from the literature. Plant $\delta^{15}N$ values were extrapolated from contemporary animal remains. Some of the problems in using this method to estimate archaeological plant $\delta^{13}C$ and $\delta^{15}N$ values are also discussed.

6.3.1. Wheat and Barley: Wheat and barley $\delta^{13}C$ values have been reported by a number of studies for a variety of locations (e.g. Bender, 1968; DeNiro and Epstein, 1978a; Hare et al. 1991; Nakamura et al. 1982; Smith and Epstein, 1971). Whole seed values ranged from -29.1‰ to -22.1‰ with a mean value of -25.3‰. Garvie-Lok (2001) found wheat grown in the valley of Stymphalos to show similar values, -25.5‰ and -23.7‰. These values were then used to determine seed protein $\delta^{13}C$ values. Nakamura et al. (1982) determined that whole seed values were 1.5‰ more positive compared to seed protein $\delta^{13}C$ values. If this 1.5‰ separation is applied to the material above, wheat and seed protein $\delta^{13}C$ values range from -30.6‰ to -23.6‰ with a mean of -26.8‰. When these values are corrected for the -1.5‰ atmospheric shift in $\delta^{13}C$ that has occurred since the Industrial Revolution (see Chapter 3) they produced estimates for wheat and barley $\delta^{13}C$ values of -29.1‰ to -22.1‰ (mean = -25.3‰) for seed protein.[4]

Unlike $\delta^{13}C$, which falls into a relatively small range, the $\delta^{15}N$ values of non-symbiotic plants can vary dramatically due to their dependence on soil $\delta^{15}N$. This makes it impossible to use modern $\delta^{15}N$ values to reconstruct past grain $\delta^{15}N$ values (see

[4] These values could be too low. Van Klinken et al. (2000) observed that $\delta^{13}C$ values of C3 plants during the Holocene were affected by temperature changes with cooler temperatures leading to slightly lower $\delta^{13}C$ values. As many of the literature values above are from cooler climates, they might be low compared to the $\delta^{13}C$ values generated from the warmer climate of Greece.

Chapter 3). This is particularly true when the impact of modern fertilizers on soil $\delta^{15}N$ and thus modern plant $\delta^{15}N$ values is taken into consideration. One method that has been used to reconstruct plant protein $\delta^{15}N$ values in the past is to use archaeological faunal stable isotope values to extrapolate historical plant $\delta^{15}N$ values. The technique uses animal collagen values to propose a mean value for local plant protein as consumed by the specific animals tested. The benefit of this technique is it provides an idea of what the local $\delta^{15}N$ baseline might have been. However, this value might not accurately reflect the $\delta^{15}N$ values of the plants consumed by humans. Animals often ate different plants and plant parts than humans did (Schwarcz et al. 1999). In addition, as traditional agricultural practices would have affected soil $\delta^{15}N$ in cultivated areas, animals foraging for wild plants could have distinctive values compared to humans primarily subsisting on cultivated plants (Van Klinken et al. 2000).

Only the herbivore faunal $\delta^{15}N$ values were used in the estimation; these give a mean $\delta^{15}N$ value of 4.7‰ for the valley of Stymphalos. When the 3-5‰ elevation of the animals' collagen over its dietary protein recommended by Bocherens et al. (2003) is considered, the plant protein of their diet would have $\delta^{15}N$ values ranging from -0.3‰ to 1.7‰ with a midpoint of 0.7‰. While these values seem low compared to many modern plant $\delta^{15}N$ values (see Chapter 3), it must be remembered that plant $\delta^{15}N$ values are extremely variable and low plant $\delta^{15}N$ values have been reported in other locales (e.g. Ambrose, 1991). It was considered that the low $\delta^{15}N$ values could also be the result of some legume consumption by the herbivores. While this could be a possibility for the cows which would have been fed on mostly on fodder, it probably does not hold true for foraging animals such as sheep and goats, which would have spent the majority of the

year foraging on non-leguminous plants. Thus it appears that the plant protein $\delta^{15}N$ values reconstructed from faunal collagen $\delta^{15}N$ do suggest that the valley of Stymphalos had a low $\delta^{15}N$ baseline value causing low $\delta^{15}N$ values for wild plant protein and grain.

6.3.2. Millet: $\delta^{13}C$ values for C4 plants have been recorded to range from -9.0‰ to -19.5‰ with some variation depending on which C4 plant is being studied (Bender, 1971, Deines, 1980; Smith and Epstein, 1971). White (1993) recorded millet seed values ranging from -10.6‰ to -13.1‰ with an average of -11.7‰. Studies on other C4 plants have shown seed protein $\delta^{13}C$ values to have the same 1.5‰ separation from bulk tissues as in C3 plants (Tieszen and Fagre, 1993). Using this value and the range above for millet, the $\delta^{13}C$ value for seed protein is -12.1‰ to -14.6‰ with a mean of -13.2‰. This $\delta^{13}C$ value, when corrected for the atmospheric shift, becomes -11.7‰ and will be used as the estimate for Byzantine and Frankish millet protein $\delta^{13}C$ values. Based on the argument above that plant $\delta^{15}N$ values can be extrapolated from archaeological faunal collagen, the $\delta^{15}N$ values of C4 grain from Stymphalos and Zaraka are estimated to have the same typical $\delta^{15}N$ values as C3 plants, ranging from -0.3‰ to 1.7‰ with a midpoint of 0.7‰.

6.3.3. Legumes: Modern legume $\delta^{13}C$ values have been recorded in a number of studies. Whole plant $\delta^{13}C$ values were seen to range from -28.9‰ to -22.9‰, with seed $\delta^{13}C$ values ranging from -27.2‰ to -22.9‰ with an average of -24.8‰ (Bender, 1968; Smith and Epstein, 1971; White, 1991). Nakamura et al. (1982) determined that legume seed protein $\delta^{13}C$ was about 1.0‰ more negative than whole seed $\delta^{13}C$. Using this 1.0‰

separation, seed protein $\delta^{13}C$ values are seen to range from -28.2‰ to -23.9‰ with a mean of -25.8‰. Corrected for the modern atmospheric shift, the legume seed protein values for Byzantine and Frankish Greece are estimated to be -26.7‰ to -22.4‰ with a mean of -24.3‰.

Unlike C3 and C4 plants where using modern plants to estimate archaeological $\delta^{15}N$ values is impossible, it is feasible for legumes. Modern legume $\delta^{15}N$ values are generally quite low, particularly when extra sources of ^{15}N such as fertilizer are absent (See Chapter 3). However, it is likely that the people of the valley of Stymphalos were utilizing traditional fertilizing techniques which could have affected the soil $\delta^{15}N$ values and thus the legume $\delta^{15}N$ values. Unfortunately, it is impossible to ascertain how much these fertilizing techniques would have affected soil $\delta^{15}N$ values and thus the legume $\delta^{15}N$ values from Stymphalos and Zaraka are theorized to be similar to modern legume $\delta^{15}N$ values grown in unfertilized soil, generally seen to fall around 0‰.

6.4. Summary

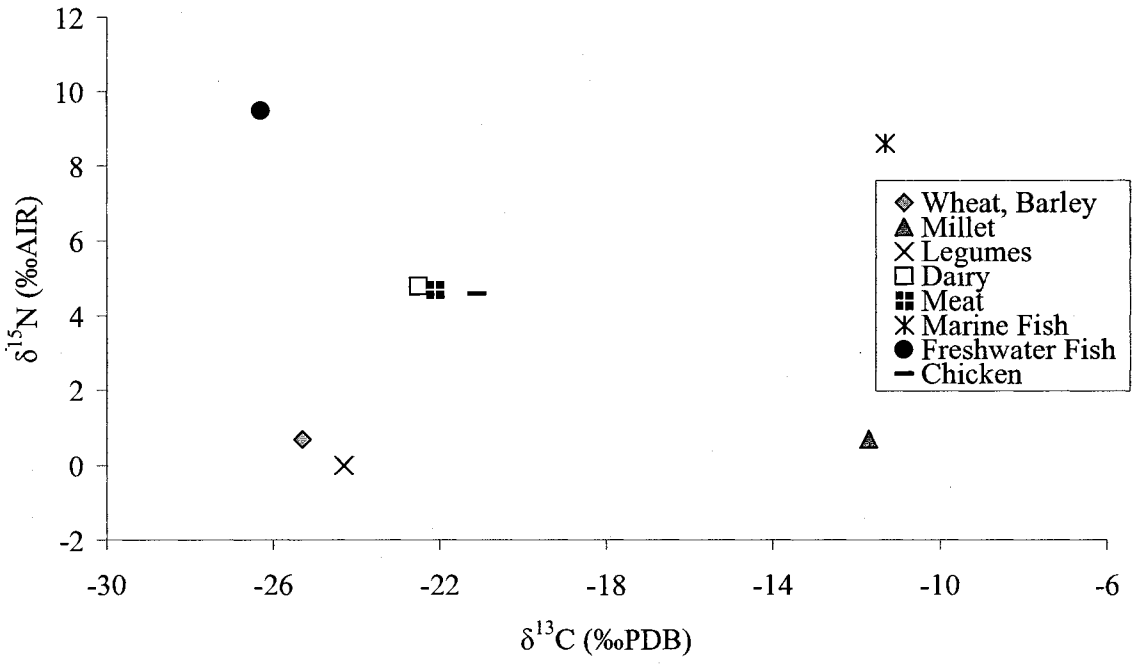
The estimated dietary values discussed above are presented in Table 6.5. While these estimates do help in dietary reconstructions, they are not without problems. One of the most problematic is the grain products. In particular, it is possible that the estimates are too low for both carbon and nitrogen isotopes: $\delta^{13}C$ due to the effects of a warmer climate and $\delta^{15}N$ due to the possible elevation of grain $\delta^{15}N$ over the $\delta^{15}N$ values of wild plant eaten by animals. Even with these problems, these estimates are the only way at this time to provide hypothetical $\delta^{13}C$ and $\delta^{15}N$ values for the foods available during the Byzantine and Frankish periods.

Table 6.5: Summary of Estimated Mean $\delta^{13}C$ and $\delta^{15}N$ of Byzantine and Frankish Foods

Food	Protein $\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)
Wheat, Barley	-25.3	0.7
Millet	-11.7	0.7
Legumes	-24.3	0.0
Dairy	-22.5	4.8
Meat	-22.1	4.7
Chicken	-21.1	4.6
Marine Fish	-11.3	8.6
Freshwater Fish	-26.3	9.5

The estimated food protein $\delta^{13}C$ and $\delta^{15}N$ values are depicted in Figure 6.3. The reconstructed values indicate a Byzantine and Frankish environment dominated by low $\delta^{13}C$ values. As seen in Table 6.5 meat, dairy, and chicken $\delta^{13}C$ and $\delta^{15}N$ values hover closely to those of the C3 grains and legumes. The highest $\delta^{13}C$ values are seen in the marine resources (-11.3‰) with C4 grains showing values are slightly lower (-11.7‰). The freshwater resources (-26.3‰) showed lower values than both the C3 grains (-25.3‰) and the terrestrial animal products which ranged from -21.8‰ to -22.6‰. The food $\delta^{15}N$ values are also generally low with the exception of the marine and freshwater resources. The freshwater (9.5‰) and marine (8.6‰) resources are around 3.0‰ higher than the terrestrial animal products which range from 4.2‰ to 5.1‰.The low extrapolated grain values cause little difference to be seen between $\delta^{15}N$ values of the grains and legumes. While there is clear separation between the freshwater and marine resources and the terrestrial animal products, the terrestrial animal products are indistinguishable from each other.

Figure 6.3: Reconstructed Food $\delta^{13}C$ and $\delta^{15}N$ Values



6.5. The Isotopic Implications of Variation Discussed in Chapter 2

A number of questions were posed at the end of Chapter 2 regarding the Byzantine and Frankish diets as reconstructed by the historical sources. After the stable isotope analysis of the faunal samples, these questions can now be examined in the context of local food values.

The first question is that of the importance of millet to the diet. The C3 and C4 plants in the valley of Stymphalos clearly show distinct $\delta^{13}C$ and $\delta^{15}N$ values from other resources, allowing for their use to be easily distinguished using human $\delta^{13}C$ and $\delta^{15}N$ values and allow variations to be seen both regionally and temporally (see Figure 6.3). However, this patterning could be somewhat complicated by the use of marine resources or olive oil. If marine resources constituted part of the diet, it could cause human $\delta^{13}C$ to increase in a way that mimics a diet including millet. Substantial consumption of olive oil

which is depleted in ^{13}C would have the opposite effect, helping to mask the isotopic effects of C4 grain consumption (see Ambrose and Norr, 1993 for more information).

The second question posed related to the importance of marine resources. If there was a heavy reliance on marine resources, particularly high trophic-level marine animals, it would definitely be reflected in higher collagen $\delta^{13}C$ and $\delta^{15}N$ values (see Figure 6.3). If the diet was based largely on terrestrial resources, the $\delta^{13}C$ and $\delta^{15}N$ values would be much lower, and allowing for easy separation of marine resource consumption from the terrestrial resources. However, if the marine resources largely consisted of lower trophic-level animals, the separation would be much less clear. While diets based largely on lower trophic-level marine fish would have low $\delta^{15}N$ values, similar to those of terrestrial animals, their collagen $\delta^{13}C$ values would generally be distinct enough to allow for the consumption of marine resources to be detected.

6.6. Conclusions

Food values for the Byzantine and Frankish periods were reconstructed using the analysis of archaeological faunal collagen in combination with literature values of modern food and animal tissue $\delta^{13}C$ and $\delta^{15}N$. These reconstructed values were to determine the potential isotopic space for diets in the valley of Stymphalos. It appears the dietary possibilities were dominated by items with low $\delta^{13}C$ and $\delta^{15}N$ values, with only C4 grains, marine and freshwater resources standing apart. Most variation in diets should occur within the ranges put forward for the reconstructed food values: protein $\delta^{13}C$ values of -11.3‰ to -27.2‰ and $\delta^{15}N$ values varying between 0‰ and 9.5‰. Obviously

different potential diets do differ isotopically and the questions posed in Chapter 2 could possibly be answered through stable isotope analysis of human bone.

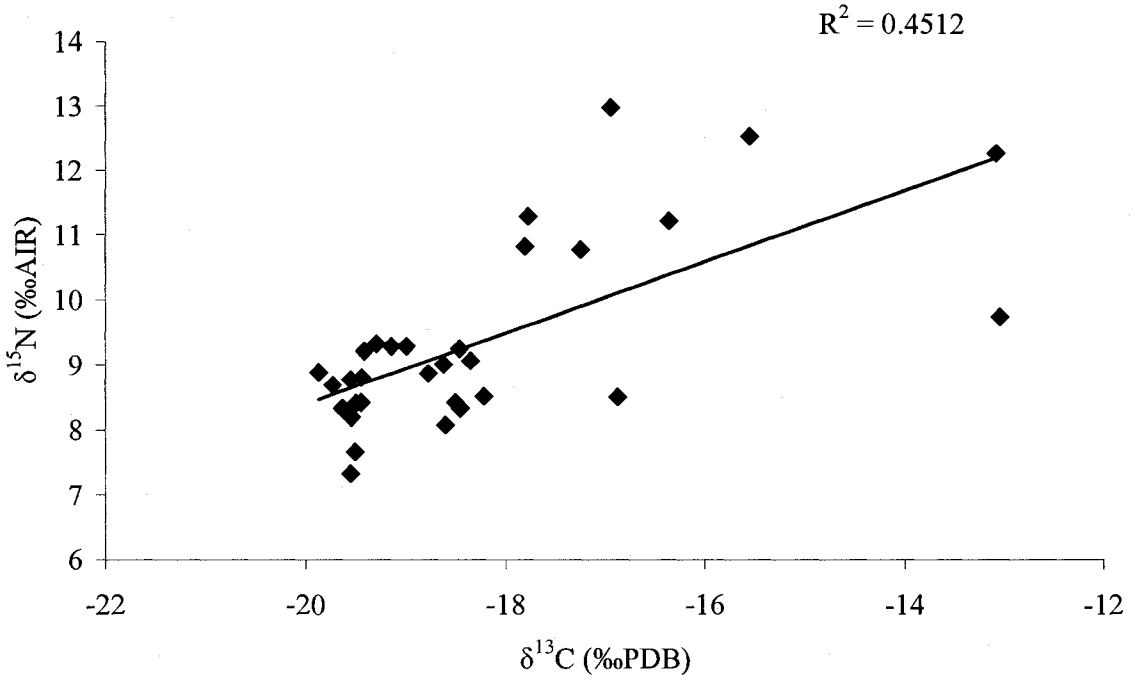
Chapter 7: Interpretation of Results

In this chapter, the human $\delta^{13}C$ and $\delta^{15}N$ values are presented and discussed. The chapter will first focus on the stable isotope patterning seen between and within the sites. This general review of the human stable isotope values acts as an introduction to the interpretation of the results. It will provide context for the individual site data and enable a greater understanding of the sites' dietary reconstructions. The next section focuses on dietary interpretation using the human stable isotope values. First a general discussion of the values and the reconstructed Byzantine and Frankish food values determined in Chapter 6 will be used to propose diets for the majority of the populations. Any mismatches between expected and observed values will also be assessed. Afterwards the variability between and within sites is examined and reasons behind these variations are given. In the internal variation section emphasis will be placed on the effects of nursing and weaning. The values will also be compared to literature stable isotope values for other Greek populations from various areas and time periods. Finally, the hypotheses set out in Chapter 2 will be revisited to see if the stable isotopes give any support to them.

