PALEODIETARY CHANGE AMONG PRE-STATE METAL AGE SOCIETIES IN NORTHEAST THAILAND: A STABLE ISOTOPE APPROACH

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ABSTRACT

Using northeast Thailand as a model, this dissertation uses stable isotopes of carbon ($\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$) and nitrogen ($\delta^{15}N_{collagen}$) to infer paleodietary change in subtropical monsoon Asia. It is hypothesized that in northeast Thailand during the pre-state Metal Age (2000 B.C. to A.D. 500) there are distinct differences among the populations during this time period which coincide with human induced environmental changes and developments of alternative subsistence technologies. It is further hypothesized that female and male diets differed, possibly from social circumstances, such as sex related food accessibility. The archaeological skeletal series is from Ban Chiang, Ban Na Di, Ban Lum Khao, and Noen U-Loke. Stable isotope analysis of local flora and fauna provide a baseline for interpreting stable isotope data from human samples for this and future studies of paleodiet.

Temporal variation (sexes combined) in isotopic results show a statistically significant positive shift in $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$, and $\delta^{13}C_{apatite}$ values. Individuals from both the second and first millennium B.C. have varied diets consisting principally of C_3 plants, C_3 terrestrial animals, and freshwater fish.

During the second millennium B.C., the $\delta^{15}N_{collagen}$ values suggest consumption of a wider array of protein sources for females than for males. During the first millennium B.C., $\delta^{15}N_{collagen}$ and $\delta^{13}C_{apatite}$ values in females suggest an increase in open field carbohydrate foods and a shift to a greater consumption of either fish and/or carnivorous animals. For males, evidence suggests the consumption of more domesticated animals and less emphasis on wild game.

This dissertation makes a significant contribution to studies of subsistence changes from extensive to intensive agriculture in subtropical monsoon Asia. These stable isotope data substantiate archaeological and paleoenvironmental evidence, and corroborate bioarchaeological information from paleodemography and dental pathological conditions that suggest changes in dietary patterns over time and between the sexes. The use of stable isotopes from human remains from northeast Thailand has provided a direct indication for diet change from pre-state Metal Age societies. This research is relevant to debates of agricultural change as well as the effect of cultural changes on subsistence patterns and the evolution of human diet.

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Chapter I. Introduction and Research Questions

The ability to reconstruct prehistoric diet is an important aspect of archaeology and biological anthropology that attempts to understand the transformation of human foodways over time and space (Armelagos 1987; Cohen 1989; Larsen 1997). Food procurement and subsistence practices for any group can vary markedly, depending on the local landscape and on the number of people the area can support by food collection or production (Cohen et al. 1991; Harlan 1992; Orlove and Brush 1996). As the size of a population increases, so do the opportunities for individuals in the community to devote themselves to tasks not related to the growing or procurement of food. This may lead to changes in political organization, material goods, and so on. In order to understand how prehistoric populations adapted to the more subtle relationships among environment, diet, health, and cultural change, greater knowledge of the prehistoric people is needed. This is especially true for people who lived in subtropical monsoon regions of the world where species diversity is high and subsistence alternatives can be many. In order to understand the biocultural effects of prehistoric subsistence and diet, it is necessary to analyze multiple lines of evidence.

The reasons for changing from one mode of food production to another are varied and typically span a long period of time. For the inhabitants, this factor of time essentially precludes a shift in how they produce food. Food production is a continuum in which various environmental, social, political, economic, and demographic factors complicate theories of evolutionary progression (Hutterer 1983). In Southeast Asia shifts in

agricultural production are associated with changes in political organization and ethnic succession (O'Connor 1995).

Mainland Southeast Asia is an important location for understanding the transition from horticultural (extensive) to agricultural (intensive) cultivation for subtropical monsoonal regions of the world. Early wet rice cultivation was extensive, not intensive, and rice was just one of many components of a broad subsistence strategy (Higham 1989:29; White 1995b).

Northeast Thailand is an important region for understanding biocultural changes during the prehistoric transition from extensive to intensive food production in subtropical monsoonal Southeast Asia. Not only does northeast Thailand have a long continuous occupational history but also has extensive bioarchaeological documentation. Previous research in biological anthropology during this transition period examined the assumption that the overall health of any population would decline with a shift from extensive to intensive cultivation (Cohen and Armelagos 1984; Larsen 1997; Steckel and Rose 2002). Current bioarchaeological research in mainland Southeast Asia, most occurring in northeast Thailand, does not support this expectation of a decline in health (Domett 2001, 2006; Domett and Tayles 2006; Douglas 2006; Oxenham et al. 2006; Pietrusewsky and Douglas 2002a,b; Tayles et al. 2000). While bioarchaeological analysis of skeletal remains interprets human subsistence with respect to health and disease, a more direct approach to understanding subsistence and paleodietary[1] change is through bone chemistry. Stable isotope analysis has become a common tool in investigations of diet for both prehistoric and historic populations (Katzenberg 2000), but

[1] Paleodiet is defined as a study of feeding patterns and food consumption in the past (Krigbaum 2001:106).

has only recently been used in Southeast Asia (e.g., Krigbaum 2001, 2003, 2005; Bentley et al. 2005).

Shortly after the beginning of the second millennium B.C. in northeast Thailand there is a marked decline in concentration and diversity of pollen taxa, as observed by pollen and phytolith analysis which suggests increased human occupation of lowland wetland niches (White et al. 2004:123). In addition, evidence of forest recovery during the beginning of the first millennium B.C. supports an interpretation of a shift from unmanaged burning of forests to controlled burns of ground cover (White et al. 2004:129). Each of these paleoenvironmental changes corresponds roughly with archaeological evidence for the beginning of bronze technologies and the appearance of iron and domestic water buffalo, respectively.

This dissertation builds on earlier studies in bioarchaeology with a particular emphasis on skeletal remains from northeast Thailand (Domett 1999; Pietrusewsky and Douglas 2002a). The purpose of this dissertation research is to use stable isotopic analysis of carbon and nitrogen to better understand prehistoric dietary patterns of the inhabitants living a subtropical monsoonal region during the transition from horticulture to agricultural intensification. Archaeological sites from northeast Thailand which date from the second and first millennium B.C. are used for this study. These time periods have also been referred to as the Pre-State Metal Age of Thailand (c. 2000 B.C. – A.D. 500) (Onsuwan 2003:7). Thailand's Pre-State Metal Age refers to the period of socio-cultural status of two major periods: the Bronze Age (ca. 2000-800 B.C.) and the Iron Age (ca. 700 B.C-A.D. 100) (Pigott et al. 1997; White 1988). This information will

allow for greater insight into how prehistoric populations adapted and thrived in subtropical monsoonal regions of the world.

Dietary reconstruction is an important aspect of archaeological investigation. Most often, dietary reconstruction is explored through faunal or archaeobotanical analysis. Dietary reconstruction and nutritional analysis provide information on the subsistence strategies of the group under study. Through this knowledge, information on how people culturally adapted to their surrounding environment is brought to light. Data related to dietary change in prehistory has pertained almost exclusively to subsistence, with very little research pertaining specifically to diet. From the cultural and biological material record, archaeologists have speculated on the causes of changes in subsistence resources over time.

Subsistence and diet are not the same. Subsistence is a strategy by which resources are procured for a community: for example, agriculture or hunting-gathering (Greenlee 2001:223). These strategies are often linked to other aspects of culture besides food consumption, such as the degree of sedentism, population density, disease occurrence, and specialization. Groups that follow different subsistence strategies thus consume food resources in varying quantities and diversity, depending on their mobile and/or sedentary lifestyles.

Diet, on the other hand, refers only to those plants and animals that are consumed as food. Diet is a multifaceted set of choices by an individual that includes factors such as geography; resource availability; cultural traditions; as well as socio-economic and political considerations. As a result, diet is best studied at the individual level. Consequently, questions can then be asked whether the diet of some individuals changed

(e.g., as a consequence of social differences), or whether these changes characterized the entire population. Bone chemistry, particularly as determined by stable isotopic analysis, is well suited to answer questions concerning the diet of past populations.

Paleodietary Reconstruction

Faunal remains from archaeological sites often give an adequate picture of subsistence, but do not allow the determination of the importance of the various food categories. Some record of dietary habits is also available in the ethnohistorical literature. Even though ethnographic analogy is instrumental in comparing cultures over time and space, exclusive reliance on analogy may hinder the development of alternative models in understanding prehistoric lifeways. Likewise, it cannot be assumed that early food procurement practices are the same today as in the past. Thus, analogies, which take the characteristics of a particular group and generalize them to other groups, are problematic when applied to prehistoric societies.

Evidence from teeth has also been used to infer paleodietary changes. Dental studies have always been an important component in analyzes of archaeological human skeletal remains due to the durability of teeth. Teeth can be used for evidence of disease, prenatal and childhood health, consistency (coarse or soft) of food ingested, abnormalities, anomalies, and cultural modifications, thus providing valuable clues to life in the past (Hillson 1992; Larsen 1997). Dental conditions are all attributes of the long-term effects of nutritional quality and disease processes of the community, as a consequence of food selection by individuals in the population.

Bone chemical analysis, particularly stable isotope analysis of individuals, is another method that attempts to provide more specific information on the types of foods

consumed by a population and to better understand the role of the biocultural system in human-environment interactions (Greenlee 2001:223). This technique makes use of the stable isotopic signatures of carbon and nitrogen in certain food resource categories. These signatures are transferred directly to the tissues (including bone) of their consumers during life (see summations from Ambrose 1993; Katzenberg 2000; Schoeninger and Moore 1992). Using these isotopic signatures, it may be possible to establish the relative contribution of distinctive food groups to the diet of individuals, which in turn reflects on the community as a whole. This in turn can be linked to cultural material goods and other biological attributes from individual burials, spatially and temporally, to provide a fuller picture of life during prehistory.

Research Problem

The environment and landscape of a region have a significant role in food resource availability and in understanding dietary change in human populations. In northeast Thailand, paleoenvironmental changes have been deduced from geoarchaeological studies of pollen and phytoliths during the Holocene (Boyd and McGrath 2001a; Boyd et al. 1999a,b; Habberfield-Short 1999; Kealhofer 1996a,b, 1997; Kealhofer and Penny 1998; Penny 1998, 1999a,b, 2001). These studies document changes in the environment that suggest the possibility of anthropogenic burning beginning in the Early Holocene (8000-7000 B.C.). During the Late Holocene (3000 B.C. - Present), rapid expansion and diversification of mixed-deciduous forests may indicate that people modified the landscape through burning (Kealhofer and Penny 1998:90). Results of these pollen studies, coupled with aerial photography and sediment mapping, show significant climatic changes during the Late Holocene that suggest the Bronze Age was more arid

than the succeeding Iron Age (Habberfield-Short 1999:217-18). These changes in climate and landscape coincide with archaeological data for intensification of land use in northeast Thailand suggesting a shift in economic and social activity (Habberfield-Short 1999:220).

This dissertation research has two central objectives: 1) to characterize possible dietary changes that occurred among the prehistoric inhabitants of northeast Thailand, and 2) to expand on the first by investigating the possibility of variable diets between the sexes.

Feasibility Study

A pilot study of stable isotopes in prehistoric human bone from the archaeological site of Ban Chiang, northeast Thailand (n=33) was conducted to determine (1) whether isotope data could be obtained from archaeological human remains from mainland Southeast Asia, (2) whether secular changes in diet could be detected using carbon and nitrogen isotopic analysis, and (3) if dietary variation may occur by sex (King and Norr 2006). Results of the pilot study confirmed that the methodology was viable and also suggested that dietary variation occurred across time and by sex.

The levels of $\delta^{15}N_{collagen}$, $\delta^{13}C_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite\text{-}collagen}$ found in the pilot study all suggested the diets of these individuals were highly mixed, with both terrestrial and aquatic proteins. While the narrow range of variation in $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ isotopic values over time suggested little dietary change, there was a trend towards positive enrichment over time. Isotopic analyses by sex within each time period showed statistically significant differences in $\delta^{13}C_{collagen}$ in the Iron Age and in $\delta^{15}N$ in the Bronze

Age. These differences may represent differential access to food resources, a finding supported by osteological research (Pietrusewsky and Douglas 2002a,b).

This dissertation research utilizes isotopic values of plant and animal samples collected in northeast Thailand and additional human archaeological samples to refine these interpretations of dietary changes. From this expanded research it may be possible to make trophic level distinctions, which assist in the explanation of the subtle variations in isotopic values found in mainland Southeast Asia.

Objectives and Hypotheses

The primary objective of this dissertation is to better understand how environment and cultural changes affect the diet of these prehistoric inhabitants of northeast Thailand. This research follows an ecological framework and relies upon analyses using stable isotopes of carbon and nitrogen from modern plants, animals (modern and archaeological), and human samples from four archaeological sites in northeast Thailand (Ban Chiang, Ban Na Di, Ban Lum Khao, and Noen U-Loke). Burials from four different archaeological sites, from two different regions in northeast Thailand, allows for the comparison of dietary patterns and resource allocation in slightly different geographic, political and economic environment. In order to determine the likely dietary contributors to protein and potential wild plant food species (carbohydrates), the isotopic signatures of many species of plants and animals are assessed.

Dietary reconstruction of human populations from northeast Thailand allows several questions of archaeological interest to be addressed (Pietrusewsky and Douglas 2002b). It is hypothesized that there are distinct differences among the populations of different time periods in northeast Thailand due to natural environmental changes and

developments of alternative subsistence technologies, namely the iron plow. It is further hypothesized that female and male diets within these sites differed as a result of social conditions related to food accessibility based on sex. Stable isotopic analysis should provide the evidence to address these claims. To answer these questions, two working hypotheses are addressed. In each case, the null hypothesis is that there are no differences in diet.

Hypothesis 1: Diet changed over time in northeast Thailand

Recent paleodietary research in insular Southeast Asia has shown isotopic variability through time (Krigbaum 2001, 2003, 2005). A more positive shift in carbon isotopic values from the pre-Neolithic to the Neolithic suggested increased consumption of plant foods obtained from more open habitats. An opening of the forest canopy would most likely be the result of human land clearance for cultivation of C_3 crops, namely rice. In mainland Southeast Asia, archaeological evidence indicates that an increase in forest clearance, agriculture, and animal husbandry took place between the second and first millennium B.C.

A test of Hypothesis 1 would include positive shifts in the isotopic values for $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$ or $\delta^{13}C_{apatite}$ during Pre-State Metal Age societies. The temporal division that marks an important transition in the history of Pre-State Metal Age societies in northeast Thailand involves the employment of iron technology and water buffalo. These are key variables for implying agricultural intensification to plowed, inundated rice cultivation (White 1982c:27). If indeed the agricultural intensification around the middle of the first millennium B.C. changed the diets of people in northeast Thailand, then isotopic ratios should have changed as well.

Hypothesis 2: Differences exist in dietary intakes between females and males for each time period

The second question expands on the first by investigating to what extent females and males consumed an isotopically homogenous diet, and whether or not differences in diet within a population can be related to social organization such as status or demographic factors such as sex.

In northeast Thailand, dental paleopathological analyses of dietary change indicate inter- and intra-site differences between females and males (Domett 2001; Douglas 1996; Pietrusewsky and Douglas 2002b; White 1982c; Wiriyaromp 1984a,b) that may result from factors such as environmental differences, a sexual division of food resources, or inter-site variation (Domett 1999; Douglas 1996; Tayles 1992). When dental pathological data from northeast Thailand are combined, significant temporal changes in caries, advanced attrition, and antemortem loss are apparent (Domett 1999; Domett and Tayles 2006). Significant differences are also apparent between females and males within each millennium to suggest the possibility of cultural differences in dietary intake between the sexes. These dental pathological patterns are further elaborated in Chapter III. A test of Hypothesis 2 would include a difference in the carbon and nitrogen isotopic signatures for females and males over time.

Implications of Research

By combining stable isotope data of carbon and nitrogen from human bone with existing studies of prehistoric diet and subsistence, this research amplifies our understanding of the relative contribution of distinctive food classes to the diet and correlates changes in diet with changes in health status.

Stable isotopic work in Southeast Asia is only just beginning (Krigbaum 2001, 2003, 2005; Bentley 2005). Results of this dissertation provide a greater understanding of the articulation between environment and culture in changing food consumption patterns of subtropical monsoon Asia. This study addresses site-specific problems of subsistence and settlement, as well as regional and temporal dietary trends for the inhabitants of this region. In sum, this analysis provides the foundation for interpreting prehistoric dietary change in mainland Southeast Asia as well as other subtropical monsoon regions of the world.

Dissertation Organization

Chapter I provides an overview of the research project and presents the research questions.

Chapter II provides the environmental context and includes a discussion of the plant and animal species relevant to the study area. Overviews of knowledge regarding prehistoric diet from ethnographic and archaeological sources are discussed.

Chapter III presents a brief prehistory of the region, including summaries of the four archaeological sites used in this research.

Chapter IV considers the theoretical background behind stable isotope analysis and dietary reconstruction. The various metabolic pathways utilized by plants and the way in which diets based on certain groups of plants can be detected in bone are presented, as well as the consequences of these differences to human groups.

Chapter V presents the modern plant and animal samples, describes the archaeological faunal and human bone samples, and the methods used in the field, the laboratory sample preparation, and the stable isotope laboratory.

Chapter VI documents the results of the stable isotope analysis of the modern plants, modern and archaeological animals.

Chapter VII documents the results of the stable isotope analysis from the human skeletal remains.

Chapter VIII provides an interpretation and discussion of the results, conclusions, and indicates directions for future research.

Chapter II. Geography, Climate and Natural History

Modern Topography and Physiography

The modern nation of Thailand is in a key location for migratory routes between island Southeast Asia and parts of northern Asia, because of its wide latitudinal range (5º 40' and 20º 30' North latitude and 90º 70' and 105º 45' East longitude). Thailand includes fully subtropical to subequatorial environments. As a mainland country in Southeast Asia, it is bordered on the northwest by Myanmar, on the northeast by Laos, on the east by Cambodia, and on the south by Malaysia. The total area of Thailand is 513,115 sq. km. The country is divided into five major geographical areas: south, southeast, central, north, and northeast (Figure 2.1). Due to these variations, Thailand possesses tremendous natural and cultural diversity. Forest vegetation, for example, ranges from pine forests in the north, to lowland rain forests or tropical mangrove forests in the south.

Northeast Thailand is the location for this research project. It lies between 14º-18º North latitude and 101º-105º East longitudes. Conventionally, northeast Thailand consists of the following areas: (1) the Khorat Plateau made up of the Khorat Basin, drained by the Mun and Chi Rivers, and the Sakon Nakon Basin, drained by the Songkhram and other rivers; (2) the Phetchabun mountain range and the piedmont areas to the west of the Khorat Plateau; and (3) the northern side of the Dangrek mountain range (Figure 2.2).

This dissertation research utilizes bone samples from four archaeological sites in northeast Thailand: (1) Ban Chiang, (2) Ban Na Di, (3) Ban Lum Khao, and (4) Noen U-

Loke (Figure 2.2). Ban Chiang and Ban Na Di are located along nearby tributaries of the Songkhram River, in the heart of the Sakon Nakon Basin. Ban Lum Khao and Noen U-Loke are located in the upper Mun River Valley, in the southwest corner of the Khorat Basin.

Figure 2.1. Major geographical areas of Thailand (Adapted from Higham and Thosarat 1998a:15).

Utilizing information primarily from Wilen (1987b:73-80) and generalizing from the more detailed information within Lekagul and McNeely (1977:XXII-XXX) the landscape of northeast Thailand can be divided into three major environmental zones: the alluvial plain, the terrace zone, and the uplands. The alluvial plains are low-lying areas that are

annually flooded by a major river or its tributaries. Today the alluvial plains are almost completely covered with wet rice fields. During prehistory the alluvial plains would have mostly been marshes, open grasslands, and scattered dipterocarp trees that could have supported a wide array of crops, fish, and small game.

The terraced zone or rolling lowlands is not as prone to annual flooding. This area consists of a mixture of deciduous forest and undulating plains. It is this ecosystem, grasses and shrubs sustain an abundance of browsers and grazers, such as deer, wild cattle, water buffalo, elephant, as well as top carnivores, such as the tiger. Most of the modern villages, as well as archaeological habitation sites, are found in the terraced zone. Lastly, the uplands are mountainous areas of deciduous and evergreen forests. These areas would have reduced food resources due to the heavy forest canopy and steep slopes, but still would have been utilized for hunting of medium to large game animals.

The temperature and rainfall in Thailand generate a moist, tropical climate that is influenced chiefly by monsoon winds that vary in direction according to the season. From April to October the winds are mainly from the southwest and are moisture laden; during the rest of the year the winds blow from the northeast. Temperatures are higher while the country is under the influence of the southwestern winds and cooler during the remainder of the year. Temperatures are somewhat higher inland than they are along the coast, except at points of great elevation.

Local variation in rainfall is the result of a rain shadow effect. As the monsoon rains move across Myanmar into Thailand they first travel over the Bilauktaung mountains, dropping off large amounts of water. As the rain moves northeast through the Chao Phraya valley it comes to the Phetchabun, Dong Phrayayen, and Dang Rek mountain

ranges, which capture a lot of water that normally would have been more evenly spread over the plateau. As a result of this rain shadowing effect, microclimate variation exists on the Khorat plateau, with the western and central portions receiving the least rain, followed by the eastern plateau, while the most rain falls on the northern and northeastern margins of the plateau.

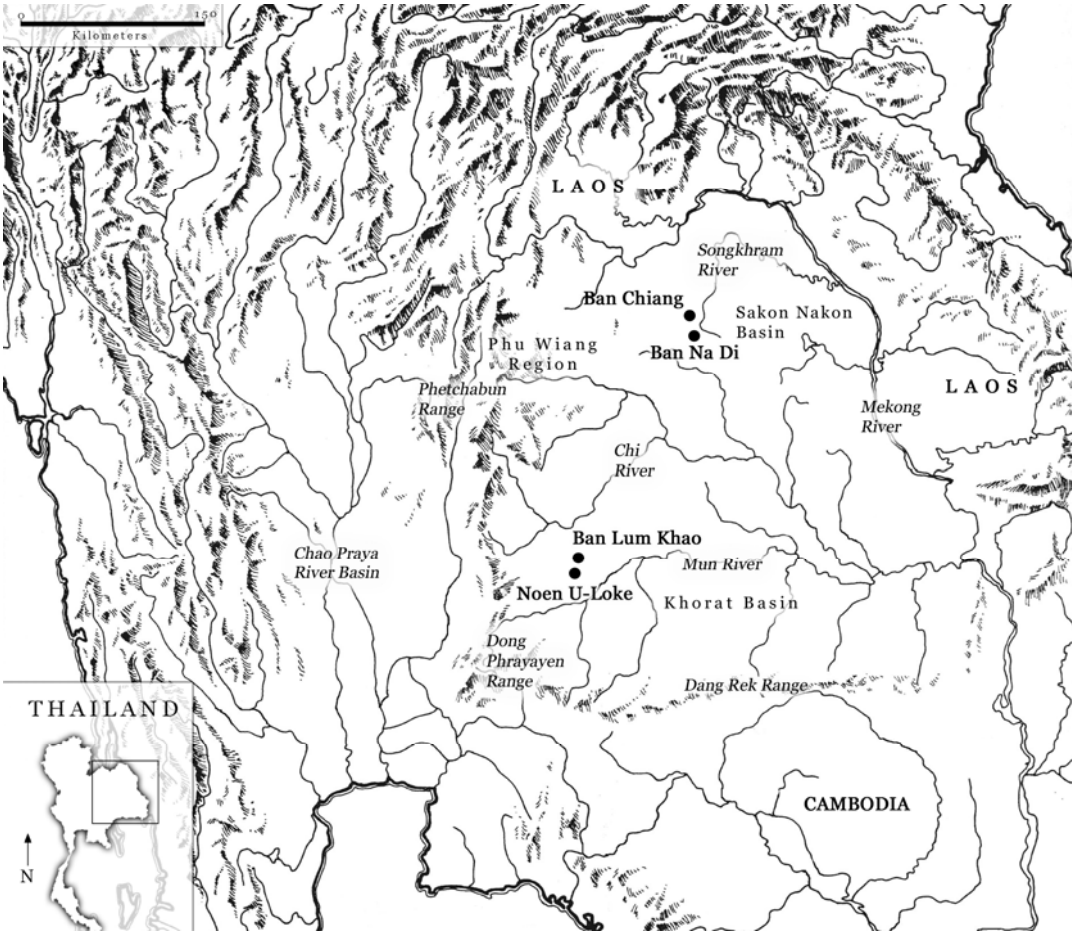

Figure 2.2. Northeast Thailand showing major geographical features and archaeological sites used in this study (Adapted from Higham 1975a).

Northeast Thailand has always been one of the country's economically poorer regions. Although there are historical reasons for this, a significant factor is the overall

quality of the soil, which is typically poor sandstone-derived soil with a high silica concentration (Fukui 1993:25). Further, Fukui (1993:25) points out that soil from northeast Thailand contains some of the lowest levels of organic matter, nitrogen, and phosphorus among rice producing countries in tropical Asia. In many parts of the region the soils also suffer from lateritization[2] of the predominantly sandy soils as well as salinization (Acker 2001:44). The rain shadow effect of the mountains means this region is more susceptible to drought than other parts of mainland Southeast Asia. Irrigated land area is limited, making up only 10% of total farm land area in the region. Paddy land has occupied most lowland cultivated areas, whereas cassava and sugar cane have mainly occupied the upland cultivated areas.

Paleoenvironmental Background

Even with these obstacles, this area still produces large quantities of rice. Moreover, inter-regional variation in soil and moisture has produced a wide array of wild edible plants. It has been estimated that as much as 50% of the total food consumed by some modern-day rural villages consists of an array of indigenous foods grown or found locally (Desai and Somnasang 1996:44). As a result of a combination of population growth and an increased usage of land for crop production, human induced manipulation of the landscape has greatly changed the face of this region from prehistory to the present.

Of the many studies pertaining to climatic changes over time in the region, a few of the more salient early publications include Southeast Asia as a whole (e.g., Dobby 1967; Hanks 1972; Holdridge 1967) and Thailand specifically (e.g., Kaida and Surarerks 1984;

[2] Soil-forming processes typical of warm humid climates where in mature landscapes, primary minerals are essentially completely weathered away to form red soil (laterites) of high aggregate stability composed primarily of sesquioxides (oxides and hydroxides of iron and aluminum).

Pendleton 1962). Although this type of research has been conducted since the early 1980's, much of the initial research focused on sea level changes of the middle to late Holocene, with little regard to regional climatic fluctuations or the general regional development of monsoon forests (Takaya 1969). Given only minor climatic "amelioration," the Pleistocene-Recent boundary brought little environmental change to any part of the mainland Southeast Asian sector except its coastal zones (Dunn and Dunn 1977).

To understand the role of environmental change in prehistoric human adaptation in mainland Southeast Asia, archaeologists have relied upon pollen and phytolith remains from lake core samples. Until very recently, the human impact on a region's environment was noticeably missing. Bernard Maloney's research at the archaeological site of Khok Phanom Di provided some of the earliest paleoenvironmental inferences in Thailand that suggested vegetation changes not attributable to sea-level fluctuations. This research suggested the possibility of human interventions (Maloney 1985a,b, 1986, 1987, 1988a,b, 1991a,b,c,d,e, 1992a,b, 1998; Maloney and Brown 1987, 1990; Maloney and McAlister 1990a,b; Maloney et al. 1989, 1990). Maloney's data however were derived from the mangrove regions of central Thailand, which have never been heavily utilized by prehistoric human populations. In 1992, Maloney called for additional research in more climatically sensitive areas with clear seasonal change and suggested northeast Thailand as an ideal area, due to the active archaeological research already being conducted there (Maloney 1992a:29-30).

This call was answered in spades during the 1990's and early 2000's. With geoarchaeological studies of pollen and phytoliths, paleoenvironmental changes within

the Holocene in northeast Thailand have received much attention in recent years (Boyd and McGrath 2001a,b; Boyd et al. 1999a,b; Habberfield-Short 1999; Kealhofer 1996a,b; Kealhofer and Penny 1998; Penny 1998, 1999a,b, 2001; Penny et al. 1996). These studies suggest the possibility of anthropogenic burning beginning in the Early Holocene (8,000-7,000 B.C.). During the Late Holocene (3000 B.C. - Present), rapid expansion and diversification of mixed-deciduous forests may indicate that people modified the landscape through burning (Kealhofer and Penny 1998:90). Pollen studies, coupled with aerial photography and sediment mapping, also substantiate climatic changes during the Late Holocene that suggest the second millennium B.C. was more arid (Kaida and Surarerks 1984) than the succeeding first millennium B.C. (Habberfield-Short 1999:217-18). These changes in climate and landscape coincide with archaeological evidence for intensification of land use in northeast Thailand, suggesting a shift in economic and social activity (Habberfield-Short 1999:220).

One of the largest and most comprehensive paleoenvironmental projects undertaken in mainland Southeast Asia to date is the Thailand Palaeoenvironment Project (TPP), co-directed by Drs. Joyce White and Lisa Kealhofer. The TPP utilized lake core samples in three geographically diverse areas of Thailand with important archaeological sites (south, north, and northeast Thailand). The goal was to document environmental differences that contrast latitude, longitude, altitude, rainfall, and other variables and establish 1) details of Pleistocene/Holocene climate change, 2) regional Holocene climate changes, and 3) the regional development of monsoon forests (White et al. 2004:111). The data demonstrated regionally diverse environments and cultural trajectories, suggesting a

mixture of environmental and cultural modification to the natural landscape in each of the three regions in Thailand.

Whereas all three sampled lakes provided important clues to their respective regions, results from the northeastern lake samples are most applicable to this research. The 6.8m core samples were extracted from lake Nong Ham Kumphawapi (henceforth, NHK), located in Udon Thani province (17º11'N; 103º2'E; ca. 170m above sea level). The lake is surrounded by numerous rivers and streams of different sizes. Today, the area averages 1521 mm of annual rainfall, with pronounced wet and dry seasons. Vegetative species are comparable to modern mixed deciduous/dry deciduous dipterocarp forest (Penny 1998; White et al. 2004:120). Ethnographic research as well as aerial photographs indicates a patchwork of natural vegetation and forest types that are influenced by edaphic[3] factors. As a result there is a wide range of subtropical wild and domestic animals and edible plants in the region (Somnasang and Moreno-Black 2000; White 1995b). NHK Lake is also in relatively close proximity to several archaeological sites, most notably Ban Chiang and Ban Na Di (see Figure 2.2). Although Ban Na Di does not possess a long occupation history during the early to mid-first millennium B.C., Ban Chiang stretches through the second millennium and into the first couple of hundred years A.D., providing important human occupation information that compliments the biogeographical data from the pollen and phytoliths.

The lake core sediment data from NHK indicated that by the Middle Holocene (ca. 4400 B.C. cal.) major forest disturbances were present that must be attributed to human-

[3] Edaphic is when the surrounding vegetation results from or is influenced by the soil conditions rather than the climate. Such soil related factors may include soil moisture available to plant roots, soil temperature, soil chemicals in liquid and solid phases, or soil gases.

induced landscape change and not solely to natural occurrences (Kealhofer and Penny 1998; Penny et al. 1996; White 1997). Beginning as early as the late Holocene (1800 B.C. cal.) and peaking around 890 B.C. cal., the lake core samples contain a greater concentration and diversity of pollen taxa associated with a recovery of forest cover (i.e., Celtis, Dipterocarpus, Lagerstroemia, Macaranga, Mallotus, Mussaenda, Myrica, and Trema, and possibly Combretaceae/Melastomataceae and Quercus) (White et al. 2004:123). This recovery was interpreted as a gradual, yet determined, human modification of the landscape, which coincides with a shift in archaeological material culture remains (White et al. 2004:123). Within a short period of time after the start of the first millennium B.C., innovations in iron tools technology, domesticated water buffalo, and wet-rice agriculture resulted in further modification of the surrounding landscape.

The possibility of natural fires or intermittent anthropogenic activity (e.g., hunter-gatherers) was also suggested as possible explanations for changes in the natural landscape (cf. Higham and Lu 1998:873; Maxwell and Liu 2002). However, based on the scale and duration of the pollen data from the NHK core samples, White and colleagues conclude that this is highly unlikely, and that the evidence is more consistent with "sustained and intentional anthropogenic activities" (White et al. 2004:123).

Food Resources in Northeast Thailand

It is unknown when and why people in northeast Thailand went from simply modifying pre-existing habitats of naturally occurring swamp and flooded areas, to an agricultural economy of greater landscape modification to open fields. The waterways and freshwater swamps with its rolling lowlands and sparse forest cover would have been

ideal locations for habitation, due to the rich wildlife in the surrounding area as well as the greater edible plant food diversity (Higham and Thosarat 1998b:10). But, plants, insects, and even many small animals typically are not preserved in archaeological sites in Southeast Asia. As a result it is necessary to look at food resource availability in modern rural villages of northeast Thailand. Even when forced to migrate to other regions, peoples' the taste for plants or food dishes from native lands remains strong, so the types and choices of foods available in rural villages now can serve as a proxy for villages in the past (Wester and Yongvanit 1995:83).

As was likely the case in the past, agricultural production in northeast Thailand is almost solely dependent on rain, although there is some small scale channeling of streams by modern farmers (White 1989:155). As a result, seasonal variation in rainfall as well as soil variability in holding moisture creates year-to-year unpredictability in overall food production. While this may be the case, a wide variety of plants and animals are consumed. Below are the main components of foods utilized in a modern diet from northeast Thailand, and where possible, archaeological evidence for food resources during the second and first millennium B.C. are also provided.

Flora

Fruits and vegetables

As with all of Southeast Asia, northeast Thailand is blessed with a wide variety of fruits and vegetables which are abundant year round (Buergin 2003; Smitinand 1972, 1975, 1980, 1983; Somnasang and Moreno-Black 2000; Somnasang et al. 1999). Some examples include bananas (*Musa sp.*), jackfruit (*Artocarpus* heterophylla), bitter melon (*Momordica charantia* L.), swamp pea (*Sesbania* grandiflora), black eyed pea (*Vigna*

sinensis), morning glory (*Ipomoea aquatica* Forks.), tamarind (*Tamarandus indica*), bamboo (*Bambusa sp*.), limes (*Citrus hystrix*), pomelo (*Citrus grandis*), and mushrooms (e.g., *Auricularia auricular*). Both fruits and vegetables are eaten raw, dried, fermented, and cooked. A list of fruits and vegetables sampled for this study can be found in Appendix A.

Cereal crops

Today when one pictures an image of Southeast Asia it is easy to visualize vast fields of rice and abundant surpluses. In spite of these areas of large fields, in many places farmers still report rice deficit periods of almost four months on average (Roder et al. 1996:406). These shortages are the result of either localized shortages from drought, pests or disease, lack of labor; lack of a major trade market; and inclusion of households with other major sources of income. Thus most farmers produce only enough rice for 8-10 months rather than having a large surplus, forcing them to rely on hunting and gathering for provisions when rice supplies run low (Roder et al. 1996:406).

Rice has two broad forms, wild (*Oryza rufipogon* and *Oryza nivara*) and domestic (*Oryza sativa*). Wild rice varieties are finicky, because the maturation time is short and seeds separate easily due to weak rachis[4] making harvesting difficult (White 1982c:30). However, due to the short seed maturation and limited natural growing area of wild rice, it is doubtful a large enough quantity could have supported a small, settled community (Hanks 1972:28; White 1982c:30).

Millet (*Panicum sp.*) and Job's Tears (*Coix lachyma-jobi*) are two other cereal crops that are grown in Southeast Asia. While there is only one type of Job's Tears grown for

[4] A rachis is a hinge that joins a seed to a plant.

human consumption, millet has several varieties with foxtail millet (*Setaria italica*) being the most common in Asia. Since the historic period, the importance of these two crops in mainland and island Southeast Asia has clearly been superseded by rice cultivation. Further, neither one has been documented in the archaeological record in Thailand. Millet however, dates back to at least 8500-7000 B.P. and possibly as early as 12,000 B.P. (Pechenkina et al. 2005:1177). Ethnographic and historic accounts document millet in island Southeast Asia (Bellwood 1985:244-245) so it is possible millet was grown at least in small amounts in northeast Thailand. This possibility is further elucidated by Mudar's (1995) paper on dryland farming in central Thailand. Mudar argues that soil conditions surrounding prehistoric sites located in upper or high terrace soils are not suitable for growing rice but they may have been used for other more suitable crops such as millet or root crops.

Root crops

Yams (*Dioscorea* sp.), and taro (*Colocasia esculenta*) (dry and wet) are two other carbohydrate resources documented in the ethnographic record in northeast Thailand (Fukui 1993; Wester and Yongvanit 1995; White 1982d, 1984, 1989). Roots and tubers (wild and domesticated) are common food supplements as they can be exploited with little or no land clearance or attention. They are also useful during times in which rice production was lean from unpredictable rainfall.

Through ethnographic analysis of plant crops, White (1984, 1989) showed that yams and taro are a good supplement during the dry season, the middle of the rainy season when last year's stores are low, as well as before the next year's harvesting begins. Wild yam growth patterns are similar to other crops that follow the rainfall pattern; developing

during the rainy season and then being harvested near the end of the season. The advantage of yams over other starchy crops such as rice is that the tubers remain viable well into the dry season. This would be particularly important during the early stages of rice domestication since seeds from wild rice varieties are smaller in size, have fewer numbers per head, and have high rates of shedding, compared to cultivated ones. Thus, until human modification of the rice plant produced a heartier and more productive plant, the unreliability of yields would have made rice an unlikely crop for the sole carbohydrate source (White 1984:31).

Fauna

The modern people of northeast Thailand, besides eating a variety of plant foods, consume a wide variety of animals as well. Fish, chicken, and pork are the primary protein sources today, as well as in the past. However, insects, crustaceans, amphibians, reptiles, and other mammals supplement the diet (Fukui 1993; Grünbühel et al. 2003; Somnasang 1996; Somnasang and Moreno-Black 2000).

Insects

Insect and insect eggs are excellent sources of nutrients and are traditional food sources. Types of insects collected and eaten include all kinds of beetles and larvae of beetles, waterbugs, grasshoppers, crickets, grub worms, silk worms, and egg and larvae of red ants. Insects are consumed in both raw and cooked formats.

Reptiles and birds

Reptiles and birds have long been hunted in northeast Thailand and there is evidence in both the ethnographic and archaeological records (Higham 1989; Higham and Kijngam 1979; Wilen 1987b). These include the frogs, crocodile, snakes, and lizards for reptiles

with birds being hunted for their meat and for their eggs, especially wild ducks and wild chickens.

Aquatic animals

Because northeast Thailand is hundreds of kilometers from the Gulf of Thailand, no marine food resources would have been consumed in prehistory in any great quantity. However, the region has several large river systems with adjoining smaller tributaries that either drain into lakes or lead to the Mekong River. All these provide a large diversity of aquatic fauna.

Villagers today frequently catch up to 14 different species of aquatic animals with another 21 more seldom caught varieties (Buergin 2003:15). The most common types of fish are the snakehead fish (*Ophicephalus striatus*), catfish (*Clarias sp.*, *Hemibagrus (Mystus) nemurus*), swamp eel (*Monopterus alba*), and climbing perch (*Anabas testudineus*). Larger varieties of these fish today are sold, eaten, or sold to middlemen, while smaller and less valuable ones are used to produce fish sauce (Buergin 2003; Somnasang 1996; Somnasang and Moreno-Black 2000; Somnasang et al. 1999).

Evidence for utilization of these aquatic resources has been recovered from all archaeological sites at which fine screening was performed. Through the use of fine screening and floatation, the archaeological faunal data indicate similar relative abundances of types of fish consumed today in the same areas (Higham and Kijngam 1984a:376-378; Kijngam 1991:224-226). Relative frequencies of fish remains recovered from northeast Thailand indicate that *Ophicephalus* is the most abundant, followed by *Mystus*, *Anabus*, *Clarius*, *Fluta*, and *Wallagonia*. These fish occupy a wide range of habitats, including swamps, streams, and wet season rice fields. Other common aquatic

fauna consumed include the small land crab, freshwater shrimp, and pond and river snails.

Mammals

Paleoenvironmental studies indicate the presence of large forested areas alongside marshes and open grasslands that last until the early proto-historic period. These forested areas were interspersed with open low-lying valleys. These conjoining contrasts produced a wide array of wild and eventually domesticated terrestrial mammals. Large animal species found in these parks include wild buffalo, sambar deer (*Cervus unicolor*), banteng (*Bibos javanicus*), gaur (*Bibos gaurus*), elephant, tiger, bear, wild pig, and other kinds of deer. Smaller animals were also abundant, such as monkey, gibbon, pangolin, mongoose, barking deer (*Muntiacus muntjak*), civet, hog badger, marten, squirrel, hare, porcupine, snakes, as well as many kinds of birds.

Bovidae

Archaeological bones from prehistoric sites in Thailand for Bovids comes from either of the two wild varieties; the gaur (*Bibos gaur*) or the banteng (*Bos javanicus*), or from *Bubalus bubalis*, the water buffalo. The gaur is adapted to upland and lowland forest zones, whereas the banteng prefer open grassland. Swampy lowlands are preferred by water buffalo. Kijngam (1979) has worked out many of the distinctions in separating out water buffalo from cattle bones. Further, Higham and colleagues (1981) have been able to further refine domestic versus wild varieties of bovids through discriminant function analysis of the third phalanx.

Canidae

There are two types of wild dog: the Asiatic jackal (*Canis aureus*) and the Asian wild dog (*Cuon alpinus*) but domesticate varieties are found as early as the second millennium B.C. The preferred habitat for both is upland forest regions (Lekagul and McNeely 1977:517). Multivariate analyses of cranial measurements from Ban Chiang and Ban Na Di dogs demonstrated these animals were domesticated and migrated into human communities from northern Asia (Higham and Thosarat 1998a). Cut marks or other indication for human consumption has not been provided archaeologically. While dogs may not have been eaten, at least in large quantities, they do serve a purpose in understanding human dietary change. Domesticated dogs commonly scavenge human refuse for food. Thus, their stable isotope profiles tend to imitate those of their owners and would be different from their wild counterparts (Hogue 2003).

Suidae

Pig remains have always been a large portion of the total faunal assemblage from archaeological sites in northeast Thailand. Even today they make up a large portion of the diet. Unfortunately, to distinguish wild and domestic varieties from immature specimens is not possible. However, a predominance of subadult suids recovered from mortuary sites (Higham and Kijngam 1979, 1984a:359, 1984d) indicates they were reliant on humans for food. Like domestic dogs, pigs are also typically fed the refuse or scraps of food consumed by humans. As a result, their isotope signatures differ from their wild equivalent (Hogue 2003).

Cervidae and Tragulidae

There are seven species of deer from two separates families found in Thailand. From the Cervidae family, six deer species are found with the *Muntiacus feae* (Fea's Barking Deer), *Cervus schomburgki* (Schomburgk's Deer), *Cervus eldi* (brow-antlered or Eld's deer), *Cervus unicolor* (sambar deer) the *Muntiacus muntjak* (common barking deer) and the less common *Cervus porcinus* (hog deer) (Lekagul and McNeely 1977:672). *Cervus unicolor* and *Cervus schomburgki* are considered large deer. *Cervus eldi* is medium in size and *Muntiacus muntjak* and *Cervus porcinus* are both considered small deer. An even smaller variety of deer is called the mouse deer (*Tragulus* sp.), and these can be easily differentiated due to their comparatively tiny size. The *Muntiacus muntjak* and the *Tragulus* sp. are the most common species in Thailand today. These two, along with *Cervus unicolor*, prefer the forest and forest margins. The *Cervus eldi*, *Cervus schomburgki*, and the *Cervus porcinus* are adapted to low-lying, swampy conditions. All of these have been found through all time periods in the archaeological record.

Prehistoric Diet

During the second and first millennium B.C., human populations in northeast Thailand shifted from semi-sedentary to year-round settlements (Higham 2002). Most of what is known about food consumption in the past is based upon archaeological faunal analysis and studies of human skeletal and dental remains. Archaeological faunal remains indicate a large variety of animals were hunted, and a wide variety of fish and shellfish were utilized in the past. Some of the more common terrestrial animals recovered include the domesticated pigs, water buffalo, cattle, and deer (Higham and Thosarat 1998a). Analyses of human skeletal and dental remains from several areas

suggest that food consumption patterns changed little over time, with populations maintaining a broad spectrum diet of wild and domestic foods (Domett 2001; Pietrusewsky and Douglas 2002a).

Second millennium B.C.

The second millennium B.C. was a transitional period for these human groups from their previous strictly hunting-and-gathering lifestyle to more sedentary agrarian ways of living. During this period semi-permanent to permanent settlements become visible in the archaeological record in this region. These settlements were located on slightly elevated terrain along flood prone areas along rivers, streams, and lakes (Higham 1989:130; Kijngam et al. 1980). This low-lying landscape required a less invasive method of crop production than the slash-and-burn cultivation of upland inhabitants (White 1995b). This change in settlement pattern is corroborated through paleoenvironmental data from lake core samples that suggest a shift from upland to wetland locations (White et al. 2004). The subsistence economy was broad and not reliant on a single crop or activity. Food resources included the harvesting of wild and domestic rice, hunting of wild game, fishing, collecting shellfish, and collecting wild plants (Higham 2002:163). Domestic animals included water buffalo, cattle, pigs, chickens, and dogs.

First millennium B.C.

Paleoenvironmental data from this time period indicate a larger degree of forest regeneration than in the previous period (White et al. 2004). This suggests an even greater reliance and intensification of low lying wetland cultivation. The flood plains

would have been modified in various ways, either by clearing patches in forests, use of fire, weeding, and even rudimentary bunding[5] or levees of perennial or seasonal streams.

These environmental and human induced landscape changes coincide with the introduction of iron technology, the use of water buffalo for traction, and an increase in exotic goods recovered from burials (Higham 1983:251-252; Higham and Kijngam 1979; Wilen 1987a). By turning to plows and buffaloes in the wetlands and bunded fields, even larger crops (presumably wet-rice cultivation) could be used to support more people, increase trade networks, or as tribute (Kealhofer 2002). Even today, rice yields are not always sufficient for many villages. This may be due to drought or out of season floods which often destroy or damage crops (Buergin 2003). As a result, rice is commonly used as an exchange item against fish, fishery products, and charcoal.

Near the beginning of the first millennium B.C., archaeologists have documented an increase in the number of settlements in northeast Thailand (Higham 1989). This increase was accompanied by a trend for settlements closer to floodplains as well as further away from nearby permanent water sources. Also during the first millennium B.C. domesticated animals, such as water buffalo, cattle and pig, begin to dominate the faunal spectrum. While there are fluctuations in fish and shellfish remains, the amount of change from the second millennium to first millennium B.C. is unremarkable. Interestingly, there is a subsequent decrease in the diversity of wild terrestrial fauna suggesting a greater reliance on terrestrial fauna as the main source of protein.

[5] Bunding is a technique to prevent erosion and promote better utilization of rainwater by using soil and/or stones to build up an area.

Concluding Remarks

The current archaeological and human osteological evidence for northeast Thailand during the second millennium B.C. suggests the diet was broad-spectrum in both plants and animals consumed from upland/lowland and forest/open plains areas. By the first millennium B.C. staple food crops such as rice and yams are a dominant feature in the landscape along with a subsequent decrease in faunal diversity. There is a reliance on domesticated animals such as pig and chicken and an increased consumption of river fish and shellfish (Higham and Kijngam 1982, 1984a,d).

Over the years, archaeological and paleoenvironmental research has provided much information about food resources utilized by prehistoric peoples of northeast Thailand. However, there are still some uncertainties regarding general resource use and the variation of diet over time and by gender within time periods. Several of these food resources have distinctive stable isotope values, and could thus help clarify potential dietary differences in the stable isotopic analysis of human remains. This topic is taken up in Chapter 4.

Chapter III. Culture History and Site Descriptions

Brief history of Archaeology in Thailand

This chapter provides an overview of archaeological research into the prehistory of Thailand. This background is followed by descriptions of the four archaeological sites used for this research project. The background and descriptions are not intended to be an exhaustive review as greater detail has been provided elsewhere (e.g., Higham 1989, 1996; Higham and Thosarat 1998a).

As a region of mainland Southeast Asia that has been the most socio-politically stable in the last 50 years, Thailand has received much attention from archaeologists. During this time, explanatory models have been devised to try to fully articulate the big picture of the cultural history of this region and its relationship to the rest of Southeast Asia. Two of the earliest models, dating back to the 1970's, were Higham's (1972) 'stadial model' and Gorman's (1977) 'techno-environmental' model. Both of these models attempted to explain changes in cultural innovations and subsistence practices in the transition from hunting and gathering groups through the development of settled agricultural communities. As a result, much of the early archaeological research on subsistence and dietary change primarily focused on the origins of domesticated plants and animals (Gorman 1971; Higham 1977a, 1995; Higham and Kijngam 1979).

Culture History

Bayard's divisions

In the 1980's as more prehistoric sites were excavated, especially in northeast Thailand, a slightly more encompassing explanatory model was developed by Bayard

(1984:163-164). This model attempted to explain cultural development specifically in northeast Thailand. Bayard suggested four General Periods (GP A-D) beginning with hunter-gatherers and ending with state civilizations. The transition from mobile hunter-gatherers to sedentary communities occurs during GP A. There is no evidence of metallurgy during this time period. GP B encompasses the growth of sedentary communities into simple-ranked societies as well as the development of bronze metallurgy. GP C is signaled by iron technology, intensive rice farming and marked increase in social ranking. Finally, GP D is defined by the appearance of minimally complex chiefdoms and the transition to state-level organizations. This scheme would be later modified and further codified by Higham's (1989) synthesis of the archaeology of mainland Southeast Asia. This modification of the original allowed the general temporal sequence to be utilized by all areas of mainland Southeast Asia; particularly coastal sites. Both the original and modified schemes place an emphasis on technological innovations, particularly metallurgy, and archaeological evidence to denote cultural development.

An alternative to those models that utilize technology to delineate cultural change are models that emphasize environmental variability and adaptation strategies specific to a particular environment. While this is an old approach (Hutterer 1976, 1977; see Hutterer and Macdonald 1982; Welch 1984) more recent paleoenvironmental and ethnographic work has brought this approach back to the forefront. These models provide a means for investigating cultural changes in response to certain environmental characteristics between regions, as well as investigating the effects of subsistence and dietary change over time (Higham and Bannanurag 1990, 1991; Higham et al. 1992; Kealhofer and

Piperno 1994; Maloney et al. 1989; Penny 1999a; White 1989, 1995b; White, J.C. et al. 2001, 2003).

The environmental approach does not use a chronological scheme with temporal periods based on artifact typologies. Instead, fluctuations in the paleoenvironmental record caused by natural climatic shifts, as well as human induced modifications to the surrounding environment, are the driving force for cultural innovations such as metallurgy and intensive agriculture. As mentioned in Chapter 2, lake core sediment analysis from pollen and phytoliths suggests shifts in land use strategies occurring around both the second and first millennium B.C. Around the beginning of the second millennium B.C. there is a sharp decline in burning and the beginnings of forest regeneration suggesting a shift from upland to open field lowlands (White et al. 2004:123). In addition, research in settlement patterns suggests a preference for site locations where wet cultivation of rice is possible (Kijngam et al. 1980). This forest recovery trend peaks shortly into the first millennium B.C. marking a greater concentration and diversity of plant taxa that suggest a recovery of forest cover (White et al. 2004:123). Both of these shifts in land use strategies generated changes or adaptations in the material culture. These changes are described below.

Available technology

Changes in technology between the second and first millennium B.C. are attributed to innovations in metallurgy. Sometime near the middle of the second millennium B.C. evidence for bronze artifact crafting, principally in the form of jewelry, is found in the archaeological record. Of particular interest to archaeologists during this time period is material evidence for bronze production is also recovered from many sites (Stech and

Maddin 1988:165). This has important implications for interregional trade and long distance interactions since often the required tin deposits are sometimes hundreds of kilometers away from the manufacture site (Pigott 1985; White and Pigott 1996).

During the first millennium B.C. there is evidence for two major technological innovations -- the domestication of the water buffalo and knowledge for making iron objects. Evidence from grave goods suggests an increased emphasis on social status over time through prestige goods that included gold beads, silver rings, bronze and marble bracelets, semi-precious stone and metals (Chang 2001; O'Reilly 1999). The disparity in grave goods and the clustering of burials found at many sites may indicate a shift in the importance of kinship relationships rather than the development of hierarchically organized societies (O'Reilly 2001:12).

Subsistence base

Archaeological survey and excavation suggest that habitation sites during the second millennium B.C. most likely did not exceed 5 hectares (~12 acres) in area or approximately 250 people in size (Higham and Thosarat 1998a:127). Settlements were located near perennial streams, rivers, and lakes, with subsistence strategies changing little from the second millennium B.C. to the middle of the first millennium B.C. Hunting and gathering of game, fish, shellfish, nuts, berries and other plant foods continued with a seasonal round influenced by the availability of the various resources. Pig and cattle bones predominate in the archaeological faunal assemblage, both within and outside burial contexts, suggesting a great reliance on these two animal food resources during both time periods. Other animals present include different species of deer, chicken, dog, turtle, shellfish, and a number of species of freshwater fish. While

rice during the second millennium B.C. may not have been the pre-eminent staple plant food as it became during the first millennium, it was still a significant crop (Higham and Kijngam 1984d; Welch 1985).

Cultural history during the second millennium B.C.

The second millennium B.C. marks an important transition in human prehistory in northeast Thailand. While archaeological evidence during the first half of this millennium is scant, there is evidence for human settlements in the region possibly even extending back into the third millennium B.C. These settlements, most of which are located in the Sakon Nakhon Basin, are characterized as autonomous, culturally localized villages with knowledge of rice harvesting, regionalized pottery forms, and copper and bronze metal production (Higham 2002:112-167). The subsistence regime is broad spectrum, meaning utilization of a wide array of food procurement techniques and food resources – upland, lowland, forest, meadow, swamp, water, animals, plants, amphibians, fish, birds, insects, etc. The general lack of weaponry and absence of skeletal evidence for violence during this period suggests a lack of conflict (Domett 2001:112; Pietrusewsky and Douglas 2002a:117; White 1982a:45-49). This lack of violence may be the result of non-circumscribed access to local resources (White 1995a:107).

Settlements are typically located along streams and the margins of river floodplains. The technique of rice cultivation probably involved the exploitation of enclaves of land subjected to a limited degree of flooding following the onset of the rainy season. Broad spectrum subsistence strategies would have served as a buffer to the effects of climatic extremes (i.e., drought). Settlement size during this period has been estimated to a maximum of around 500 individuals (Higham 1989:187-188).

By the middle of the second millennium B.C. knowledge of bronze metallurgy becomes apparent in the archaeological record in the form of jewelry. This introduction also coincides with changes in ceramic styles, with a greater variety and richness in grave goods. These changes in the grave good assemblages suggest an increase in ranking within these small communities but an overarching social structure that is heterarchical[6] rather than hierarchical (O'Reilly 2001, 2003; White 1995a; White and Pigott 1996:157).

The temporal transition from the second to the first millennium B.C. is not typified by the appearance of a particular food, technology, or idea. Archaeological data demonstrate a gradual change in burial offerings that demonstrate gradual changes in social structure and technology (Chang 2001).

Cultural history during the first millennium B.C.