7.1. General Overview

The collagen stable isotope values obtained for the human samples are presented in Figure 7.1. In general, most of the human collagen $\delta^{13}C$ values are quite low, closely clustered together around the region of -19.0‰. There is some scatter from the original cluster in the direction of higher $\delta^{13}C$ with the highest $\delta^{13}C$ value at -13.0‰. The $\delta^{15}N$ values show a general cluster at 9.0‰ with some spread to a higher grouping of $\delta^{15}N$

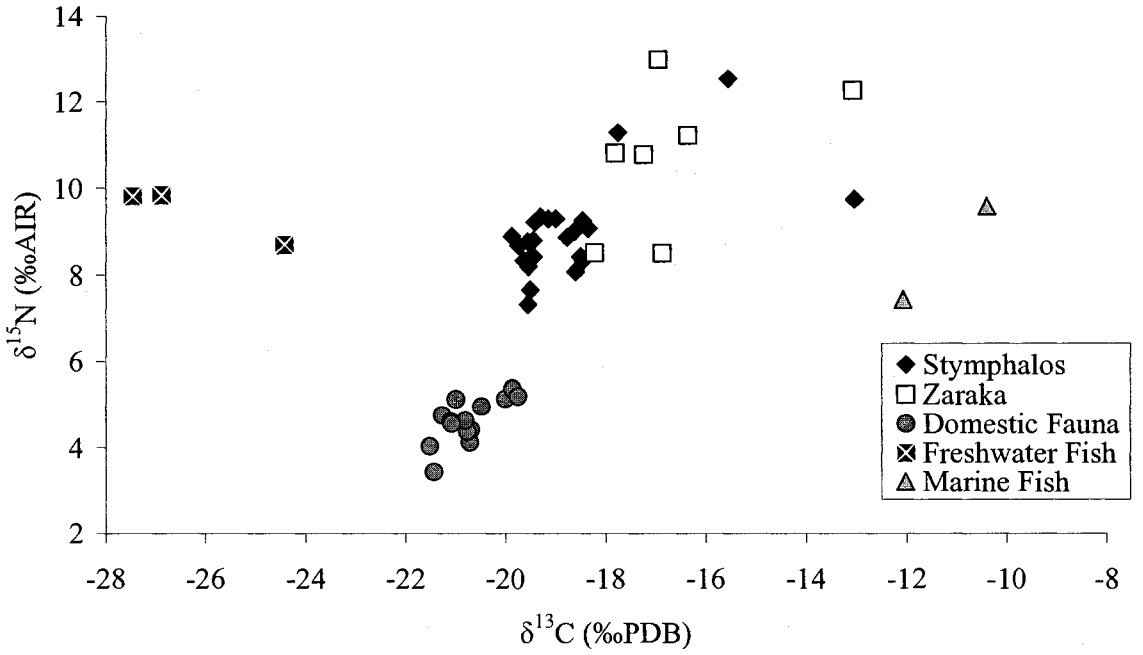
Figure 7.1: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, All Humans



values around 11.0‰. When the human samples are taken as a whole, $\delta^{13}C$ and $\delta^{15}N$ show a relationship ($F = 23.84$, $p < 0.05$). This relationship appears to be due to the Zaraka human values creating a trail in the direction of higher $\delta^{13}C$ and $\delta^{15}N$ values. These higher values at Zaraka will be discussed in greater detail below.

When the human stable isotope values are compared to the raw values of the domestic animals and the marine and freshwater resources, we see a systematic difference between the groups (Figure 7.2). The domestic faunal samples' $\delta^{13}C$ values are set apart from the main cluster of humans by almost 2.0‰ and their $\delta^{15}N$ values are separated by around 4.0‰. This pattern is consistent with observations on trophic level differences in $\delta^{13}C$ and $\delta^{15}N$ made by Bocherens et al. (2003). In that study, Bocherens et al. (2003) suggest that for a given ecosystem, herbivores and carnivores will be separated on average by 0 to 2.0‰ for $\delta^{13}C$ and 3.0 to 5.0‰ for $\delta^{15}N$. The Stymphalos

Figure 7.2: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, All Samples



and Zaraka data fit the pattern extremely well for both $\delta^{13}C$ and $\delta^{15}N$, if it is assumed that human diets drew primarily on the same general terrestrial ecosystems as did the diets of the fauna. This assumption seems likely as the majority of the human samples fall nowhere near the marine/freshwater values.

7.2. Human Values, Stymphalos

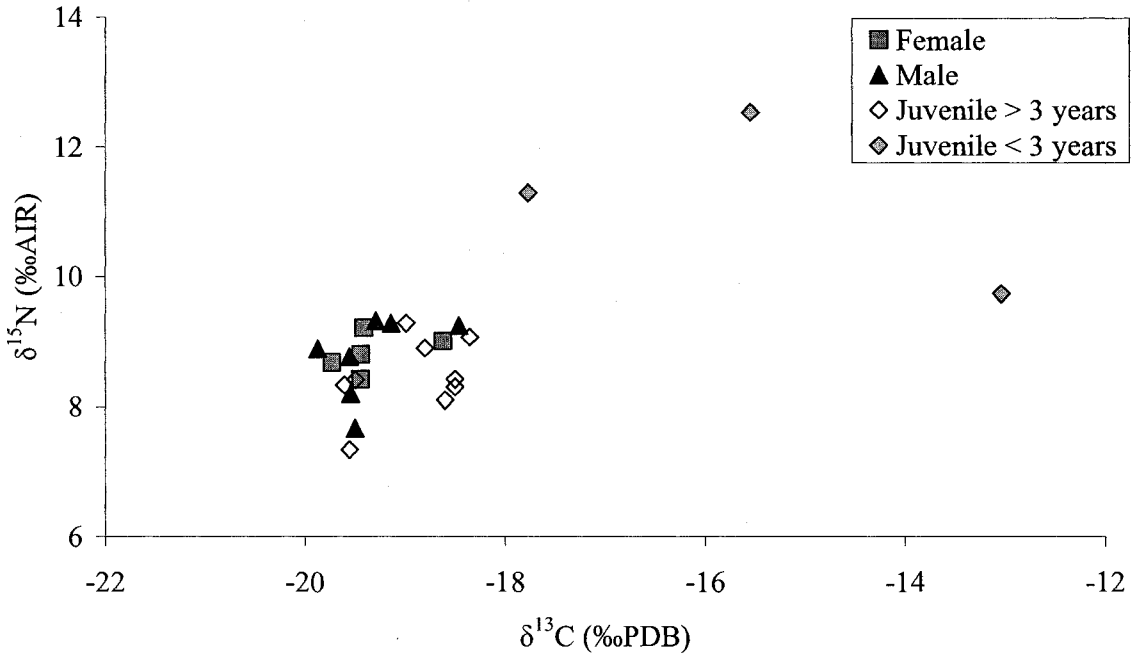
The final Stymphalos human sample consists of 24 individuals. Their isotope values, sex and age are presented in Table 7.1. Mean values for the site are $\delta^{13}C = -18.7 \pm 1.5‰$ and $\delta^{15}N = 9.0 \pm 1.1‰$ with the majority of the samples tightly clustered. As seen in Figure 7.3 where age and sex are plotted for the Stymphalos human $\delta^{13}C$ and $\delta^{15}N$ values, three samples are separated from the main grouping. These samples all represent

Table 7.1: Stymphalos Human Data

	Age	$\delta^{15}N$	$\delta^{13}C$
Juveniles	*0-1 mo	9.7	-13.0
	6-12 mo	11.3	-17.8
	1.5-2.5 yr	12.5	-15.6
	2-4 yr	8.1	-18.6
	4-6 yr	9.1	-18.4
	6-8 yr	8.4	-18.5
	5-9 yr	8.4	-19.5
	8-12 yr	8.3	-19.6
	9-11 yr	8.3	-18.5
	ca. 10 yr	8.9	-18.8
	10-12 yr	7.3	-19.6
	teen	9.3	-19.0
	Mean	**9.1**	**-18.1**
	s.d.	**1.4**	**1.8**
Adult Females	young	8.4	-19.4
	middle	9.2	-19.4
	middle	8.7	-19.7
	adult	8.8	-19.4
	old	9.0	-18.6
	Mean	**8.9**	**-19.3**
	s.d.	**0.3**	**0.4**
Adult Males	young	9.3	-19.1
	young	7.7	-19.5
	middle	9.3	-19.3
	middle	8.8	-19.6
	middle	8.9	-19.9
	middle	8.2	-19.5
	adult	9.3	-18.5
	Mean	**8.8**	**-19.3**
	s.d.	**0.6**	**0.4**
All	**Mean**	**9.0**	**-18.7**
	s.d.	**1.1**	**1.5**

*infant to be used as proxy for female adult values

Figure 7.3: $\delta^{13}C$ vs. $\delta^{15}N$ by Sex, Stymphalos



juveniles under the age of 3. The sample closest to the main grouping had $\delta^{13}C$ and $\delta^{15}N$ values of -17.8‰ and 11.3‰ respectively. These elevated values and the age of the individual suggests a nursing pattern is present. The individual situated furthest from the adults on the other hand had $\delta^{13}C$ and $\delta^{15}N$ values (-13.0‰ and 9.7‰ respectively), substantially different from the rest of the sample. This individual, identified as a neonate, was probably too young at time of death for bone collagen to have remodeled to reflect nursing. If this is true, theoretically the infant's tissues should retain similar values to the mother's (Fuller et al. 2006). If we take this to be correct, the sample actually serves as a proxy for one adult female's $\delta^{13}C$ and $\delta^{15}N$ values and thus will be discussed as such for the rest of the interpretation. The last juvenile had a $\delta^{15}N$ value of 12.5‰ and a $\delta^{13}C$ value of -15.6‰, too high to be reflecting the 1.0‰ enrichment seen during nursing. This suggests the difference between this individual and the rest of the

population cannot only be a reflection of breastfeeding. Why this individual is showing higher $\delta^{13}C$ and $\delta^{15}N$ values will be discussed in detail below.

When these outlying juveniles are omitted, the mean $\delta^{13}C$ and $\delta^{15}N$ values for Stymphalos become -18.9‰ and 8.7‰ respectively. Taken altogether, the Stymphalos samples show no sign of patterning by age or sex aside from the high juvenile $\delta^{13}C$ and $\delta^{15}N$ values mentioned above. Only one female (based on the neonate proxy) shows different stable isotope values from the main grouping of adults.

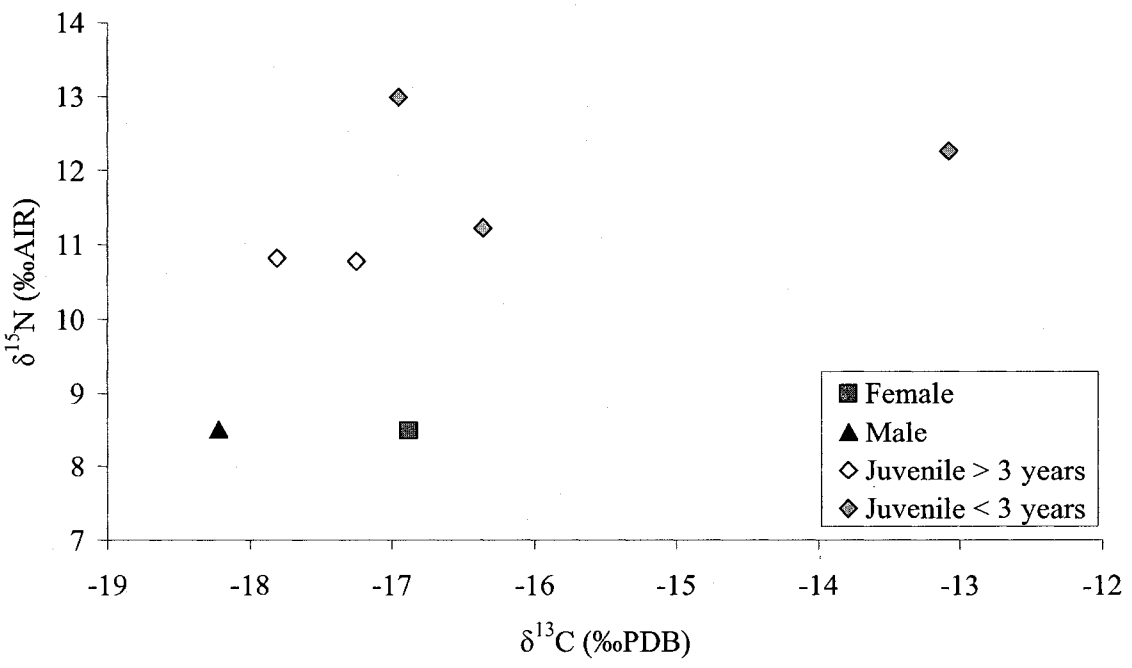
7.3. Human Values, Zaraka

The final sample for Zaraka consisted of 7 individuals. Their stable isotope values, age and sex information are provided in Table 7.2. The overall mean values of Zaraka are $\delta^{13}C = -16.7 \pm 1.6$‰ and $\delta^{15}N = 10.7 \pm 1.6$‰ making them higher than the Stymphalos values.

Table 7.2: Zaraka Human Data

	Age	$\delta^{15}N$	$\delta^{13}C$
Juveniles	0-6 mo	13.0	-17.0
	6-9 mo	11.2	-16.4
	12-24 mo	12.3	-13.1
	3-4 yr	10.8	-17.8
	teen	10.8	-17.3
	Mean	**11.6**	**-16.3**
	s.d.	**0.9**	**1.7**
Adult Females	adult	8.5	-16.9
Adult Males	middle	8.5	-18.2
All	**Mean**	**10.7**	**-16.7**
	s.d.	**1.6**	**1.6**

Figure 7.4: $\delta^{13}C$ vs. $\delta^{15}N$ by Sex, Zaraka



The Zaraka human $\delta^{13}C$ and $\delta^{15}N$ values are plotted by age and sex in Figure 7.4. Determining if there are any correlations between $\delta^{13}C$ and $\delta^{15}N$ values and age and sex is complicated by the fact that the sample size is extremely small. Only one adult female and one adult male are present in the sample making any patterning between the sexes impossible to investigate. The five juveniles present have quite varied $\delta^{13}C$ and $\delta^{15}N$ values. As with the Stymphalos humans, juveniles under the age of 3 years show higher $\delta^{13}C$ and $\delta^{15}N$ values than the rest of the population. One juvenile, with a $\delta^{13}C$ value of -15.6‰ and a $\delta^{15}N$ value of 12.5‰, is substantially separated from the main group suggesting that its values are not just reflecting a nursing signal. The other two juveniles under the age of 3 are closer to the older individuals suggesting that they are likely reflecting a nursing pattern.

7.4. Patterning Between Sites

$\delta^{13}C$ and $\delta^{15}N$ values for all individuals by site are presented in Figure 7.5. A visual analysis shows a general separation between the Stymphalos and Zaraka material with the Zaraka humans having mean $\delta^{13}C$ values about 2.0‰ and $\delta^{15}N$ values 1.7‰ higher than the humans from Stymphalos. Both sites have juveniles whose reflection of nursing patterns could be potentially affecting the mean $\delta^{13}C$ and $\delta^{15}N$ values of the sites.

The extent to which young children can contribute to variation in the overall human sample can be seen in Figure 7.6. All five juveniles under 3 years of age (excluding the neonate) at age of death show not only higher $\delta^{15}N$ values but also higher $\delta^{13}C$ values, setting them apart both from the adults and the older juveniles.[5] The children older than three years tend to occupy the same isotopic space as the adults with the exception of the two older juveniles from Zaraka, whose values are similar to the younger juveniles. The implications of these data for infant feeding customs will be discussed later but it is clear that the younger juveniles (from now on referred to as infants) show $\delta^{13}C$ and $\delta^{15}N$ values distinct from those of the adults. Once the samples representing the infants were removed, the samples were plotted in Figure 7.7 and the group averages were calculated again.

This time the separation between the groups is much smaller with Zaraka having mean $\delta^{13}C$ and $\delta^{15}N$ values only 1.4‰ and 1.0‰ higher respectively than the Stymphalos material. It appears that for Stymphalos, the stable isotope values show little variability. The sample from Zaraka is too small to determine how much variability is seen within the

[5] The Stymphalos juvenile aged around 2-4 years was placed in the 3-10 age group as its $\delta^{13}C$ and $\delta^{15}N$ values indicate that it is similar to the older individuals.

Figure 7.5: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Stymphalos and Zaraka