During the beginning of the first millennium B.C. archaeological research documents a proliferation of settlements in the Khorat Basin that in the previous millennium was nearly devoid of occupation. This increase in recovered settlements appears to result from population expansion from Sakon Nakhon Basin to the Khorat Basin (Higham 1975b, 1977a,b, 1979:679). Alternatively, the number of sites found in field reconnaissance surveys in Sakon Nakhon may also be the product of increased archaeological interest in this region during this time period just prior to Khmer empire control. Some sites during this period grew very large with numbers upwards of 1000-2000 people (Higham 1989:219; Wilen 1987a:107-110).

In the previous millennium and earlier personal ornaments were mostly from natural and easily worked materials such as shell, marble, copper, and finally copper mixed with

[6] Heterarchy is the horizontal (unranked) conception of power among individuals or groups in a community (Crumley 1995:3).

tin. At approximately 900 B.C. personal ornaments changed. Styles became more complex and sheer quantity increased. Also, glass beads and hard stone beads increased while ornaments made of natural materials declined (Chang 2001:226; O'Reilly 1999:289). This trend continued into the early A.D. periods.

Bronze artifacts continued to be a common grave item but the craftsmanship of these objects is much more sophisticated (Chang 2001). In addition there was a substantial increase in diversity and number of grave goods as well as the introduction of iron objects, glass and carnelian beads, gold jewelry, and marble bangles suggesting differential social status at the level of complex chiefdom (Welch 1984:184). However, new data and re-analysis of personal ornaments from grave goods have challenged the general acceptance of a chiefdom-like social structure developing alongside iron technology and other new artifacts in the region around 500 B.C. as originally proposed by Bayard (1984:163-164) (Chang 2001:243). The development of iron technology in conjunction with changes in social structure was gradual and non-distinctive over time.

As a by-product of increased settlement size there was an equally impressive increase in the number of surrounding settlements. These settlements most likely developed as overflow from over-populated locations. This resulted in utilization of a previously untapped area of northeast Thailand, the agriculturally marginal lands (Moore 1990; Welch and McNeill 1991). In addition, pollen data provide evidence for management/modification of the surrounding landscape, including an expansion and contraction of various landscape forms (grasslands, sedge lands, cultivated lands, and managed/cultivated natural forest and woodland) (Boyd and McGrath 2001b:322; White et al. 2004).

The Mun River Valley in particular is at a pivotal juncture since this region is at the crossroad of the Mekong River, the Khmer Civilization, and the Thai Civilizations of the Chao Phraya. While it is not until the second-half of the first millennium A.D. that the Mun Region came under the control of the Khmer empire of now Cambodia, the second half of the first millennium B.C. witnessed the establishment of extensive trade networks, and highly ranked human groups in centers of intensified production.

In addition to increased trade from areas outside of the plateau, the first millennium B.C. is also characterized by the development of certain cultural innovations. While these innovations make a strong appearance in the archaeological record half-way through this time period, they most likely have been around on a small scale since nearly the beginning of this millennium. Rice planting also intensified with the introduction of water buffalo and plow to utilize the method of transplanting in bunded fields (Welch 1989:17). There is also a consistent body of evidence for the use of iron and importation of glass and exotic stone beads.

By the end of this millennium, more coordinated society-wide projects, in the form of earthen ramparts (moats) are found, particularly in the Mun River Valley. While the function of these earthen works is not fully known, their use as a defensive feature has been suggested (Moore 1988:29) though the bioarchaeological evidence indicates a lack of large scale violence during this period anywhere in northeast Thailand (Domett 2001; Pietrusewsky and Douglas 2002a). Others have suggested the moats were created to serve as water retention/flow control devices (Moore 1988:121; White and Pigott 1996:167) in these newly occupied flood-prone valleys.

These moated sites may constitute regional administrative centers with the largest moated settlements at the core (Welch 1989:23). These regional centers served as redistribution zones that allowed for intensified specialist-produced utilitarian goods, long distance trade, and food regulation among a growing elite class (Macdonald 1980; O'Reilly 2001:11; Welch 1989:23). Several researchers have suggested an increase in craft specialization in the manufacture of various goods such as jewelry, stone tools, and metal from the second to first millennium B.C. (Ciarla 1992; Higham 1989; Higham and Thosarat 1998a; McNeill and Welch 1991; Welch 1989; White and Pigott 1996). This however does not imply standardization in the manufacture of material goods. To the contrary, even basic goods such as pottery do not indicate uniformity in technique, temper, or shape in northeast Thailand. In addition, the large scale projects may not be under the control of a centralized authority. These moated constructions could easily have been organized by local groups or big-man organizations (Chang 2001:243).

Toward the end of the first millennium B.C. and into the early A.D. periods of northeast Thailand an additional presence was beginning to be felt as the Central Plains of Thailand and Mekong delta begins it ascent in the world trading system (Glover 1989). During this time carnelian and agate, probably of Indian origin, were common in northeast Thailand. By the early A.D. period, the fledgling Khmer empire moves from the Mekong mainstream to the North Cambodian Plain between A.D. 550 and 802. Chiefdoms, in the sense of regional polities with formalized hierarchies, have not existed in northeast Thailand before A.D. 500 (Chang 2001:244). By A.D. 600-650, Dvaravati building artifact styles are found in northeast Thailand as well as the first inscriptions. During the period of A.D. c. 802-1000 the Khmer expanded across the Dangrek range to

the Mun Valley and eventually into the Chao Phraya Valley. Using Phimai as its center, Phimai would become the largest Khmer settlement north of the Dangrek and serve as Angkor's communications link with Champasak, the lower Mun Valley, and the Chao Phraya valley (particularly with Lopburi) to the west (Acker 2001:90).

Site Descriptions

Sakon Nakon Basin

Ban Chiang

The archaeological site of Ban Chiang is located under the modern-day village bearing the same name. This mound village is located near the junction of three small streams, surrounded by rolling lowlands. There were three excavations of this site. The first took place in 1967 by the Fine Arts Department of Thailand (FAD hereafter) under the direction of Vidya Intakosai to investigate surface findings of red-on-buff pottery fragments in the area (Higham 1989:106; You-di 1972, 1975). This small investigation uncovered more pottery, a human skeleton, some glass beads, and bronze and iron artifacts. This led to several other smaller excavations by the FAD either on or near the mound during the early 1970's which clearly documented a long history and a pottery style distinct from other sites in this region (Suthiragsa 1979).

Two large excavations by the FAD and the University of Pennsylvania under the direction of Pisit Charoenwongsa and Dr. Chester Gorman were conducted in 1974 and 1975 (Gorman and Charoenwongsa 1976; Higham 1983; White 1986). Three cultural periods (Early, Middle, and Late) and ten subphases were identified to explain stylistic variation in grave goods (primarily pottery) found within each major mortuary period (White 1982b, 1986). Current dating of the Ban Chiang site spans approximately from

2100 B.C. to A.D. 200 encompassing pre-metal, bronze, and iron deposits (Pietrusewsky and Douglas 2002a). The Early Period (EP) includes five phases (EP I-V) and is thought to date from 2100-900 B.C. The Middle Period (MP) includes three phases (MPVI-VIII) and has been dated to 900-300 B.C. and the Late Period (LP) is divided just once LP (IX-X) with a proposed span of 300 B.C. to A.D. 200. Pietrusewsky and Douglas grouped the skeletons into two temporal samples. The Early Group includes burials from Early Periods I-V and the Late Group includes burials from the Middle Period VI through VIII and Late Period IX-X. This configuration approximately coincides with the chronological separation of the second and first millennium B.C. as well as the cultural typological categories of bronze and iron ages respectively.

Subsistence practices reconstructed from faunal and botanical remains have been conducted at Ban Chiang. The presence of rice chaff used for ceramic temper suggests some sort of rice cultivation during the initial occupation of the site (Higham and Thosarat 1998a:110). The faunal material from the second field season revealed much information on environmental conditions and subsistence. The inhabitants hunted a wide array of animals, while keeping domestic cattle, water buffalo, pigs, chickens, and dogs (Higham and Kijngam 1979, 1982; Kijngam 1979). Shellfish, turtles, fish, and frogs were also included in the diet. There was an increase in terrestrial herbivores and a decrease in aquatic species over time that can be attributed to an increase in grasslands and decrease in standing water during the middle and later occupational periods (Higham and Kijngam 1979:230). This change is attributed to human induced forest clearance possibly because of the increasing emphasis on intensified rice cultivation. Domestic

animals such as chicken, pig, cattle, water buffalo, and dog remains are more abundant over time as well.

Osteological analysis of the human remains from both excavations at Ban Chiang was done by Michael Pietrusewsky and Michele Douglas (Douglas 1996; Pietrusewsky 1982, 1997; Pietrusewsky and Douglas 2002a,b). A total of 142 skeletons make up the series. Twenty-nine individuals are from the pre-metal period, 74 from the Bronze Age, and 39 from the Iron Age. The long occupation of this site allows for inter- and intra-site comparisons. The temporal subgroups can be hypothetically divided at points of major changes in subsistence technology (introduction of iron) and food production (intensification of agriculture). Evidence for the introduction of iron and an increased utilization of water buffalo occurs during the mid-first millennium B.C. at Ban Chiang (White 1982d).

Recently, two stable isotope studies were conducted using samples from Ban Chiang. In 2001, a pilot study, which culminated into this dissertation, was conducted to investigate the viability of using stable isotope methods in mainland Southeast Asia. The study explored whether secular changes in diet could be detected using carbon and nitrogen isotopic analysis, and if dietary variation may occur by sex. Results of the pilot study confirm that the methodology is viable and also suggest that dietary variation occurred across time and by sex.

An additional study was also recently reported using strontium ($^{87}Sr/^{86}Sr$), carbon ($\delta^{13}C_{apatite}$), and oxygen ($\delta^{18}O$) isotopes (Bentley et al. 2005). This study investigated if there was a correlation between local adult inhabitants and geographic locations of their childhood homes. The results of this study suggested that men immigrated to the Ban

Chiang village whereas women remained local. This suggests the possibility of a matrilocal system at prehistoric Ban Chiang (Bentley et al. 2005).

Ban Na Di

Ban Na Di, located in the Pao River Valley approximately 20 km southwest of Ban Chiang, was excavated in 1980-81 with the aim of building on earlier work at Ban Chiang. This was a joint effort by the FAD and the University of Otago (Higham and Kijngam 1984d,e). A revised mortuary phase chronology (Higham 1996:204) compressed the sequence to the first few hundred years of the mid-first millennium B.C. Evidence for bronze is found at the earliest levels of the site. The first evidence for iron-working occurs sometime between the end of the first millennium B.C. and the first few centuries of the first millennium A.D. (Higham and Kijngam 1984b:707). The mortuary practices at Ban Na Di resemble those of Ban Chiang. In each cemetery evidence was recovered for metal and ceramic technologies, and a wide array of faunal material was recovered. A total of 78 individuals were recovered at this site.

The stratigraphy has been divided into eight main layers of which the top two are modern or historic. In turn, these eight layers have been divided into mortuary phases. Phase 1 is designated for layers 6-8 and has 71 burials. Layer 8 represents the basal layer and first occupation with 14 burials while layers 6 and 7 contained 56 burials. One individual, BND41 has no layer designation but is associated with phase 1. Layer 5 is characterized by metal working furnaces and a lack of burials. Layer 4 contains four burials, two containing glass beads, and is designated phase 2. Three disturbed burials are linked to layer 3 along with numerous postholes and pits. The two separate areas of excavation also revealed the possibility of burial grouping by status or some sort of

affiliation. Burials from one of these two areas were notably richer in mortuary goods than the other, prompting Higham and Kijngam to suggest the presence of two distinct hereditary, ranked groups with a burial area reserved for those with higher status (Higham 1984:83-85; Higham and Kijngam 1984c:440).

Faunal analysis conducted at Ban Na Di showed similarity to the faunal results from Ban Chiang. The faunal remains suggested an economy that involved keeping domestic stock animals and hunting or trapping in the surrounding forest or forest margin (Higham and Thosarat 1998a:108). Of particular interest however was the use of fine screening (1mm mesh) which was not performed at Ban Chiang. The use of fine screening at Ban Na Di produced an even broader array of smaller terrestrial and aquatic fauna than recovered from Ban Chiang indicating an even greater range of food resources being utilized throughout this region (Higham 1989:137-138).

The initial examination of the skeletal remains described 73 individuals (Houghton and Wiriyaromp 1984a,b; Wiriyaromp 1984a,b) but reanalysis of this collection increased the number of individuals to 78 (Domett 1999, 2001:23). The burials at Ban Na Di are divided into three phases based upon their superposition. Phase 1 is divided into three subphases and encompassed a time period from c. 1200-400 B.C. (Phase 1a 1200-700 B.C., Phase 1b 700-600 B.C., Phase 1c 600-400 B.C. (Wiriyaromp 1984a:16). Phases 1a and 1b are distinguished by the relative scarcity of mortuary artifacts. It is during the last phase (1c) that increases in the number of grave goods are revealed. Phase 2 burials comprise five jar burials containing the remains of infants dated about A.D. 100 (Wiriyaromp 1984a:16). Phase 3 contains three very fragmentary and late burials that probably date to the mid first millennium A.D. (Wiriyaromp 1984a:16).

Khorat Basin

Ban Lum Khao

Present day Ban Lum Khao is a village which overlays a second millennium B.C. age mound that was excavated for one field season in 1996 led by Prof. Charles Higham of the University of Otago and Dr. Ratchanie Thosarat, FAD, Thailand. The excavation identified three layers of cultural deposits. Radiocarbon dating was only available for the lowest occupation layer with initial occupation of the site between 1400 B.C. and 1000 B.C. The cemetery remains however only span from 1000 B.C. to 500 B.C. (Higham and Thosarat 1998a:114)

Of the three cultural layers, the first comprises of modern domestic deposits a few disassociated prehistoric artifacts and two burials. Layer 2 contained most of the burials that are estimated to be from 1100 B.C. to 400 B.C. or 500-1000 years after the initial occupation of the site (Higham 2002:142). Layer 3 is considered late Neolithic in occupation and includes pits cut into the natural substrate and areas of dense shell midden (Chang 2001:96). Layer 3 contained the only datable charcoal.

Faunal remains from this site have only been descriptively studied and preliminary analysis has been undertaken. No report of the faunal remains has been published but a project report on this site which included the faunal (terrestrial and aquatic) remains is on file at the FAD Office in Bangkok (Higham 2000; Thosarat 2000b). From this report it can be stated that a wide array of terrestrial and aquatic animals were recovered with a particularly large array of fish species.

A total of 110 burials were recovered and divided into four mortuary phases. Only two burials are located within Layer 1 and the remaining are located in Layer 2 though

some cut into Layer 3. Analyses of the remains have been published in Domett (2001) and Domett and Tayles (2006). In total there were 25 adult females, 19 adult males, 15 adults of unknown sex, 16 children (5-14) and 35 infants (<5 years). Overall, the skeletal material was well preserved and is stored at the FAD office in Phimai, Thailand.

Noen U-Loke

Noen U-Loke is a site approximately 20km west of Ban Lum Khao that dates from 300 B.C. to A.D. 600. The site was excavated three times. The first excavation was by Mr. Meta Wichakana in 1986 (Wichakana 1991). The two other excavations were from 1997-1998 and led by Dr. Charles Higham of the University of Otago and Dr. Rachanie Thosarat, FAD, Thailand. A mounded site, Noen U-Loke is surrounded by what appears to be five concentric channels and is situated between the Huai Don Man Kasak and the Huai Yai Rivers in the Khorat Basin (O'Reilly 1999:120). This first millennium site has a second millennium component at its base (Wichakana 1991). The site was occupied from perhaps as early as 1000 B.C. through to about A.D. 600 and has been divided into five mortuary phases. The earliest burials recovered date to about 300-200 B.C. however the exact date of any one burial is unknown. The site contains evidence of domestic structures in the form of postholes, clay floors and walls and metal smelting or casting furnaces. Iron, glass beads, and agate pendants were encountered for the first time within the third mortuary phase.

There are several moats surrounding the main mound of the site. These moats are typically wide and shallow, although deep geoarchaeological trenches have revealed some deeper disturbances (Boyd and McGrath 2001b; Boyd et al. 1999a,b). This is

significant for Noen U-Loke since Mortuary Phase 3 either predates or is contemporaneous with the earliest labor intensive construction of these moats.

Brief descriptions of the faunal remains from Noen U-Loke indicate the presence of mostly domesticated cattle, pigs and water buffalo with very few wild animals (Higham and Thosarat 1998a:156; McCaw 2000). As for fish remains, the number of fish represented in the assemblage was considered low when compared to Ban Lum Khao but the range is just as diverse (Thosarat 2000a:217).

A total of 120 burials, 27 males, 21 females, 19 unknown adults sex, 7 children (5-15 years old) and 46 infants and neonates are represented and have been described in Domett and Tayles (2006) and also in Nelson (1999). Analysis of the excavation revealed five mortuary phases. Preservation of these remains is not as good as that found in nearby Ban Lum Khao. Much of the material is fragmented and many individuals are incomplete. The fourth mortuary phase contains most of the individuals and dates not long after A.D. 250. Also of note during this phase is the recovery of what has been termed rice bed burials (Higham and Thosarat 1998a:154). These graves start with a layer of burnt rice that serves as 'bed' in which the human remains were laid. Once in place, more rice was placed to cover the body. This mortuary practice occurred in all types of graves (male/female/adult/subadult).

Bioarchaeological Evidence for Dietary Change

Demographic changes in a population (past or present) are dependent on a number of inter-related factors that include environment, subsistence, technology, and culture. The basic idea behind this is that as long as these factors remain constant then there should be no significant changes in the demography of a population over time. In reality this is

rarely the case and the time it takes for these changes varies from region to region, population to population.

In understanding temporal changes in diet in prehistoric northeast Thailand it is important to have an understanding of the paleodemographic changes since diet and nutrition are major factors influencing demographic parameters. Conventional thinking suggests the demographic patterns between the second and first millennium B.C. in northeast Thailand would be different due to the changes in cultural technology and more intensive cereal cultivation practices between these periods. The consequence of these changes that led to agricultural intensification of rice is usually a decline in health of populations over time (e.g., Cohen and Armelagos 1984) though this is not consistent worldwide (Larsen 1995, 1997; Steckel and Rose 2002).

Paleodemography

Paleodemography is a statistical study of the human skeletal remains that provides information for describing biological and social aspects of a population in space and through time. Data are collected from individuals with the assumption that the entire skeletal series is representative of the population, estimates of age and sex are accurate, and the living population was stable or stationary in numbers (Hoppa and Vaupel 2002:3; Saunders and Hoppa 1993; Wood et al. 1992). These data are then used to estimate population mortality, fertility, and disease prevalence. Tables 3.1 and 3.2 provide a summary of paleodemographic data for the four samples used in this study. Tables 3.3-3.8 include the abridged life tables for each skeletal series. The skeletal collections used in this dissertation cover both the second (Ban Chiang, Ban Lum Khao) and first millennium B.C. (Ban Chiang, Ban Na Di, Noen U-Loke).

Changes between millennia

A summary of paleodemographic results from all sites used in this study can be found in Domett (2001), Domett and Tayles (2006), Douglas (1996), and Pietrusewsky and Douglas (2002a). Ban Chiang is currently the only well documented archaeological site in northeast Thailand that spans two millennia of occupation[7]. In order to assess paleodemographic changes between millennia, Ban Chiang is divided into two broad categories of Early Group (EP I-V) and Late Group (MP VI-LP X).

Based on the age and sex distributions there are demographic shifts over time (Table 3.1). The sex ratio suggests males are overrepresented in the Early Group and underrepresented in Late Group. This shift however can be interpreted as a product of sampling error rather than true demographic shifts resulting from disease or conflict.

Paleodemographic parameters which include both mortality and fertility based estimates to document demographic changes are presented (Table 3.2). Mortality based assessments such as life expectancy at birth, life expectancy by age 15, mean adult (>15 years) age-at-death, and birth rate are all consistent with a decline in population health from the second millennium to first millennium B.C. Life expectancy at birth, life expectancy at 15 years of age and mean age, at death are all lower over time by at least 5 years. This suggests a higher mortality rate during the first millennium B.C. Birth rates (inverse of life expectancy at birth) are also consistent with a change from hunter-gatherer-cultivators to one of intensive agriculturalists. The birth rate during the second millennium B.C. is 33/1000 (1/30.1 = 0.033) and increases during the first millennium B.C. to 44/1000 (1/22.5 = 0.044) (Table 3.2). An increase in fertility along with

[7] Ban Non Wat near Phimai, Thailand is the one other archaeological site spanning two millennia. It is currently still being excavated (Higham 2004).

subsequent decreases in life expectancy have both been implicated as being a consequence of the transition to intensified agriculture (Pietrusewsky and Douglas 2002b:163)

Fertility-based estimates (D20+/D5+ ratio, Juvenile/Adult ratio (JA), Mean Childhood Mortality (MCM)) are useful because they eliminate inherent biases that may be attributed to methods of adult aging and/or an under representation of subadults. The slight decline in the D20+/D5+ ratio over time (0.851:0.832) suggests an increase in fertility which is consistent with the change in birth rates noted above. Similarly, the increase in the JA ratio between these two groups (0.111 to 0.148) would also suggest an increase in fertility. Lastly, the MCM suggests an increase (0.097 and 0.160) in the childhood mortality rate that implies fertility must be increasing over time (Jackes 1994:179).

Based on the combined results from these four archaeological sites in northeast Thailand, mortality and fertility estimates imply demographic change over time but not a significant decline in health as demonstrated in other parts of the world (Cohen and Armelagos 1984; Larsen 1997). These paleodemographic data infer that the overall lifestyles between the second and first millennium B.C. are different and consistent with changes in the material culture and subsistence practices.

Regional differences in paleodemography during the first millennium B.C.

It is not until recently that skeletal samples have become numerous enough to fully document paleodemography and health with interpretative power across different regions of northeast Thailand. Unfortunately while several sites with sufficient skeletal sample size exist for the first millennium B.C. only Ban Chiang provides a skeletal sample for

the second millennium B.C. Therefore no regional analysis of the second millennium B.C. is attempted.

An evaluation of skeletal series from the Sakon Nakhon Basin (Ban Chiang and Ban Na Di) and Khorat Basin (Ban Lum Khao and Noen U-Loke) indicate regional differences during the first millennium. Sex ratios indicate males are overrepresented in the Sakhon Nakon region (n = 119) while in the Khorat region there appears to be equal representation of females and males (n = 100) (Table 3.1). Once again, this can easily be interpreted as a product of sampling error rather than true demographic shifts.

From Table 3.2, the life expectancy at birth, life expectancy at 15 years of age, and mean adult (>15 years) age-at-death indicate a higher mortality in the Khorat region than the Sakon Nakhon. Birth rates are also consistent in demonstrating regional differences. A higher birth rate in the Khorat Basin (52/1000) than in the Sakon Nakhon Basin (39/1000) indicates a higher fertility rate in the Khorat Basin (Table 3.2). The higher fertility rate in the Khorat Basin is further corroborated by the D20+/D5+ ratio, Juvenile/Adult ratio, and Mean Childhood Mortality rates. The differences in the D20+/D5+ ratio (0.875 : 0.788), JA ratio (0.097 to 0.199), and MCM (0.122 : 0.199) values suggests a lower mortality and higher fertility rates in the Khorat Basin than in the Sakon Nakhon Basin.

This comparison demonstrates regional differences in paleodemography between the Sakon Nakhon and Khorat Basins. The Khorat Basin with its higher mortality and fertility rates would suggest an environment that is harsher than in the northern region of the Khorat Plateau.

Dental Pathological Conditions

An important source of information for assessing the health status and changes in the diet of a population is provided by studies of dental remains. Dental caries, attrition, and antemortem tooth loss are all conditions which are directly linked to shifts in diet. These dental pathologies reflect the relative frequencies of carbohydrates versus proteins in the diet, food processing techniques (course vs. soft ground starches), as well as track the transition of subsistence economies (Larsen 1995, 1997). Dental caries rates are important for investigating the reliance on starchy food crops such as yams, rice, etc (Larsen et al. 1991). A rise in carious lesions would indicate an increase in starchy-sticky foodstuffs which implies a greater reliance on these foods as a primary staple food source. Dental attrition is the gradual loss of the tooth surface through abrasion. This abrasion is produced by tooth-on-tooth contact, contact with coarse food particles and/or by using teeth as tools such as in holding/cutting line or chewing sinew (Pietrusewsky and Douglas 2002a:61). The premature loss of a tooth during life is complex since a tooth may be lost as a result of infection (carious/abscessing/severe attrition) or cultural behaviors such as tooth ablation or trauma. Differentiation of the two involves careful analysis of the overall dental health and the pattern of tooth loss per individual (Pietrusewsky and Douglas 2002a:55).

Dental caries

Overall the rate of carious lesions in northeast Thailand is low which is consistent with a mixed food economy (Table 3.9). While this suggests that the diet of prehistoric inhabitants of northeast Thailand did not significantly rely on starchy/sticky carbohydrates as a primary food source the archaeological evidence is contrary. Even

during the earliest occupation of Ban Chiang during the second millennium B.C. the subsistence economy of rice appears in the mortuary sequence (White 1986, 1995b). Based on ethnoarchaeological research it is also assumed that yams and other starchy root crops contributed to the subsistence economy (White 1984, 1989).

While the rate of cariogenic infection in any one individual has a genetic component (e.g., oral bacterial flora or saliva flow), food preparation techniques and food intake also play a role. In a recent literature review and analysis of dental caries from archaeological samples in Thailand, Tayles and colleagues (Tayles et al. 2000) point out that rice is less cariogenic than other starchy foods like corn, wheat flour, and potatoes. Furthermore, fluoride that is commonly ingested through whole fish consumption or through the utilization of the condiment, fish sauce, that is common all over Southeast Asia today and presumably has a deep history, may have aided in keeping carious lesions to a minimum.

In northeast Thailand, carious lesion rates (7.6%:4.7%) decline over time which is statistically significant ($\chi^2 = 10.48$, $p \leq 0.001$) (Table 3.9). This finding is contrary to the expectation of increased cariogenic activity with intensification of agriculture (Cohen and Armelagos 1984; Turner 1979) and suggests that diets during both time periods remained broadly-based and not dominated by a single food product (Pietrusewsky and Douglas 2002a:201). When this temporal difference is compared by sex, there is a significant increase in carious lesion in males ($\chi^2 = 4.80$, $p \leq 0.05$) but not in females (Table 3.10).

The frequency of carious lesions between females and males also changed between time periods. There are no significant differences in carious lesions between females and males during the second millennium B.C. Over time however, females (5.4%)

demonstrate significantly more carious lesions than males (3.1%) during the first millennium B.C. ($\chi^2 = 5.17$, $p \leq 0.025$) (Table 3.10).

Behavioral differences are the most likely explanation for the difference in female and male incidences of carious lesions. During the first millennium B.C. females may have consumed more carbohydrates and/or ate more starches in frequent amounts increasing the rate of dental exposure to acidic sugars.

When comparing regional differences within the Khorat Plateau, individuals in Sakon Nakhon Basin have a higher carious lesion rate than in the Khorat Basin. This difference is statistically significant ($\chi^2 = 4.99$, $p \leq 0.025$) (Table 3.9). The regional differences may be associated with climatic differences in rainfall since the Sakon Nakhon is typically wetter than the most central plateau region, resulting in a greater abundance of other starchy foods such as bananas and palm sugar. No significant differences in carious lesion rates are observed within or between the sexes with these regions of the Khorat Plateau.

Dental attrition

Dental attrition is the loss of the surface of the tooth and is the result of both chewing and the use of teeth as tools during life. The amount of wear is age progressive making it a valuable tool for age estimation. Since chewing is the primary means by which the enamel of teeth is worn, diet and texture of foods are closely linked to attrition. As a result, food production and food preparation techniques (e.g., stone grinding) directly affect the rate of tooth wear.

In northeast Thailand, the rate of dental attrition over time does not significantly change ($\chi^2 = p \leq 0.823$) (Table 3.9). This suggests even though agricultural production

increased over time the level of grittiness, or more fibrous diet, has not changed. Similar insignificant results are also shown between regions of northeast Thailand. While the rate of attrition in the Sakon Nakhon Basin burials is slightly higher than the Khorat Basin burials (15.1%:13.9%, respectively), the difference is not significant, and overall suggests a consistent pattern of food choices and/or use of the teeth as tools.

The rate of dental attrition does change when comparing females to males within a given time period (Table 3.10). During the second millennium B.C., males were significantly more likely to have advanced dental attrition than females ($\chi^2 = 21.37$, $p \leq 0.001$). This is almost completely reversed during the first millennium B.C. where females had significantly higher incidences of advanced attrition compared to males ($\chi^2 = 8.32$, $p \leq 0.01$). Both females and males also had significantly different rates of attrition over time. The rate of dental attrition in females significantly increased from 10.4% to 18.4% from the second to the first millennium B.C. ($\chi^2 = 18.97$, $p \leq 0.001$). The rate of dental attrition in males however significantly decreased from 18.5% to 13.2% ($\chi^2 = 9.97$, $p \leq 0.01$).

There are two possible explanations for these significant differences in attrition between females and males. The first is dietary influence in which the coarseness of the food changed between females and males over time. Individuals with advanced attrition are thought to have high amounts of grit and sand in their diet. The other explanation is age distribution of the samples. Ban Na Di, for example, has adults which are mostly older females (>30 years) and younger males (<30 years) (Domett 2001). This may result in significant differences between the sexes because of age disparities in the available samples.

Antemortem tooth loss

Antemortem tooth loss suggests the presence of dental pathology including caries, periodontal disease, and severe attrition. These dental pathologies are associated with diet and an increase in carbohydrate consumption increases the likelihood of tooth loss. However, in northeast Thailand this is not the case. The rate of antemortem tooth loss decreases ($\chi^2 = 1.29$, $p \leq 0.257$) though it is not a significant change over time (Table 3.9). Regional variation is also apparent with a 6.3% rate of antemortem tooth loss in the Sakon Nakhon Basin compared to 5.1% in the Khorat Basin, though the difference is not significantly different ($\chi^2 = 2.74$, $p \leq 0.982$).

When the sexes are combined there are no significant differences in antemortem tooth in northeast Thailand. However, when comparing females to males significant differences in antemortem tooth loss are apparent (Table 3.10). In northeast Thailand, females have significantly higher rates of antemortem tooth loss than males ($\chi^2 = 13.50$, $p \leq 0.001$). This difference is not apparent during the second millennium B.C. but occurs during the first millennium B.C. with females having significantly more antemortem tooth than males (9.0%:3.4%, respectively) ($\chi^2 = 29.20$, $p \leq 0.001$).

This sex difference in the first millennium is also reflected over time. Antemortem tooth loss is nearly twice as high (5.6:9.0) in first millennium B.C. females ($\chi^2 = 8.56$, $p \leq 0.01$), while in males there is a significant decrease in antemortem tooth loss from 5.8% to 3.4% ($\chi^2 = 7.10$, $p \leq 0.01$) (Table 3.10).

Significant sex differences in antemortem tooth loss are also apparent within specific regions of northeast Thailand. In both the Sakon Nakhon ($\chi^2 = 6.50$, $p \leq 0.025$); and

Khorat Basins (χ^2 =7.56, p≤ 0.01) females have significantly higher rates of antemortem tooth loss than males (Table 3.10).

Summary of Cultural History and Bioarchaeological Evidence

The purpose of this chapter is to present a collection of well documented archaeological sites with human skeletal remains (Table 3.1) to address the questions that have been posed regarding prehistoric diet in northeast Thailand. These four sites cover a time span from the beginning of the second millennium B.C. on into the first few centuries A.D.

The time range of these samples is well-suited to the problems at hand. During the time from the second through the first millennium B.C. a wide swath of cultural changes took place. Between these periods, there is an apparent change in subsistence patterns associated with settlement size increases. There is also archaeological evidence for change in pottery and complex metallurgical crafts. Once into the first millennium B.C., there is sufficient archaeological evidence to document increases in settlement size, changes in technology and faunal assemblages, and climatic shifts. The transition to a more intensified production of rice cropping develops in tandem with the domestication of water buffalo as a traction animal for the now present iron plowshares. During the latter half of the first millennium B.C. there is some evidence to indicate that northeast Thailand is incorporated into a larger social system.

A summary of several dental indicators of health and disease recorded in skeletal series for the region demonstrates subsistence change within the region and a pattern that is consistent with a long-standing mixed hunter/gatherer/cultivator economy. Paleodemographic indicators provide no clear indication of a decline in health over time.

There is also little or conflicting evidence to suggest any temporal change in diet that would be expected to occur in populations undergoing agricultural intensification.

Diets are presumed to have changed over time as a result of human induced changes to the environment. Greater land clearance for more intensive cultivations of rice and increases in population settlement sizes are suggested to have introduced a certain amount of variability in dietary practices over time. In addition, while societies in the second millennium B.C. is considered relatively egalitarian, societies in the first millennium B.C. demonstrate an increase in prestige goods among certain individuals. This disparity among grave goods may also suggest inter-site variation in diet that may be associated with the sex of the individual, a topic that is addressed in this dissertation. In all, the skeletal samples should allow for greater clarity in understanding the lifeways of prehistoric inhabitants of northeast Thailand.

Table 3.1. Age and sex distribution of four skeletal series.

	Subadult[a]		Adults		Sex Distribution				
Skeletal Series	**n**	**%**	**N**	**%**	**M**	**F**	**?**	**Sex Ratio[b]**	**N[c]**
Ban Chiang	42	30.2	97	69.8	52	47	5	111	139
Early Group	27	19.4	63	70.0	37	27	3	137	90
Late Group	14	10.1	32	69.6	15	18	2	83	46
Ban Na Di	28	35.9	50	64.1	22	13	1	169	78
Ban Lum Khao	51	46.4	59	53.6	26	32	1	81	110
Noen U-Loke	53	44.2	67	55.8	27	21	19	129	120
Second Millennium B.C.[d]	78	86.7	63	70.0	37	27	3	137	90
First Millennium B.C.[e]	95	26.8	208	58.8	90	84	23	107	354
Sakon Nakhon Basin	70	56.5	82	66.1	37	31	3	119	124
Khorat Basin	104	45.2	126	54.8	53	53	20	100	230
Total	173	39.0	271	61.0	127	111	26	114	444

Note: Burials with ambiguous or unknown temporal assignments are excluded from this table.
Data: Ban Chiang (Pietrusewsky and Douglas 2002a); Ban Na Di (Domett 2001); Ban Lum Khao and Noen U-Loke (Domett and Tayles 2006).

[a] Subadults = individuals aged < 20 years not including fetal remains, Adults ≥ 20 years of age unless otherwise stated.

[b] M = Males; F= Females; Sex Ratio = proportion of (≥15 years) males to females (Males/Females x 100).

[c] N = total number of individuals used to construct life table (fetal remains omitted).

[d] Sites include Ban Chiang Early Group and Ban Lum Khao

[e] Sites include Ban Chiang Late Group, Ban Na Di, and Noen U-Loke

Table 3.2. Paleodemographic features of the four skeletal series.

Skeletal Series	*e°* at Birth[a]	*e°* at 15[a]	Mean Age at Death[b]	D20+ / D5+[c]	JA Ratio[d]	MCM[e]
Ban Chiang						
Early Group	30.1	24.1	39.1	0.851	0.111	0.097
Late Group	27.6	20.2	35.2	0.842	0.094	0.107
Combined	29.2	22.8	37.8	0.851	0.103	0.100
Ban Na Di	24.0	20.9	35.9	0.909	0.100	0.137
Ban Lum Khao	19.1	17.3	32.3	0.720	0.296	0.209
Noen U-Loke	19.3	17.9	32.9	0.856	0.102	0.190
Second Millennium B.C.	30.1	24.1	39.1	0.851	0.111	0.097
First Millennium B.C.	22.5	19.1	34.1	0.832	0.148	0.160
Sakon Nakhon Basin	25.8	20.5	35.5	0.875	0.097	0.122
Khorat Basin	19.2	17.6	32.6	0.788	0.199	0.199

Data: Ban Chiang (Pietrusewsky and Douglas 2002a); Ban Na Di (Domett 2001); Ban Lum Khao and Noen U-Loke (Domett and Tayles 2006).

[a] e° = life expectancy at birth and at 15 years of age (or nearest age to 15 in life table).

[b] Mean age-at-death in individuals age ≥ 15 years.

[c] D20+/D5+ = proportion of individuals who live beyond 20 years to those who survive 5 years of life.

[d] JA Ratio = Juvenile : Adult Ratio, the ratio of individuals aged from five to 14.9 years to those over 20 years of age.

[e] MCM = Mean Childhood Mortality : the average of childhood mortality rates (5q5 + 5q10 + 5q15 / 3).

Table 3.3. Abridged Life Table for the Ban Chiang Skeletons (BC and BCES).

x	n_x	D_x	d_x	l_x	q_x	L_x	m_x	T_x	e^o_{birth}
NB-0.9	1	9.00	6.48	100.00	0.0648	96.76	0.0670	2924.81	29.25
1.0-4.9	4	16.00	11.52	93.52	0.1232	351.02	0.0328	2828.05	30.24
5.0-9.9	5	8.00	5.76	81.99	0.0703	395.56	0.0146	2477.02	30.21
10.0-14.9	5	2.00	1.44	76.23	0.0189	377.56	0.0038	2081.46	27.30
15.0-19.9	5	7.00	5.04	74.79	0.0674	361.35	0.0140	1703.90	22.78
< 20 years		42							
20.0-29.9	10	20.78	14.97	69.75	0.2146	622.66	0.0240	1342.55	19.25
30.0-39.9	10	34.78	25.05	54.78	0.4573	422.57	0.0593	719.89	13.14
40.0-59.9+	20	41.28	29.73	29.73	1.0000	297.32	0.1000	297.32	10.00
> 20 years		97							
Total		139							

Note: Forty-one adults with non-specific ages are included in this life table: 16 adults distributed over three age intervals, seven young adults distributed over two intervals, and 18 middle-aged adults distributed over two intervals.

Data: Re-calculated from Pietrusewsky and Douglas (2002a).

Table 3.4. Abridged Life Table for Early Group (EP I-IV) Ban Chiang Skeletons.

x	n_x	D_x	d_x	l_x	q_x	L_x	m_x	T_x	e^o_{birth}
NB-0.9	1	6.00	6.67	100.00	0.0667	96.66	0.0690	3012.79	30.13
1.0-4.9	4	10.00	11.12	93.33	0.1192	351.06	0.0317	2916.13	31.25
5.0-9.9	5	5.00	5.56	82.20	0.0677	397.11	0.0140	2565.07	31.20
10.0-14.9	5	2.00	2.22	76.64	0.0290	377.64	0.0059	2167.96	28.29
15.0-19.9	5	4.00	4.45	74.42	0.0598	360.96	0.0123	1790.32	24.06
< 20 years		27							
20.0-29.9	10	12.80	14.24	69.97	0.2035	628.48	0.0227	1429.37	20.43
30.0-39.9	10	18.80	20.91	55.73	0.3752	452.73	0.0462	800.89	14.37
40.0-59.9+	20	31.30	34.82	34.82	1.0000	348.16	0.1000	348.16	10.00
> 20 years		63							
Total		90							

Note: Twenty-one adults with non-specific ages are included in this life table: 10 adults distributed over three age intervals, one young adult distributed over two intervals, and 10 middle-aged adults distributed over two intervals.

Data: Re-calculated from Pietrusewsky and Douglas (2002a).

Table 3.5. Abridged Life Table for Late Group (MP VI-LP X) Ban Chiang Skeletons.

x	n_x	D_x	d_x	l_x	q_x	L_x	m_x	T_x	e^o_{birth}
NB-0.9	1	3.00	6.53	100.00	0.0653	96.73	0.0675	2762.95	27.63
1.0-4.9	4	5.00	10.88	93.47	0.1164	352.11	0.0309	2666.22	28.52
5.0-9.9	5	3.00	6.53	82.59	0.0791	396.60	0.0165	2314.11	28.02
10.0-14.9	5	0.00	0.00	76.06	0.0000	380.28	0.0000	1917.50	25.21
15.0-19.9	5	3.00	6.53	76.06	0.0859	363.95	0.0179	1537.22	20.21
< 20 years		14							
20.0-29.9	10	7.48	16.28	69.53	0.2342	613.84	0.0265	1173.27	16.88
30.0-39.9	10	15.48	33.70	53.24	0.6329	363.95	0.0926	559.43	10.51
40.0-59.9+	20	8.98	19.55	19.55	1.0000	195.47	0.1000	195.47	10.00
> 20 years		32							
Total		46							

Note: Nineteen adults with non-specific ages are included in this life table: six adults distributed over three age intervals, five young adults distributed over two intervals, and eight middle-aged adults distributed over two intervals.

Data: Re-calculated from Pietrusewsky and Douglas (2002a).

Table 3.6. Abridged Life Table for the Ban Na Di Skeletons.

x	n_x	D_x	d_x	l_x	q_x	L_x	m_x	T_x	e^o_{birth}
0-0.9	1	15.00	19.27	100.00	0.1927	90.37	0.2132	2404.57	24.05
1.0-4.9	4	8.00	10.27	80.73	0.1273	302.39	0.0340	2314.20	28.66
5.0-9.9	5	2.00	2.57	70.46	0.0365	345.88	0.0074	2011.82	28.55
10.0-14.9	5	3.00	3.85	67.89	0.0568	329.82	0.0117	1665.94	24.54
15.0-19.9	5	0.00	0.00	64.04	0.0000	320.19	0.0000	1336.12	20.86
< 20 years		28							
20.0-29.9	10	17.62	22.63	64.04	0.3534	527.23	0.0429	1015.93	15.86
30.0-39.9	10	17.62	22.63	41.41	0.5465	300.92	0.0752	488.70	11.80
40.0-59.9+	20	14.62	18.78	18.78	1.0000	187.77	0.1000	187.77	10.00
> 20 years		50							
Total		78							

Note: Fourteen adults with non-specific ages are included in this life table and distributed over three age intervals.

Data: Calculated from Domett (2001).

Table 3.7. Abridged Life Table for the Ban Lum Khao Skeletons.

x	n_x	D_x	d_x	l_x	q_x	L_x	m_x	T_x	e^o_{birth}
0-0.9	1	21.00	19.10	100.00	0.1910	90.45	0.2111	1913.16	19.13
1.0-4.9	4	14.00	12.73	80.90	0.1574	298.15	0.0427	1822.71	22.53
5.0-9.9	5	11.00	10.00	68.17	0.1467	315.86	0.0317	1524.55	22.36
10.0-14.9	5	5.00	4.55	58.17	0.0782	279.49	0.0163	1208.69	20.78
15.0-19.9	5	5.00	4.55	53.62	0.0848	256.75	0.0177	929.21	17.33
< 20 years		56							
20.0-29.9	10	24.99	22.72	49.08	0.4630	377.15	0.0603	672.46	13.70
30.0-39.9	10	16.99	15.45	26.35	0.5863	186.28	0.0829	295.31	11.21
40.0-59.9+	20	11.99	10.90	10.90	1.0000	109.03	0.1000	109.03	10.00
> 20 years		54							
Total		110							

Note: Three adults with non-specific ages are included in this life table and distributed over three age intervals.

Data: Calculated from Domett and Tayles (2006).

Table 3.8. Abridged Life Table for the Noen U-Loke Skeletons.

x	n_x	D_x	d_x	l_x	q_x	L_x	m_x	T_x	e^o_{birth}
0-0.9	1	37.20	31.03	100.00	0.3103	84.48	0.3673	1934.68	19.35
1.0-4.9	4	9.20	7.67	68.97	0.1113	260.53	0.0295	1850.20	26.83
5.0-9.9	5	3.20	2.67	61.29	0.0435	299.80	0.0089	1589.67	25.93
10.0-14.9	5	3.20	2.67	58.63	0.0455	286.45	0.0093	1289.87	22.00
15.0-19.9	5	4.20	3.50	55.96	0.0626	271.02	0.0129	1003.42	17.93
< 20 years		57							
20.0-29.9	10	28.96	24.16	52.45	0.4606	403.74	0.0598	732.40	13.96
30.0-39.9	10	18.96	15.82	28.29	0.5590	203.87	0.0776	328.66	11.62
40.0-59.9+	20	14.96	12.48	12.48	1.0000	124.79	0.1000	124.79	10.00
> 20 years		63							
Total		120							

Note: One subadult with a non-specific age is included in this life table and distributed over five age intervals. Twelve adults distributed over three age intervals.

Data: Calculated from Domett and Tayles (2006).

Table 3.9. Dental pathological conditions from Ban Chiang, Ban Lum Khao, Ban Na Di, and Noen U-Loke permanent teeth.

Skeletal Series[a]	Caries[d]		Advanced Attrition[b]		Antemortem Loss	
	A/O[c]	%	A/O	%	A/O	%
Ban Chiang	74/1016	7.3	169/1015	16.7	87/1279	6.8
Early Group	65/857	7.6	73/502	14.5	44/667	6.6
Late Group	12/232	5.2	96/568	16.9	48/698	6.9
Ban Na Di	24/515	4.7	61/510	12.0	38/707	5.4
Ban Lum Khao	39/874	4.5	104/861	12.1	59/1154	5.1
Noen U-Loke	46/956	4.8	152/977	15.6	69/1334	5.2
Northeast Thailand	183/3361	5.4	486/3363	14.5	253/4474	5.7
2nd Millennium B.C.	**65/857**	**7.6**	73/502	14.5	44/667	6.6
1st Millennium B.C.	**121/2577**	**4.7**	413/2916	14.2	214/3893	5.5
Sakon Nakhon Basin	**98/1531**	**6.4**	230/1525	15.1	125/1986	6.3
Khorat Basin	**85/1830**	**4.6**	256/1838	13.9	128/2488	5.1

[a] Data: Ban Chiang (Pietrusewsky and Douglas 2002a); Ban Na Di (Domett 2001); Ban Lum Khao and Noen U-Loke (Domett and Tayles 2006). Includes all adult females, males, and individuals of indeterminate sex.

[b] Advanced attrition is defined as where the enamel has been completely abraded from the occlusal surface.

[c] Affected/Observed

[d] Caries bold face = statistical significance; second vs. first millennium B.C. ($\chi^2 = 10.48$, $p \leq 0.001$); Sakon Nakhon vs. Khorat Basin ($\chi^2 = 4.99$, $p \leq 0.025$)

Table 3.10. Dental pathological conditions from Ban Chiang, Ban Na Di, Ban Lum Khao, and Noen U-Loke by sex for adult permanent teeth by sex.

Skeletal Series[a]	Caries[d]				Advanced Attrition[b, e]				Antemortem Loss[f]			
	Female		Male		Female		Male		Female		Male	
	A/O[c]	%	A/O	%	A/O	%	A/O	%	A/O	%	A/O	%
Ban Chiang	30/513	5.8	40/548	7.3	60/469	12.8	109/592	18.4	36/611	5.9	53/713	7.4
Early Group	25/410	6.1	35/416	8.4	54/332	16.3	70/422	16.6	30/483	6.2	34/529	6.4
Late Group	5/103	4.9	5/132	3.8	6/137	4.4	39/170	22.9	6/128	4.7	19/184	10.3
Ban Na Di	12/147	8.2	12/368	3.3	25/140	17.9	36/370	9.7	31/241	12.9	7/466	1.5
Ban Lum Khao	32/477	6.7	7/397	1.8	29/463	6.3	84/409	20.5	31/607	5.1	28/547	5.1
Noen U-Loke	19/422	4.5	22/382	5.8	92/392	23.5	53/432	12.3	46/557	8.3	16/569	2.8
Northeast Thailand	73/1559	4.7	81/1695	4.8	206/1464	14.1	282/1803	15.6	**144/2016**	**7.1**	**104/2295**	**4.5**
Second Millennium B.C.	57/887	6.4	**42/813**	**5.2**	**83/795**	**10.4**	**154/831**	**18.5**	**61/1090**	**5.6**	**62/1076**	**5.8**
First Millennium B.C.	**36/672**	**5.4**	**27/882**	**3.1**	**123/669**	**18.4**	**128/972**	**13.2**	**83/926**	**9.0**	**42/1219**	**3.4**
Sakon Nakhon Basin	42/660	6.4	52/916	5.7	85/609	14.0	145/962	15.1	**67/852**	**7.9**	**60/1179**	**5.1**
Khorat Basin	51/899	5.7	29/779	3.7	121/855	14.2	137/841	16.3	**77/1164**	**6.6**	**44/1116**	**3.9**

[a] Data: Ban Chiang (Pietrusewsky and Douglas 2002a); Ban Na Di (Domett 2001); Ban Lum Khao and Noen U-Loke (Domett and Tayles 2006).

[b] Advanced attrition is defined as where the enamel has been completely abraded from the occlusal surface.

[c] Affected/Observed

[d] Caries bold face = statistical significance. First millennium Females vs. Males ($\chi^2 = 5.17$, $p \leq 0.025$); Males over time ($\chi^2 = 4.80$, $p \leq 0.05$)

[e] Advanced attrition bold face = statistical significance. Second millennium Females vs. Males ($\chi^2 = 21.37$, $p \leq 0.001$); First millennium Females vs. Males ($\chi^2 = 8.32$, $p \leq 0.01$); Females over time ($\chi^2 = 18.97$, $p \leq 0.001$); Males over time ($\chi^2 = 9.77$, $p \leq 0.01$)

[f] Antemortem loss bold face = statistical significance. Females vs. Males in northeast Thailand ($\chi^2 = 13.50$, $p \leq 0.001$); First millennium Females vs. Males ($\chi^2 = 29.20$, $p \leq 0.001$); Females vs. Males in Sakon Nakhon Basin ($\chi^2 = 6.50$, $p \leq 0.025$); Females vs. Males in Khorat Basin ($\chi^2 = 7.56$, $p \leq 0.01$); Females over time ($\chi^2 = 8.56$, $p \leq 0.01$); Males over time ($\chi^2 = 7.10$, $p \leq 0.01$)

Chapter IV. Stable Isotope Geochemistry and Paleodietary Reconstruction

Paleodietary Reconstruction

Previous research on subsistence in mainland Southeast Asia has focused on faunal remains (e.g., Higham 1975b; Higham and Kijngam 1979), human dental remains (e.g., Domett 2001; Pietrusewsky and Douglas 2002a,b; Tayles 1992; Tayles et al. 2000) and ethnographic analogy (e.g., White 1984, 1989, 1995). These data provide a measure of the subsistence economy but issues of differential preservation and methods of archaeological excavation inhibit the determination of the importance of various food categories (Dufour et al. 1999). Some record of dietary habits is available using ethnographic analogy (White 1984, 1989), but food procurement practices are not necessarily the same today as in the past. This dissertation utilizes two elements commonly analyzed in paleodietary research - carbon and nitrogen. Stable carbon and nitrogen isotope analyses are well established in archaeological applications (for reviews see Jim et al. 2004; Katzenberg 2000; Katzenberg and Harrison 1997; Philips and Koch 2002).

Stable isotope ratios of carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$) have been used in determining dietary changes from the body tissues of living and archaeological animal and human skeletal remains since the late 1970's (DeNiro and Epstein 1978a,b, 1981; Vogel and van der Merwe 1977; van der Merwe and Vogel 1978). From these early experiments, stable carbon and nitrogen isotope research has been applied to various groups of the world to help trace temporal patterns in diet, most recently in both island

(Krigbaum 2003) and mainland (Bentley et al. 2005; King and Norr 2006) Southeast Asia.

Examples of topical areas of research include the introduction of new foodstuffs such as maize into northeastern America (e.g. Katzenberg et al. 1995; van der Merwe and Vogel 1978) or millet into northern China (Pechenkina et al. 2002, 2005), estimating reliance on marine versus terrestrial resources (Keegan and DeNiro 1988; Walker and DeNiro 1986), tracing patterns of human migration (Bentley et al. 2002, 2004, 2005), and examining patterns of behavior and health related to infant weaning (Dupras et al. 2001; Fuller et al. 2006; Katzenberg and Pfeiffer 1995; Schurr and Powell 2005; Wright and Schwarcz 1998). Other applications include food web ecology and climatic conditions (Anson 1997; Katzenberg 2000; Katzenberg and Weber 1999; Loader and Hemming 2004; Rubenstein and Hobson 2004).

With the notable exception of maize, stable isotope ratios rarely provide information on specific food items, providing instead information on general food groups. From the faunal, botanical, and ethnographic information about a particular location or region, a "menu" is established that provides a list of possible food items available for consumption and aids in the interpretation of human stable isotope ratios (Ambrose 1993; Bumstead 1985). An example of isotopic composition of food resources is illustrated in Figure 4.1. Through the use of stable isotope analysis, questions can then be asked whether the diet of some individuals changed (e.g., as a consequence of social differences), or whether these changes characterized the entire population.

Tissues used for Stable Isotope Analysis

All tissues in the body reflect the diet and the stable isotopic values within the same sample from various tissues differ (DeNiro and Epstein 1978a,b; Lyon and Baxter 1978; Tieszen et al. 1983; Vogel 1978). However, soft tissue rarely survives in the archaeological record due to decomposition and diagenesis.

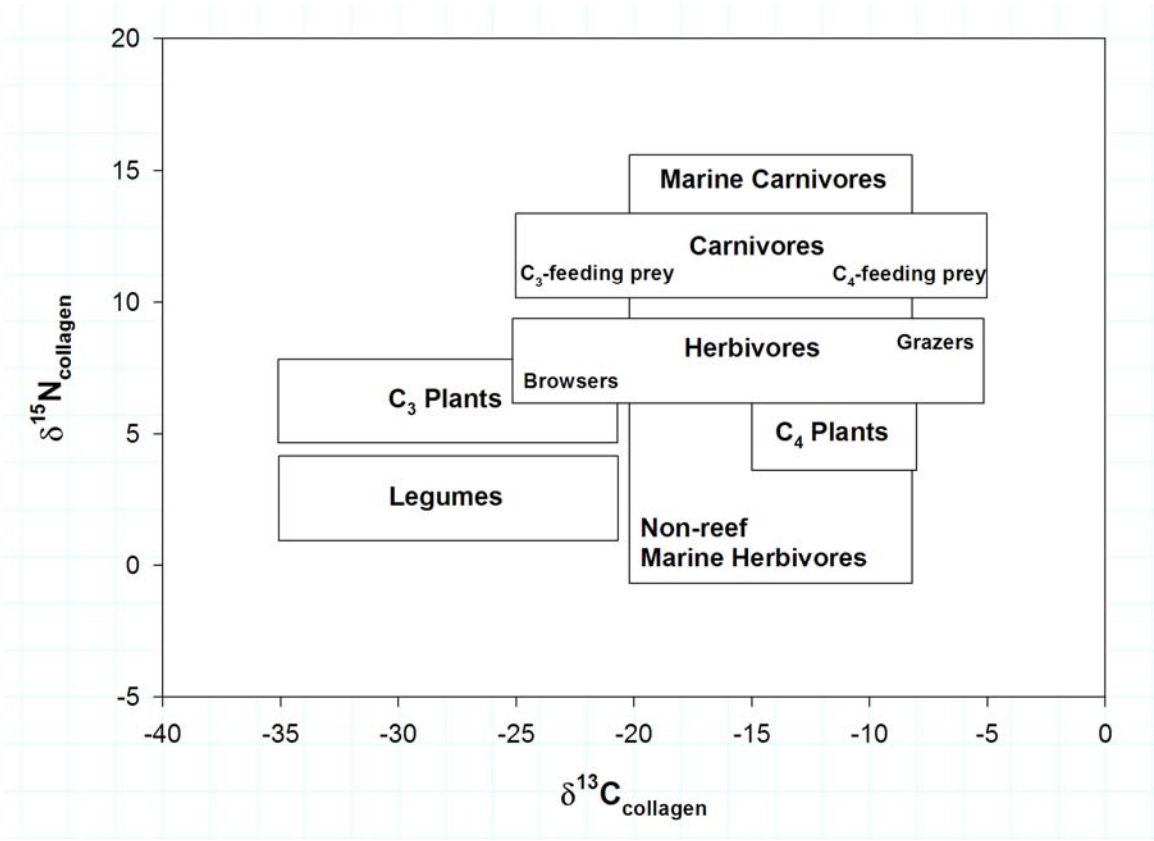

Figure 4.1. Stable isotopic composition of food resources (adapted from Ambrose 1993:87).