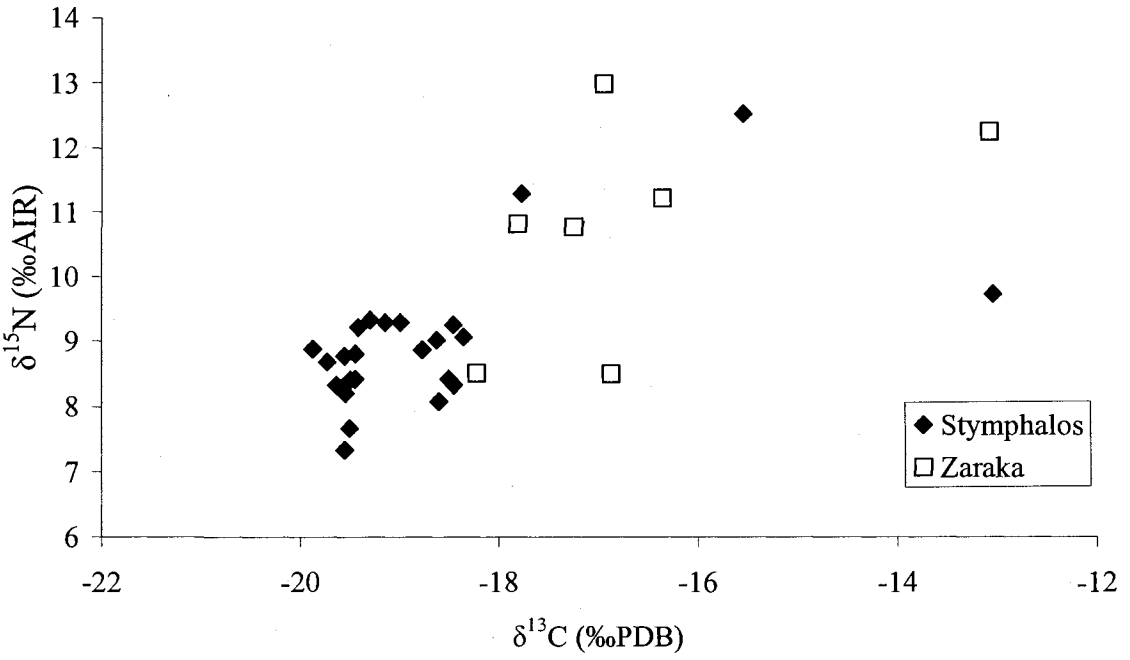


Figure 7.6: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, All Juveniles

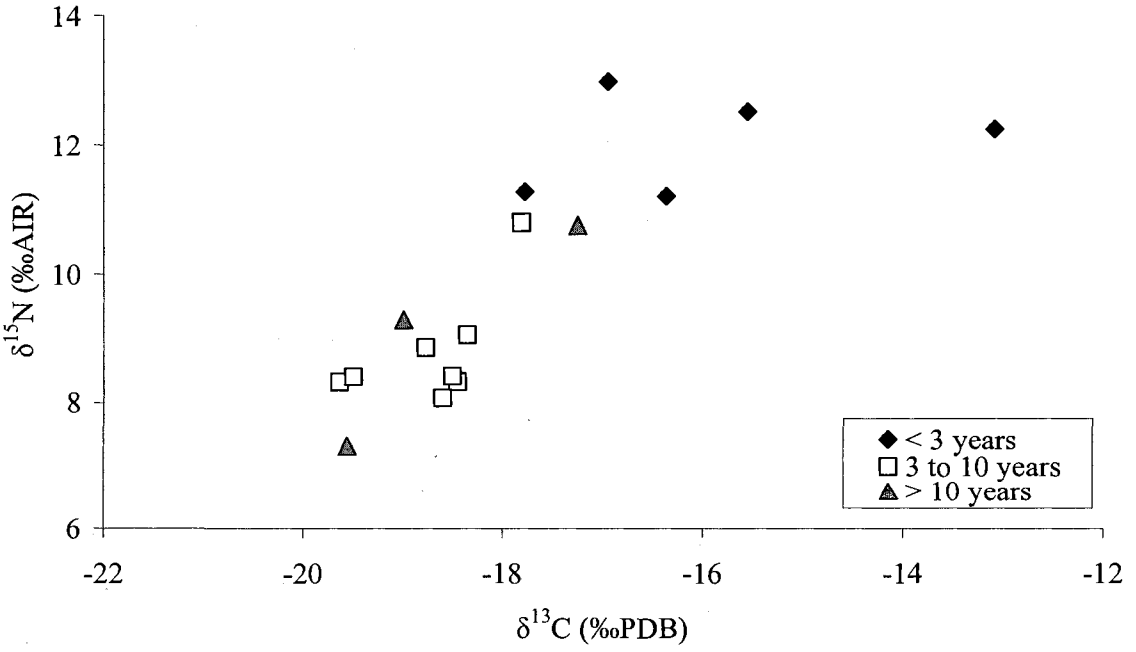
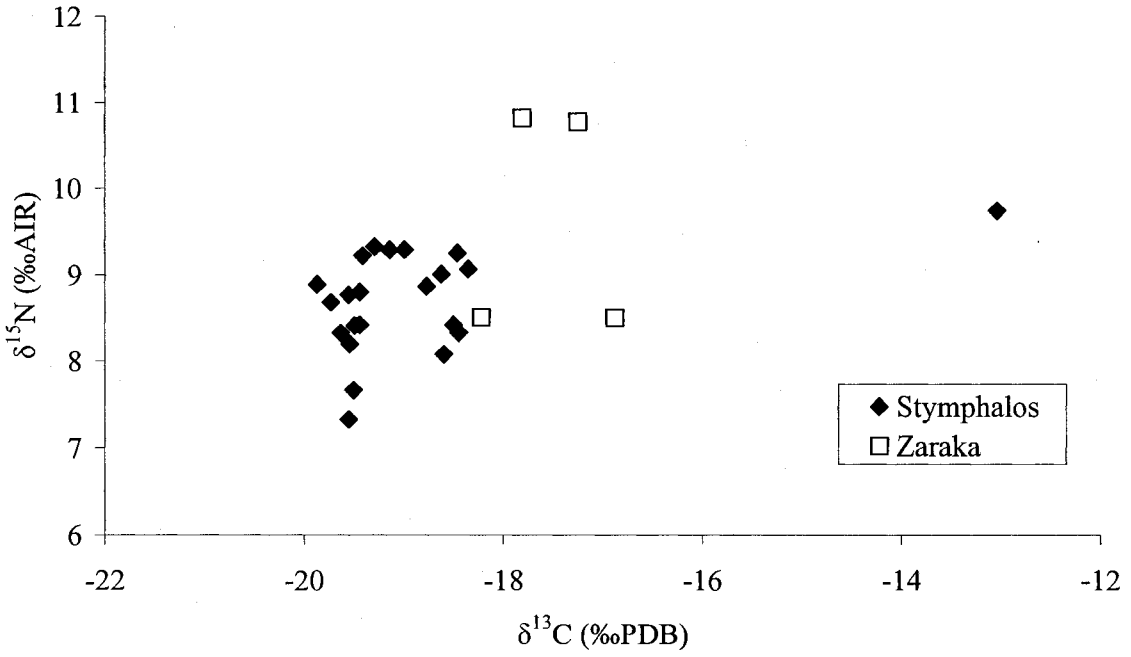


Figure 7.7: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Omitting Infants



population. Stymphalos shows no significant difference between the sexes and the sample from Zaraka is too small to determine whether there was any gender variability. When the sites are compared to each other, the only visual difference between the two is a slight elevation of mean $\delta^{13}C$ and $\delta^{15}N$ values and a greater scatter at Zaraka. The differences seen between the sites could in fact have some impact on the dietary reconstruction and the implications of these differences will be discussed below.

7.5. Dietary Interpretation of Human Stable Isotope Values

With the human values compared to some of the faunal $\delta^{13}C$ and $\delta^{15}N$ values and the variability within and between the sites discussed, we can now turn to dietary interpretation of the human stable isotope values.

7.5.1. Human Stable Isotope Values Compared to Other C3 Agriculturalists: In order to proceed with a discussion of the human stable isotope values at Stymphalos and Zaraka, it is useful to first compare them to those seen for other C3 agricultural groups (see Figure 7.8 for locations). Table 7.3 (below) shows some comparative values for some C3-based agricultural groups located in the Mediterranean with particular focus on those from Greece. At all these sites, diets were concluded to be C3-dominated but C4 grains, marine and/or freshwater resources were known to be available.

When the values of Stymphalos and Zaraka are compared to these different groups we see that their mean $\delta^{13}C$ values (-18.9 ± 1.4‰ and -17.5 ± 0.5‰ respectively) are quite similar. The Stymphalos $\delta^{13}C$ values correspond particularly well to values from Nemea, located not far from the valley of Stymphalos. As all the sites are from warm areas in the Mediterranean, the climate-related trend discussed in Chapter 6 when reconstructing grain $\delta^{13}C$ values has little effect on the comparison.

The mean $\delta^{15}N$ values from this study (8.7 ± 0.6‰ for Stymphalos and 9.7 ±1.1‰ for Zaraka) also fall within the general range of $\delta^{15}N$ values reported for the C3 agricultural groups. Thus the $\delta^{13}C$ and $\delta^{15}N$ values for Stymphalos and Zaraka are generally similar to those reported for other C3 agriculturalists from warmer regions in and around the Mediterranean. This finding is not surprising as the historical data reviewed in Chapter 2 indicated that within the Mediterranean there was a strong focus on C3 grains that stayed relatively constant over time.

Figure 7.8: Sites Discussed in Text

Adapted from Paniglobe 2004

7.5.2. Human Stable Isotope Values Relative to Reconstructed Food Values: When the human $\delta^{13}C$ and $\delta^{15}N$ values are compared to the reconstructed food values determined in Chapter 6, the collagen values indicate a focus on C3/terrestrial protein sources both for Stymphalos and for Zaraka (see Figure 7.9). The low $\delta^{13}C$ values fall close to the reconstructed $\delta^{13}C$ values for C3 grains and animal products, which suggests it is unlikely that C4 grains with their higher $\delta^{13}C$ values were consumed to any great extent. The $\delta^{15}N$ values from Stymphalos and Zaraka are high for populations subsisting primarily on

C3/terrestrial protein which is surprising given the amount of grain they must have been consuming. These high $\delta^{15}N$ values are not localized to the valley of Stymphalos but have been seen for many of the other Mediterranean populations seen in Table 7.3. One possibility for the high $\delta^{15}N$ values is that both populations were utilizing some marine resources. Higher $\delta^{15}N$ values are often seen in populations relying more on marine rather than terrestrial resources for protein (Richards and Hedges, 1999). However, if marine resources were making up a substantial portion of the diet, both $\delta^{15}N$ and $\delta^{13}C$ values would be elevated. The fact that both Stymphalos and Zaraka have low $\delta^{13}C$ values makes it unlikely that these populations were using marine resources to any large extent. The presence of marine fish remains at Zaraka does indicate that marine resources were available in the valley of Stymphalos through trade from other regions closer to the coast. Historical sources also indicate that marine resources were important in the elite Greek diet, but the stable isotopes suggest that the trade was not often enough for marine resources to be a substantial part of the diet for the populations of Stymphalos and Zaraka.

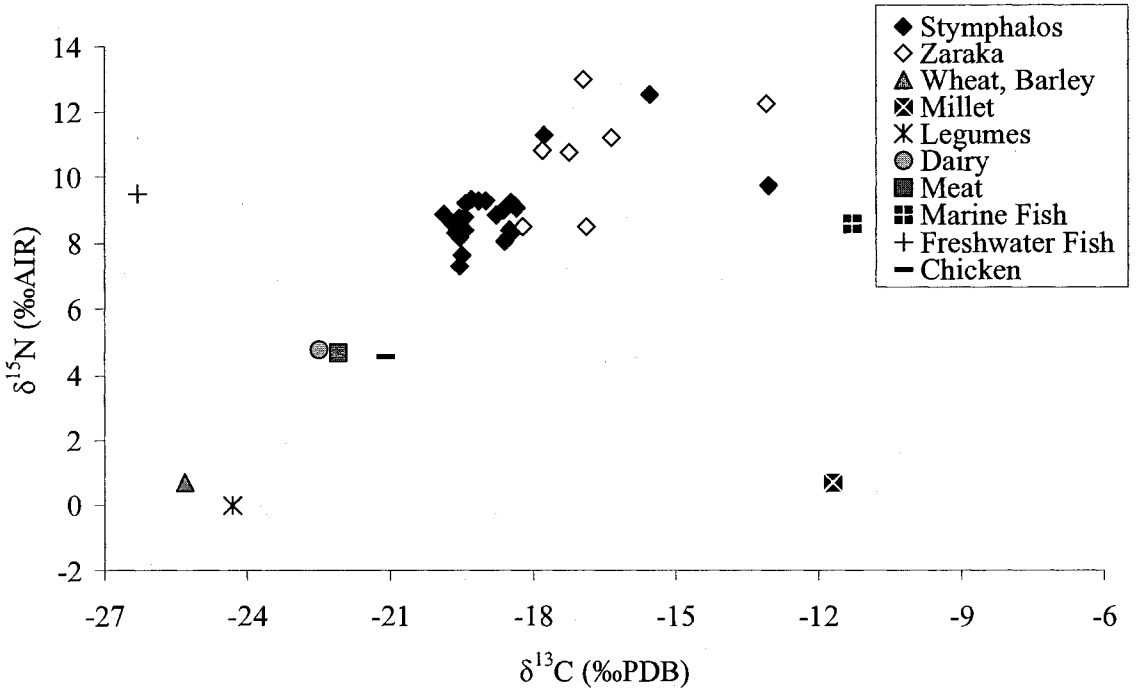
Freshwater fish also appear to have been used rarely by the populations of Stymphalos and Zaraka. Although the Stymphalos and Zaraka human $\delta^{15}N$ values are similar to the reconstructed freshwater fish values, their $\delta^{13}C$ values are separated by almost 8.0‰. Although freshwater fish were readily available and their remains were discovered at Zaraka and Stymphalos, it appears that the use of the lake's resources was sporadic and freshwater fish were not major sources of protein in the diet. Thus, the general pattern created by the site's collagen $\delta^{13}C$ and $\delta^{15}N$ means is strongly suggestive

Table 7.3: Collagen $\delta^{13}C$ and $\delta^{15}N$ for some C3 Agricultural Populations

Population	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	Comments
Early Christian Nemea[1]	-19.0 ± 0.8	8.6 ± 0.6	C4, marine and freshwater resources available
Medieval Nemea[1]	-19.1 ± 0.3	8.8 ± 0.5	C4, marine and freshwater resources available
Frankish Corinth[1]	-18.8 ± 0.3	10.0 ± 1.0	C4, marine resources available
Servia[1]	-18.7 ± 0.3	8.8 ± 0.6	C4, marine resources available
Byzantine Greece[2]	-18.8 ± 0.4	9.2 ± 1.1	C4, marine and freshwater resources available
Neolithic Greece[3]	-19.9 ± 0.2	7.3 ± 0.8	marine resources available
1st-3rd c. Isola Sacra[4]	-18.8 ± 0.3	10.8 ± 1.2	marine and freshwater resources available
6th c. Rome[5]	ca. -20.0	ca. 7.5	freshwater and marine resources available

1.Garvie-Lok, 2001
2. Bourbou and Richards, 2007
3. Papathanasiou et al. 2000
4. Prowse et al. 2004
5. Salamon et al. (in press)

Figure 7.9: Reconstructed Food Values vs. All Humans

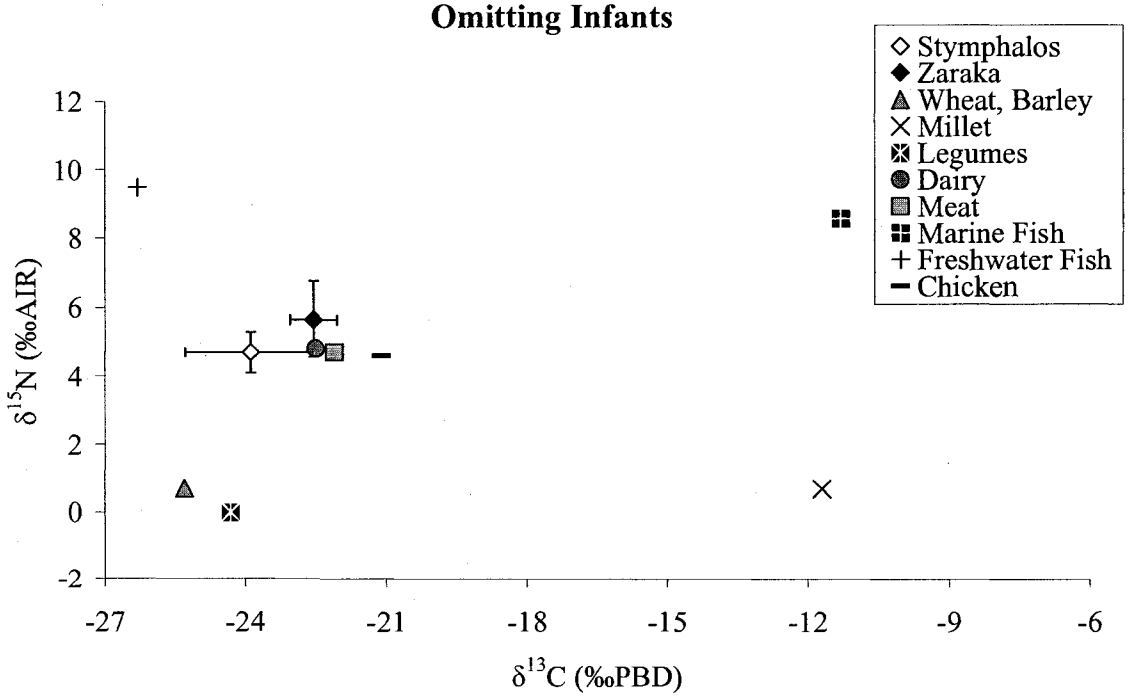


of C3 grain and terrestrial dependence, with little reliance on C4 grains, marine and freshwater foods.

If the diet was largely C3 based as the data seem to suggest, it is reasonable to attempt to relate the collagen $\delta^{13}C$ values from Stymphalos and Zaraka to the dietary protein values created in Chapter 6 using the 5‰ protein-collagen separation typical of pure C3 diets. This attempt can be seen in Figure 7.10 where the mean collagen $\delta^{13}C$ and $\delta^{15}N$ values for Stymphalos and Zaraka are corrected by 5‰ and 4‰ respectively and compared to the reconstructed protein values for Byzantine and Frankish foods. The $\delta^{13}C$ and $\delta^{15}N$ values for Zaraka are slightly higher than the reconstructed meat and dairy products but still match well. The Stymphalos $\delta^{15}N$ values are similar, but the $\delta^{13}C$ values are about 1.0‰ lower. There are a number of reasons that could be behind the low $\delta^{13}C$ values seen at Stymphalos. First, the population of Stymphalos could have been relying

to a greater extent on grain and some legumes for their dietary protein, leading to lower $\delta^{13}C$ and $\delta^{15}N$ values. Although the $\delta^{15}N$ values appear to be too high for this, the use of traditional fertilizing techniques such as manuring could cause higher $\delta^{15}N$ values to be seen in grain. As this pattern of low $\delta^{13}C$ and high $\delta^{15}N$ values is seen in other populations in Greece subsisting primarily on C3-resources where manuring was likely (see Table 7.3), this hypothesis could explain the similarities between the groups. Another possibility is the people of Stymphalos were consuming large amounts of a protein-rich food with high $\delta^{15}N$ values and relatively low $\delta^{13}C$ values. One possible candidate is chicken or chicken eggs. If chickens and their eggs was an important dietary item for the people of Stymphalos, and if the stable isotope values of the chicken recovered are typical of chickens in the region, it would result in $\delta^{15}N$ values similar to

Figure 7.10: Human Values vs. Reconstructed Food Values, Omitting Infants



the other domestic animals but lower $\delta^{13}C$ values. However with only one chicken found at Zaraka, there is little strength to this argument. A final possibility is the use of waterfowl inhabiting the lake. Lake Stymphalia is situated on a bird migratory route and is an important waterfowl habitat (Bourne, 1982; Economidis et al. 2000; Vassilakis et al. 1994). Waterfowl, which feed primarily on plants, could have similar $\delta^{13}C$ values to many freshwater fish but lower $\delta^{15}N$ values due to their lower trophic level. The consumption of these birds could explain the combination of low $\delta^{13}C$ values and higher $\delta^{15}N$ values seen for Stymphalos humans. The large variety of bird remains found at both Stymphalos and Zaraka supports this idea but as none were suitable for stable isotope analysis due to preservation, this hypothesis remains only an intriguing possibility.

While there is still some uncertainty regarding the general diets of Stymphalos and Zaraka, a few important conclusions can be drawn. First, the generally low $\delta^{13}C$ values, both for humans and domestic animals, suggest a largely C3 based diet with little reliance on C4 grains. Secondly, the high $\delta^{15}N$ values are not likely a reflection of marine or freshwater resource dependence due to the corresponding $\delta^{13}C$ values. Finally, it is interesting to note that although the historical sources state that animal resource dependence was limited, the $\delta^{15}N$ values suggest that at least for these populations, animal resources made up the major portion of their dietary protein.