Calcified tissues (bone and teeth), however, do tend to survive and thus provide the only means available for direct paleodietary studies of an individual (Lee-Thorp 1989). While isotope values vary between tissues of different composition, due to varying formation and turnover rates (DeNiro and Epstein 1978a; Lee-Thorp 1989) the variation

among specimens of the same tissue (e.g. bone sections from a femur and rib) are not significant (Chisholm 1989). Both the organic (collagen) and inorganic (hydroxyapatite) bone portions can be used singularly and in combination to reconstruct diet through isotopic analysis on the premise that the chemistry of our bodies reflects the chemistry of the food we eat (Ambrose 1993; Schoeninger and Moore 1992:252).

Bone Composition

Bone can be classified as either compact (cortical) or spongy (trabecular). These two types of bones do not differ in composition but rather in organization and are associated with different kinds of marrow which serve different metabolic functions; fatty marrow is associated with compact bone and red marrow is associated with spongy bone.

The composition of bone can further be divided into its organic (25% bone weight) and inorganic (75% of bone weight) constituents. Bone collagen makes up almost 90% of the organic component of bone and contains both carbon and nitrogen. Collagen provides mechanical strength to bone, tendon and cartilage.

Organic bone collagen is made up of a supportive matrix protein called Type I collagen. Type I collagen is a three-chain polypeptide that is coiled to form a molecule of collagen. These molecules aggregate to form a framework of fibers which, along with inorganic mineral crystals, provide mechanical strength to the bone, tendon and cartilage.

If the conditions for preservation are good, collagen can survive for thousands of years, and if the conditions are excellent collagen may survive for more than 10,000 years in bone tissue, although alteration to the chemical characteristics of collagen is typical (Tuross 2002). Since collagen does degrade over time, the level of degradation can lead to loss of isotopic signals. The rate of postmortem degradation varies depending upon

the condition of the burial environment, so relatively young remains may not retain collagen that is preserved well enough to be used for paleodietary reconstruction (Tuross et al. 1988). This study uses three standard methods to assess collagen sample quality: collagen yield by weight, atomic C/N ratio, %C and %N (Ambrose 1990, 1993), discussed in further detail later in this chapter.

The inorganic or carbonate (mineral) portion of bone is predominately calcium and phosphate in the form of hydroxyapatite, usually referred to simply as apatite. This inorganic portion surrounds the collagen portions of bone, providing needed structural support. These carbonate ions are the main substituted group in bone apatite, and may substitute for either the OH^- or the PO_4^- ions. Bicarbonate found in the blood is the source of the carbonate, which is introduced into bone mineral through blood-bone exchange via the Haversian system.

There are two types of bone mineral, Type A and Type B with the latter being predominant in all mammalian bone. These two types are collectively referred to as structural carbonate as they are located primarily within the apatite crystal lattice but also on the surface of apatite crystal in areas of poorly organized mineral (Rey et al. 1989). The bone mineral located on the surface is referred to as labile carbonate and helps to provide flexibility to the bone structure. Labile carbonate is most abundant in children and gradually decreases over time as bone ages and matures (Rey et al. 1991a,b). Bone carbonate has been used singularly when collagen preservation was poor and as a means to supplement collagen isotopes in paleodietary interpretations (Katzenberg 2000; Norr 1995). The use of bone apatite as a medium for interpreting prehistoric human diet was first proposed by Sullivan and Krueger (1981, 1983, 1984), amid much debate about the

validity of the stable isotope data due to concerns of diagenic susceptibility. Most pretreatment methods for carbonate preparation involve the dissolution of collagen with bleach and treatment of the remaining inorganic material with acetic acid to remove secondary carbonate minerals (Koch et al. 1997). Recently, more sophisticated methods for investigating diagenic concerns for carbonates such as the crystallinity index or X-ray diffraction have been introduced (Lee-Thorp and Sponheimer 2003; Lee-Thorp and van der Merwe 1991). When carbon isotope data from a single individual from both bone collagen and bone apatite are used a more comprehensive reconstruction of diet can be achieved. The isotopic compositions of the two components reflect primarily the protein component (collagen) and the whole diet (apatite) (Ambrose and Norr 1993; Krueger and Sullivan 1984).

Dental Tissue

There are three main types of tissue in teeth: enamel, dentine, and cement, all of which have organic and inorganic components, but differ in proportion between organic and inorganic. Enamel has very little organic material, usually about 0.4%, and the organic material is mainly (90%) protein amelogenin rather than collagen (Hillson 1996). Dentine consists of 20% organic material, of which about 18% is collagen (Hillson 1996). Cement has an organic content similar to bone.

It is the inorganic portion of dental tissue that is most important for paleodietary reconstruction. The inorganic component is very similar to bone apatite in composition; however, the apatite of enamel is more crystalline, larger, and structurally more organized. As a result, apatite from dental enamel tissue is less susceptible to diagenic alterations than bone apatite, making it much more suitable for stable isotope studies,

particularly of fossil material (Lee-Thorp and van der Merwe 1991; Sponheimer and Lee-Thorp 1999). In dentine, the collagen and apatite components are also less susceptible to diagenic alteration (Koch et al. 1997).

Stable Isotope Terminology

Elements with the same number of protons, but different numbers of neutrons, are called isotopes. Isotopes are variations of the same element but with differing atomic weights. As such, isotopes of a given element have the same chemical properties but the speed at which they react is different. Lighter isotopes react at faster rates than heavier isotopes, leading to discrimination against the latter in chemical reactions (Hoefs 1987).

Isotopes are either radioactive or stable. Radioactive isotopes (e.g., ^{14}C) decay into other elements at a constant rate through loss of protons and/or other subatomic particles. Stable isotopes however, retain their original atomic structure through time and occur in the same relative abundance in certain systems worldwide (e.g., ^{12}C & ^{13}C). The lighter stable isotopes exist at a much higher abundance than the heavier isotopes.

The process by which different isotopes are partitioned between beginning and end products of a chemical reaction is called fractionation. For example, isotopic fractionation occurs because heavier isotopes (^{13}C) enter into chemical reactions at a slower rate than lighter isotopes (^{12}C). The resulting outcome of these different reaction rates results in differences in melting, freezing, crystallization, condensation, evaporation rates and temperatures. Equilibrium and kinetic fractionation are the two processes by which heavy and light isotopes partition differently.

Equilibrium fractionation describes isotopic exchange reactions that occur between two different phases of a compound at a rate that maintains equilibrium, as with the

transformation of water vapor to liquid precipitation (Criss 1999). Although the process is in equilibrium, the rate of these exchanges is different so that the result is an enrichment of one of the isotopes. The surrounding temperature plays a large role in equilibrium fractionation since the vibrational energy cause by the raise or fall in temperature will affect the rate of the exchange reaction.

Kinetic fractionation is fractionation that is unidirectional, where equilibrium is not attained. This type of fractionation applies to evaporation of surface waters and to most biogeochemical reactions, where the lighter isotope is faster reacting and becomes concentrated in the products (Criss 1999). Biological processes such as photosynthesis, respiration, and evaporation are generally unidirectional and are examples of kinetic fractionation. Organisms preferentially use the lighter isotopic species because of the lower energy "costs", resulting in significant fractionations between the substrate (heavier) and the biologically mediated product (lighter). The magnitude of the fractionation depends on the reaction pathway utilized and the relative energies of the bonds being severed and formed by the reaction. In general, slower reaction steps show greater isotopic fractionation than faster steps because the organism has time to be more selective. Kinetic reactions can result in fractionations very different from, and typically larger than, the equivalent equilibrium reaction.

Measuring Stable Isotopes

By comparing the differential fractionation of stable isotopes in plants, animals that consume plants, and animals that consume other animals, these trophic levels (steps in the food chain) form the basis from which inferences are made about human dietary change in prehistory. Typically, the raw isotopic value *R* is not reported because the

natural abundance of stable isotopes for an element is numerically quite small. Instead the unknown sample is compared to a known standard thus providing a precise measurement of the difference in the isotopic ratios between the sample and a specified standard (Criss 1999:35). This difference, or delta (δ) value, reported in parts per thousand or per mille (‰), is used for easier reporting and comparison. A negative value indicates that the sample is depleted in the heavier isotope relative to the standard, while a positive value indicates that the sample is enriched in the heavier isotope relative to the standard.

As mentioned above, the unknown sample is compared to a standard. A standard is a sample of known isotopic value from which all samples of unknown isotopic values are based. The original standard used for carbon is a marine carbonate fossil, *Belemnitella americana* from the Peedee formation in South Carolina and is referred to as PDB (Peedee Belemnite) (Craig 1957). Although this standard has been exhausted and several others are now in use, the international standard $\delta^{13}C$ values are calibrated using V-PDB which is based upon calibration of a working gas using NBS 19. The carbon standard contains more ^{13}C than all human dietary resources and human tissues, therefore $\delta^{13}C$ values are negative (Ambrose 1993; DeNiro and Epstein 1978b). The standard for nitrogen is atmospheric di-nitrogen gas, AIR (Criss 1999). Nitrogen isotopic values in plants and animals are usually positive in relation to atmospheric nitrogen (Ambrose 1993; DeNiro and Epstein 1981). Using carbon as an example, the following equation illustrates the calculation of stable isotopic ratios (McKinney et al. 1950):

$$\delta^{13}C\ (‰) = [\ (^{13}C/^{12}C_{sample}\ /\ ^{13}C/^{12}C_{standard}) - 1\ ] \times 1000$$

Carbon Isotopes

Carbon has two stable isotopes, ^{12}C and ^{13}C, that are approximately 98.99% and 1.11% abundant in nature (Criss 1999). Plants are the most basic food source used for carbon-based paleodietary research. Carbon is introduced into the food chain from atmospheric carbon dioxide (CO_2) and is metabolized during photosynthesis by terrestrial plants. Photosynthesis is the respiratory process of plants. Plants "inhale" or absorb CO_2 from the air and "exhale" oxygen and water vapor. The process by which plants perform this action is dependent on leaf structure, light intensity, temperature, and availability of water and CO_2 concentration (Ehleringer and Rundel 1989; Tieszen 1991).

It was originally understood that all plants conducted photosynthesis the same way. During the late 1960's however ^{14}C dating of corn cobs produced younger dates than wood of the same age by several 100's of years. Hall (1967) discussed this problem and Bender (1968) explained that the corn plant was more enriched in ^{13}C (more positive in $\delta^{13}C$) than woody plants. From this research scientists began to become aware of the differential photosynthetic pathways among plants.

Plant types can be determined based on the photosynthetic pathway they utilize. As mentioned above there are a number of factors that affect the photosynthetic process in plants. These factors affect the way in which a plant converts CO_2 into food making a distinction between the numbers of carbon atoms in a molecule formed during the first stage of photosynthesis. During this first stage, plants either produce a three- or four-carbon compound, $C_3H_6O_3$ or $C_4H_8O_4$ respectively. Plants that synthesize the three carbon compound only utilize the Calvin-Benson photosynthetic pathway (Calvin and Benson 1948) and are referred to as C_3 plants. The Hatch-Slack pathway is the process

that makes use of the four carbon compound during photosynthesis (Hatch and Slack 1966; Hatch et al. 1967). Plants that follow this cycle are referred to as C_4 plants. Why certain plants favor the Calvin-Benson pathway or the Hatch-Slack pathway is based on how well a particular plant "inhales" CO_2. C_3 plants must keep stomata in their leaves open in order to take up CO_2 during photosynthesis, which means that they can lose water through these openings.

Photosynthesis in C_3 plants is catalyzed by Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase [RuBP]); CO_2 and RuBP produce 2 three-carbon (hence C_3) phosphoglycerate (PGA) molecules. PGA is reduced to sugar by ATP and NADPH. The sugar is then converted to starch and regenerates RUBISCO and O_2 is released to atmosphere. Rubisco can also catalyze the oxidation of RuBP, the net reaction consuming O_2. Decreasing CO_2 levels in the atmosphere (especially at high temperatures) reduces photosynthetic potential of C_3 plants. C_3 plants occur in conditions in which fresh water vapor is more abundant. Nutritionally important C_3 plants to humans include all root crops, legumes, vegetables, nuts, wheat, barley, rice, woody plants, most broadleaf plants, montane and wetland grasses, and fruits. As stated above, C_3 plants have more negative isotopic values. The $\delta^{13}C$ values of these plants range between -22 and -36‰, with an average of about -26‰ (Bender 1971; O'Leary 1988; Smith and Epstein 1971). C_3 plants utilize a photosynthetic process which favors the lighter ^{12}C during photosynthetic CO_2-fixation. This is important from a dietary research perspective since C_3 plants have lighter, or more negative, $\delta^{13}C$ values than C_4 plants (Katzenberg 1992:106).

The C_4 plants, which first fix inorganic carbon as bicarbonate using the Hatch-Slack pathway, prefer dry climates (for which water loss is a problem) or salt water regions (where loss of fresh water is a problem). To compensate for these harsher conditions C_4 plants open their stomata sparingly and create a four carbon compound, oxaloacetic acid, which then binds to RuBP, before entering the Calvin cycle.

The anatomy of C_4 plants differs from that of their C_3 counterparts in that a mesophyll cell comes in contact with a bundle sheath cell. Photosynthesis involves initial CO_2 fixation in the mesophyll cell using phosphenol pyruvate carboxylate (PEP) to fix the carbon as bicarbonate initially and for oxaloacetate, a 4-carbon acid (hence C_4) which is then transported to the bundle sheath. CO_2 is released and then fixed by RUBISCO as for the C_3 pathway. Concentrations of CO_2 in the bundle sheath are much higher than in the atmosphere; spatial separation of CO_2 uptake and reduction, internal CO_2 concentrations can be optimized before exposure to RUBISCO. The adaptive advantage of this compartmentalization of processes in C_4 plant photosynthesis is that the CO_2 is temporarily cut off by the closing of the leaf pores. The closing of the leaf pores allows for less moisture loss which is very important in hot dry climates.

C_4 plants also do better at higher temperatures than C_3 plants. Plants using the C_4 reaction pathway include most tropical grasses and salt marsh grasses. C_4 plants show less isotopic fractionation of carbon than C_3 plants because the process of CO_2 fixation by phosphoenolpruvate discriminates against ^{13}C far less than the ribulose biphosphate reaction (Whelan et al. 1973). The $\delta^{13}C$ average for C_4 plants is about -13‰, ranging from -6 to -19‰ (Smith and Epstein 1971). Corn, sorghum, millet, and some chenopods and amaranth, and tropical pasture grasses make up the nutritionally important C_4 plants.

A third type of plant group, CAM (Crassulacean Acid Metabolism), is distinctive because these plants can utilize either the C_3 or C_4 photosynthetic pathways depending on the plant's current environment. By modifying the rate at which the plant opens or closes its stomata for photosynthesis, photosynthesis concentrates CO_2 by employing a temporal rather than structural separation of fixation and synthesis. This means that CO_2 can be fixed either day or night by either C_3 or C_4 photosynthetic cycles depending on the environment. If days are hot and short and/or dry these plants utilize the C_4 cycle and if days are cool, long and/or moist they utilize the C_3 process. CAM is found in many plants such as succulents, cacti, pineapple, bromeliads, and vanilla. According to Troughton and colleagues (1974), prickly pear cacti can have a carbon isotopic range between 13.9‰ during dry conditions and -21.9‰ during relatively temperate periods. Most CAM plants however are relatively minor elements in their respective communities, which include semi-deserts, deserts and savannas thus not relevant to a discussion of prehistoric diets of northeast Thailand.

Temporal changes in $\delta^{13}C$ values have also been documented as a result of the industrial revolution and the burning of fossil fuels. The extra amount of carbon released into the atmosphere has contributed $\delta^{12}C$ to the atmospheric CO_2, causing a relative decrease in its $\delta^{13}C$ value. As result, modern plants typically have $\delta^{13}C$ values of -30‰ to -25‰. Carbon fixed by plant tissues prior to about A.D. 1500 has $\delta^{13}C$ values that are approximately 1.5‰ heavier in $\delta^{13}C$ than that of their modern counterparts and probably ranged from -25.5‰-11.5‰ (DeNiro 1987:183; Smith and Epstein 1971:380; van der Merwe 1989). This is an important consideration to archaeological studies in which modern samples are often used to create a baseline for comparison. Modern samples

(post A.D. 1500) must be adjusted accordingly before comparisons can be made with older samples (Tieszen 1994).

The $\delta^{13}C$ values from plants are also influenced by other environmental factors such as micro-habitat variation in atmospheric CO_2, aridity, temperature, altitude, and salinity (Heaton 1999; Koch et al. 1994; Körner and Diemer 1987; Tieszen 1991:228-234). In the absence of C_4 plants, these secondary factors could explain most of the observed differences; especially given the remarkably small range over the two millennia period of study (cf. Figure 8.6, page 240).

In canopied forests, there is a thick cover of top vegetation that restricts the amount of 'open air' between the lower plants and the atmosphere. Plants which are nearer to the ground become more depleted of ^{13}C resulting in more negative carbon isotope ratios for both C_3 and C_4 plants (Tieszen 1991). As light intensity decreases, such as in dense forests, the carbon isotope composition of plants similarly becomes more negative (Ehleringer and Cerling 2001; Ehleringer and Rundel 1989).

Plants in drier or saline soils tend to have more positive values than the same plants that are grown in wetter or non-saline soils (Tieszen 1991). Altitude increases the partial pressure of CO_2 which increases the efficiency of plant uptake of CO_2. This in turn decreases discrimination against ^{13}C, thus producing more positive $\delta^{13}C$ values in plants at high altitude (Körner and Diemer 1987).

Furthermore, changes in $\delta^{13}C$ values are generally twice as great in C_3 plants as in C_4 plants (Tieszen 1991). Plants grown in regions that are either very arid or contain saline soils have more positive $\delta^{13}C$ values than those plants grown in regions with wetter or non-saline soils. According to Tieszen (1991) C_3 plants can vary by up to 4‰ in water

stressed, arid environments. This distortion can be even greater (+3.4‰ to 10.8‰) with plants in saline soils (Guy et al. 1980).

Food webs depicted in carbon isotopes

Isotopic values among living organisms vary according to how they obtain food. One way to establish the relationships between plants and animals (heterotrophs) is by understanding the local food web. The terms "food chain" and "food web" are often easily confused. Although both are grounded on a similar idea, a food chain is very different from a food web. A food chain is a simplified illustration of the predator-prey relationships between a few organisms within an environment. A food chain depicts the transfer of energy from the sun to plants to a plant-eating animal and then to animal-eating animals. A food web, on the other hand, shows the predator/prey relationships of many organisms in an environment and may have many different food chains embedded in it. A food web is the elaborate, interconnected feeding relationships of who eats whom in an ecosystem (Wada et al. 1991).

The trophic level is the position that an organism occupies in a food chain - what it eats, and what eats it. Between trophic levels there is a fractionation effect in which there is enrichment in ^{13}C for each level (DeNiro and Epstein 1978b; Tieszen et al. 1983). This in turn produces more positive stable isotope values for each step upward through the food continuum, regardless of which plant type was originally consumed. These enrichment factors occur between producers (autotrophs), and primary and secondary consumers (heterotrophs) in the food chain.

For carbon isotopes the trophic level effect is generally small though broad ranges have been reported from laboratory experiments (Ambrose 1993). Laboratory studies of

small mammals have found a shift of about 3‰ in $\delta^{13}C_{collagen}$ from diet (DeNiro and Epstein 1978b; Tieszen and Boutton 1989). Values of up to 6‰ have been suggested, though a fractionation of 3-5‰ is most often cited (DeNiro 1987; Kruger and Sullivan 1984; Schwarcz et al. 1985; van der Merwe and Vogel 1978; Vogel and van der Merwe 1977). Collagen enrichments of 4.5 to 5.0‰ from herbivore to carnivore have also been observed (Lee-Thorp et al 1989). These differences may reflect metabolic differences between animals of small and large body size (Ambrose 1993), or alternatively, in the biochemical composition of different foods (Tieszen 1991).

Environmental factors affecting plant $\delta^{13}C$ values

Plants are autotrophs meaning they are able to make their own food using carbon dioxide, principally through photosynthesis. As stated above there are two types of photosynthetic pathways that plants use to obtain energy. While this is the case, there are also many ways the environment can affect the overall $\delta^{13}C$ value of a plant. Atmospheric CO_2 is the main source of carbon for terrestrial plants with the average present-day $\delta^{13}C$ value are approximately -7‰ but variable depending on the local environment (van der Merwe 1989). This is particularly apparent in dense forest environments which have a closed canopy, such as in parts of island Southeast Asia, as there is restricted mixing of air between the open atmosphere and the ground (Krigbaum 2003). As a result, CO_2 is recycled, thus depleting the local environment of ^{13}C by up to 14‰ on or near the forest floor (van der Merwe and Medina 1989).

Water retention and loss are the primary sources of stress for a plant. Mechanisms which cause this include cold night temperatures, high salinity, and long day length. The $\delta^{13}C$ ratios of C_3 and CAM plants are more sensitive to environmental variations than C_4

plants. C_4 plants are associated with regions with higher temperatures, low humidity, high salinity, and aridity. Arid environments can cause water stress in C_3 and CAM plants which can vary the $\delta^{13}C$ values by up to 4‰ (Tieszen 1991). Research on the effects of soil salinity has been found to produce even greater variation. Plants in drier or saline soils have more positive values than wetter or non-saline soils (Tieszen 1991).

C_3 versus C_4 plant consumption

A consequence of heavier isotopes being discriminated against more in the C_3 pathway than in C_4 photosynthesis is non-overlapping $\delta^{13}C$ values. As a result, these two types of plant groups can be discriminated (Ambrose 1993). The $\delta^{13}C$ values of plants are passed up the food web such that the $\delta^{13}C$ value of an animal's tissues reflects its diet (DeNiro and Epstein 1978b). This information is then applied to the reconstruction of past human diet.

The use of stable isotopes for reconstructing human diet resulted from an accumulation of research from various fields including botany, biochemistry, geochemistry, marine biology and archaeology beginning in the late 1960's. The idea that stable isotopes could be used to reconstruct paleodiet came from P. L. Parker, who suggested that carbon isotopes from marine animals could reflect the types of foods they eat, and that this might be applicable to reconstructions of human diet (Parker 1964). Up to this time it was thought that all plants utilized the Calvin photosynthetic pathway, a three-carbon molecule.

Another advancement, in the latter half of the 1960's, was research on the use of radiocarbon dating. Hall (1967) noted that maize and other grasses which have high $\delta^{13}C$ values produced younger ^{14}C dates. This prompted Hall to suggest that grass-eating and

leaf-eating animals could be theoretically differentiated using stable carbon isotopes (Hall 1967). It was not until ten years later that the variation in $\delta^{13}C$ values was used to recognize that animals and humans eating plants with C_3 and C_4 pathways would incorporate different isotopic values into bodily tissues (Vogel and van der Merwe 1977). Using skeletal samples from New York State, Vogel and van der Merwe analyzed bone collagen from prehorticultural and horticultural groups and found that quantity of maize in the diet could be estimated by determining where the $\delta^{13}C$ values fell on the scale between C_3 and C_4 plants.

Aquatic versus terrestrial protein diets

Not only can stable carbon isotopes be used to distinguish between C_3 and C_4 terrestrial plant groups they can also detect differences in marine versus freshwater plants. Carbon from marine environments is mainly derived from dissolved carbonate which has a higher $\delta^{13}C$ value (0‰) than atmospheric CO_2 (-7‰). In addition, the food chain associated with aquatic food webs has more steps. As a result, marine plants and animals have higher $\delta^{13}C$ values than terrestrial plants and animals. There is an 8‰ overlap in the range of $\delta^{13}C$ values of terrestrial and marine animals (including humans) feeding exclusively in one environment or the other (Schoeninger and DeNiro 1984). As a result of the higher $\delta^{13}C$ values found in marine resources, groups that rely heavily on marine foods generally have bone collagen $\delta^{13}C$ values in the range of -17 to -11‰. The degree of their dietary dependence upon marine resources can also be estimated from their $\delta^{13}C$ values (Chisholm et al. 1982; Schoeninger et al. 1983; Tauber 1981).

Freshwater food webs also have more enriched $\delta^{13}C$ values than terrestrial food webs because of their multiple sources of carbon (atmospheric CO_2, dissolved CO_2, soil and rock bicarbonate, and organic carbon from waste products and decomposition) for the aquatic plants at the base of the food chain (Katzenberg 2000; Krigbaum 2003). Early work on understanding isotope values from freshwater fish found $\delta^{13}C$ values indistinguishable from those of terrestrial animals (Schoeninger and DeNiro 1984). Other studies however reported $\delta^{13}C$ values were slightly elevated in several freshwater species relative to most terrestrial animals (Katzenberg 1989). It was further demonstrated that $\delta^{13}C$ values in freshwater fish can range from -24.6 to -14.2‰, with higher values being from fish living in shallow waters (Katzenberg and Weber 1999).

This estimation of resource dependence between aquatic (freshwater and marine environments) and terrestrial resources is complicated in environments where C_4 plants are also consumed (Chisholm et al. 1982; Schoeninger and DeNiro 1984; Schoeninger et al. 1983; Tauber 1981). A consumer of C_3 plants yields a $\delta^{13}C$ value close to that of the C_3 plants; a consumer of C_4 plants shows a $\delta^{13}C$ value close to that of C_4 plants. The difference between the carbon isotopic values of diet items and bone collagen, from which both the carbon and nitrogen isotope values are determined, is fairly constant, being about 4.5‰. Thus, if an animal solely consumed C_3 plants, its collagen would yield $\delta^{13}C$ values between -18.5 and -25.5‰ with an average of -22.5‰; if an animal consumed only C_4 plants, the value would be between -4.5 and -10.5‰ with an average of -8.0‰. If an animal's diet consists of 50% from C_3 and 50% from C_4, the value would be found around the midpoint, between -8.0 and -22.5‰, or about -15.25‰. Thus, while there are carbon isotopic differences between terrestrial and aquatic plants and animals,

carbon isotope analysis only works well when humans are consuming exclusively one type of plant (C_3 or C_4). If both C_3 and C_4 plants are utilized along with aquatic resources in the human diet, the resulting enrichment can possibly lead to data misinterpretations (Chisholm et al. 1982; Schoeninger and DeNiro 1984; Schoeninger et al. 1983; Tauber 1981). Fortunately the inclusion of $\delta^{15}N$ values (discussed below) in the analysis aids in more accurate and detailed dietary reconstruction (Walker and DeNiro 1986).

How dietary carbon is incorporated in bone

Early in paleodietary research there was a debate about what carbon isotope ratios from bone collagen actually represent in terms of dietary fraction (protein, carbohydrates, or fats). Two models have been proposed for understanding the relationship between dietary carbon and bone tissue.

Linear Mixing Model

The first model is referred to as the linear mixing model (LMM) or "scrambled egg model". In this model, carbon comes from the whole diet (protein, carbohydrates and fats), no matter the food source, "scrambled" together, and thus contributing to the carbon in bone collagen equally (Schoeninger 1989; Schwarcz 1991; van der Merwe 1982). This assumption is the basis of attempts to calculate specific percentages of food groups in the diet, such as percent dietary maize or percent marine input (Schoeninger 1989; Schwarcz et al. 1985; Spielmann et al. 1990; van der Merwe 1982; White and Schwarcz 1989). Vogel and van der Merwe (1977) in their study of prehistoric maize utilization in New York State applied this assumption to humans. They assumed the $\delta^{13}C$ of collagen varied linearly and thus believed they could calculate the percent maize consumed over time. Later this assumption would be further applied to maize studies to estimate the percent

intake of marine versus terrestrial resources (Chisholm et al. 1982, 1983; Schoeninger 1989; Schoeninger et al. 1983; Schwarcz et al. 1985; Spielmann et al. 1990; Tauber 1981; Walker and DeNiro 1986; van der Merwe 1982; White and Schwarcz 1989). Although the linear mixing model is only applicable in detecting dietary differences of the same type of animal, such as identifying browsers versus grazers (Tieszen 1991; Vogel 1978), the assumption is problematic for omnivores (i.e., humans) who potentially consume proteins, carbohydrates, and lipids with different carbon isotopic compositions (Klepinger and Mintel 1986).