7.5.3. Stymphalos - Probable Diet: The human collagen $\delta^{13}C$ and $\delta^{15}N$ values of the Late Roman/Early Byzantine population of Stymphalos suggest little use of C4 grain or marine resources. While millet was known to be available and often used as animal fodder during this time period, the stable isotope values for both humans and domestic

animals indicate that at Stymphalos, it was not so used. Marine resources are also historically noted as playing a major dietary role in Greece. However, although archaeological evidence shows that marine resources were transported into the area in later times (likely in the form of preserved fish), the low $\delta^{13}C$ values indicate that they did not make up a significant portion of the general diet in the Late Roman/Early Byzantine era. Freshwater fish were also of little apparent dietary importance even though a large lake was located in the valley. As the collagen $\delta^{13}C$ values appear to indicate C3 reliance, a 5‰ separation for dietary protein and collagen is likely appropriate. While the 4.7‰ $\delta^{15}N$ value agrees with predicted $\delta^{15}N$ values for C3-based diets rich in meat or dairy foods, the lower $\delta^{13}C$ value of -23.9‰ suggests the presence of another resource, such as the waterfowl known to inhabit the lake. It is possible, however, that these values are in fact showing a dependence on grains and other plant products as well as animal products. The reconstructed grain values fail to take traditional fertilizing techniques like manuring into account. If this was occurring in the valley during the Late Roman/Early Byzantine era, it would explain the high $\delta^{15}N$ value and low $\delta^{13}C$ value seen at Stymphalos.

While the majority of the population of Stymphalos shows little dependence on marine resources or C4 grains there are three outlying individuals showing differences in diet. The neonate used as a proxy for an adult female shows elevated $\delta^{15}N$ (9.7‰) and $\delta^{13}C$ (-13.1‰) values, close to those of reconstructed marine resources. There are a few possible reasons as to why this one individual is so different from the rest of the population. First, this individual could be from a wealthy higher class family compared to the rest of the population. If this individual did come from a wealthier family, they likely

could afford to have marine resources brought in regularly and thus consumed with greater frequency. However, this is unlikely. This was a rural lower class population where social stratification and thus differences in wealth would have been minimal. The similar orientation of all the burials and the general absence of associated grave goods lends credibility to the idea that this was a rural poor population with few class differences (Williams et al. 2002). A more plausible explanation for the higher $\delta^{13}C$ and $\delta^{15}N$ values seen in this individual is immigration into the area of Stymphalos from an area where marine resources or C4 grains were consumed on a regular basis. The movement of one individual into a different area was probably not unheard of. Garvie-Lok (2001) suggested that immigration explained the presence of one adult male with substantially different $\delta^{13}C$ and $\delta^{15}N$ values from the rest of the population found at Early Christian Nemea. For the individual at Stymphalos, the fact that the sample represents a female suggests her move into the area could have been the result of marriage. Intermarriage between the population of Stymphalos and a population consuming greater amounts of marine resources or C4 grains could account for the elevated bone collagen values seen in this female. If her child was delivered and died soon after she arrived at Stymphalos, her tissues would not have had time to turnover and would still reflect the $\delta^{13}C$ and $\delta^{15}N$ values of her previous diet as would the tissues of her child. The other two outlying individuals in the Stymphalos group were both infants under the age of 3 years and so will be examined in connection with the other infant stable isotope values from Stymphalos and Zaraka.

Other than the three individuals discussed above, there were no differences between male and female $\delta^{13}C$ and $\delta^{15}N$ values at Stymphalos. This does not necessarily

mean there was no dietary variation between the sexes but only shows that any difference is not isotopically visible. For example, if women were eating different cuts of meat than the men or consuming more dairy products in the place of meat, the sexes would still show similar $\delta^{13}C$ and $\delta^{15}N$ values even though the diet was in fact different.

7.5.4. Zaraka- Probable Diet: At the Frankish period site of Zaraka, the $\delta^{13}C$ and $\delta^{15}N$ values reflect a largely C3-based diet. Much as with the Stymphalos samples, a 5‰ separation for dietary protein and collagen is appropriate for the Zaraka human samples. With a mean $\delta^{13}C$ value of -22.5‰ and a $\delta^{15}N$ value of 5.7‰ the dietary values suggested by the samples are very similar to the reconstructed $\delta^{13}C$ and $\delta^{15}N$ values of the terrestrial animal products. This suggests that the Zaraka population were relying heavily on meat and dairy for their dietary protein.

The slight elevation of the $\delta^{13}C$ and $\delta^{15}N$ values over the terrestrial animal protein could suggest some use of marine resources or C4 grains by the population. However, the fact that the Zaraka sample is extremely small makes it difficult to determine whether the higher stable isotope values show greater reliance on terrestrial animal protein rather than C3 grain protein or whether there was some marine resource or C4 grain consumption. The only individuals showing $\delta^{13}C$ and $\delta^{15}N$ values much different from the rest were both under the age of 3 at death and thus will be discussed with the other infants from Stymphalos and Zaraka.

7.6. Comparison to Other Stable Isotope Data for Greece

At this point in the discussion it is interesting to compare the values found for this study with those obtained from other Greek populations (see Figure 7.8 for locations). A number of recent stable isotope studies focusing on Byzantine Greece have provided stable isotope values for different populations throughout Greece. Garvie-Lok (2001) surveyed the sites of Athens, Corinth, Nemea, Mitlini, Servia and Petras to examine Medieval Greek diet. The results indicated that for all populations, which date from the Early Christian period well into the Ottoman period, the diet was C3 dominated, included a large amount of terrestrial animal protein, and showed little use of marine resources, C4 grains or legumes. The only evidence for some marine resource consumption came from the two island populations, Mitilini and Petras. C4 grain consumption was limited until the late Frankish period. Nemea, the closest site to Stymphalos in terms of location and time period, had values clustering around -19.0‰ and 8.6‰, similar to the values obtained in this study and suggesting that the diet might have been similar in the two regions. Further work on Byzantine populations has confirmed that the general Greek diet during the medieval period was largely C3-based. Bourbou and Richards (2007) studied material from the site of Kastella on the island of Crete. The resulting values clustered around -18.8‰ and 9.9‰ indicating that even through this population had ready access to marine resources, the diet was largely based on C3/terrestrial animal proteins. Only a small portion of the diet was actually made up of marine resources.

Sites dating from earlier time periods have also produced stable isotope values in agreement with the values obtained for Medieval Greek populations. Papathanasiou et al. (2000) analyzed a number of individuals from the Neolithic site at the Alepotrypa Cave

on Diros. The values obtained suggested again that the diet was predominantly based on C3 resources. Although marine faunal remains were recovered from the site, the $\delta^{13}C$ and $\delta^{15}N$ values showed little evidence of marine resource consumption. A more recent survey of six Neolithic sites located both on the coast and inland confirmed that for many populations, marine resources made up only a small portion of the general diet compared to C3/terrestrial resources (Papathanasiou, 2003).

The values obtained in these stable isotope studies are presented in Table 7.4. When the Byzantine and medieval isotope values are compared to those from earlier periods, the values are all higher. The mean collagen $\delta^{13}C$ values for this study -18.7 ± 1.5‰ and -16.7 ± 1.6‰, fall close to the mean $\delta^{13}C$ values both from the medieval and Byzantine populations. The $\delta^{13}C$ values for Zaraka are somewhat higher than those determined for other medieval sites (e.g. Garvie-Lok, 2001) but the difference is not extreme. The large number of young juveniles in the Zaraka population with their higher $\delta^{13}C$ values could be affecting the mean $\delta^{13}C$ value. When these young juveniles are omitted, the mean collagen $\delta^{13}C$ value of Zaraka is -17.5 ± 0.5‰ which agrees with the other medieval values. Mean $\delta^{15}N$ values for this study fall at 8.7 ± 0.6‰ for Stymphalos and around 9.7 ± 1.1‰ for Zaraka. Again the values for Stymphalos and Zaraka are more similar to the medieval values than the earlier periods which tend to have lower $\delta^{15}N$ values.

The authors of the studies presented below all concluded that diet in these eras was dominated by terrestrial resources. Garvie-Lok (2001) saw no evidence for heavy marine resource use at her medieval sites. However the higher $\delta^{13}C$ and $\delta^{15}N$ values seen

Table 7.4: $\delta^{13}C$ and $\delta^{15}N$ Values of Archaeological Greek Populations

Locale	Era	$\delta^{13}C$	$\delta^{15}N$
Corinth[1]	Frankish	-18.8 ± 0.3	10.0 ± 1.0
Corinth[1]	Ottoman	-17.8 ± 1.1	9.8 ± 2.0
Mitilini[1]	Ottoman	-17.6 ± 3.2	9.8 ± 1.4
Nemea[1]	Early Christian	-19.0 ± 0.8	8.6 ± 0.6
Nemea[1]	Medieval	-19.1 ± 0.3	8.8 ± 0.5
Servia[1]	Medieval	-18.7 ± 0.3	8.8 ± 0.6
Petras[1]	Medieval	-19.2 ± 0.4	9.4 ± 0.6
Kastella[2]	Byzantine	-18.8 ± 0.4	9.2 ± 1.1
Alepotrypa Cave[3]	Neolithic	-19.9 ± 0.2	7.3 ± 0.8
Franchthi[4]	Neolithic	-18.7 ± 0.8	9.2 ± 1.8
Kephala[4]	Neolithic	-19.1 ± 1.2	9.2 ± 1.0
Tharrounia[4]	Neolithic	-20.0 ± 0.2	8.0 ± 0.7
Theopetra[4]	Neolithic	-19.8 ± 0.9	7.4 ± 1.1
Kouveleiki[4]	Neolithic	-19.8 ± 0.0	8.1 ± 0.3

1.Garvie-Lok 2001

2. Bourbou and Richards, 2007

3. Papathanasiou et al. 2000

4. Papathanasiou, 2003

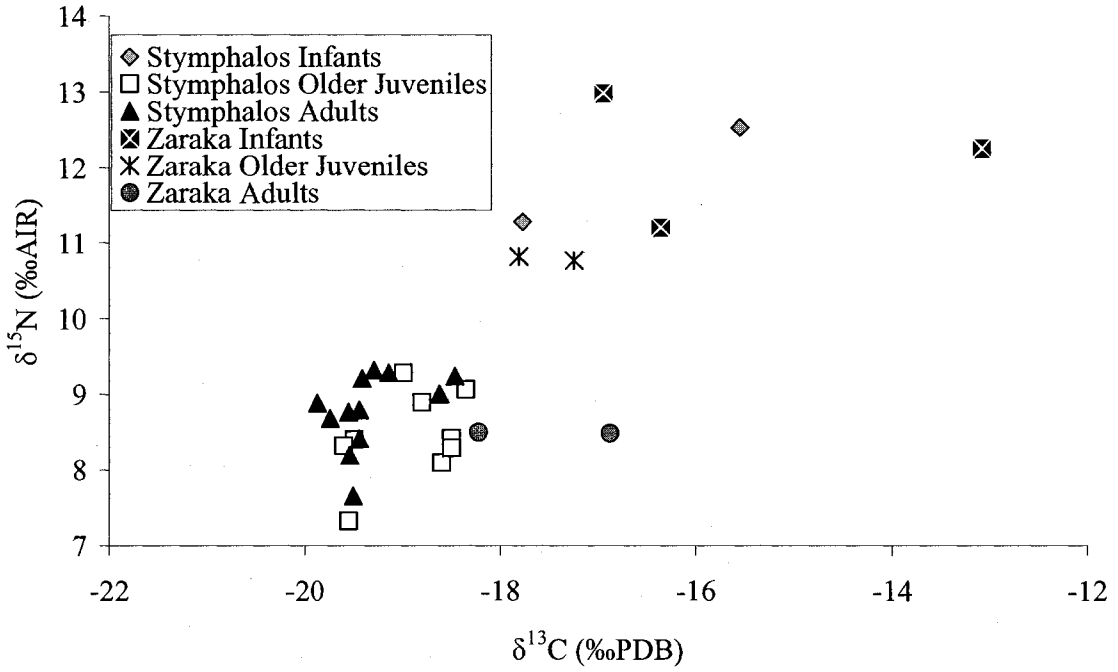
at the two island sites caused her to suggest that at least for these two populations, marine resources played a supplementary role in the diet. She theorized that there was a strong focus on terrestrial animal protein obtained from eating meat and dairy products in the Medieval Greek diet. Bourbou and Richards (2007) reached similar conclusions in their study of the site of Kastella. Although Kastella is an island site, the authors interpreted the data as indicating the diet relied heavily on terrestrial animal proteins and marine resources played only a limited role. The studies examining Greek Neolithic sites reported a smaller range of $\delta^{13}C$ values and lower $\delta^{15}N$ values than the medieval populations but again these studies suggest that the general diet during the Neolithic included little marine resource consumption and focused more on cultivated C3 plants

(Papathanasiou, 2003; Papathanasiou et al. 2000). However unlike the Medieval Greek populations, there appeared to be limited use of animal protein of any type. This smaller focus on terrestrial animal protein helps to explain why the $\delta^{15}N$ values of these groups are lower than those found in the medieval populations.

7.7. Infant Stable Isotope Values, Nursing and Weaning

As we have seen throughout this discussion on diet at Stymphalos and Zaraka, the most prominent internal patterning in both sites is the patterning in the $\delta^{13}C$ and $\delta^{15}N$ values of infants. The general pattern which can be seen in Figure 7.11 is presented in Stymphalos and Zaraka, all the infants show apparent $\delta^{15}N$ elevation with maximum values for this elevation varying between sites, +3.5‰ for Stymphalos and +4.5‰ for Zaraka. This variation most likely reflects a number of things including the time along the curve (first increasing and then decreasing) of $\delta^{15}N$ that traces nursing in infants as well as variability in maternal diet which would affect the mother's $\delta^{15}N$ value. Unfortunately the number of samples available for Stymphalos and Zaraka is too small to accurately trace weaning age. In addition, as only one adult female was available from Zaraka, it is impossible to determine if the estimated adult female mean used here is the actual average female value for the population. However, there are some indications of weaning practices and when combined with the results from other stable isotope studies on medieval Greek populations, it can suggest a likely scenario for Greek breastfeeding and weaning practices during the medieval period. Both the samples from Stymphalos and those from Zaraka suggest that a shift in $\delta^{15}N$ began taking place around 2 to 3 years of age and the individuals older than 3 years seem to show $\delta^{15}N$ values similar to the mean

Figure 7.11: All Human $\delta^{13}C$ and $\delta^{15}N$ Values by Age



adult female $\delta^{15}N$ values. These results provide support for the historical medical sources which stated that the recommended age to start weaning was around 3 years (Fildes, 1986, 1988). The $\delta^{13}C$ and $\delta^{15}N$ values also match well with other medieval Greek stable isotope studies. Bourbou and Garvie-Lok (in press) found that Byzantine infant $\delta^{13}C$ and $\delta^{15}N$ values from a number of sites generally started to shift towards adult values around the age of 3 years. Bourbou and Richards (2007) found a similar pattern appearing for the Byzantine site of Kastella. Unlike the $\delta^{15}N$ values where all infants show elevation over that of the adults, the $\delta^{13}C$ values are variable. Four out of the five infants show higher $\delta^{13}C$ values than the adult female mean, with the difference being 0.5‰ and 2.7‰ for the two Stymphalos infants and 0.5‰ and 3.8‰ for the Zaraka infants. The separation seen between the infants and the mean adult females is interesting and could suggest the possibility of a trophic level effect for $\delta^{13}C$ in addition to the trophic level shift seen for

$\delta^{15}N$. This shift in $\delta^{13}C$ values has been documented in modern stable isotope studies of infant-mother pairs and generally results in an enrichment of around 1‰ (Fuller et al. 2006).

While the infant collagen values of Stymphalos and Zaraka show elevated $\delta^{13}C$ and $\delta^{15}N$ values, which is typically interpreted as reflecting a nursing signal, the situation is actually somewhat more complex. Two individuals (one from Stymphalos and one from Zaraka) show values for $\delta^{13}C$ that are too high to be explained only by nursing. It is possible that the higher $\delta^{13}C$ values are due to the introduction of weaning foods. Ancient and Byzantine physicians recommended the introduction of solid foods around 6 months

Table 7.5: Juvenile and Adult Female Values by Site*

Site	Age	$\delta^{15}N$	$\delta^{13}C$
Stymphalos	6 - 12 mo	11.3	-17.8
	1.5 - 2.5 yrs	12.5	-15.6
	2.5 - 4 yrs	8.1	-18.6
	4 - 6 yrs	9.1	-18.4
	6 - 8 yrs	8.4	-18.5
	5 - 9 yrs	8.4	-19.5
	8 - 10 yrs	8.9	-18.8
	9 - 11 yrs	8.3	-18.5
	8 - 12 yrs	8.3	-19.6
	10 - 12 yrs	7.3	-19.6
	16 - 18 yrs	9.3	-19.0
	Adult Females	**9.0**	**-18.3**
Zaraka	0 - 6 mo	13.0	-17.0
	6 - 9 mo	11.2	-16.4
	12 - 24 mo	12.3	-13.1
	3 - 4 yrs	10.8	-17.8
	12 - 15 yrs	10.8	-17.3
	Adult Females	**8.5**	**-16.9**

* Stymphalos neonate included as an adult female

of age (Fildes, 1986). If C4 grains were utilized as a weaning food, this could explain the higher $\delta^{13}C$ values seen for these infants. If C4 grains were used however, the adults show no little evidence of it. While it is possible that C4 grains were grown exclusively for infants, it seems unlikely that the rest of the population would not take at least some advantage of this resource. Another possible explanation for the higher $\delta^{13}C$ values seen for these infants is that like the neonate discussed above, they immigrated into the area as part of a group from a region with significant C4 and/or marine dependence. As there is already evidence of some immigration into the area (the neonate from Stymphalos), this is not a stretch to suggest.

The infant collagen values of Stymphalos and Zaraka fit the pattern of a trophic level effect of nursing quite well. A $\delta^{13}C$ increase is seen in connection with elevated $\delta^{15}N$ in younger juveniles under the age of 3, and this effect is absent after 3 years of age with the $\delta^{13}C$ and $\delta^{15}N$ becoming similar to the adult values. While the increase in $\delta^{15}N$ is apparent for all infants, $\delta^{13}C$ elevation occurred in only 4 of the 5 infants available for study. It is possible that these individuals were consuming weaning foods (possibly C4 grains) more often than other infants leading to $\delta^{13}C$ values similar to those of the adults but still showing higher $\delta^{15}N$. The extremely high $\delta^{13}C$ values seen for two of the infants could also suggest possible immigration into the area. Even with these inconsistencies, it is apparent that both Stymphalos and Zaraka infant show $\delta^{15}N$ and $\delta^{13}C$ trophic level difference from adult females similar to that seen in modern infant-mother pairs (Fuller et al. 2006).

7.8. Revisiting the Original Research Questions

With the interpretation complete, we return again to the original research questions posed in Chapter 2. The first question posed was of the importance of C4 grains (millet) to the Byzantine and Frankish diets. The faunal stable isotope values documented in Chapter 6 indicate that C4 grains were not used as fodder for domesticated animals at Stymphalos and Zaraka. The human $\delta^{13}C$ and $\delta^{15}N$ values for both sites also show that C4 grains did not have much importance to the general diet. While it does appear that the diet was primarily C3-dominated, there is still some uncertainty as to how much of the diet was based on C3 grains and how much was on C3 consuming animals. The low $\delta^{13}C$ values and the high $\delta^{15}N$ values suggest heavy dependence on terrestrial animal products. The use of waterfowl from the lake could account for the lower $\delta^{13}C$ values and the high $\delta^{15}N$ values seen at Stymphalos as compared to Zaraka. While the stable isotope values do appear to show substantial consumption of animal resources, it is also possible that the C3 grain dependence has been underestimated. As dietary protein primarily comes from animal sources and not grains, consuming large amounts of animal protein would mask the amount of grain being consumed. In addition, traditional fertilizing techniques were not taken into account during the reconstruction of grain values. If these techniques were used, grain $\delta^{15}N$ values would be higher than suggested and heavy grain dependence could result in the human $\delta^{13}C$ and $\delta^{15}N$ values seen at Stymphalos and Zaraka. While there is still some questions as to C3 grain vs. animal resource dependence, it appears that for both humans and domestic animals, the primary grain stable was C3 (most likely wheat and/or barley) and millet did not play a major part.

The second question was how pervasive marine resource consumption was and if freshwater resources played a role in the general diet. The stable isotope evidence from this study suggests that at least for the populations of Stymphalos and Zaraka, marine and freshwater resources played almost no role in the diet. The pattern of high $\delta^{15}N$ and low $\delta^{13}C$ values agrees with diets where much of the protein is provided by terrestrial animals and not marine resources. The extremely low $\delta^{13}C$ values for the freshwater resources indicate that they too played only a small role in the general diet. The stable isotope patterning, combined with historical sources documenting the wide availability of animal products suggests that the general diet for Stymphalos and Zaraka was predominantly based around terrestrial animal products such as meat, eggs and dairy.

The final question posed was at what age did weaning typically occur. The historical literature indicates that for most of the Greek population weaning occurred rather late, around 2 to 3 years of age. The human $\delta^{13}C$ and $\delta^{15}N$ values at Stymphalos and Zaraka seem to agree with the historical sources however the sample is too small for this to be definate. The high stable isotope values seen in infants under the age of 3 appear to be a trophic level effect and reflect a nursing pattern. Juveniles over the age of 3 begin to show a shift in $\delta^{13}C$ and $\delta^{15}N$ values shift towards the values of the adults suggesting that weaning around the ages of 2 to 3.

The questions put forward in Chapter 2 were largely answered successfully through stable isotope analysis of human remains from Stymphalos and Zaraka. At Stymphalos and Zaraka, the general diet appears to have been based largely around C3 grains and the consumption of terrestrial animal proteins with little use of marine and freshwater resources and C4 grains such as millet. Although the two sites date from

different eras (Stymphalos dates roughly from the Late Roman/Early Byzantine period while Zaraka was occupied around the 14th century) their diets appear to have been similar with a possible slight increase in terrestrial animal protein at Zaraka. The infant feeding practices also appear to have been similar with breastfeeding being the most common and weaning occurring around the age of 3. While the analysis of bone collagen $\delta^{13}C$ and $\delta^{15}N$ values has shed some light on the diet of the populations occupying the valley of Stymphalos, stable isotope analysis does have some limitations that must be recognized. Firstly, bone collagen $\delta^{13}C$ and $\delta^{15}N$ only examine the protein component of the diet and do little to determine what the bulk diet consists of. Examining the $\delta^{13}C$ values of bone carbonate would help to answer some of the lingering questions left by the bone collagen stable isotope analysis. Second, minor marine, freshwater and C4 use in the diet would not be detected, as the major part of the diet would help to mask their $\delta^{13}C$ and $\delta^{15}N$ values. In addition, the consumption of different terrestrial animal products (e.g. meat, eggs, dairy, etc.) cannot be distinguished making it difficult to determine what played a more dominant role. Although there are limitations to what stable isotope analysis can tell us about Byzantine and Frankish Greece, significant information on resource use was obtained by this study and further work on these individuals could reveal even more detailed information on the rural Greeks from the Early Byzantine and Frankish periods.

Chapter 8: Conclusions

The results of this study offer some insight into life in rural Greece during the Early Byzantine and Frankish periods. The analysis has helped to address questions of resource use, and produce insights into the methods of stable isotope work with European agricultural populations and the stable isotope effects of nursing in humans. This purpose of this chapter is to summarize the important findings of the work and discuss some possible directions for future study.

8.1. Diet in Byzantine and Frankish Greece: The Isotopic Viewpoint

The first step in this study was to review historical and other sources on Greek diet from the Byzantine and Frankish periods. These sources provided a wealth of detailed information and helped to show how useful these sources are to researchers examining diet in the past. However, these sources did have some weaknesses. In general, these sources focused only on what was eaten instead of how much and focus was often placed on one specific group within the population (e.g. monks). In addition, the writer's perceptions were often coloured by social attitudes towards eating and drinking. The result was that while historical sources go into great detail about the identities of the foods eaten during the Byzantine and Frankish periods in Greece, they provide little information about the importance of these foods to the general Greek diet. In order to resolve some of these lingering uncertainties, three questions were posed at the end of the review for which stable isotope analysis could help to bring greater insight. How significant was millet use in the Byzantine and Frankish diet? Did marine resources and

freshwater resources play major roles in the diet? Finally, at what age did weaning typically occur?

The likely $\delta^{13}C$ and $\delta^{15}N$ values for available food items in the Byzantine and Frankish periods were obtained through the analysis of the faunal material and from the literature. The clear separation of fauna by their $\delta^{13}C$ and $\delta^{15}N$ values showed the potential of stable isotope analysis to answer the questions posed above. However there are some limitations to the procedure. Although marine and freshwater resources are clearly separated from the terrestrial resources, thus allowing for their consumption to be differentiated from one another, the different terrestrial animal products (e.g. meat, dairy products, eggs, etc.) are less clearly defined. For this study, meat and dairy products are isotopically similar. For any study looking for gender differences in meat and dairy consumption in the area, this isotopic similarity could have a serious impact, as any difference in meat consumption could be erased, isotopically speaking, through the increased consumption of dairy products by those with limited access to meat. In addition, both the archaeological evidence and stable isotope results suggest there were few if any differences in social status within the valley that would have affected the diet.

8.1.1. The Importance of Millet: The stable isotope results for both humans and domestic fauna showed that little if any millet was utilized in the Stymphalos valley during the Byzantine and Frankish periods. The historical sources mentioned that millet was used as both animal fodder and as a supplement to the primary C3 stable grains in human food. However, its use varied by region and by economic status. For Stymphalos and Zaraka, the stable isotope data do not support millet as having a major role as animal fodder or as

a supplement in the human diet. The faunal $\delta^{13}C$ and $\delta^{15}N$ values fall closely to the reconstructed values of C3 grains suggested they were the primary sources of nutrition. The human $\delta^{13}C$ values are similar to the domestic animals suggesting that they too had a C3 based diet. While the study did show that the populations inhabiting the valley of Stymphalos had a diet based on C3 grains and animal proteins, the bone collagen stable isotope analysis was limited in the fact that it could not detect small amounts of millet consumption. The application of bone carbonate $\delta^{13}C$ analysis to the Stymphalos and Zaraka samples would allow for more precision and thus a greater possibility for the detection of millet.

8.1.2. The Importance of Marine Resources: While the collagen isotope values from Stymphalos and Zaraka suggest animal protein played a significant role in the general diet during the Byzantine and Frankish periods, they do not suggest this protein was from marine and/or freshwater resources. This is supported by the absence of an overall relationship between collagen $\delta^{13}C$ and $\delta^{15}N$ values in the whole human data set. The combination of high $\delta^{15}N$ and low $\delta^{13}C$ does not support a diet relying heavily on marine and freshwater resources. Although the high human $\delta^{15}N$ values fit well with the marine and freshwater $\delta^{15}N$ values obtained for this study, the $\delta^{13}C$ values show clear separation from the high $\delta^{13}C$ values seen for the marine samples and the extremely low $\delta^{13}C$ values seen for the freshwater samples. The human $\delta^{13}C$ and $\delta^{15}N$ values are more suggestive of a C3 based diet dependent on C3 grains and animal products such as meat, eggs, and/or dairy products. These results indicate that in this region, if there was marine/freshwater

resource consumption, it could be differentiated from the background of general terrestrial resource dependence.

8.1.3. Nursing and the Trophic Level $\delta^{13}C$ and $\delta^{15}N$ Effect: Although the infant sample size was small, the stable isotope results are consistent with data from the historical sources. Medical texts from the Byzantine and Frankish periods recommend breastfeeding as the best feeding practice for infants and for this to continue until weaning around the ages of 2 and 3. The infant remains from both sites show the expected $\delta^{15}N$ value increase related to nursing. Interestingly, the majority also show higher $\delta^{13}C$ values. Unfortunately, the small number of infants available does not allow for much explanation as to what this pattern means. However the stable isotope results do give some idea of the infant feeding practices during the Byzantine and Frankish periods. Supplemental feeding with animal milk is unlikely due to the high $\delta^{13}C$ values. The use of millet as a weaning food is a possibility, but the limited sample size and the fact that there is no other evidence of millet use by the rest of the humans and the fauna, makes it difficult to determine. It could be that the increase in $\delta^{13}C$ seen in the infants is in fact reflecting a $\delta^{13}C$ trophic level shift due to nursing. This type of shift, seen in nature as well as documented in modern humans is reflected by higher $\delta^{15}N$ values being accompanied by higher $\delta^{13}C$. However for some of the infants, this increase in $\delta^{13}C$ could be reflecting population mobility. The populations of Stymphalos and Zaraka where the diet is largely C3-based are the sort where the small $\delta^{13}C$ (about 1‰) nursing effect would be expected to be seen. The infant $\delta^{13}C$ and $\delta^{15}N$ values also give some indication as to when weaning occurred. The higher infant $\delta^{13}C$ and $\delta^{15}N$ values appear to start

shifting towards values similar to the adults around 3 years of age at both Stymphalos and Zaraka. This information agrees well with the historical sources.

8.1.4. Stable Isotope Values in Greek Agriculturalists: This study's results fall in line with prior studies on Greek agriculturalists in a number of ways. First the $\delta^{13}C$ values fall into the range of $\delta^{13}C$ values found for sites dated to the same time periods as the sites analyzed here. Secondly, the high $\delta^{15}N$ values found at Stymphalos and Zaraka are similar to those reported for other agricultural groups located throughout Greece. The historical sources describe the Greek diet to be heavily dependent on grain. The stable isotope values appear to contradict this. Much like the Stymphalos and Zaraka, many sites show low reconstructed grain $\delta^{15}N$ values. If the Greek diet was dependent on grain, human $\delta^{15}N$ values would also be expected to be low. However, the humans of Stymphalos and Zaraka show $\delta^{15}N$ values elevated a full trophic level above the local domesticate fauna from which most of their animal protein would have come from. This suggests that the populations of Stymphalos and Zaraka were relying heavily on animal proteins and not on grains. It is possible that the high $\delta^{15}N$ values are due to other factors. The fertilizing of the crops by manuring could cause higher grain $\delta^{15}N$ values than expected. Further research could help to remove some of the uncertainties involved in interpreting $\delta^{15}N$ in agricultural groups.

This research had helped to advance understanding of Byzantine and Frankish rural Greek way of life and the use of archaeological stable isotope analysis. The results

of this study demonstrate the potential of stable isotope analysis in investigating historical populations and the breadth of information it can provide.

Bibliography

The early sources used in this thesis are referred to by the original author's name only and as such the bibliographic information on the translations used is listed alphabetically under the original author's name.

Adamson, M.W.
2004 *Food in Medieval Times*. Greenwood Press, Westport Connecticut.

Alcock, S.H.
1993 *Graecia Capta: The Landscapes of Roman Greece*. Cambridge University Press, Cambridge.

Ambrose, S.H.
1990 Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science* 17:431-451.
1991 Effects of diet, climate and physiology on nitrogen isotope abundances in terrestrial foodwebs. *Journal of Archaeological Science* 18:293-317.
1993 Isotopic analysis of paleodiets: Methodological and interpretive considerations. In: *Investigations of Ancient Human Tissue: Chemical Analyses in Anthropology*, edited by M.K. Sandford, pp. 59-130. Gordon and Breach, Langhorne, Pennsylvania.

Ambrose, S.H. and M.J. DeNiro.
1986 The isotopic ecology of East African mammals. *Oecologia* 69:395-406.

Ambrose, S.H. and J. Krigbaum.
2003 Bone chemistry and bioarchaeology. *Journal of Anthropological Archaeology* 22(3):193-199.

Ambrose, S.H. and L. Norr.
1993 Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In: *Prehistoric Human Bone: Archaeology at the Molecular Level*, edited by J.B. Lambert and G. Grupe, pp. 1-37. Springer-Verlag, Berlin.

Ambrose, S.H., B.M. Bulter, D.B. Hanson, R.L. Hunter-Anderson and H.W. Krueger.
1997 Stable isotope analysis of human diet in the Marianas Archipelago, Western Pacific. *American Journal of Physical Anthropology* 104:343-361.

Anderson-Stojanovic, V.R. and J.E. Jones.
2002 Ancient beehives from Isthmia. *Hesperia* 71(4):345-376.

Andrews, T.J. and K.M. Abel.
1979 Photosynthetic carbon metabolism in seagrasses: ^{14}C-labelling evidence for the C_3 pathway. *Plant Physiology* 63:650-656.

Angold, M.
1997 *The Byzantine Empire, 1025-1204: A Political History*. Longman, New York.

Arneborg, J., J. Heinemeier, N. Lynnerup, H.L. Nielson, N. Rud and A.E. Sveinbjörnsdóttir.
1999 Change of diet of the Greenland Vikings determined from stable carbon isotope analysis and ^{14}C dating of their bones. *Radiocarbon* 41(2):157-168.

Aufderheide, A.C., M.A. Kelley, M. Rivera, L. Gray, L.L. Tieszen, E. Iversen, H.R. Krouse and A. Carevic.
1994 Contributions of chemical dietary reconstruction to the assessment of adaptation by ancient highland immigrants (Alto Ramirez) to coastal conditions at Pisagua, North Chile. *Journal of Archaeological Science* 21:515-524.

Babraj, J.A., K. Smith, D.J.R. Cuthbertson, P. Rickhuss, J.S. Dorling and M.J. Rennie.
2005 Human bone collagen synthesis is a rapid, nutritionally modulated process. *Journal of Bone and Mineral Research* 20(6):930-937.

Bass, G.F. and F.H. van Doornick, Jr.
1978 An 11th century shipwreck at Serçe Liman, Turkey. *The International Journal of Nautical Archaeology and Underwater Exploration* 7(2):119-132.

Bender, M.M.
1968 Mass spectrometric studies of carbon 13 variations in corn and other grasses. *Radiocarbon* 10:468-472.
1971 Variations in the $^{12}C/^{13}C$ ratios of plants in relation to the pathway of photosynthetic carbon dioxide fixation. *Phytochemistry* 10:1239-1244.

Bender, M.M., D.A. Baerreis and R.L. Steventon.
1981 Further light on carbon isotopes and Hopewell agriculture. *American Antiquity* 46(2):346-353.

Bender, M.M., I. Rouhani, H.M. Vines and C.C. Black, Jr.
1973 $^{12}C/^{13}C$ ratio changes in crassulacean acid metabolism plants. *Plant Physiology* 52:427-430.

Benedict, C.R., W.W.L. Wong and J.H.H. Wong.
1980 Fractionation of the stable isotopes of inorganic carbon by seagrasses. *Plant Physiology* 65:512-517.

Biek, L.
1993 The nature and condition of the metalwork. In: *A Medieval Industrial Complex and its Landscaping: The Metalworking Watermills and Workshops of Bordesley Abbey*, edited by G.G. Astill, pp. 200-201. CBA Research Report 92, Council for British Archaeology. York, UK.

Bintliff, J.
1991 The Roman Countryside in central Greece: Observation and theories from the Boetia Survey. In: *Roman Landscapes: Archaeological Survey in the Mediterranean Region*, edited by G. Barker and J. Lloyd, pp. 122-132. British School at Rome, London.
1996 Frankish countryside in central Greece: The evidence from archaeological field survey. In: *Archaeology in Medieval Greece*, edited by P. Lock, pp. 1-18. Oxbow Books, Oxford.

Björkman, O. and J. Berry.
1972 Photosynthetic adaptation to high temperatures: A field study in Death Valley, California. *Science* 175:786-789.

Bocherens, H. and D. 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* 13:46-53.

Bocherens, H., D. Billou, A. Mariotti, M. Patou-Mathis, M. Otte, D. Bonjean and M. Toussaint.
1999 Palaeoenvironmental and palaeodietary implications of isotopic biogeochemistry of last interglacial Neanderthal and mammal bones in Scladina Cave (Belgium). *Journal of Archaeological Science* 26:599-607.

Bogaard, A., T.H.E. Heaton, P. Poulton and I. Merbach.
2007 The impact of manuring on nitrogen isotope ratios in cereals: Archaeological implications for reconstruction of diet and crop management practices. *Journal of Archaeological Science* 34(3):335-343.

Bourbou, C. and M.P. Richards.
2007 The Middle Byzantine menu: Palaeodietary information from isotopic analysis of humans and fauna from Kastella, Crete. *International Journal of Osteoarchaeology* 17(1):63-72.