However, experiments performed by Kennedy (1988) using rats demonstrated a diet deficient in animal protein could receive a significantly larger contribution of carbon in collagen from carbohydrates. Therefore some of the carbon in collagen must have come from non-protein sources. Kennedy (1988) concluded that some of the amino acids, and hence carbon, in collagen reflected non-protein portions of the diet. How much depends on how great a proportion of the diet is derived from protein.

Routing model

The second model is the direct transmission or routing model in which the isotopic ratio in any tissue in the consumer directly reflects the isotopic ratios of ingested foods (Chisholm 1989; Chisholm et al. 1982; Sullivan and Krueger 1983, 1984). In the case of protein, the carbon atoms are preferentially routed to the synthesis of body proteins and bone collagen (Chisholm 1989; Chisholm et al. 1982; Krueger and Sullivan 1984).

Krueger and Sullivan (1984) proposed that the $\delta^{13}C$ value of bone collagen is a function of the growth substrate (protein), whereas the $\delta^{13}C$ value of bone mineral is a function of the energy substrate (fats, carbohydrates, and proteins not used for protein

tissue synthesis). They proposed that dietary protein is selectively routed for the synthesis of protein tissues, including collagen. In contrast, carbohydrates, lipids and excess protein not needed for tissue synthesis, are metabolized for energy to CO_2 that is transported in the blood as bicarbonate. If true, then the $\delta^{13}C$ value of bone collagen and apatite could be manipulated experimentally depending on the relative proportions of protein, fats, and carbohydrates in the diet. The difference between the $\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$ ($\Delta^{13}C_{apatite\text{-}collagen}$) was predicted at +7‰ for herbivores and +3‰ for carnivores (Krueger and Sullivan 1984). Humans as omnivores were expected to fall between these two extremes. This research was later corroborated by Lee-Thorp (1989).

The Routing Model was tested separately by Ambrose and Norr (1993) and Tieszen and Fagre (1993) in order to clarify the relationship of bone collagen and bone apatite to whole diet and dietary components. Both studies were based on controlled feeding of rats in which Ambrose and Norr (1993) varied the source of (C_3 or C_4) proteins, cellulose, starch, and oils, while Tieszen and Fagre (1993) controlled for protein, cellulose, starch, and lipids. In addition to both sets of research supporting Krueger and Sullivan's (1984) results, they also concluded that carbon isotope values from bone apatite should reflect trophic levels since the spacing (value of $\delta^{13}C_{apatite}$ minus $\delta^{13}C_{collagen}$) is smaller in carnivores (+3 to +4‰) than in herbivores at around +7‰ (Krueger and Sullivan 1984; Lee-Thorp et al. 1989). Thus, differences in human $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values ($\Delta^{13}C_{apatite\text{-}collagen}$) allow the differentiation between energy and growth components of the diet therefore increasing the amount of available interpretable data (Krueger and Sullivan 1984).

These experimental studies with rats confirmed that there is 5‰ enrichment in bone collagen when diet consists of protein and non-protein components with the same $\delta^{13}C$ values. Therefore, you are what you eat plus 5‰ in collagen, but only if the $\delta^{13}C$ value of the protein portion of the diet and whole diet are the same (van der Merwe 1982). This is because collagen follows the routing model. However, when the protein and non-protein components differ in isotopic composition, collagen enrichment can vary between -2.2‰ and +9.6‰ (range 11.8%), suggesting that it was not the carbon isotopic composition of the whole diet which was affecting the $\delta^{13}C$ value of bone collagen (Ambrose and Norr 1993; Ambrose et al. 1997). Diets in which the $\delta^{13}C$ value of protein ($\delta^{13}C_{protein}$) was more negative than that of the whole diet (i.e. C_3 carbohydrates and C_4 protein) resulted in small or negative $\Delta^{13}C_{diet\text{-}collagen}$ values (-2.2 to 1.8‰) (Ambrose and Norr 1993). $\Delta^{13}C_{diet\text{-}collagen}$ values like these suggest a diet principally of C_4 carbohydrates and C_3 protein. This is consistent with a situation where C_4 cultigens such as millet or maize are introduced into a C_3 diet. If $\delta^{13}C_{protein}$ is more positive (less negative) than that of the whole diet (i.e. C_4 protein and C_3 energy), a larger $\Delta^{13}C_{diet\text{-}collagen}$ value is the result (+7.4 to 9.6‰) suggesting a diet of C_3 carbohydrates and aquatic protein (Ambrose and Norr 1993). This is typically associated with coastal groups who obtain their protein from marine animals while utilizing C_3 terrestrial plants.

Experiments of Ambrose and Norr (1993), Tieszen and Fagre (1993), and human case studies by Ambrose and colleagues (1997) and Norr (1995) suggest that collagen follows the 'routing' model (Chisholm 1989; Chisholm et al. 1982) whereby amino acids from the protein portion of diet preferentially go toward forming collagen. Bone apatite on the other hand reflects the whole diet adhering to the 'linear mixing model' (Schwarcz 1991).

Through the analysis of the spacing between $\delta^{13}C$ values of collagen and apatite, one can determine whether collagen reflects the whole diet in a particular situation, or whether it reflects primarily the protein portion of the diet.

What is important from the Ambrose and Norr study is the demonstration that for animals (like humans) that have a varied diet across populations and over time within a population, the small, medium, or large $\Delta^{13}C_{apatite\text{-}collagen}$ spacing is not indicative of herbivore, omnivore, carnivore respectively. Also, collagen and apatite represent a particular portion of the diet, and the relationship between carbon and collagen has predictable variation.

Nitrogen Isotopes

The analysis of nitrogen isotope values ($\delta^{15}N_{collagen}$) is useful for assessing isotopic variation in food resources, such as the contributions of legumes to a terrestrial diet, or to distinguish between aquatic and terrestrial proteins. Nitrogen is an abundant element that makes up approximately 78% of atmospheric air. The ratio of ^{14}N and ^{15}N between these two isotopes is determined using the same formula as that for carbon isotopes. Unlike $\delta^{13}C$ values which are always more negative than the standard, $\delta^{15}N$ values are generally more positive. Values for $\delta^{15}N$ may range from -6‰ to +21‰ (DeNiro and Epstein 1981; Minagawa and Wada 1984).

Variation in the $^{15}N/^{14}N$ ratio in the environment can be explained by kinetic isotope fractionations in biochemical reactions such as the assimilation of inorganic nitrogen, nitrogen fixation, nitrification, ammonification, denitrification, and other processes of nitrogen metabolism. Through these processes, microorganisms convert atmospheric nitrogen into a more usable form, such as ammonia, using an enzyme called nitrogenase.

Ammonia (NH_3) is the direct product of this reaction but is quickly converted to ammonium (NH_4^+). The ammonification and denitrification processes in soils and water result in forms of nitrogen usable in plants. Soil moisture, pH, salinity, root depth, and reproductive stage govern a plants use of soil nitrates and thus, the $\delta^{15}N$ ratio of a given plant (Virginia and Delwiche 1982).

Terrestrial plants can be separated into two categories based on how they obtain nitrogen. The first are nitrogen-fixing plants and the most common plants are from the Rhizobium family. These plants have a symbiotic relationship with bacteria in the soil that grow on the roots of leguminous plants by producing cellulose tubes, which permit the bacteria to invade the cortical cells of the root (Virginia and Delwiche 1982). The waste product of these bacteria is ammonium (NH_4^+) which combines with carbon compounds producing amino acids (Delwiche and Steyn 1970). As a result of this fixation of nitrogen by soil bacteria, $\delta^{15}N$ values are similar to that of air 0‰, ranging from -3‰ to +5‰ with a mean of 1‰ (DeNiro 1987; Hoefs 1987; Virginia and Delwiche 1982). Wet rice systems are another example of nitrogen fixation. Bacteria living in the water around the root systems produce excess nitrogen as metabolic waste which then gets absorbed in the roots of the rice plants.

Non-nitrogen fixing plants are the second type of plants. Instead of deriving nitrogen from bacteria they use ion assimilation to absorb nitrogen from the soil in some form, such as NH_4^+ (ammonium) and NO_3^- (nitrates), thus $\delta^{15}N$ values are dependent on that of the soil (DeNiro and Epstein 1981). These non-leguminous plants exhibit isotopic ratios which are on average 8.8‰, ranging from -4‰ to +10‰ (DeNiro 1987; Rennie et al. 1976).

DeNiro and Epstein (1981) were the first to study the relationship between diet and nitrogen isotope composition of the consumer. By studying the tissues from laboratory animals consuming diets of known isotopic composition, they were able to conclude that dietary reconstruction may be possible if the isotopic composition of food sources were varied enough to have distinct isotopic signatures in the animal (DeNiro and Epstein 1981).

As with carbon, the enrichment of an animal's tissue occurs in a unidirectional fashion from primary producer, to primary, secondary, or tertiary consumers. These stages, or trophic levels, result in an average of 3-4‰ increase in nitrogen isotope ratios between each level of a food chain (DeNiro and Epstein 1981; Minagawa and Wada 1984; Schoeninger and DeNiro 1984). Worldwide the values for herbivores range from 1.0-12.7‰, while the values for carnivores range from 5.3-18.8 ‰, with respective means of 5.8±2.6 and 10.2±2.9‰ (Ambrose and DeNiro 1986a; Bocherens and Drucker 2003; DeNiro 1985; Katzenberg 1989; Nelson et al. 1986; Schoeninger 1985, 1989; Schoeninger and DeNiro 1984).

Aquatic plants (either freshwater or marine) are typically enriched (more positive values) in ^{15}N relative to terrestrial plants (DeNiro 1987). Marine plants have $\delta^{15}N$ values average about 7‰, which is about +4‰ higher than those of terrestrial plants (Ambrose 1993; DeNiro 1987). As a result, it is possible to distinguish between marine and terrestrial fauna (Minagawa and Wada 1984; Schoeninger and DeNiro 1984). While marine resources did not play a role in the history of northeast Thailand, riverine and lacustrine (lake) faunal resources were important. The nitrogen isotopic composition of aquatic fauna varies for a variety of reasons, but broadly these differences are related to

differences in the diet, habitat, and growth maturity of the animal (Katzenberg and Weber 1999:655). Great variability also has been demonstrated in populations of the same species that consume the same foods but are located in different aquatic sources.

In both terrestrial and aquatic/marine environments, the available data support a ^{15}N enrichment of approximately +4‰ between overlapping trophic levels (Ambrose 1993). Furthermore, the greatest difference in the isotopic fractionation from the trophic effect is found within a particular region due to environmental variables. These environmental variables include trophic level, aquatic versus terrestrial diets, climate, and inadequate protein intake. This underscores the importance of obtaining isotopic values of not only terrestrial fauna but also aquatic/marine resources close to the archaeological sites being investigated (Dufour et al. 1999; Schoeninger 1985; Schoeninger and DeNiro 1984).

$\delta^{13}C$ and $\delta^{15}N$ as Complementary Measures of Dietary Reconstruction

The use of bone collagen and bone apatite provides different windows to view changes in diet within and between human groups in the past. $\delta^{13}C$ values from bone collagen are used to reflect changes in the protein component of diet. $\delta^{13}C$ values from bone apatite reflect the energy component of diet. When combined, along with the spacing between these separate carbon isotope values ($\Delta^{13}C_{apatite\text{-}collagen}$) more precise information can be garnered then used alone. When human populations utilize C_3 and C_4 plants, and aquatic and terrestrial animal protein, $\delta^{15}N$ from bone collagen can help tease out patterns in areas which would otherwise be obfuscated by overlapping isotopic values in $\delta^{13}C$ value from collagen and apatite. Utilizing multiple hard tissues to obtain the stable isotopic values of $\delta^{13}C_{collagen}$, $\delta^{13}C_{apatite}$, $\delta^{15}N_{collagen}$, along with $\Delta^{13}C_{apatite\text{-}collagen}$

spacing allows for a better tracking of dietary differences between groups and over time and space.

Chapter V. Research Sampling and Methodology

Isotope data for this study are derived from both modern and archaeological samples from Udon Thani and Nakhon Ratchasima provinces in northeast Thailand. Modern plants as well as modern and archaeological animal samples are compared to elucidate the diets of other animals not typically recovered from archaeological site due to poor preservation. The data from modern plants and animals thus provide the biogeochemical baseline data to interpret the prehistoric results from the human skeletal remains.

Human Sampling

Four archaeological sites from two regions in northeast Thailand were selected (Table 5.1) that represent human skeletal sample collections of the pre-state Metal Age inhabitants in northeast Thailand. These pre-state Metal Age sites encompass General Periods B (second millennium B.C.) and C (first millennium B.C.) following Bayard's (1984) chronology (discussed in Chapter III). The sites are Ban Chiang, Ban Na Di, Ban Lum Khao, and Noen U-Loke. Site selection was based on their extensive research documentation and the relatively long history of use during the time period in question. Overall, the human remains from all the sites ranged from excellent to poor cortical bone integrity.

Table 5.1. Human Skeletal Database from Major Archaeological Sites of Two Regions of Northeast Thailand

Region	Site	Total Size	Dates
Sakon Nakhon	Ban Chiang	142	2100 B.C. - A.D. 200
Sakon Nakhon	Ban Na Di	73	600 B.C. - 400 B.C.
Khorat	Ban Lum Khao	110	1400 B.C. - 500 B.C.
Khorat	Noen U-Loke	120	300 B.C. - A.D. 300

[1]All field seasons combined for each site.

Ban Chiang

The human skeletal material from Ban Chiang is housed in the Department of Anthropology, University of Hawai‘i, Honolulu, whereas the faunal material from this site is curated at the Department of Anthropology, University of Otago, Dunedin. Samples from 80 adult individuals (31 females; 7 probable females; 36 males; 6 probable males) excavated from Ban Chiang were sampled for this study (Table 5.2). A comprehensive list of all individuals excavated from Ban Chiang can be found in Pietrusewsky and Douglas (2002a).

Ban Na Di

The human skeletal and faunal materials from Ban Na Di are curated in the Department of Anthropology, University of Otago, Dunedin. Samples from 35 adult individuals (11 females; 3 probable females; 18 males; 3 probable males) excavated from Ban Na Di were sampled for this study (Table 5.3).

Ban Lum Khao

The human skeletal and faunal materials from Ban Lum Khao are housed at the Archaeological Laboratory at the Ninth Office of the Fine Arts Department, Phimai, Thailand. Samples from 22 adult individuals (14 females; 8 males) excavated from Ban Lum Khao were sampled for this study. Table 5.4 provides a list of individuals sample for this study (Table 5.4).

Noen U-Loke

The human skeletal and faunal materials from the Noen U-Loke site are housed at the Phimai Museum, Thailand. Samples from 42 adult individuals (19 females; 23 males) excavated from Noen U-Loke were sampled for this study (Table 5.5).

Table 5.2. Ban Chiang cemetery samples.

Burial no.[1]	Sex[2]	Age[3]	Burial no.	Sex	Age	Burial no.	Sex	Age
BC01	Female	A	BC41	Female	35-40	BCES36	Male	45-50
BC02	Female	35-40	BC43	Male	35-40	BCES40	Male	45-50
BC06	Male	MA	BC44	Male	40-45	BCES41	Female?	YA-A
BC07	Male	MA	BC45	Female	18-22	BCES42	Male	40-45
BC08	Female	35-40	BC47	Male	25-30	BCES45	Male	45-50
BC09	Male	MA	BCES01	Female	18-22	BCES46	Female	45-50
BC11	Female	17-23	BCES02	Male	35-40	BCES47	Male	45-50
BC12	Male	MA	BCES03	Female	MA	BCES49	Male	35-40
BC13	Male	A	BCES06	Male	40-45	BCES49A	Male	45-50
BC16	Female	20-30	BCES07	Male	45-55	BCES50	Male	25-30
BC17	Female	M-O	BCES09	Female	35-40	BCES51	Male	40-45
BC18	Male	MA	BCES10	Male?	17-19	BCES53	Male?	A
BC19	Female	YA	BCES19	Female	30-35	BCES55	Male?	14-16
BC20	Male	35-40	BCES20	Female	35-40	BCES56	Male	45-50
BC21	Female	A	BCES23	Female?	A	BCES57	Female?	MA
BC22	Male?	18-20	BCES24	Male	30-35	BCES59	Female	45-50
BC23	Male	45-50	BCES25	Male?	MA	BCES61	Female?	MA
BC24	Female	O	BCES27	Female	35-40	BCES65	Male	40-45
BC26	Male	MA	BCES28	Female	35-40	BCES69	Female	25-30
BC27	Female	25-30	BCES29	Female	18-20	BCES72	Male	35-40
BC28	Female	45-50	BCES30	Female	20-25	BCES73	Male	35-40
BC30	Female?	A	BCES31	Male	45-50	BCES74	Male?	MA-O
BC31	Female	50-60	BCES32	Male	MA	BCES75	Female?	YA
BC33	Female	45-50	BCES33	Female	25-30	BCES76	Male	25-30
BC34	Female	40-45	BCES34	Female	25-30	BCES78	Male	MA
BC35	Male	40-50	BCES35	Male	45-50	BCES81	Female?	A
BC39	Male	35-40						

[1] BC = 1974 excavation season; BCES = 1975 excavation season

[2] Female? = probable female; Male? = probable male. Probable females and males are grouped together as female and male during isotopic analysis.

[3] A = Adult; MA = Mature Adult; M-O = Mature to Old Adult; O = Old; YA = Young Adult; YA-A = Young Adult to Adult

Table 5.3. Ban Na Di cemetery samples.

Burial no.	Sex[1]	Age
BND01	Female?	20-24 y
BND03	Male	45-49+ y
BND10	Female	45-49 y
BND11	Male	35-39 y
BND12	Male?	Adult
BND13	Male?	35-39 y
BND16	Male	25-29 y
BND17	Male	40-44 y
BND18	Female	30-34 y
BND20.2	Female	Adult
BND22	Female	35-39 y
BND23	Male?	35-39 y
BND26	Female	45-49+ y
BND28	Female	40-44 y
BND31	Male	Adult
BND32	Male	25-29 y
BND35	Male	35-39 y
BND36	Female	25-29 y

Burial no.	Sex	Age
BND37	Male	25-29 y
BND39	Male	20-24 y
BND40	Female	40-44 y
BND42	Male	30-34 y
BND47	Male	35-39 y
BND48	Female?	25-29 y
BND49	Female	30-34 y
BNDT05	Male	Adult
BNDT08	Female	40-44 y
BNDT08.1	Male	25-29 y
BNDT09	Male	30-34 y
BNDT12	Female	Adult
BNDT15	Male	40-44 y
BNDT17	Male	35-39 y
BNDT19	Male	45-49+ y
BNDT20	Male	25-29 y
BNDT21	Female?	Adult

[1] Female? = probable female; Male? = probable male. Probable females and males are grouped together as female and male during isotopic analysis.

Table 5.4. Ban Lum Khao cemetery samples.

Burial #	Sex	Age
BLK21	Female	30-39
BLK28	Male	35-39
BLK34	Female	30-39
BLK36	Female	30-39
BLK37	Male	30-39
BLK38	Female	30-39
BLK39	Female	25-29
BLK42	Female	20-29
BLK47	Male	30-39
BLK48	Male	40-49+
BLK49	Female	20-24

Burial #	Sex	Age
BLK55	Male	18
BLK59	Male	30-39
BLK61	Female	19
BLK64	Female	40-44
BLK67	Male	25-29
BLK75	Female	40-49+
BLK80	Female	25-29
BLK82	Male	20
BLK85	Female	25-29
BLK95	Female	20-29
BLK98	Female	35-39

Table 5.5. Noen U-Loke cemetery samples.

Burial #	Sex	Age
NUL001	Male	35-40
NUL005	Male	20-25
NUL012	Female	40-49+
NUL014	Male	35-40
NUL016	Female	20-25
NUL026	Male	Adult
NUL027	Male	Midage
NUL030	Female	25-30
NUL032	Male	Midage
NUL033	Male	25-30
NUL035	Female	35-40
NUL036	Female	20-25
NUL037	Female	Old
NUL039	Male	20-25
NUL040	Female	20-25
NUL042	Male	Old
NUL044	Male	Young
NUL045	Male	25-30
NUL048	Female	25-30
NUL049	Female	35-40
NUL050	Male	20-25

Burial #	Sex	Age
NUL052	Female	Midage
NUL060	Male	20-25
NUL061	Male	Young
NUL062	Female	35-40
NUL064	Female	Adult
NUL066	Male	35-40
NUL069	Male	25-30
NUL074	Male	25-30
NUL082	Female	35-40
NUL084	Male	Adult
NUL086	Male	25-30
NUL094	Male	40-49+
NUL098	Male	old
NUL099	Female	40-49+
NUL104	Female	25-30
NUL107	Male	Young?
NUL108	Female	40-49+
NUL110	Female	37-42
NUL111	Male	25-30
NUL113	Female	25-30
NUL114	Female	35-40

Plant and Animal Sampling

To better interpret and understand the diet of past human populations, it is important to have knowledge of the local or regional food web. For example, Norr (1995:208) pointed out that a $\delta^{15}N$‰ of +15‰ and a $\delta^{13}C$‰ of -8‰ from the neotropics may suggest a coastal agricultural diet of marine fish and maize. The same data from East Africa, however, could be the result of meat from large herbivores that grazed on C_4 grasses (Ambrose and DeNiro 1986a,b). In order to facilitate the interpretations of the stable isotopic signatures from the human skeletal samples, this research included the isotopic analyses of modern plants and animals, and archaeological faunal bone from Thailand. The stable isotope data from these plant and animal samples are provided in Chapter VI.

Plant samples

Modern plants were used since floral samples from archaeological contexts in Southeast Asia are very rare and do not cover the numerous edible plants (wild and domestic) available in the region. Northeast Thailand has a long history of primarily glutinous rice (sticky rice) consumption (Fukui 1978, 1993). Glutinous, non-glutinous, wild rice, as well as multiple other plants were analyzed to provide an indication of the amount of isotopic variability in this region. Stable isotope data for the plant remains are presented in Appendix A.

The plant samples were collected in March 2003 from the village (Ban) of Ban Pulu in the County (Amphoe) Nong Han, Udon Thani province. These were collected and identified from the modern landscape with the assistance of Dr. Joyce White, Senior Research Scientist at the University of Pennsylvania Museum of Archaeology and Anthropology, and Director of the Ban Chiang Project, and Mr. Long Lee, a local

villager. The types of plants collected includes stem and leaf portions of the plants, and when available, the edible fruits or vegetables portions. Emphasis was given to plants that were endemic to the region and may have existed in prehistory. A total of 89 commonly consumed plants from 41 different species were collected and isotopically analyzed. These plants include fruit, vegetables, and cereals (C_3 and C_4 varieties).

Not all edible plants were encountered on this collection trip due to seasonality and / or environmental variability. In some cases, more than one part of the plant is edible, in which case all useful parts were collected. For instances in which the edible portion of the plant was not available, other parts of the plant were collected, such as substituting leaves for seeds, or unripe fruit for ripe fruit. Wild plants that are solely used as medicine, teas, condiments and spices are not considered, with emphasis being given to those plants that more likely contributed to the diets of these past populations.

Insects and modern animal samples

Archaeological sites may yield a wide variety of mammals, birds, reptiles, fish, and invertebrate species. However, differential preservation and collection methods greatly affect what are recovered as potential foods, such as insects and land crab, which are consumed today and most likely also eaten in the past. As a result modern insects and animals (meat and bone samples) were collected for isotopic analysis. These samples provide additional data for those samples which are not recovered archaeologically and also serve as a means to interpret isotopic bone values of animals and the flesh (meat) portion of the animals which may have been eaten.

The silk worm, water beetle, and land crab were collected from the night market in the city of Phimai, Nakhon Ratchasima province. Silk worms were purchased already

boiled by the vendor while the water beetle and land crab were purchased alive. Both insect types were later frozen.

Modern bone samples from mammals, Aves, and reptiles were collected at Otago University in June 2003. These mammals originated from the Mae Hon Son region of northern Thailand and were collected and identified in 1968 and 1972 by either Dr. Donn Bayard (in 1968) or Dr. Charles Higham (in 1972). While these samples originated from a different region within Thailand these samples provide an additional baseline for comparison of the archaeological faunal remains and warrant their inclusion in this study.

Archaeological faunal bone samples were collected from all sites. Either long limb bones or metatarsals were collected. Only samples that were identified at least to the genus level were sampled. Faunal identifications were performed prior to sampling by either Dr. Charles Higham (Ban Chiang, Ban Na Di, Noen U-Loke) or Mr. M. McCaw (Ban Lum Khao). Their analysis suggests that the inhabitants hunted mammals, while keeping domestic cattle, water buffalo, pigs, chickens, and dogs. Shellfish, turtles, fish, and frogs were also included in the diet. Temporal changes were also detected in the faunal record. These changes resulted in an increase in herbivores and a decrease in aquatic species with time which can be attributed to an increase in grasslands and decrease in standing water during the middle and later occupational periods (Higham and Kijngam 1979:230).

Human remains

A total of 179 human samples were collected from four archaeological sites and are presented in Table 5.6. A sample of 47 individuals collected from Ban Chiang are in

addition to the 33 individuals already collected and analyzed from a pilot study and are used to fill in gaps across the time periods of the site and between females and males.

Table 5.6. Total numbers of adult individuals sampled from each site sorted by time period

Region	Site	Total Size	Samples Collected[1]	Data Samples[2]
Sakon Nakhon	Ban Chiang	142	80	66
Sakon Nakhon	Ban Na Di	73	35	29
Khorat	Ban Lum Khao	110	22	5
Khorat	Noen U-Loke	120	42	5

[1] Samples = human samples collected for chemical extraction of bone collagen and bone apatite
[2] Data Samples = human samples that successfully produced usable data after chemical extraction and mass spectrographic analysis.

Criteria for selection of human and faunal bone samples include: 1) burials derive from secure archaeological contexts whenever possible; 2) bones are in reasonable condition and sufficient quantity to provide for replicate measurements; 3) individuals are adults (>15 years) without grossly abnormal pathological lesions, to avoid potential variation associated with age-based metabolic or dietary differences (Katzenberg 1993; Schwarcz et al. 1985); 4) the sex of individuals is provided; and 5) samples treated with Polyvinyl acetate (PVA) and other preservative compounds are avoided whenever possible. Animal remains from the same archaeological context as the human samples are utilized to serve as important controls in detecting the values of the potential food sources. Schoeninger and Moore (1992) recommend at least 10 grams per sample from human skeletal and faunal remains to compensate for loss in cleaning, and to allow for replicate analysis.

Laboratory Methodology

Procedures for cleaning, collagen and apatite extractions, and diagenic protocols follow those in Ambrose (1990, 1993) and Norr (1995) are outlined below. Table 5.7

provides a sample recording form for listing weights, measures, and results. Sample preparation for chemical analysis of the human skeletal material, faunal, and floral remains undertaken at the Department of Anthropology, University of Hawai‘i. Mass spectrographic analysis of carbon and nitrogen isotopes from collagen and carbon isotopic analysis of carbonate in bone and plant materials was conducted in the Stable Isotopic Laboratory, Department of Geology and Geophysics, University of Hawai‘i.