Bourne, W.R.P.
1982 The Stymphalian birds. *Journal of Hellenistic Studies* 52:234-235.

Boyer, E.W., C.L. Goodale, N.A. Jaworski and R.W. Howarth.
2002 Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern U.S.A. *Biogeochemistry* 57/58:137-169.

Braudel, F.
1992 *The Mediterranean and the Mediterranean World in the Age of Philip II*, translated by S. Reynolds. Harper Collins Publishers, Great Britain.

Braun, T.
1996 Barley cakes and emmer bread. In: *Food in Antiquity*, edited by J. Wilkins, D. Harvey and M. Dobson, pp. 25-37. University of Exeter Press, Exeter.

Braund, D.
1996 Fish from the Black Sea: Classical Byzantium and the Greekness of trade. In: *Food in Antiquity*, edited by J. Wilkins, D. Harvey and M. Dobson, pp. 162-170. University of Exeter Press, London.

Brown, E.A.R.
1958 The Cistercians in the Latin Empire of Constantinople and Greece. *Traditio* 14:63-120.

Burleigh, R. and D. Brothwell.
1978 Studies on Amerindian dogs, 1: Carbon isotopes in relation to maize in the diet of domestic dogs from early Peru and Ecuador. *Journal of Archaeological Science* 5:355-362.

Burns, R.C. and R.W.F. Hardy.
1975 *Nitrogen fixation in bacteria and higher plants*. Springer-Verlag, New York.

Burton, R.K. and P.L. Koch.
1999 Isotopic tracking of foraging and long-distance migration in northeastern Pacific pinnipeds. *Oecologia* 119:578-585.

Burton, R.K., D. Gifford-Gonzalez, J.J. Snodgrass and P.L. Koch.
2002 Isotopic tracking of prehistoric pinniped foraging and distribution along the central California coast: Preliminary results. *International Journal of Osteoarchaeology* 12:4-11.

Burton, R.K., J.J. Snodgrass, D. Gifford-Gonzalez, T. Guilderson, T. Brown and P.L. Koch.
2001 Holocene changes in the ecology of northern fur seals: Insights from stable isotopes and archaeofauna. *Oceologia* 128:107-115.

Calvin, M. and A.A. Benson.
1948 The path of carbon in photosynthesis. *Science* 107:476-480.

Campbell, S.D.
1997 The Cistercian monastery of Zaraka. *Echos du Monde Classique/Classical Views* 16:177-196.

Cannon, A., H.P. Schwarcz and M. Knyf.
1999 Marine-based subsistence trends and the stable isotope analysis of dog bones from Namu, British Columbia. *Journal of Archaeological Science* 26:399-407.

Cato, *On Agriculture*.
1934 Marcus Porcius Cato, *On Agriculture*. With an English translation by W.D. Hooper. Loeb Classical Library. Harvard University Press, Cambridge.

Cheng, H.H., J.M. Bremner and A.P. Edwards.
1964 Variations of nitrogen-15 abundance in soils. *Science* 146(3651):1574-1575.

Chisholm, B.S.
1989 Variation in diet reconstructions based on stable carbon isotopic evidence. In: *The Chemistry of Prehistoric Bone*, edited by T.D. Price, pp. 10-37. Cambridge University Press, Cambridge.

Chisholm, B.S., D.E. Nelson and H.P. Schwarcz.
1982 Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science* 216:1131-1132.

Niketas Choniates, *Historia*.
1984 *O City of Byzantium, Annals of Niketas Choniates*. With an English translation by H.J. Magoulias. Wayne State University, Detroit.

Cifuentes, L.A., M.L. Fogel, J.R. Pennock and J.H. Sharp.
1989 Biogeochemical factors that influence the stable nitrogen isotope ratio of dissolved ammonium in the Delaware Estuary. *Geochimica et Cosmochimica Acta* 53:2713-2721.

Clark, R.M.
1979 Calibration, cross-validation and carbon-14. I. *Journal of the Royal Statistical Society. Series A (General)* 142(1):47-62.

Clayton, F., J. Sealy and S. Pfeiffer.
2006 Weaning age among foragers at Matjes River Rock Shelter, South Africa, from stable nitrogen and carbon isotope analyses. *American Journal of Physical Anthropology* 129:311-317.

Columella, *On Agriculture*.
1941 Lucius Junius Moderatus Columella, *On Agriculture*. With an English translation by H.B. Ash. Harvard University Press, Cambridge.

Copley, M.S., S. Jim, V. Jones, P. Rose, A. Clapham, D.N. Edwards, M Horton, P. Rowley-Conwy and R.P. Evershed.
2004 Short- and long-term foraging and foddering strategies of domesticated animals from Qasr Ibrim, Egypt. *Journal of Archaeological Science* 31:1273-1286.

Corr, L.T., J.C. Sealy, M.C. Horton and R.P. Evershed.
2005 A novel marine dietary indicator utilizing compound-specific bone collagen amino $\delta^{13}C$ values of ancient humans. *Journal of Archaeological Science* 32:321-330.

Counihan, C.M.
1999 *The Anthropology of Food and Body: Gender, Meaning and Power*. Routledge, New York.

Craig, H.
1953 The geochemistry of the stable carbon isotopes. *Geochimica et Cosmochimica Acta* 3:53-92.
1957 Isotope standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochimica et Cosmochimica Acta* 12:133-149.

Dalby, A.
1996 *Siren Feasts: A History of Food and Gastronomy in Greece*. Routledge, London.

Dar, S.
1995 Food and archaeology in Romano-Byzantine Palestine. In: *Food in Antiquity*, edited by J. Wilkins, pp. 326-335. University of Exeter Press, Exeter UK.

Deines, P.
1980 The isotopic composition of reduced carbon. In: *Handbook of Stable Isotope Geochemistry. Volume 1: The Terrestrial Environment, A*, edited by P. Fritz and J.C. Fontes, pp. 329-406. Elsevier, Amsterdam.

Delwiche, C.C. and P.L. Steyn.
1970 Nitrogen isotope fractionation in soils and microbial reactions. *Environmental Science and Technology* 4:929-235.

Delwiche, C.C., P.J. Zinke, C.M. Johnson and R.A. Virginia.
1979 Nitrogen isotope distribution as a presumptive indicator of nitrogen fixation. *Botanical Gazette* 140(Suppl.):S65-S69.

Dembińska, M.
1985 Diet: A comparison of food consumption between some Eastern and Western monasteries in the 4^{th}-12^{th} centuries. *Byzantion* 55:431-462.

DeNiro, M.J.
1985 Postmortem preservation and alteration of *in vivo* bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* 317:806-809.
1987 Stable Isotopy and Archaeology. *American Scientist* 75:182-191.

DeNiro, M.J. and S. Epstein.
1978a Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta* 42:495-506.
1978b Carbon isotopic evidence for different feeding patterns in two hyrax species occupying the same habitat. *Science* 201:906-908.
1981 Influence of diet on the distribution of nitrogen isotopes in animals. *Geochimica et Cosmochimica Acta* 45:341-351.

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

DeNiro, M.J. and S. Weiner.
1988a Chemical, enzymatic and spectroscopic characterization of "collagen" and other organic fractions from prehistoric bones. *Geochimica et Cosmochimica Acta* 52:2197-2206.

Dercon, G., E. Clymans, J. Diels, R. Merckx and J. Deckers.
2006 Differential ^{13}C isotopic discrimination in maize at varying water stress and at low to high nitrogen availability. *Plant and Soil* 282:313-326.

Dupras, T.L., and H.P. Schwarcz.
2001 Strangers in a strange land: Stable isotope evidence for human migration in the Dakhleh Oasis, Egypt. *Journal of Archaeological Science* 28:1199-1208.

Dupras, T.L., H.P. Schwarcz and S.I. Fairgrieve.
2001 Infant feeding and weaning practices in Roman Egypt. *American Journal of Physical Anthropology* 115:204-212.

Economidis, P.S., E. Dimitriou, R. Pagoni, E. Michaloudi and L. Natsis.
2000 Introduced and translocated fish species in the inland waters of Greece. *Fisheries Management and Ecology* 7:239-250.

Ejstrud, B.
2005 Size matters: Estimating trade of wine, oil and fish-sauce from amphorae in the first century A.D. In: *Ancient Fishing and Fish Processing in the Black Sea Region*, Black Sea Studies 2, edited by T. Bekker-Nielsen, pp. 171-181. Aarhus University Press, Aarhus.

Elliot, A.
2003 *Roman Food Poems: A Modern Translation.* Prospect, Totnes, England.

Estep, M.L.F. and S. Vigg.
1985 Stable carbon and nitrogen isotope tracers of trophic dynamics in natural populations and fisheries of the Lahotan Lake System, Nevada. *Canadian Journal of Fisheries and Aquatic Science* 42:1712-1719.

Faas, P.
2003 *Around the Roman Table: Food and Feasting in Ancient Rome.* Palgrave Macmillan, New York.

Fildes, V.A.
1986 *Breasts, Bottles and Babies: A History of Infant Feeding.* Edinburgh University Press, Edinburgh.
1988 *Wet Nursing: A History From Antiquity to the Present.* Basil Blackwell Ltd., Oxford.

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

Flint-Hamilton, K.B.
1999 Legumes in ancient Greece and Rome: Food, medicine, or poison? *Hesperia* 68(3):371-385.

Fogel, M.L., N. Tuross, B.J. Johnson and G.H. Miller.
1997 Biogeochemical record of ancient humans. *Organic Geochemistry* 27(5/6):275-287.

Forbes, H. and L. Foxhall.
1995 Ethnoarchaeology and storage in the ancient Mediterranean: Beyond risk and survival. In: *Food in Antiquity*, edited by J. Wilkins, pp. 69-86. University of Exeter Press, Exeter UK.

Foxhall, L. and H.A. Forbes.
1982 Σιτομετρεία: The role of grain as a stable food in Classical Antiquity. *Chiron* 12:41-90.

Foss, C.
1995 The Near Eastern countryside in late antiquity: A review article. *Journal of Roman Archaeology.* Suppl. Series no. 14 The Roman and Byzantine Near East: Some Recent Archaeological Research, edited by J.H. Humphrey. pp. 213-234.

Frayn, J.
1995 The Roman meat trade. In: *Food in Antiquity*, edited by. J. Wilkins. pp. 107-114. University of Exeter Press, Exeter UK.

Friedman, J.
1992 The past in the future: History and the politics of identity. *American Anthropologist* 94(4):837-859.

Fuller, B.T., M.P. Richards and S.A. Mays.
2003 Stable carbon and nitrogen isotope variations in tooth dentine serial sections from Wharram Percy. *Journal of Archaeological Science* 30:1673-1684.

Fuller, B.T., J.L. Fuller, N.E. Sage, D.A. Harris, T.C. O'Connell and R.E.M. Hedges.
2004 Nitrogen balance and $\delta^{15}N$: Why you're not what you eat during pregnancy. *Rapid Communications in Mass Spectrometry* 18:2889-2896.

Fuller, B.T., J.L. Fuller, D.A. Harris and R.E.M. Hedges.
2006a Detection of breastfeeding and weaning in modern human infants with carbon and nitrogen stable isotope ratios. *American Journal of Physical Anthropology* 129:279-293.

Fuller, B.T., T.I. Molleson, D.A. Harris, L.T. Gilmour and R.E.M. Hedges.
2006b Evidence for breastfeeding and possible adult dietary differences from Late/Sub-Roman Britain. *American Journal of Physical Anthropology* 129:45-54.

Galen, *On the Properties of Foodstuffs.*
2003 Galen, *On the Properties of Foodstuffs*. With an English translation by O. Powell. Cambridge University Press, Cambridge.

Galloway, J.N.
1998 The global nitrogen cycle: Changes and consequences. *Environmental Pollution* 102(S1):15-24.

Garnsey, P.
1988 *Famine and Food Supply in the Graeco-Roman World: Responses to Risk and Crisis*. Cambridge University Press, Cambridge.
1999 *Food and Society in Classical Antiquity*. University of Cambridge Press, Cambridge.

Garvie-Lok, S.J.
1993 *Stable Carbon Isotope Analysis of Human Bone Collagen from Fidler Mounds, Manitoba: An Investigation of Maize Consumption*. M.A. thesis, University of Calgary Dept. of Archaeology.
2001 *Loaves and Fishes: A Stable Isotope Reconstruction of Diet in Medieval Greece.* Unpublished PhD dissertation. Department of Anthropology, University of Calgary, Alberta.

Gerhardsson, L., R. Attewell, D.R. Chettle, V. Englyst, N-G. Lunström, G.F. Nordberg, H. Nyhlin, M.C. Scott and A.C. Todd.
1993 *In vivo* measurements of lead in bone in long-term exposed lead smelter workers. *Archives of Environmental Health* 48:147-156.

Grant, M.
1998 *From Rome to Byzantium: The Fifth Century AD*. Routledge, London.

Gregory, T.E.
1982 Fortification and urban design in Early Byzantine Greece: In: *City, Town and Countryside in the Early Byzantine Era*, edited by R.L. Hohlfelder, pp. 43-64. Columbia University Press, New York.

Grimm, V.
1995 Fasting women in Judaism and Christianity in Late Antiquity. In: *Food in Antiquity*, edited by J. Wilkins, pp. 225-240. University of Exeter Press, Exeter UK.

Hare, P.E., M.L. Fogel, T.W. Stafford Jr., A.D. Mitchell and T.C. Hoering.
1991 The isotopic composition of carbon and nitrogen in individual amino acids isolated from modern and fossil proteins. *Journal of Archaeological Science* 18:277-292.

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* 22:227-244.

Hatch, C.A. and C.R. Slack.
1970 Photosynthetic CO_2 fixation pathways. *Annual Review of Plant Physiology* 21:141-162

Heaton, T.H.E.
1987 The $^{15}N/^{14}N$ ratios of plants in South Africa and Namibia: Relationship to climate and coastal/saline environments. *Oecologia* 74:236-246.

Heaton, T.H.E., J.C. Vogel, G. von la Chevallerie and G. Collett.
1986 Climatic influence on the isotopic composition of bone nitrogen. *Nature* 322:822-823.

Higgins, M.D.
1996 *A Geological Companion to Greece and the Aegean*. Cornell University Press, Ithaca, New York.

Hilderbrand, G.V., T.A. Hauley, C.T. Robbins and C.C. Schwartz.
1999 Role of brown bears (Ursus arctos) in the flow of marine nitrogen into a terrestrial ecosystem. *Oecologia* 121:546-550.

Hobson, K.A. and D.M. Schell.
1998 Stable carbon and nitrogen isotope patterns in baleen from eastern Arctic bowhead whales (Balaena mysticetus). *Canadian Journal of Fisheries and Aquatic Science* 55:2601-2607.

Hobson, K. A. and R.G. Clark.
1992 Assessing avian diets using stable isotopes II: Factors influencing diet-tissue fractionation. *The Condor* 94(1):189-197.

Hobson, K.A. and H.E. Welch.
1992 Determination of trophic relationships within a high Arctic marine food web using $\delta^{13}C$ and $\delta^{15}N$ analysis. *Marine Ecology Progress Series* 84:9-18.

Hobson, K.A., R.T. Alisaukas and R.G. Clark.
1993 Stable-nitrogen isotope enrichment in avian tissues due to fasting and nutritional stress: Implications for isotopic analyses of diet. *The Condor* 95:388-394.

Hocker, F.
2005 Sampling a Byzantine Vintage: Bozburun, Turkey. In: *Beneath the Seven Seas: Adventures with the Institute of Nautical Archaeology*, edited by G.F. Bass, pp. 100-105. Thames and Hudson, London.

Hoefs, J.
2004 *Stable Isotope Geochemistry*. Fifth Edition. Springer-Verlag, Berlin.

Hoering, T.C. and H.T. Ford.
1960 The isotope effect in the fixation of nitrogen by Azobacter. *Journal of the American Chemical Society* 82:376-378.

Honch, N.V., T.F.G. Higham, J. Chapman, B. Gaydarska and R.E.M. Hedges.
2006 A palaeodietary investigation of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) in human and faunal bones from the Copper Age cemeteries of Varna I and Durankulak, Bulgaria. *Journal of Archaeological Science* 33:1493-1504.

Horrigan, S.G., J.P. Montoya, J.L. Nevins and J.J. McCarthy.
1990 Natural isotopic composition of dissolved inorganic nitrogen in the Chesapeake Bay. *Estuarine, Coastal and Shelf Science* 30:393-410.

Iacumin, P., H. Bocherens, L. Chaix and A. Marioth.
1998 Stable carbon and nitrogen isotopes as dietary indicators of ancient Nubian populations (Northern Sudan). *Journal of Archaeological Science* 25:293-301.

Iacumin, P., H. Bocherens, A. Mariotti and A. Longinelli.
1996 An isotopic palaeoenvironmental study of human skeletal remains from the Nile Valley. *Palaeogeography, Palaeoclimatology, Palaeoecology* 126:15-30.

Iacumin, P., V. Nikolaev, L. Genoni, M. Ramigni, Ya G. Ryskov and A. Longinelli.
2004 Stable isotope analyses of mammal skeletal remains of Holocene age from European Russia: A way to trace dietary and environmental changes. *Geobios* 37:37-47.

Jenkins, S.G., S.T. Partridge, T.R. Stephenson, S.D. Farley and C.T. Robbins.
2001 Nitrogen and carbon isotope fractionation between mothers, neonates, and nursing offspring. *Oecologia* 129:336-341.

Jordan, T.E., and D.E. Weller.
1996 Human contributions to terrestrial nitrogen flux. *Bioscience* 46(9):655-664.

Katzenberg, M.A.
1989 Stable isotope analysis of archaeological faunal remains from Southern Ontario. *Journal of Archaeological Science* 16:319-329.

Katzenberg, M.A. and N.C. Lovell.
1999 Stable isotope variation in pathological bone. *International Journal of Osteoarchaeology* 9:316-324.

Katzenberg, M.A. and A. Weber.
1999 Stable isotope ecology and palaeodiet in the Lake Baikal region of Siberia. *Journal of Archaeological Science* 26(6):651-659.

Katzenberg, M.A., S.R. Saunders and W.R. Fitzgerald.
1993 Age differences in stable carbon and nitrogen isotope ratios in a population of prehistoric maize horticulturalists. *American Journal of Physical Anthropology* 90:267-281.

Kazhdan, A.P.
1997 The peasantry. In: *The Byzantines*, edited by G. Cavallo, pp. 43-73. University of Chicago Press, Chicago.

Kazhdan, A.P. and A.W. Epstein.
1985 *Change in Byzantine Culture in the Eleventh and Twelfth Centuries*. University of California Press, Berkeley.

Keegan, W.F. and M.J. DeNiro.
1988 Stable carbon- and nitrogen-isotope ratios of bone collagen used to study coral-reef and terrestrial components of prehistoric Bahamian diet. *American Antiquity* 53(2):320-336.

Keenleyside, A., H. Schwarcz and K. Panayotova.
2006 Stable isotopic evidence of diet in a Greek colonial population from the Black Sea. *Journal of Archaeological Science* 33:1205-1215.

Kelley, J.H. and M.P. Hanen
1988 *Archaeology and the Methodology of Science*. University of New Mexico Press, Albuquerque.

Kohl, D.H. and G. Shearer.
1980 Isotopic fractionation associated with symbiotic N_2 fixation and uptake of NO_3^- by plants. *Plant Physiology* 66:51-56.

Kohl, D.H., G.B. Shearer and B. Commoner.
1971 Fertilizer nitrogen: Contribution to nitrate in surface water in a corn belt watershed. *Science* 174:1331-1334.

Kohl, D.H., G. Shearer and J.E. Harper.
1980 Estimates of N_2 fixation based on differences in the natural abundance of ^{15}N in nodulating and nonnodulating isolines of soybeans. *Plant Physiology* 66:61-65.

Kornexl, B.E., T. Werner, A. Roßmann and H.-L. Schmidt.
1997 Measurements of stable isotope abundances in milk and milk ingredients – a possible tool for origin assessment and quality control. *Zeitschrift für Lebensmittel-Untersuchung und –Foschung A* 205:19-24.

Kreitler, C.W.
1979 Nitrogen-isotope ratio studies of soils and groundwater nitrate from alluvial fan aquifers in Texas. *Journal of Hydrology* 42:147-170.

Kroll, H.
1999 Byzantinischer Roggen von Aghios Mamas, Chalkidike. *Byzantinische Zeitschrift* 92:474-478.

Kroopnick, P.
1985 The distribution of ^{13}C of $\sum CO_2$ in the world oceans. *Deep Sea Research* 32(1):57-84.

Krueger, H.W. and C.H. Sullivan.
1984 Models for carbon isotope fractionation between diet and bone. In: *Stable Isotopes in Nutrition*, edited by J.E. Turnlund and P.E. Johnson, pp. 205-222. American Chemical Society Symposium Series 258.

Kuniholm, P.I. and C.L. Striker.
1983 Dendrochronological investigations in the Aegean and neighboring regions, 1977-1982. *Journal of Field Archaeology* 10(4):411-420.

Laiou-Thomadakis, A.
1977 *Peasant Society in the Late Byzantine Empire*. Princeton University Press, Princeton, New Jersey.
1980 The Byzantine economy in the Mediterranean trade system; thirteenth-fifteenth centuries. *Dumbarton Oaks Papers* 34(1980/81):177-222.

Land, L.S., E.L. Lundelius, Jr. and S. Valastro, Jr.
1980 Isotopic ecology of deer bones. *Palaeogeography, Palaeoclimatology, Palaeoecology* 32:143-151.

Lascaratos, J. and E. Poulakou-Rebelakou.
2003 Oribasius (Fourth Century) and Early Byzantine perinatal nutrition. *Journal of Pediatric Gastroenterology and Nutrition* 36:186-189.

Le-Huray, J.D. and H. Schutkowski.
2005 Diet and social status during the La Tène period in Bohemia: Carbon and nitrogen stable isotope analysis of bone collagen from Kutná Hora-Karlov and Radovesice. *Journal of Anthropological Archaeology* 24:135-147.

Lee-Thorp, J.A., J.C. Sealy and N.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* 16:585-599.

Leguilloux, M.
2003 The Delian chora in Classical and Hellenistic times: An island landscape planned for pastoralism. In: *Zooarchaeology in Greece: Recent Advances*, edited by E. Kotjabopoulou, Y. Hamilakis, P. Halstead, C. Gamble and P. Elefanti, pp. 251-256. British School at Athens Studies 9. British School at Athens, Great Britain.

Létolle, R.
1980 Nitrogen-15 in the natural environment. In: *Handbook of Stable Isotope Geochemistry. Volume 1: The Terrestrial Environment, A*, edited by P. Fritz and J.C. Fontes, pp. 407-433. Elsevier, Amsterdam.

Libby, W.F., R. Berger, J.F. Mead, G.V. Alexander and J.F. Ross.
1964 Replacement rates for human tissue from atmospheric radiocarbon. *Science* 146(3648):1170-1172.

Lillie, M.C. and M. Richards.
2000 Stable isotope analysis and dental evidence of diet at the Mesolithic-Neolithic transition in Ukraine. *Journal of Archaeological Science* 27:965-972.

Little, B.J.
2007 *Historical Archaeology: Why the Past Matters*. Left Coast Press INC. California.

Liudprand of Cremona.
1993 *The Embassy of Constantinople and Other Writings*. With an English translation by F.A. Wright. Everyman's Library, Rutland, Vermont.

Lloyd, J.
1991 Farming the highlands: Samnium and Arcadia in the Hellenistic and early Roman Imperial periods. In: *Roman Landscapes: Archaeological Survey in the Mediterranean Region*, edited by G. Barker and J. Lloyd, pp. 180-193. Archaeological Monographs of the British School at Rome 2. British School at Rome, London.

Lock P.
1995 *The Franks in the Aegean, 1204-1500*. Longman, New York.
2006 *The Routledge Companion to the Crusades*. Routledge, New York.

Lösch, S., G. Grupe and J. Peters.
2006 Stable isotopes and dietary adaptations in humans and animals at pre-pottery Neolithic Nevalı Çori, Southeast Anatolia. *American Journal of Physical Anthropology* 131:181-193.

Lovell, N.C., D.E. Nelson and H.P. Schwarcz.
1986 Carbon isotope ratios in palaeodiet: Lack of age or sex effect. *Archaeometry* 28:51-55.

Lowry, H.W.
1991 The fate of Byzantine monastic properties under the Ottomans: Examples from Mount Athos, Limnos and Trabzon. In: *Manzikert to Lepanto: The Byzantine World and the Turks 1071-1571*, edited by A. Bryer and M. Ursinus, pp. 275-311. Adolf M. Hakkert, Amsterdam.

Lubell, D., M. Jackes, H. Schwarcz, M. Knyf and C. Meikeljohn.
1994 The Mesolithic-Neolithic transition in Portugal: Isotopic and dental evidence of diet. *Journal of Archaeological Science* 21:201-216.

Lund, J. and V. Gabrielsen.
2005 A fish business. Transport amphorae of the Black Sea region as a source for the trade in fish and fish products in the Classical and Hellenistic periods. In: *Ancient Fishing and Fish Processing in the Black Sea Region*, Black Sea Studies 2, edited by T. Bekker-Nielsen, pp. 161-169. Aarhus University Press, Aarhus.

Macbeth, H. and F. Mowatt.
2004 Researching food preferences: Methods and problems for anthropologists. In: *Researching Food Habits*, edited by H. Macbeth and J. MacClancy, pp. 101-118. Berghahn Books, New York.

Mackinnon, M.R.

2003 *The Excavations of San Giovanni Di Ruoti: The Faunal and Plan Remains.* University of Toronto Press, University of Toronto.

Macko, S.A., M.H. Engel, V. Andrusevich, G. Lubec, T.C. O'Connell, R.E.M. Hedges, R.P. Ambler, B. Sykes, J.B. Griffiths, J. Bada and G. Eglinton.
1999 Documenting the diet in ancient human populations through stable isotope analysis of hair (and discussion). *Philosophical Transaction: Biological Sciences* 354(1379):65-76.

Makarewicz, C. and N. Tuross.
2006 Foddering by Mongolian pastoralists is recorded in the stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes of caprine dentinal collagen. *Journal of Archaeological Science* 33:862-870.

Maniatis, G.C.
2000 The organizational setup and functioning of the fish market in tenth-century Constantinople. *Dumbarton Oaks Papers* 54:13-42.

Marino, B.D. and M.B. McElroy.
1991 Isotopic composition of atmospheric CO_2 inferred from carbon in C4 plant cellulose. *Nature* 349(6305):127-131.

Mariotti, A.
1983 Atmospheric nitrogen is a reliable standard for natural ^{15}N abundance measurements. *Nature* 303:685-687.

Mariotti, A., J.C. Germon and A. Leclerc.
1982 Nitrogen isotope fractionation associated with the $NO_2^- \rightarrow N_2O$ step of denitrification in soils. *Canadian Journal of Soil Science* 62(2):227-241.

Mariotti, A., C. Lancelot and G. Billen.
1984 Natural isotopic composition of nitrogen as a tracer of origin for suspended organic matter in the Scheldt estuary. *Geochimica et Cosmochimica Acta* 48:549-555.

Mariotti, A., A. Landreau and B. Simon.
1988 ^{15}N isotope biogeochemistry and natural denitrification process in groundwater: Application to the chalk aquifer of northern France. *Geochimica et Cosmochimica Acta* 52:1869-1878.

Masters, P.M.
1987 Preferential preservation of noncollagenous protein during bone diagenesis: Implications for chronometric and stable isotopic measurements. *Geochimica et Cosmochimica Acta* 51:3209-3214.

Matelas, A.-L.

2006 Disparities within traditional Mediterranean food patterns: A historical approach of the Greek diet. *International Journal of Food Sciences and Nutrition* 57(7/8):529-536.

Matelas, A.-L. and L.E. Grivetti
1993 Mediterranean diet in the 19th and 20th centuries. The case of two ship crews and their provisions. *International Journal of Food Sciences and Nutrition* 44:261-279.

Mays, S.A.
1997 Carbon stable isotope ratios in Medieval and later human skeletons from Northern England. *Journal of Archaeological Science* 24:561-567.

Mays, S.A., M.P. Richards and B.T. Fuller.
2002 Bone stable isotope evidence for infant feeding in Midiaeval England. *Antiquity* 76:654-656.

McClelland, J.W., I. Valiela and R.H. Michener.
1997 Nitrogen-stable isotope signatures in estuarine food webs: A record of increasing urbanization in coastal watersheds. *Limnology and Oceanography* 42(5.1):930-937.

McGovern-Wilson, R. and C. Quinn.
1996 Stable isotope analysis of ten individuals from Afetna, Saipan, Northern Mariana Islands. *Journal of Archaeological Science* 23:59-65.

Mee, C., D. Gill, H. Forbes and L. Foxhall.
1991 Rural settlement change in the Methana Peninsula, Greece. In: *Roman Landscapes: Archaeological Survey in the Mediterranean Region*, edited by G. Barker and J. Lloyd, pp. 223-232. Archaeological Monographs of the British School at Rome 2. British School at Rome, London.

Megaloudi, F.
2006 *Plants and Diet in Greece from Neolithic to Classic Periods*. BAR International Series 1516 Archaeopress, Oxford.

Metges, C., K. Kempe and H-L. Schmidt.
1990 Dependence of the carbon-isotope contents of breath carbon dioxide, milk, serum and rumen fermentation products on the $\delta^{13}C$ value of food in dairy cows. *British Journal of Nutrition* 63:187-196.

Miller, S.G., R. Knapp, and D. Chamberlain.
2001 *Excavations at Nemea II: The Early Hellenistic Stadium*. University of California Press, Berkley.

Minagawa, M. and E. Wada.

1984 Stepwise enrichment of ^{15}N along food chains: Further evidence and the relation between $\delta^{15}N$ and animal age. *Geochimica et Cosmochimica Acta* 48:1135-1140.

Minson, D.J., M.M. Ludlow and J.H. Troughton.
1975 Differences in natural carbon isotopic ratios of milk and hair from cattle grazing tropical and temperate pastures. *Nature* 256:602.

Müldner, G. and M.P. Richards.
2005 Fast or feast: Reconstructing diet in later medieval England by stable isotope analysis. *Journal of Archaeological Science* 32:39-48.
2007 Diet and diversity at Later Medieval Fishergate: The isotopic evidence. *American Journal of Physical Anthropology* 134:162-174.

Mylona, D.
2003a Fishing in late antiquity: The case of Itanos, Crete. In: *Zooarchaeology in Greece: Recent Advances*. edited by E. Kotjabopoulou, Y. Hamilakis, P. Halstead, C. Gamble and P. Elefanti, pp. 103-110. The British School at Athens, London.
2003b Archaeological fish remains in Greece: General trends of the research and a gazetteer of sites. In: *Zooarchaeology in Greece: Recent Advances*. edited by E. Kotjabopoulou, Y. Hamilakis, P. Halstead, C. Gamble and P. Elefanti, pp. 193-200. The British School at Athens, London.

Nakamura, K., D.A. Scholler, F.J. Winkler and H.L. Schmidt.
1982 Geographical variations in the carbon isotopic composition of the diet and hair in contemporary man. *Biomedical Mass Spectrometry* 9:390-394.

Nicholson, R.A.
1998 Bone degredation in a compost heap. *Journal of Archaeological Science* 25:393-403.

Nielson-Marsh, C.M. and R.E.M. Hedges.
2000a Patterns of diagenesis in bone I: The effects of site environments. *Journal of Archaeological Science* 27:1139-1150.
2000b Patterns of diagenesis in bone II: Effects of acetic acid treatment and the removal of diagenetic CO_3^{2-}. *Journal of Archaeological Science* 27:1151-1159.

O'Connell, T.C. and R.E.M. Hedges.
1999 Isotopic composition of hair and bone: Archaeological analyses. *Journal of Archaeological Science* 26:661-665.
2001 Isotopic comparison of hair, nail and bone: Modern analyses. *Journal of Archaeological Science* 28:1247-1255.

Oikonomides, N.
1997 Entrepreneurs. In: *The Byzantines*, edited by G. Cavallo. pp. 144-171. The University of Chicago Press, Chicago.

O'Leary, M.H.
1981 Carbon isotope fractionation in plants. *Phytochemistry* 20:553-567.

Ostrogorsky, G.
1969 *History of the Byzantine State*, translated by J. Hussey. Rutgers University Press, New Brunswick.

Panagopoulos, B.K.
1979 *Cistercian and Mendicant Monasteries in Medieval Greece*. The University of Chicago Press, Chicago.

Papathanasiou, A.
2003 Stable isotope analysis in Neolithic Greece and possible implications on human health. *International Journal of Osteoarchaeology* 13:314-324.

Papathanasiou, A, C.S. Larsen, and L. Norr.
2000 Bioarchaeological inferences from a Neolithic ossuary from Alepotrypa Cave, Diros, Greece. *International Journal of Osteoarchaeology* 10:210-228.

Parker, P.L.
1964 The biogeochemistry of the stable isotopes of carbon in a marine bay. *Geochimica et Cosmochimica Acta* 28:1155-1164.

Pausanias, *Guide to Greece.*
1971 Pausanias, *Guide to Greece*. With an English translation by P. Levi. Penguin, Harmondsworth.

Pearson, K.L.
1997 Nutrition and the Early-Medieval Diet. *Speculum* 72(1):1-32.

Pearson, J.A., H. Buitenhuis, R.E.M. Hedges, L. Martin, N. Russell and K.C. Twiss.
2007 New light on early carpine herding strategies from isotope analysis: A case study from Neolithic Anatolia. *Journal of Archaeological Science* 34:2170-2179.

Pechenkina, E.A., S.H. Ambrose, M. Xialin and R.A. Benfer Jr.
2005 Reconstructing northern Chinese Neolithic subsistence practices by isotopic analysis. *Journal of Archaeological Science* 32:1176-1189.

Pennock, J.R., D.J. Velinsky, J.M. Ludlam, J.H. Sharp and M.L. Fogel.
1996 Isotopic fractionation of ammonium and nitrate during uptake by skeletonema costatum: Implications of #15N dynamics under bloom conditions. *Limnology and Oceanography* 41(3):451-459.

Pepelasis, A.A. and K. Thompson.

1960 Agriculture in a restrictive environment: The case of Greece. *Economic Geography* 36(2):145-157.

Peterson, B.J. and B. Fry.
1987 Stable isotopes in ecosystem studies. *Annual Review of Ecological Systems* 18:293-320.

Pfeiffer, S. and T.L. Varney.
2000 Quantifying histological and chemical preparation in archaeological bone. In: *Biogeochemical Approaches to Paleodietary Analysis*, edited by S. Ambrose and M. A. Katzenberg, pp. 141-158. Kluwer Acedemic/Plenum Publishers, New York.

Pindar, *Victory Songs*
1980 Pindar, *Victory Songs*. With an English translation by F. Nisetich. Johns Hopkins University Press, Balitmore.

Pinnegar, J.K. and N.V.C Polunin.
2000 Contributions of stable-isotope data to elucidating food webs of Mediterranean rocky littoral fishes. *Oecologia* 122(3):399-409.

Pliny, *Natural History*.
1938 Pliny, *Natural History*. With an English translation by H. Rackham. Harvard University Press, Cambridge.

Polet, C. and M.A. Katzenberg.
2003 Reconstruction of the diet in a mediaeval monastic community from the coast of Belgium. *Journal of Archaeological Science* 30:525-533.

Postgate, J.
1998 *Nitrogen fixation*. Third Edition. Edward Arnold, London.

Powell, J.
1996 *Fishing in the Prehistoric Aegean*. Paul Åströms Förlag, Jonsered.

Privat, K.L., T.C. O'Connell and M.P. Richards.
2002 Stable isotope analysis of human and faunal remains from the Anglo-Saxon cemetery at Berinsfield, Oxfordshire: Dietary and social implications. *Journal of Archaeological Science* 29:779-790.

Prowse, T., H.P. Schwarcz, S. Saunders, R. Macchiarelli and L. Bondioli.
2004 Isotopic paleodiet studies of skeletons from the Imperial Roman-age cemetery of Isola Sacra, Rome, Italy. *Journal of Archaeological Science* 31:259-272.

Prowse, T.L., H.P. Schwarcz, P. Garnsey, M. Knyf, R. Macchiarelli and L. Bondioli.

2007 Isotopic evidence for age-related immigration to Imperial Rome. *American Journal of Physical Anthropology* 132:510-519.