Contamination controls

The following is a description of the methods chosen for the isolation of bone collagen and for the detection of diagenic alteration in archaeological collagen and apatite samples. Diagenesis is a complex process that varies with the local environment. The most notable changes occur macroscopically. These changes can be caused by fungi, bacteria, and soil pH levels which can dissolve the bone mineral and digest the bone collagen matrix. Minerals in the soil or ground water can also hypermineralize areas of the bone, resulting from the re-precipitation of dissolved bone mineral (Grupe et al. 2000; Nielson-Marsh and Hedges 2000; Schoeninger et al. 1989). Soil humates pose an especially large problem due to their high affinity for bone collagen (van Klinken and Hedges 1995). Structural changes in the collagen have also been observed when humic acids, lipids and other contaminants bind themselves into the protein structure of the bone (van Klinken 1999; van Klinken and Hedges 1995).

Assessment of diagenesis for bone collagen

The preparation of bone collagen for analysis involves removing the mineral phase of bone and freeing the remaining collagen of as many contaminates as possible. If the

sample fails to meet a specific set of criteria used to assess diagenic alteration it is discarded.

Since nearly the beginning of stable isotope research into paleodietary reconstruction there has been concern about isolating collagen and checking for contamination problems. There are two basic methods that are used for extracting collagen. These are either the modified Longin method using crushed bone or techniques in which whole bone chunks are slowly demineralized in dilute HCl or calcium EDTA.

In the Longin method, which this study utilizes, powdered bone is demineralized in a HCl solution and soaked in dilute NaOH to remove humates; the collagen is then gelatinized, filtered to remove impurities, and dried (DeNiro and Epstein 1981; Longin 1971). Recent studies that use variations of this method include (Ambrose et al. 1997; Bocherens et al. 1999; Cannon et al. 1999; King and Norr 2006; Richards and Mellars 1998; White, C.D. et al. 2001).

The other method involves using a small chunk of whole bone, which is demineralized by soaking in a dilute HCl solution or calcium EDTA (Tuross et al. 1988). The outcome of this produces a chunk of demineralized bone that is referred to as a collagen model. Recent studies using this HCl approach include Herring, Saunders, and Katzenberg (1998); Katzenberg and Weber (1999); Lillie and Richards (2000), and Richard and Hedges (1999). Examples in the literature utilizing the EDTA method include; Iacumin, et al. (Iacumin et al. 1998); Tuross et al. (1994); Wright and Schwarcz (1996).

Both methods have yielded good results when applied to well preserved material (Ambrose 1990; DeNiro and Weiner 1988; Schoeninger et al. 1989; Tuross et al. 1988)

though evidence suggests the Longin method is better suited for poorly preserved bone (DeNiro and Weiner 1988; Pfeiffer and Varney 2000; Schoeninger et al. 1989; Tuross et al. 1988).

Assessing diagenesis in collagen

A multifactorial approach has been used to assess the level of diagenic contamination to each sample before analysis. There are three indicators used in this study to assess the diagenesis in collagen samples: collagen yield by weight, atomic C/N ratio, %C and %N. Samples that failed with a borderline value for a single criterion were not excluded as long as all other criteria met acceptability. Any samples that failed for multiple criteria were not included in the data set. These three criteria are the most widely utilized and accepted approaches to assessing diagenic contamination in samples (Ambrose 1990, 1993; Collins et al. 2002; DeNiro and Weiner 1988; Schoeninger et al. 1989; Tuross et al. 1988; van Klinken 1999). Other procedures are also known in the literature and these include histological appearance (Grupe et al. 1993), amino acid profiles (Balzer et al. 1997; e.g., DeNiro and Weiner 1988; Grupe et al. 2000; Schoeninger et al. 1989; Tuross et al. 1988) and Fourier Transform Infrared Spectroscopy (FTIR) spectra (DeNiro and Weiner 1988).

Collagen yield

Collagen yield is a quick and general indicator of the percentage of collagen remaining from the bone after chemical extraction. The basis for the use of collagen yield is that bones which produce low collagen yields have undergone severe protein loss and/or degradation to the extent that there may not be enough intact collagen or large peptides of collagen remaining to provide biogenic stable isotope values. Alternatively,

the small amount of collagen remaining may be contaminated with other substances such that isotopic values have been altered. Therefore, bones that produce low collagen yields are generally considered to be unsuitable for isotopic analysis (Ambrose 1990, 1993; DeNiro and Weiner 1988; Schoeninger 1989; Tuross et al. 1988; van Klinken 1999).

However, there is some disagreement in the literature concerning what constitutes an acceptable percentage levels before isotopic results can be accepted. While it has been suggested that 5-6% (Tuross et al. 1988) to as high as anything less than 10% (Schoeninger et al. 1989), but others have used the cut-off point to be 1% (Ambrose 1990, 1993; DeNiro and Weiner 1988; White, C.D. et al. 2001; van Klinken 1999).

%C and %N values

This measure expresses the concentrations of the two atoms in the prepared collagen sample by weight. Ambrose (1990) reported that bone from modern mammals has percent carbon (%C) values ranging from 15% to 47% and percent nitrogen (%N) values ranging from 5% to 17%. Further, results from archaeological samples indicate that %C and %N below 13% and 5% respectively should be considered suspect for contamination and/or poor preservation (Ambrose 1990). These percentages however are not the most consistent in terms of assessing sample quality and sometimes contradict C/N ratios. For example, Iacumin and colleagues (1998) have published data with acceptable %C and %N values even though a sample may have had collagen yield below 1% or a C/N ratio above 3.6.

Atomic weight C/N ratio

The atomic weight C/N ratio is a widely used diagenic indicator for collagen analysis. During elemental analysis a regression formulae is generated that provides the percentage

of carbon and nitrogen for a given sample. By dividing these percentages the atomic mass can be calculated as follows: $C/N_{(mass)}$ ratio {$C/N_{(mass)}$ = mass C / mass N}. By convention, this ratio is then multiplied by 1.16666667[8] to make the data comparable to the volumetric method, which used traditional vacuum lines originally used to extract carbon and nitrogen from samples. This however is different from atomic weight used to as a tool for diagenic control, and is due to changes in the way isotope data are generated.

The utility of this calculation is based on the rationale that as collagen breaks down the carbon or nitrogen is either lost to the environment or altered by the inclusion of carbon-rich contaminants such as lipids or humus in the soil (Ambrose 1990; Iacumin et al. 1998; Schoeninger et al. 1989). The value of modern bone collagen ranges from 2.9 to 3.6 (DeNiro 1985). This range has also been proven to demonstrate that archaeological bone collagen within this range produces $\delta^{13}C$ and $\delta^{15}N$ values consistent with the animals' known diets and habitats (Balzer et al. 1997; DeNiro 1985; DeNiro and Weiner 1988; Grupe et al. 2000; Masters 1987). Samples outside this range are considered diagenically altered either through poor preservation or foreign contamination. Ways in which collagen samples can be contaminated are varied. Bones with high C/N ratios may indicate contamination from carbon rich, nitrogen poor substances such as humic acids and lipids (Ambrose and Norr 1992; van Klinken 1999). Low C/N ratios may signal contamination with ammonia or other small amines (Masters 1987).

[8] The atomic weight of carbon is 12.011 and nitrogen is 14.0067.

Assessing diagenesis in apatite

A variety of methods have been used to assess the quality of data from bone apatite. Methods to assess sample quality that require no extra chemical or machine analysis include organic content, carbonate content, and stable oxygen isotope variation. Other measures of integrity employed include x-ray diffraction, histological preservation, porosity, infrared spectrometry profiles, crystallinity, and comparison of isotopic results with the $\delta^{13}C$ values of modern animals with known diets and/or with the $\delta^{13}C$ values of burial matrices (Ambrose 1993; Koch et al. 1997; Lee-Thorp 2002; Lee-Thorp and van der Merwe 1991; Sponheimer and Lee-Thorp 1999). While most studies cite literature values or analyze one modern sample for comparative purposes, there is no set standard for acceptable carbonate content for archaeological samples.

Summary of collagen and apatite quality assessment

There is no single method to fully assess contamination or poor preservation in samples. The best approach is to utilize a multifactorial approach to identify samples that are unsuitable for isotopic analysis (Collins et al. 2002; DeNiro 1985; DeNiro and Weiner 1988; Evans 1928; Lee-Thorp 2002; Schoeninger et al. 1989; van Klinken 1999). Collagen quality assessments utilized in this study are as follows. For collagen yield, a value of >1% is applied because some samples do produce small amounts of collagen that retains amino acid profiles similar to fresh collagen (Ambrose 1990, 1993). Following DeNiro (1985), a range of 2.9 to 3.6 is used to determine collagen quality from C/N ratios. Lastly, Ambrose (1990) suggested that good collagen samples should have a minimum of 3% carbon and 1% nitrogen by weight in order for accurate isotope ratios to be determined.

For this study, a comparative relationship between both collagen and apatite is examined to assess apatite preservation. In samples where collagen is not preserved, it is more difficult to assess the validity of bone carbonate carbon isotope ratios (Ambrose 1993). A minimum criterion for the percentage of carbon in the sample after isotopic analysis is 1%. Suitable collagen preservation and apatite carbon values >1% are the minimum criteria for bone apatite quality (Ambrose 1993).

Sample Preparation

Plant Preparation

Plant samples were air dried in the field. Leaf and stem samples were then placed in plant presses for further drying and transport. Fruit and vegetable, samples were also air dried and then bagged in the field. Leaves were cleaned by rinsing in de-ionized H_2O and oven dried at 50°C. Once dried, approximately 0.2-0.4 mg of plant material was utilized for mass spectrometric analysis.

Fruit and vegetable plant portions were also oven dried at 50°C. These samples however needed to be ground with a mortar and pestle, cleaned with dilute HCl, rinsed to pH neutral and oven dried. Approximately 0.2-0.4 mg of each sample were utilized. Both leaf and fruit/vegetable portions of the plant were analyzed for $\delta^{13}C$ and $\delta^{15}N$.

Lipid Extraction of Legumes, Insects, Muscle Tissue, Modern Bone

Since many animals, insects, and plants either do not preserve or are not placed in prehistoric burials, a sampling of modern insects, animals (meat and bone samples), and legumes were collected for isotopic analysis. These were added to the data from the archaeological faunal samples to better understand the isotopic variability among potential food resources, as well as the results from the human samples.

Fresh bone, animal muscle tissue, insects, and legumes all contain a significant level of lipids, which if not removed, skew results for carbon isotopic values more negatively (Lidén et al. 1995). The methodologies provided in the anthropological literature are variations of the Bligh and Dyer (1959) method. Variations of this method include chloroform:methanol or chloroform:methanol:water solutions (Lee-Thorp et al. 1989; Lidén et al. 1995; Sealy et al. 1987). Others have utilized a combination of diethyl ether and NaOH soaks (Garvie-Lok 2001; Garvie-Lok et al. 2004; Katzenberg and Weber 1999). These methods however are labor intensive, slow, and can present a level of unnecessary noxious chemical exposure to the researcher.

For this study, a relatively new method of lipid extraction was utilized that provided a faster, cheaper, and safer environment for extracting lipids. This procedure, called ASE (Accelerated Solvent Extraction), utilizes high temperature and pressure of a liquid solvent to extract lipids from solid samples. The solvent utilized for this study is Hexane. Elevated temperatures and pressures increase the efficiency of the extraction process. Increased temperature accelerates the extraction kinetics, while elevated pressure keeps the solvent below its boiling point, thus enabling safe and rapid extractions. As a result of the high temperature and pressure, the extraction takes about 15-20 minutes per sample (Macnaughton 1997).

Modern bone samples had to be broken into smaller pieces to fit the metal cells of the machine. Modern flesh from fish and insects were also portioned to accommodate the cells, and legumes were cracked into smaller fragments to maximize surface area. For modern bone, once the extraction process was completed, the bone samples were crushed in a mortar and pestle and the same collagen and apatite extraction procedures were

followed as for archaeological bone samples. After extraction of the modern flesh and legumes, these samples were freeze-dried and crushed to smaller portions for mass spectrometric analysis.

Bone Sample Preparation - Modern and Archaeological

The methodology for extracting collagen and apatite from modern bone is the same as that used for archaeological bone. However, an additional procedure is required that involves the removal of lipids for the modern samples. Below are the steps used to extract collagen and apatite from bone samples. Once the chemical extraction of collagen from the bone samples is completed a portion of the sample is measured into a tin foil capsule. This capsule is combusted in a Carlo-Erba NC2500 elemental analyzer connected to a Finnegan MAT ConFloII/Finnigan MAT Delta-Plus (w/source upgrade) isotope mass spectrometer. Apatite was analyzed by reaction with 100% phosphoric acid in an automated device (GasBench) connected to the Finnigan MAT Delta-Plus XP.

Bone Preparation for Collagen and Apatite Extraction Procedures

1. Photograph sample with a scale. For rib samples, about ten grams of bone is needed while limb bones can be as low at seven grams.

2. Observe bone under lighted magnifier to check for ash, textile patterning, cut marks, etc.

3. Remove obvious surface contamination and discoloration (roots, dirt, adhering tissues, etc.) with scrub brush, toothbrush, scalpel, etc. The outer and inner surfaces of bone were scraped off using a Dremel tool with Tungsten tip.

4. Sonicate in distilled water 2-3 times for 5 minutes each in labeled beaker. Change water if it becomes very dirty.

a. After first sonication, water will be cloudy as a result of bone powder and dirt from scraping.

b. Change distilled H_2O in beaker before next sonication.

5. Dry bone overnight at room temperature on paper towels covered with KimWipes (label). Be sure to create a label to delineate various bone samples which could be drying at the same time.

6. Crush bone *gently* with clean mortar and pestle. Sieve over 0.5 mm and 0.25 mm mesh, with bone powder collecting in pan and granules of bone on 0.25 mm mesh. Repeat until complete.

7. Store ground bone in annealed and labeled scintillation vials. Place fine (<0.25 mm) and coarse (0.25 - 0.5 mm) fractions in separate vials. The <0.25 mm bone samples are to be used for the apatite and 0.25-0.5 mm samples for the collagen chemical procedures respectively.

Collagen (Organic Bone) Extraction Protocol

1. Place 0.5-1.0 g (use 0.80xx g) of crushed bone (0.25 - 0.5 mm mesh fraction) in clean, annealed, labeled filter funnel on annealed Pyrex glass wool (handle wool with plastic gloves). Record the weight of the sample.

2. If bone is fresh and greasy (not archaeological) an ASE lipid extractor using a Hexane solvent was used to remove excess lipids.

3. Add ~50 ml 0.2 m HCl to filter funnel. Stir occasionally with clean glass rod. Cover with foil. Do not allow foil to get wet. Check twice daily. If demineralization is incomplete drain funnel and replace HCl. Demineralization is complete when bubbling stops and translucent isomorphs appear, which may take a few days. These isomorphs look like the snow in a snow globe.

4. Rinse to neutral pH by repeated filling and draining of funnels with distilled water (about 10 times). Use squirt bottle to rinse top edge of funnel, stir rod, and glass wool; also squirt outside of funnel, stopcock, and drip tip. Check pH of each funnel by holding pH strip beneath funnel drip tip, allowing water to drip onto strip.

5. Add ~50 ml 0.125 m NaOH to neutral, drained funnel. Cover with Al foil, let stand 10 hours or overnight (max. 20 hours).

6. Rinse to neutral pH (about 10 times). Check pH of each funnel.

7. Add 50 ml 10^{-3} m HCl (pH 3) to filter funnel. Mark level of liquid with sharpie. Cover tightly with foil. Place in drying oven at 95°C for 4-5 hours.

8. Add 100µl 1 M HCl to filter funnel, replace evaporated liquid with 10^{-3} m HCl, and stir well. Return to oven for 4-5 more hours, or overnight.

9. Drain hot solution into clean, annealed, labeled side-arm flask, using tan rubber stoppers and oven mitt if needed. Place flasks in oven at 65°C to condense solution. Do not allow sample to dry out more than one hour. Disassemble, clean, and anneal filter funnels.

10. Record weight of empty, annealed, labeled, 20 ml scintillation vial (no lid).

11. If collagen solution in flasks dries, reconstitute with a few squirts of 10^{-3} m HCl and allow reheating to 95°C for 10 minutes. When solution condenses to ~5 ml, transfer to scintillation vial. Rinse flask twice with a few squirts of 10^{-3} m HCl and add to vial. Return to oven to evaporate to < 2 ml. If solution dries in vial reconstitute with a few squirts of 10^{-3} m HCl. Clean and anneal flasks.

12. Freeze collagen in freezer. When frozen, freeze-dry for 48 hours.

13. Record weight of scintillation vial with dried collagen. Calculate *collagen yield wt.* and *% yield collagen* (collagen yield wt. / .25 - .5 bone in funnel * 100 = % yield collagen).

Apatite (Inorganic Bone) Extraction Protocol

1. Label and weigh empty 15 ml plastic centrifuge tubes (without lid). Weights should be accurate to 0.1 mg.

2. Place 100 mg powder in the labeled, pre-weighed 15 ml plastic centrifuge tubes.

3. Add ~12 ml 50% Clorox (sodium hypochlorite - NaOHCl) solution. Agitate with vortex. Let sit overnight; vortex occasionally.

4. Centrifuge 5 minutes & decant Clorox; add 12 ml fresh 50% Clorox; let reaction continue and vortex occasionally. Change Clorox twice daily until effervescence ceases. This may take several days.

5. Centrifuge 5 minutes & decant Clorox. Add 12 ml distilled water, centrifuge 5 minutes and decant water. Rinse at least four times. Check pH of one sample with test strip and centrifuge again if pH is not neutral or Clorox odor is detected.

6. Add 12 ml 1M acetic acid; vortex; let reaction continue for 4-6 hours. Very fresh bone, soft bones (e.g. vertebrae & cancellous bone) and immature bones in general dissolve in 1M acetic so shorter treatment times are preferable for modern bones. Archaeological bones are much more resistant to dissolution.

7. Centrifuge 5 minutes & decant; add 12 ml distilled water. Repeat four times. Check pH of one sample with test strip and centrifuge until pH is neutral and no acetic acid odor is detected.

8. Freeze dry.

9. Reweigh centrifuge tube; calculate % yield apatite.

Chapter VI. Results of Isotopic Composition of Food Resources

To better interpret and understand the diet of past human populations, it is important to have knowledge of the local or regional food web. In order to evaluate the hypotheses presented in Chapter I, this research includes the isotopic analyses of modern plants and animals, and archaeological faunal bone from Thailand. Interpretations of these data in terms of human diet are discussed in Chapter VII.

Precision of Stable Isotope Analyses

The accuracy and precision of isotopic compositions of materials analyzed are based on reference standards and repeated analyses of samples, respectively. Glycine and Acetenilide are used as internal lab standards for collagen analyses. National Bureau of Standards, NBS-18 NBS-19, as well as an internal standard of sodium bicarbonate ($NaCO_3$) are used to determine the accuracy for carbonate analyses. Periodic analysis of reference materials throughout sample analysis was used to check for instrumentation drift and also to measure accuracy.

Before the stable isotopic values obtained can be interpreted, the precision of the samples was assessed. The precision of sample analysis was determined by duplicate or triplicate analyses of random samples. The collagen and apatite chemical extraction procedure was the same for each bone sample.

For bone collagen, six samples were analyzed in duplicate and three samples in triplicate, indicating a precision of ±0.2‰ for both $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values. Based on duplicate analysis of 17 samples, the precision for $\delta^{13}C_{apatite}$ measurements was ±0.2‰.

Plant Foods

Modern plants are used since floral samples from archaeological contexts in Southeast Asia are very rare and do not encompass the numerous edible plants (wild and domestic) available in the region. A total of 89 C_3 and C_4-type plants from 41 different species were collected and isotopically analyzed. C_3-type plants (N=83) include cereals (n=34), fruits (n=15), legumes (n=8), tubers (n=4), and vegetables (n=22). C_4-type cereals (N=6) that potentially were part of the prehistoric human diet include millet and Job's Tears. A wide variety of rice is also included in order to assess isotopic variability among wild, glutinous, and non-glutinous varieties. All samples except for YEN002[9], YEN006, YEN011, YEN016, YEN017 originate from northeast Thailand, primarily in and around the present day village of Ban Chiang. These C_4-type plants are utilized since this group of plants is uncommon in northeast Thailand but may have been utilized in the past. A single rice sample, PIR, was collected from Phimai Mai, near the sites of Ban Lum Khao and Noen U-Loke.

Table 6.1 provides the descriptive statistics for C_3 and C_4 plant groups sampled. A complete list of the values for the plant samples can be found in Appendix A. When the $\delta^{13}C$‰ and $\delta^{15}N$‰ values for the plants are plotted against one another (Figure 6.1), the data cluster into two distinct groups based on their $\delta^{13}C$ values. C_3 photosynthetic plants have a wide range of carbon and nitrogen variation. The average $\delta^{13}C$ and $\delta^{15}N$ values for C_3 plants are -25.1‰ and +6.0‰ respectively. The average $\delta^{13}C$ and $\delta^{15}N$ values for C_4 plants, utilizing six samples from four species are -8.1‰ and 4.5‰ respectively. A single sample of Job's Tears has a higher than expected $\delta^{15}N$ value which is most likely

[9] These samples were collected by Douglas Yen.

attributed to natural fertilizers that would have enriched the surrounding soil with nitrogen. Figure 6.2 separates the $\delta^{13}C$‰ and $\delta^{15}N$‰ values by type of food. The food type with the greatest range of $\delta^{13}C$‰ values is the C_3-type cereal plants. Fruits have the greatest range of $\delta^{15}N$‰ values.

Overall, the data exhibit the generally accepted pattern of $\delta^{13}C$ variation, with C_3 plants demonstrating greater variation than C_4 plants (O'Leary 1981, 1988; Smith and Epstein 1971). These results are also similar to C_3 and C_4 plants analyzed from island Southeast Asia (Krigbaum 2001).

The nitrogen values are more difficult to interpret, as there is not much in the literature on expected stable nitrogen values for plants. Nitrogen values for plants fall between -1.5 and 13.0‰. If a human population subsisted only on plants their stable nitrogen isotope signature should fall 2‰ above that of the average value of their plant diet. For $\delta^{15}N$ values, there may be external forces at work that would enrich the stable isotopic values. There is the possibility that some plant species are affected by the application of agricultural fertilizers that then inundate ground water or surface run-off. Artificial fertilizers are uncommon in much of northeast Thailand, but animals such as oxen and water buffalo roam freely and their excrement is used to fertilize fields. This may cause some plants to have higher $\delta^{15}N$ values than what might normally be associated for a particular plant species. Perhaps further research stemming from these results will help explain the nitrogen results obtained here.

Northeast Thailand has a long history of primarily glutinous rice (sticky rice) consumption (Fukui 1978, 1993). Archaeological evidence suggests that rice cultivation was a major source of carbohydrates in northeast Thailand by at least 2000 B.C. and

became the dominant intensified crop by approximately 500 B.C. In total, 34 samples of rice were collected and analyzed. These samples include glutinous (n=22), non-glutinous (n=7), and wild rice varieties (4), and one species of *Orzya sativa* of unknown type (Table 6.2). The purpose is to document if there is isotopic variation between different types of rice. As expected, wild rice varieties have the largest standard deviation for $\delta^{13}C$ since they live in the most varied environments (Figure 6.3). Glutinous rice samples have the largest $\delta^{15}N$ values which may or may not be a result of fertilizers.

Table 6.1. Summary statistics for $\delta^{13}C$ for modern plant samples from northeast Thailand partitioned by photosynthetic type.

Stable Isotope	Pathway	Food Type	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C$‰[b]	C_3	Cereal	34	-24.8	-26.2	-23.4	2.8	0.1	0.6	0.4
		Fruit	15	-25.5	-30.6	-21.2	9.4	0.7	2.7	7.4
		Legume	8	-23.8	-25.7	-22.0	3.7	0.5	1.3	1.6
		Tuber	4	-27.4	-29.3	-23.8	5.5	1.2	2.5	6.0
		Vegetable	22	-25.2	-28.3	-21.4	6.9	0.4	1.9	3.6
	C_4	Cereal	6	-8.1	-8.3	-7.5	0.8	0.1	0.3	0.1
	C_3 Total		**83**	**-25.1**	**-30.6**	**-21.2**	**9.4**	**0.2**	**1.8**	**3.2**
	C_4 Total		**6**	**-8.1**	**-8.3**	**-7.5**	**0.8**	**0.1**	**0.3**	**0.1**
$\delta^{15}N$‰	C_3	Cereal	34	6.4	1.6	10.7	9.1	0.3	1.8	3.4
		Fruit	15	8.0	0.0	13.0	13.0	1.2	4.5	20.5
		Legume	8	2.5	-1.5	7.2	8.7	1.1	3.2	10.5
		Tuber	4	7.0	3.6	8.9	5.3	1.2	2.4	5.6
		Vegetable	22	5.2	-1.1	11.4	12.5	0.8	3.8	14.3
	C_4	Cereal	6	4.5	1.3	11.7	10.4	1.6	3.9	15.3
	C_3 Total		**83**	**6.0**	**-1.5**	**13.0**	**14.5**	**0.4**	**3.4**	**11.9**
	C_4 Total		**6**	**4.5**	**1.3**	**11.7**	**10.4**	**1.6**	**3.9**	**15.3**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance.

[b] $\delta^{13}C$‰ values corrected (+1.5‰) for the atmospheric changes in carbon composition according to Marino and McElroy (1991) and Tieszen and Fagre (1993).

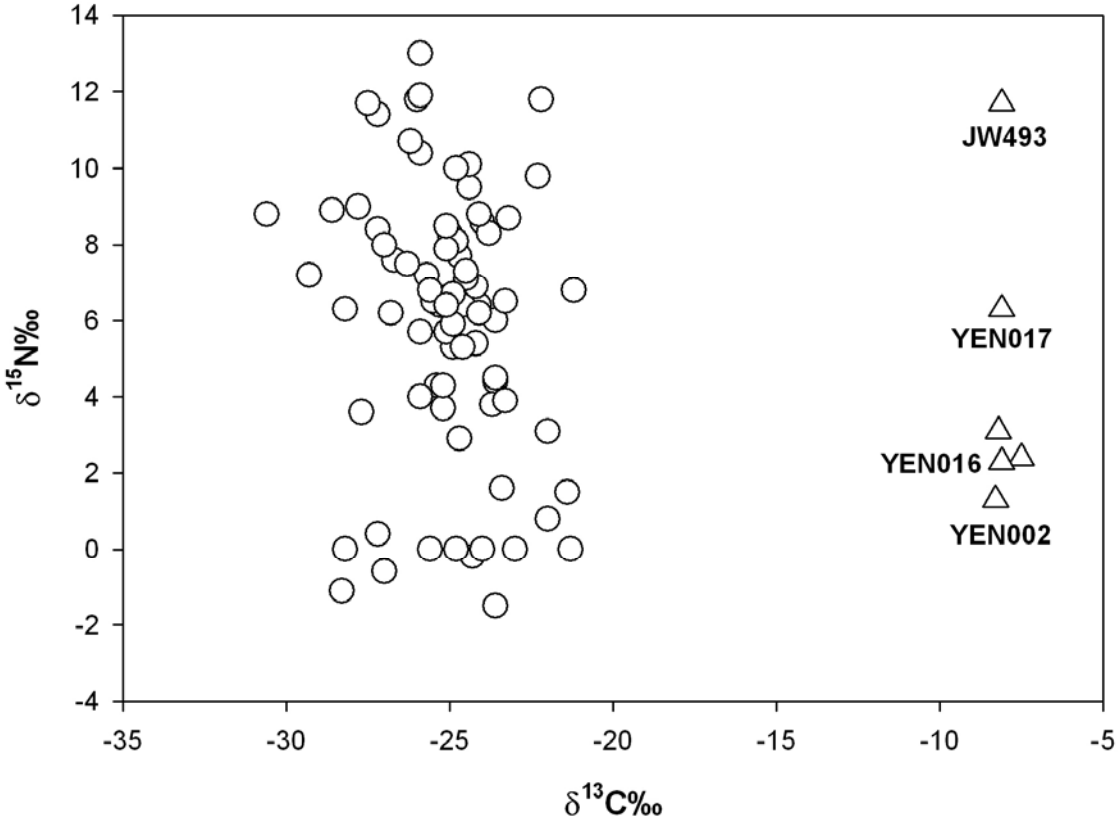

Figure 6.1. $\delta^{13}C$ and $\delta^{15}N$ values for modern plant samples from Thailand: ○ C_3-type plants; △ C_4-type plants. $\delta^{13}C$‰ values corrected (+1.5‰) for the atmospheric changes in carbon composition.