Purcell, N.
1996 Eating fish: The paradoxes of seafood. In: *Food in Antiquity*, edited by J. Wilkins, D. Harvey and M. Dobson, pp. 132-149. University of Exeter Press, London.

Rau, G.H., A.J. Mearns, D.R. Young, R.J. Olsen, H.A. Schafer and I. R. Kaplan.
1983 Animal $^{13}C/^{12}C$ correlates with trophic level in pelagic food webs. *Ecology* 64(5):1314-1318.

Rautman, M.
2006 *Daily Life in the Byzantine Empire*. Greenwood Press, Westport, Connecticut.

Rennie, D.A., E.A. Paul and L.E. Johns.
1976 Natural nitrogen-15 abundance of soil and plant samples. *Canadian Journal of Soil Science* 56:43-50.

Richards, M.P. and R.E.M. Hedges.
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* 26:717-722.

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

Richards, M.P., S. Mays and B.T. Fuller.
2002 Stable carbon and nitrogen isotope values of bone and teeth reflect weaning age at the Wharram Percy Site, Yorkshire, UK. *American Journal of Physical Anthropology* 119:205-210.

Richards, M.P., R.E.M. Hedges, R. Jacobi, A. Current and C. Stringer.
2000 FOCUS: Gough's Cave and Sun Hole Cave human stable isotope values indicate a high animal protein diet in the British Upper Palaeolithic. *Journal of Archaeological Science* 27:1-3.

Rojas, J.M.M., F. Serra, I. Giani, V.M. Moretti, F. Reniero and C. Guillou.
2007 The use of stable isotope ratio analyses to discriminate wild and farmed gilthead sea bream (*Sparus aurata*). *Rapid Communications in Mass Spectrometry* 21:207-211.

Sallares, R.

1991 *The Ecology of the Ancient Greek World.* Cornell University Press, Ithaca, New York.

Schell, D.M., S.M. Saupe and N. Haubenstock.
1989 Natural isotope abundances in bowhead whale (Balaena mysticetus) baleen: Markers of aging and habitat usage. In: *Stable Isotopes in Ecological Research,* edited by P.W. Rundel, J.R. Ehleringer, and K.A. Nagy, pp. 260-269. Springer-Verlag, New York.

Schoeninger, M.J.
1985 Trophic level effects on $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios in bone collagen and strontium levels in bone mineral. *Journal of Human Evolution* 14:515-525.
1989 Reconstructing prehistoric human diet. In: *The Chemistry of Prehistoric Human Bone*, edited by D.H. Price, pp. 38-67. Cambridge University Press, Cambridge.

Schoeninger, M.J. and M.J. DeNiro.
1982 Diagenetic effects on stable isotope ratios in bone apatite and collagen. Abstract. *American Journal of Physical Anthropology* 57:225.
1984 Nitrogen and carbon isotope composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta* 48:625-639.

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

Schoeninger, M.J., K.M. Moore, M.L. Murray and J.D. Kingston.
1989 Detection of bone preservation in archaeological and fossil samples. *Applied Geochemistry* 4:281-292.

Schulting, R.J. and M.P. Richards.
2001 Dating women and becoming farmers: New palaeodietary and AMS dating evidence from the Breton Mesolithic cemeteries of Téviec and Hoëdic. *Journal of Anthropological Archaeology* 20:314-344.

Schulting, R.J., S.M. Blockley, H. Bocherens, D. Drucker and M. Richards.
2008 Stable carbon and nitrogen isotope analysis on human remains from the Early Mesolithic site of La Vergne (Charente-Maritime, France). *Journal of Archaeological Science* 35:763-772.

Schutkowski, H., B. Herrmann, F. Wiedemann, H. Bocherens and G. Grupe.
1999 Diet, status, and decomposition at Weingarten: Trace element and isotope analyses on Early Mediaeval skeletal material. *Journal of Archaeological Science* 26:675-685.

Schurr, M.R.
1992 Isotopic and mortuary variability in a Middle Mississippian population. *American Antiquity* 57(2):300-320.

Schwarcz, H.P., T.Dupras and S. Fairgrieve.
1999 ^{15}N enrichment in the Sahara: In search of a global relationship. *Journal of Archaeological Science* 26:629-636.

Schwarcz, H. P., J. Melbye, M.A. Katzenberg and M. Knyf.
1985 Stable isotopes in human skeletons of southern Ontario: Reconstructing palaeodiet. *Journal of Archaeological Science* 12:187-206.

Sealy, J.
1986 *Stable Carbon Isotopes and Prehistoric Diets in the South-Western Cape Province, South Africa*. BAR International Series 293, Oxford, Great Britain.

Sealy, J., R. Armstrong and C. Schrire.
1995 Beyond lifetime averages: Tracing life histories through isotopic analysis of different calcified tissues from archaeological human skeletons. *Antiquity* 69:290-300.

Sealy, J.C., N.J. van der Merwe, J.A. Lee Thorp and J.L. Lanham.
1987 Nitrogen isotopic ecology in southern Africa: Implications for environmental and dietary tracing. *Geochimica et Cosmochimica Acta* 51:2707-2717.

Semple, E.C.
1921 Geographic factors in the ancient Mediterranean grain trade. *Annals of the Association of American Geographers* 11:47-74.
1922 The influence of geographic conditions upon ancient Mediterranean stock-raising. *Annals of the Association of American Geographers* 12:3-38.

Setton, K.M.
1953 On the importance of land tenure and agrarian taxation in the Byzantine Empire, from the fourth century to the Fourth Crusade. *The American Journal of Philology* 74(3):225-259.

Shearer, G. and D.H. Kohl.
1978 ^{15}N abundance in N-fixing and non-N-fixing plants. In: *Recent Developments in Mass Spectrometry in Biochemistry and Medicine*. Vol 1, edited by A. Frigerio, pp. 605-622. Plenum: New York.

Shearer, G., D.H. Kohl, and S.-H. Chien.
1978 The nitrogen-15 abundance in a wide variety of soils. *Soil Science Society of America Journal* 42:899-902.

Shearer, G., D.H. Kohl, R.A. Virginia, B.A. Bryan, J.L. Skeeters, E.T. Nilsen, M.R. Sharifi and P.W. Rundel.
1983 Estimates of N_2-fixation from variation in the natural abundance of ^{15}N in Sonoran Desert Ecosystems. *Oecologia* 56:365-373.

Sholto-Douglas, A.D., J.G. Field, A.G. James and N.J. van der Merwe.
1991 $^{12}C/^{13}C$ and $^{15}N/^{14}N$ isotope ratios in the Souther Benguela Ecosystem: Indicators of food web relationships among different size-classes of plankton and pelagic fish; differences between fish muscle and bone collagen tissues. *Marine Ecology Progress Series* 78:23-31.

Smith, B.N. and S. Epstein.
1970 Biogeochemistry of the stable isotopes of hydrogen and carbon in salt march biota. *Plant Physiology* 46:738-742.
1971 Two categories of $^{12}C/^{13}C$ ratios for higher plants. *Plant Physiology* 47:380-384.

Soranus, of Ephesus, *Gynaecia.*
1991 Soranus' Gynecology. With an English translation by O. Temkin. John Hompkins Press, Baltimore.

Spielmann, K.A., M.J. Schoeninger and K. Moore.
1990 Plains-pueblo interdependence and human diet at Pecos Pueblo, New Mexico. *American Antiquity* 55(4):745-765.

Stafford, T.W. Jr., K. Brendel and R.C. Duhamel.
1988 Radiocarbon, ^{13}C and ^{15}N analysis of fossil bone: Removal of humates with XAD-2 resin. *Geochimica et Cosmochimica Acta* 52:2257-2267.

Stedman, N.
1996 Land use and settlement in post-medieval central Greece: An interim discussion. In: *Archaeology in Medieval Greece*, edited by P. Lock, pp. 72-192. Oxbow Books, Oxford.

Steele, KW. and R.M. Daniel.
1978 Fractionation of nitrogen isotopes by animals: A further complication to the use of variations in the natural abundance of ^{15}N for tracer studies. *Journal of Agricultural Science* 90:7-9.

Stone, P.
2007 *Ritual Dining, Drinking, and Dedication at Stymphalos: A Case Study in the Influence of "Popular" Culture on Religion*. Unpublished PhD dissertation, Dept of Classics, University of Minnesota, Minnesota.

Sullivan, C.H. and H.W. Krueger.
1981 Carbon isotope analysis of separate chemical phases in modern and fossil bone. *Nature* 292:333-335.

Szepanski, M.M., M. Ben-David and V. Van Ballenberghe.
1999 Assessment of anadromous salmon resources in the diet of the Alexander Archipelago wolf using stable isotope analysis. *Oecologia* 120(3):327-335.

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

Teall, J.L.
1959 The grain supply of the Byzantine Empire, 330-1025. *Dumbarton Oaks Papers* 13:87-139.

Thackery, J.F., S.P. Henzi and C. Brain.
1996 Stable carbon and nitrogen isotope analysis of bone collagen in papio cynocephalus ursinus: Comparison with ungulates and homo sapiens from Southern and East African environments. *South African Journal of Science* (92):209-212.

Thompson, A.H., L. Chaix and M.P. Richards.
2008 Stable isotopes and diet at Ancient Kerma, Upper Nubia (Sudan). *Journal of Archaeological Science* 35:376-387.

Thorndike, L.
1956 *The History of Medieval Europe*. Houghton Mifflin Company, Cambridge, Mass.

Tieszen, L.L.
1991 Natural Variation in the carbon isotope values of plants: Implications for archaeology, ecology and paleoecology. *Journal of Archaeological Science* 18:227-248.

Tieszen, L.L. and T.W. Boutton.
1989 Stable carbon isotopes in terrestrial ecosystem research. In *Stable Isotopes in Ecological Research,* edited by P.W. Rundel, J.R. Ehleringer, and K.A. Nagy, pp. 167-195. Springer-Verlag, New York.

Tieszen, L.L. and T. Fagre.
1993 Effect of diet quality and composition on the isotopic composition of respiratory CO_2, bone collagen, bioapatite, and soft tissues. In: *Prehistoric Human Bone-Archaeology at the Molecular Level*, edited by J.B. Lambert and G. Grupe, pp. 121-155. Springer-Verlag, New York.

Tieszen, L.L., T.W. Boutton, K.G. Tesdahl and N.A. Slade.
1983 Fractionation and turnover of stable carbon isotopes in animal tissues: Implications for $\delta^{13}C$ analysis of diet. *Oecologia* 57(1-2):32-37.

Tieszen, L.L., D. Hein, S.A. Qvortrup, J.H. Troughton and S.K. Imbamba.
1979 Use of $\delta^{13}C$ values to determine vegetation selectivity in East African herbivores. *Oecologia* 37:351-359.

Ting, I.P.
1985 Crassulacean acid Metabolism. *Annual Review of Plant Physiology* 36:595-622.

Topping, P.
1977 Co-existence of Greeks and Latins in Frankish Morea and Venetian Crete. In: *Studies in Latin Greece, A.D. 1205-1715*, edited by P. Topping, pp. 109-123. London, Variorum Reprints.

Trakadas, A.
2005 The archaeological evidence for fish processing in the Western Mediterranean. In: *Ancient Fishing and Fish Processing in the Black Sea Region*, edited by T. Bekker-Nielsen, Black Sea Studies 2, pp. 47-82. Aarhus University Press, Aarhus.

Tuross, N., M.L. Fogel and P.E. Hare.
1988 Variability in the preservation of the isotopic composition of collagen from fossil bone. *Geochimica et Cosmochimica Acta* 52:929-935.

Ubelaker, D.H. and D.W. Owsley.
2003 Isotopic evidence for diet in the seventeenth-century colonial Chesapeake. *American Antiquity* 68(1):129-139.

van der Merwe, N.J. and J.C. Vogel.
1978 ^{13}C content of human collagen as a measure of prehistoric diet in Woodland North America. *Nature* 276:815-816.

van der Merwe, N.J., A.J. Roosevelt and J.C. Vogel.
1981 Isotopic evidence for prehistoric subsistence change at Parmana, Venzuela. *Nature* 292:536-538.

van Doorninck, F.
2005 The ship of Georgios, priest and sea captain: Yassiada, Turkey. In: *Beneath the Seven Seas: Adventures with the Institute of Nautical Archaeology*, edited by G.F. Bass, pp. 92-97. Thames and Hudson Ltd, London.

van Klinken, G.J.
1999 Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *Journal of Archaeological Science* 26:687-695.

van Klinken, G.J. and R.E.M. Hedges.
1995 Experiments on collagen-humic interactions: Speed of humic intake, and effects of diverse chemical treatments. *Journal of Archaeological Science* 22:263-270.

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

Varro, *On Agriculture*.
1934 Marcus Terentius Varro, *On Agriculture*. With and English translation by W.D. Hooper. Loeb Classical Library. Harvard University Press, Cambridge.

Vassilakis, K., M. Panagiotopoulou, and G. Tsakona.
1994 *Important Bird Areas of Greece*. Hellenic Ornithological Society, Athens, Greece.

Virginia, R.A. and C.C. Delwiche.
1982 Natural ^{15}N abundance of presumed N_2-fixing and non-N_2-fixing plants from selected ecosystems. *Oecologia* 54:317-325.

Virginia, R.A., W.M. Jarrell, P.W. Rundel, G. Shearer and D.H. Kohl.
1989 The use of variation in the natural abundances of ^{15}N to assess symbiotic nitrogen fixation in woody plants. In: *Stable Isotopes in Ecological Research*, edited by P.W. Rundel, J.R. Ehleringer and K.A. Nagy, pp. 375-394. Ecological Studies: Analysis and Synthesis 68. Springer-Verlag, New York.

Vizzini S. and A. Mazzola.
2003 Seasonal variations in the stable carbon and nitrogen isotope ratios ($^{13}C/^{12}C$ and $^{15}N/^{14}N$) of primary producers and consumers in a western Mediterranean coastal lagoon. *Marine Biology* 142(5):1009-1018.

Vogel, J.C.
1978 Isotopic assessment of the dietary habits of ungulates. *South African Journal of Science* 74:298-301.

Vogel, J.C., and N.J. van der Merwe.
1977 Isotopic evidence for early maize cultivation in New York state. *American Antiquity* 42:238-242.

Wada, E. and A. Hattori.
1976 Natural abundance of ^{15}N in particulate organic matter in the North Pacific Ocean. *Geochimica et Cosmochimica Acta* 40:249-251.

Wada, E., T. Kadonaga and S. Matsuo.
1975 ^{15}N abundance in nitrogen of naturally occurring substances and global assessment of denitrification from isotopic viewpoint. *Geochemical Journal* 9:139-148.

White, C.D.
1993 Isotopic determination of seasonality in diet and death from Nubian mummy hair. *Journal of Archaeological Science* 20:657-666.

White, C.D. and H.P. Schwarcz.
1989 Ancient Maya diet: As inferred from isotopic and elemental analysis of human bone. *Journal of Archaeological Science* 16:451-474.
1994 Temporal trends in stable isotopes for Nubian mummy tissues. *American Journal of Physical Anthropology* 93:165-187.

White, C.D., P.F. Healy and H.P. Schwarcz.
1993 Intensive agriculture, social status, and Maya diet at Pacbitun, Belize. *Journal of Anthropological Research* 49(4):347-375.

White, C.D., M.E.D. Pohl, H.P. Schwarcz and F. J. Longstaffe.
2001 Isotopic evidence for Maya patterns of deer and dog use at Preclassic Colha. *Journal of Archaeological Science* 28:89-107.

Wilkins, J.
2005 Fish as a source of food in antiquity. In: *Ancient Fishing and Fish Processing in the Black Sea Region*, edited by T. Bekker-Nielsen, Black Sea Studies 2, pp. 47-82. Aarhus University Press, Aarhus.

Williams, C.K., E. Barnes and L.M. Snyder.
1997 Frankish Corinth, 1996. *Hesperia* 66:1-47.

Williams, C.K., L.M. Snyder, E. Barnes and O.H. Zervos.
1998 Frankish Corinth, 1997. *Hesperia* 67:222-281.

Williams, H.
1983 Stymphalos: A planned city of ancient Arcadia. *Echos du Monde Classique/Classical Views* 27:194-205
1996 Excavations at Stymphalos, 1995. *Echos du Monde Classique/Classical Views* 40:75-98.

Williams, H., G. Schaus, S-M.C. Price, B. Gourley and H. Lutomsky.
1997 Excavations at ancient Stymphalos, 1996. *Echos du Monde Classique/Classical Views* 41:23-73.

Williams, H., G. Schaus, S-M.C. Price, B. Gourley and C. Hagerman.
1998 Excavations at Stymphalos, 1997. *Echos du Monde Classique/Classical Views* 42:261-319.

Williams, H., G. Schaus, B. Gourley, S-M.C. Price, K.D. Sherwood and Y. Lolos.
2002 Excavations at ancient Stymphalos, 1999-2002. *Mouseion Series III* 46:135-187.

Wright, L.E. and H.P. Schwarcz.
1998 Stable carbon and oxygen isotopes in human tooth enamel: Identifying breastfeeding and weaning in prehistory. *American Journal of Physical Anthropology* 106:1-18.
1999 Correspondence between stable carbon, oxygen and nitrogen isotopes in human tooth enamel and dentine: Infants diets at Kaminaljuyú. *Journal of Archaeological Science* 26:1159-1170.

Wright, L.T., C. Nancarrow and P.M.H. Kwok.
2001 Case Study: Food taste preferences and cultural influences on consumption. *British Food Journal* 103(5):348-357.

Yoneda, M., R. Suzuki, Y. Shibata, M. Morita, T. Sukegawa, N. Shigehara and T. Akazawa.
2004 Isotopic evidence of inland-water fishing by a Jomon population excavated from the Boji site, Nagano, Japan. *Journal of Archaeological Science* 31:97-107.

Yoshioka, T., and E. Wada and H. Hayashi.
1994 A stable isotope study on seasonal food web dynamics in a eutrophic lake. *Ecology* 75(3):835-846.

Zazzo, A., H. Bocherens, M. Brunet, A. Beuvilain, D. Billiou, H.T. Mackaye, P. Vignaud and A. Mariotti.
2000 Herbivore palaeodiet and paleoenvironmental changes in Chad during the Pliocene using stable isotope ratios of tooth enamel carbonate. *Paleobiology* 26(2):294-309.

Zohary, D. and M. Hopf.
2000 *Domestication of Plants in the Old World.* Third Edition. Oxford University Press, Oxford.