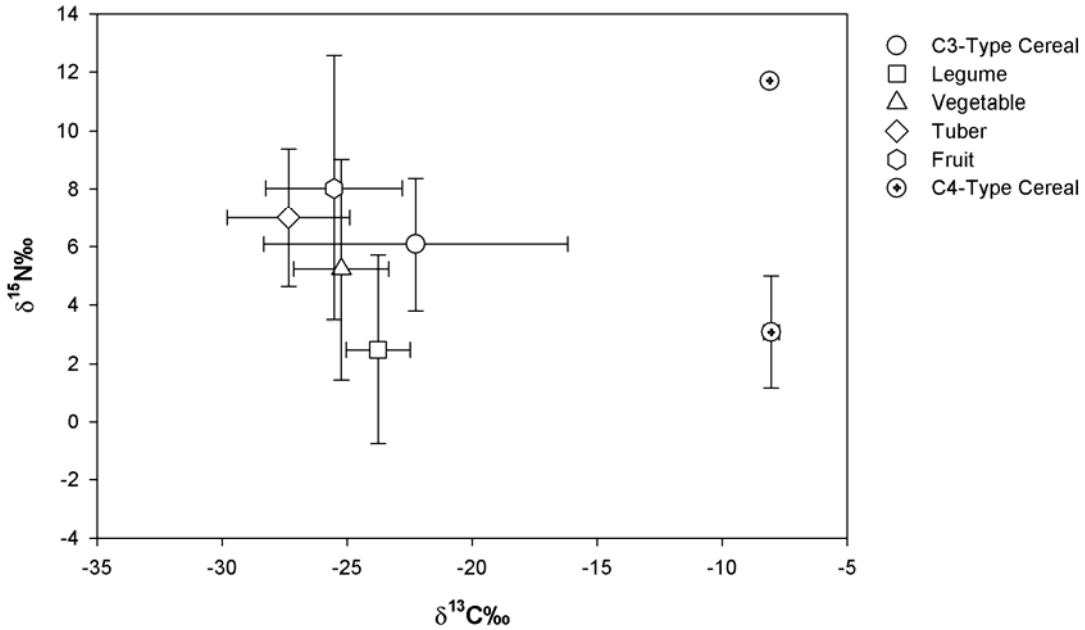

Figure 6.2. $\delta^{13}C$ and $\delta^{15}N$ mean values with one standard deviation for modern plant samples from Thailand by food type. $\delta^{13}C$‰ values corrected (+1.5‰) for the atmospheric changes in carbon composition.

Table 6.2. Summary statistics for $\delta^{13}C$ and $\delta^{15}N$ values for modern rice samples from northeast Thailand.

Scientific Name	Stable Isotope	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
Glutinous Varieties									
Oryza sativa	$\delta^{13}C$[b]	22	-24.7	-26.2	-23.4	2.8	0.1	0.6	0.4
	$\delta^{15}N$	22	6.5	1.6	10.7	9.1	0.4	2.1	4.3
Non-Glutinous Varieties									
Oryza sativa	$\delta^{13}C$	7	-24.8	-25.5	-24.1	1.4	0.2	0.6	0.3
	$\delta^{15}N$	7	6.6	4.3	8.8	4.5	0.5	1.3	1.8
Wild Varieties									
Oryza nivara	$\delta^{13}C$	2	-25.2	-25.9	-24.6	1.3	0.7	0.9	0.9
	$\delta^{15}N$	2	4.7	4.0	5.3	1.3	0.7	0.9	0.9
Oryza rufipogon	$\delta^{13}C$	1	-25.6	-25.6	-25.6	---	---	---	---
	$\delta^{15}N$	1	6.8	6.8	6.8	---	---	---	---
Oryza sp.	$\delta^{13}C$	1	-23.6	-23.6	-23.6	---	---	---	---
	$\delta^{15}N$	1	4.5	4.5	4.5	---	---	---	---
Total	$\delta^{13}C$	4	-24.9	-25.9	-23.6	2.3	0.5	1.1	1.1
	$\delta^{15}N$	4	5.2	4.0	6.8	2.8	0.6	1.2	1.5
Unknown Variety									
Oryza sativa	$\delta^{13}C$	1	-25.1	-25.1	-25.1	---	---	---	---
	$\delta^{15}N$	1	6.4	6.4	6.4	---	---	---	---
Overall Total									
Total	$\delta^{13}C$	34	-24.8	-26.2	-23.4	2.8	0.1	0.6	0.4
	$\delta^{15}N$	34	6.4	1.6	10.7	9.1	0.3	1.8	3.4

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

[b] $\delta^{13}C$‰ values corrected (+1.5‰) for the atmospheric changes in carbon composition according to Marino and McElroy (1991) and Tieszen and Fagre (1993).

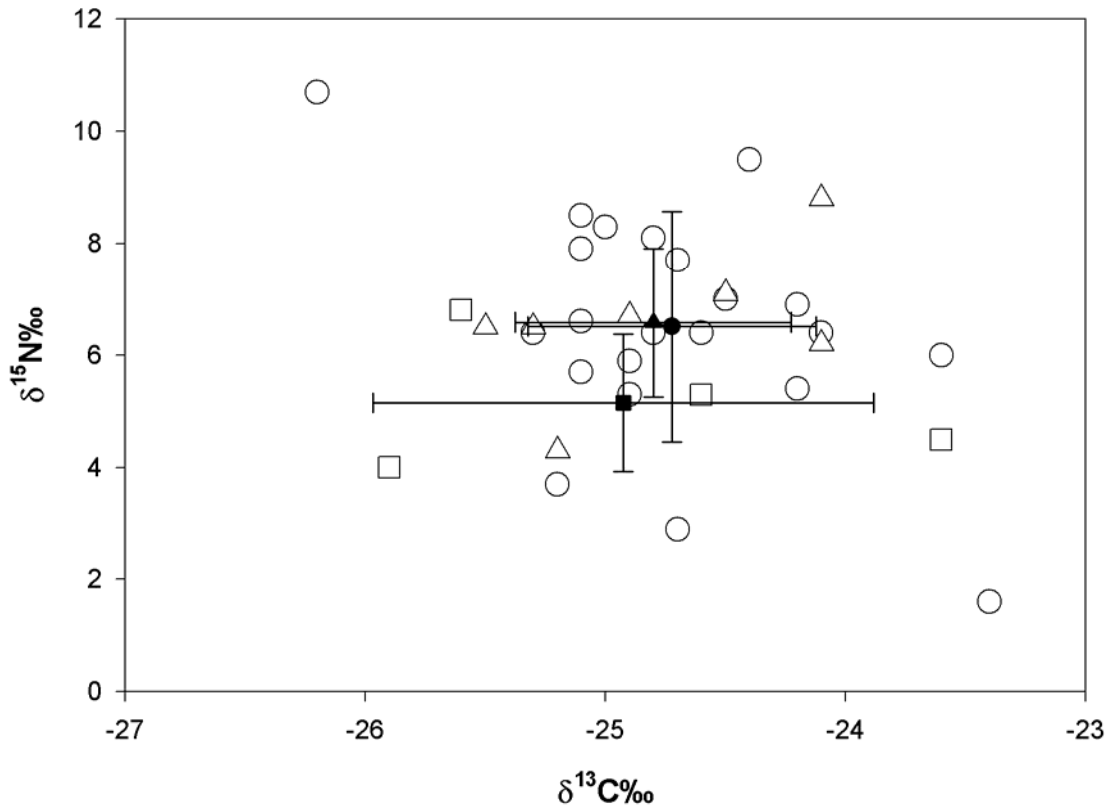

Figure 6.3. δ^{13}C‰ and δ^{15}N‰ values for modern rice samples from northeast Thailand including mean range values with one standard deviation: ○ Glutinous Rice; △ Non-Glutinous Rice; □ Wild Rice; ● Glutinous Rice Range; ▲ Non-Glutinous Rice Range; ■ Wild Rice Range.

Meat Foods

Modern tissue samples

As described in Chapter V, a different approach had to be taken to estimate $\delta^{13}C$ and $\delta^{15}N$ values for edible protein resources that typically are not either recoverable or usable from archaeological samples. A select sample of insects, frog, river fish, eel, and snails were analyzed and used to estimate prehistoric values. Details of the preparation of the samples were discussed in Chapter V.

The modern flesh values of $\delta^{13}C$ and $\delta^{15}N$ are consistent with diets from C_3-type environments (Table 6.3). The eel and fish species values are very consistent and suggest very little difference between pond and shallow river environments in the area. The two separate snail species have very different $\delta^{15}N$ values, mostly attributable to different environments, since one is a water snail and the other is a land snail.

Using modern flesh samples as proxies for food resources in the past is not without complications, since both $\delta^{13}C$ and $\delta^{15}N$ values of organisms from northeast Thailand may have changed since prehistoric times. It is possible that changes have occurred in specific locales, since influence by anthropogenic CO_2 is greater in shallow water and near the outlets of rivers. Because the amount of carbon is variable depending on local conditions no correction factors are applied in this study. As well, the baseline $\delta^{15}N$ may have moved in either direction on the local level as a response to human activity. Discharge of fertilizer nitrogen from farmland would be expected to cause lower baseline $\delta^{15}N$ values; discharge of sewage would be expected to lead to higher values. While the effect of fertilization and other factors may have changed the $\delta^{13}C$ and $\delta^{15}N$ values of

these modern samples compared to their prehistoric ancestors, these values are the only possible link to certain prehistoric food resources and thus are used this is study.

Table 6.3. $\delta^{13}C$ and $\delta^{15}N$ values of modern faunal tissue from northeast Thailand.

Type	Common Name	Scientific Name	$\delta^{13}C$‰	$\delta^{15}N$‰
Crab	Crab	---	-21.7	7.4
Eel	Swamp Eel	Monopterus alba	-21.0	7.3
Fish	Air-breathing Catfish	Clarias sp.	-20.3	8.0
	Climbing Perch	Anabas testudineus	-20.7	7.2
	Snakehead murrel	Ophicephalus striatus	-25.8	8.0
Frog	Frog	Rana sp.	-22.8	7.6
Snail	Pond snail, River snail	Sinotaia ingallsiana	-29.1	7.3
	Snail	Pila ampullacea	-21.8	1.1
Insect	Beetle, Water	Lethocerus indicus	-22.5	7.4
	Silk Worms	Bombyx mori	-28.3	10.1

Faunal bone samples

Skeletal samples of both modern and archaeological fauna were analyzed to provide a biogeographical baseline for understanding prehistoric diet. These include 57 modern and 90 archaeological faunal samples. All modern samples passed tests for sample quality and are included in the analysis (Appendix C.1). Of the 90 archaeological samples, only 47 (54.4%) passed tests for sample quality (Appendix C.2).

Summary descriptive statistics for $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$ from bone collagen for both modern and archaeological fauna are provided in Table 6.4. These samples are a broad selection of animals found in Thailand, however, only a few faunal specimens are consistently found in the archaeological record. These include different types of deer, pig (wild and domestic), fish, shellfish, chicken, cattle, water buffalo, and rat (Table 6.5).

In order to compare potential differences over time, archaeological samples which cover both time periods were analyzed for diet change (Table 6.5). Statistical analysis of mean values for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values between each time period did not reveal any significant differences in dietary patterns for these fauna. As a result, the archaeological samples are combined along with modern fauna as one dataset.

Figure 6.4 provides a reflection of the type of diet these animals were consuming. Animals consuming diets dominated by C_3 resources have relatively negative $\delta^{13}C$ values, such as the rat, pig, and dog. The $\delta^{15}N$ values for the dog, turtle, and rat indicate the consumption of a high percentage of animal flesh in their diets.

The primary deer species recovered from archaeological sites in Thailand are the *Muntiacus muntjak* (small browser), *Cervus unicolor* (large browser), and *Cervus eldi* (large grazer). The *Muntiacus muntjak* is considered a small/medium size deer (~15-20kg) while the *Cervus unicolor* is a larger variety (150-300kg). The *Muntiacus muntjak* is a true browser living in forested conditions and eating a mixture of leaves, fruits, and twigs. *Cervus unicolor* on the other hand is more opportunistic and is considered a mixed browser/grazer. They are adaptable to forest browsing of leaves, fruit, and the bark of trees, but also to grazing on grasses when in open plains. *Cervus eldi* (100-150kg) on the other hand is principally a grazing deer of medium/large size that stays in the forest fringe during the day but feeds in open spaces or along riverbanks at night. While they primarily graze on grass they are also known to eat fruits.

The isotopic values for deer are interesting as there are not only differences in the dietary patterns between browsers and grazers, but also differences between the types of

browser species. The smaller browser (*Muntiacus muntjak*) has herbivore values for an animal consuming a range of plant foods. The grazer (*Cervus eldi*) and the large browser (*Cervus unicolor*) show evidence of a diet mainly of C_4-type grasses which are commonly found in open plains environments.

Bovid isotopic values are a little unexpected considering six of eight specimens are identified as water buffalo (*Bos*) and there is one unknown variety. Of these seven water buffalo, six are archaeological specimens with two from the second millennium B.C. and four from the first millennium B.C (Table 6.5). The stable isotopic values for these archaeological water buffalo samples indicate they were not consuming rice plants in paddy fields but were consuming open plain grasses of the C_4 variety.

There are two varieties of fish that yielded stable isotope data from archaeological bone samples. These are the air-breathing catfish (*Clarias* sp.) and the climbing perch (*Anabas testudineus*). Both varieties eat a mixture of aquatic plants, small fish, and insect larvae. $\delta^{15}N$ values for these fish reflect this omnivorous lifestyle.

Table 6.4. Summary statistics for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values of bone collagen from modern and archaeological faunal samples from Thailand (N=104).

Animal		N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
Bat	$\delta^{13}C_{collagen}$	2	-19.7	-19.9	-19.4	0.5	0.3	0.4	0.1
	$\delta^{15}N_{collagen}$	2	8.2	7.6	8.8	1.2	0.6	0.8	0.7
Bird	$\delta^{13}C_{collagen}$	10	-18.7	-21.4	-14.2	7.2	0.7	2.2	4.8
	$\delta^{15}N_{collagen}$	10	9.8	7.9	13.4	5.5	0.6	2.0	4.0
Bos	$\delta^{13}C_{collagen}$	8	-10.6	-12.6	-9.2	3.4	0.4	1.2	1.3
	$\delta^{15}N_{collagen}$	8	7.2	5.9	9.1	3.2	0.5	1.4	1.9
Cat	$\delta^{13}C_{collagen}$	3	-19.0	-19.6	-18.3	1.3	0.4	0.7	0.4
	$\delta^{15}N_{collagen}$	3	8.5	7.5	9.9	2.4	0.7	1.3	1.6
Chicken	$\delta^{13}C_{collagen}$	4	-20.2	-21.6	-16.3	5.3	1.3	2.6	6.7
	$\delta^{15}N_{collagen}$	4	7.9	6.7	10.7	4.0	0.9	1.9	3.5
Civet	$\delta^{13}C_{collagen}$	4	-18.7	-20.2	-15.6	4.6	1.1	2.1	4.5
	$\delta^{15}N_{collagen}$	4	9.2	8.3	10.5	2.2	0.5	0.9	0.9
Deer, *Cervus eldi*	$\delta^{13}C_{collagen}$	2	-11.3	-12.4	-10.1	2.3	1.2	1.6	2.6
	$\delta^{15}N_{collagen}$	2	5.8	5.6	6.0	0.4	0.2	0.3	0.1
Deer *Cervus unicolor*	$\delta^{13}C_{collagen}$	4	-9.2	-10.1	-8.6	1.5	0.4	0.7	0.5
	$\delta^{15}N_{collagen}$	4	4.7	4.5	5.0	0.5	0.1	0.2	0.0
Deer *Muntiacus muntjak*	$\delta^{13}C_{collagen}$	7	-16.3	-22.4	-10.4	12.0	2.0	5.2	27.4
	$\delta^{15}N_{collagen}$	7	5.0	4.6	5.5	0.9	0.1	0.3	0.1
Deer, unknown species	$\delta^{13}C_{collagen}$	3	-10.4	-11.9	-7.7	4.2	1.4	2.3	5.5
	$\delta^{15}N_{collagen}$	3	5.1	4.0	6.1	2.1	0.6	1.1	1.1
Dog	$\delta^{13}C_{collagen}$	9	-18.2	-21.0	-16.9	4.1	0.5	1.5	2.2
	$\delta^{15}N_{collagen}$	9	9.5	7.6	13.3	5.7	0.6	1.9	3.7
Fish	$\delta^{13}C_{collagen}$	3	-15.6	-17.2	-14.6	2.6	0.8	1.4	2.0
	$\delta^{15}N_{collagen}$	3	6.9	6.2	7.6	1.4	0.4	0.7	0.5
Frog	$\delta^{13}C_{collagen}$	6	-17.8	-21.2	-15.3	5.9	0.8	2.0	4.0
	$\delta^{15}N_{collagen}$	6	9.4	7.0	12.0	5.0	0.8	1.9	3.5
Monkey	$\delta^{13}C_{collagen}$	5	-20.3	-20.7	-19.1	1.6	0.3	0.7	0.5
	$\delta^{15}N_{collagen}$	5	6.0	4.5	7.6	3.1	0.6	1.4	1.8
Pig	$\delta^{13}C_{collagen}$	13	-17.5	-22.7	-9.4	13.3	1.2	4.2	17.4
	$\delta^{15}N_{collagen}$	13	7.0	4.4	10.4	6.0	0.5	1.8	3.3
Rat	$\delta^{13}C_{collagen}$	7	-18.9	-21.3	-16.7	4.6	0.6	1.7	2.7
	$\delta^{15}N_{collagen}$	7	8.0	5.4	10.7	5.3	0.7	1.9	3.6
Snake	$\delta^{13}C_{collagen}$	1	-15.4	-15.4	-15.4	---	---	---	---
	$\delta^{15}N_{collagen}$	1	13.9	13.9	13.9	---	---	---	---
Squirrel	$\delta^{13}C_{collagen}$	5	-20.4	-20.7	-19.9	0.8	0.1	0.3	0.1
	$\delta^{15}N_{collagen}$	5	5.7	3.6	7.1	3.5	0.6	1.3	1.6
Turtle	$\delta^{13}C_{collagen}$	8	-19.1	-26.8	-12.9	13.9	1.6	4.6	21.5
	$\delta^{15}N_{collagen}$	8	10.3	4.4	13.3	8.9	0.9	2.7	7.1
Overage Average	$\delta^{13}C_{collagen}$	104	-17.1	-26.8	-7.7	19.1	0.4	4.1	17.1
	$\delta^{15}N_{collagen}$	104	7.8	3.6	13.9	10.3	0.2	2.4	5.8

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

Table 6.5. Summary statistics for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values of bone collagen from common archaeological faunal from Thailand.

Type	Millennium	Count	Yield (%)	Carbon (%)	Nitrogen (%)	C/N Ratio	$\delta^{13}C$ (‰)	$\delta^{15}N$ ‰
Bos	Second	2	7.6	38.8	13.9	3.2	-9.3	6.5
	First	4	5.8	34.3	12.5	3.2	-10.5	6.6
Deer, unknown species	Second	2	4.0	19.3	6.9	3.3	-9.7	4.6
	First	1	-9.3	14.9	5.3	3.3	-11.9	6.1
Deer *Cervus unicolor*	Second	1	8.1	40.2	14.4	3.3	-8.7	4.7
	First	3	4.0	26.5	9.7	3.2	-9.4	4.7
Deer *Muntiacus muntjak*	Second	2	3.3	15.5	5.5	3.3	-15.1	5.2
	First	4	3.2	15.2	5.5	3.2	-15.5	5.0
Dog	Second	2	3.9	11.3	4.0	3.3	-17.7	8.2
	First	5	2.7	17.3	6.3	3.2	-17.8	9.8
Pig	Second	3	5.5	28.9	10.5	3.2	-16.5	7.0
	First	5	4.0	22.1	8.0	3.3	-18.0	8.2
Rat	Second	2	3.9	17.7	6.4	3.2	-18.1	7.7
	First	1	3.6	17.3	6.2	3.3	-16.7	7.9
Turtle	Second	1	4.1	7.7	2.7	3.3	-19.8	10.0
	First	3	2.3	11.7	4.3	3.2	-16.7	8.5
Second Millennium Total		**15**	**4.9**	**22.6**	**8.1**	**3.3**	**-14.5**	**6.7**
First Millennium Total		**26**	**3.6**	**20.8**	**7.6**	**3.2**	**-15.0**	**7.3**
Overall Average		**41**	**4.1**	**21.5**	**7.8**	**3.2**	**-14.8**	**7.1**

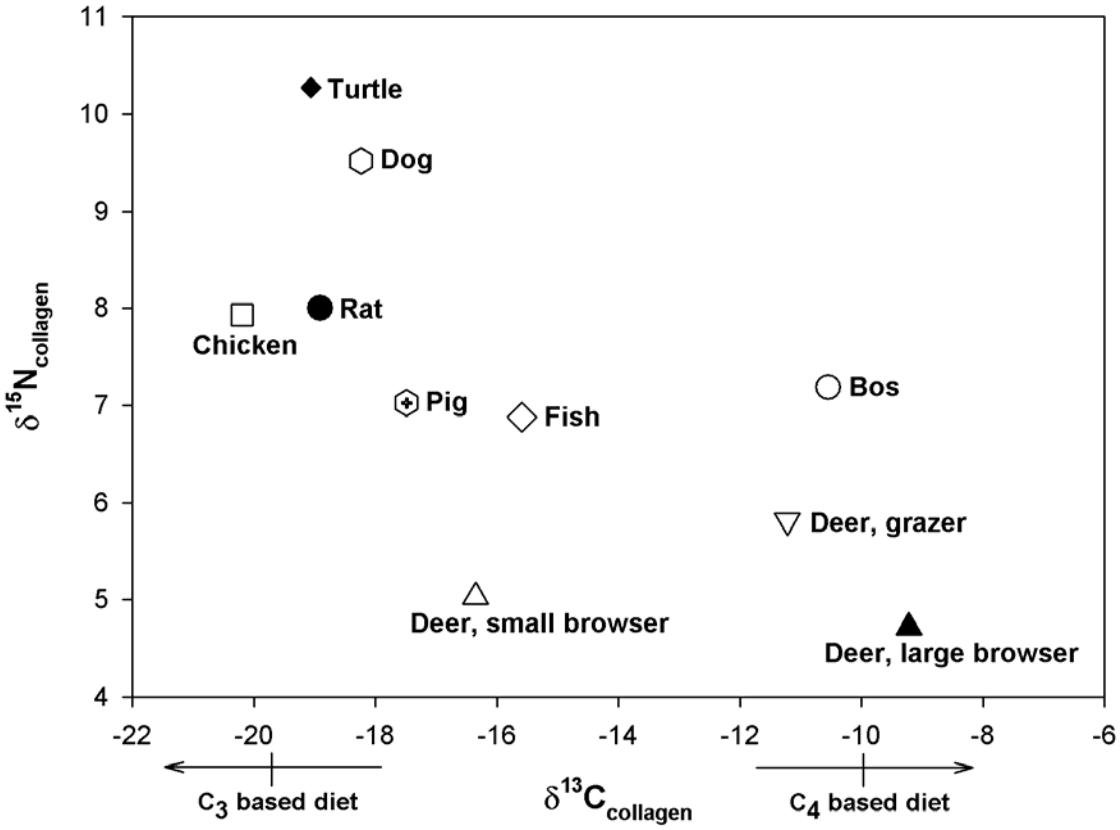

Figure 6.4. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from common archaeological fauna recovered in northeast Thailand.

Summary

The data for modern plants as well as modern and archaeological faunal presented in this chapter. The modern plant data demonstrated distinct stable isotopic variation in $\delta^{13}C$ values for C_3 and C_4-type plants. With one exception, $\delta^{15}N$ values were typical of terrestrial plants. The animal samples represent samples collected from Thailand.

The largest terrestrial faunal resources available in prehistoric northeast Thailand were the deer and pig. Stable isotope data from the deer indicate distinct dietary patterns. Since grazers (*Cervus eldi*) almost exclusively eat only grass, it was not surprising to find the stable isotopic values in the C_4 plant range because many types of grass fall into this category. The $\delta^{13}C$ values for the large browsers (*Cervus unicolor*) were unexpected since this type of deer has a mixed grass/shrubbery diet. The strong C_4 signature from this deer suggests mostly open plains dietary patterns away from forests. The $\delta^{13}C$ values from the small browsers (*Muntiacus muntjak*) demonstrated what would be expected for browsers which would be predominately consuming C_3 plants. Also unexpected were the values from the Bos samples. Like the large browser, these too indicated diets which were predominately based on C_4 plants.

Further discussion of these plant and animal data are presented in Chapter VIII in the context of understanding the overall changes in the diet of prehistoric human inhabitants of northeast Thailand.

Chapter VII. Stable Isotope Results from Prehistoric Human Samples

The stable isotopic ratios of 178 human skeletal samples from four archaeological sites in northeast Thailand are analyzed. These archaeological sites are in Sakon Nakhon Basin (Ban Chiang and Ban Na Di) and the Khorat Basin (Ban Lum Khao and Noen U-Loke) and were occupied for more than two millennia. Sites from the second millennium B.C. include Ban Chiang and Ban Lum Khao. Sites from the first millennium B.C. include Ban Chiang, Ban Na Di, and Noen U-Loke. The stable isotope data from human bone collagen and bone apatite are presented in Appendix C. To test the integrity of the skeletal material, the % carbon by weight and % nitrogen by weight for collagen were determined, and the C/N ratios for collagen were calculated, as were the % yield for collagen and % yield for apatite. Of the 178 individuals analyzed, 83 (47%) had values outside acceptable ranges (Appendix C).

This chapter presents the results of the isotopic analysis for each site, along with an examination of sex differences if possible. Because of Ban Chiang's long temporal span and large sample size, additional analyses to investigate dietary changes over time are included.

Ban Chiang Human Samples

Sample integrity

The human skeletal remains from Ban Chiang are well preserved. Ban Chiang is a unique archaeological site as it is currently the only well documented site in northeast Thailand which was occupied for a span of two millennia. Of the sampled sites, Ban Chiang has the highest percentage (83.5%) of bone samples passing quality tests for

preservation (66 out of 79). Thirteen individuals failed to meet standards for sample integrity (Appendix C, Table C.1). BC08 and BC19 were the only individuals excluded because of poor collagen yield. Ten individuals were excluded due to poor carbon and nitrogen percent values for collagen (BC01, BC02, BC06, BC07, BC09, BC17, BC22, BC27, BC30, and BC35). One individual (BCES40) was excluded from carbon apatite analyses due to failure to produce $\delta^{13}C_{apatite}$ values. Lastly, one additional sample was eliminated as an outlier. This female (BC16), dating to the second millennium B.C., met all of the above sample integrity criteria but her stable isotopic values are far outside the ranges of all other samples at Ban Chiang and are even outside the ranges at the other three sites. Some type of diagenic contamination is suggested though it is possible the individual had a very different diet, particularly since the $\delta^{13}C$ measured in tooth enamel carbonate from this individuals was the lowest (i.e., most depleted in ^{13}C) of all Ban Chiang individuals sampled by Bentley and colleagues (2005:Table 2).

Temporal variation

Sexes combined

There are 46 individuals from the second millennium B.C. and 20 from the first millennium B.C. (Table 7.1). The smaller number of individuals from the first millennium B.C. is the result of availability of adult individuals from this time period and not preservation. A total of 14 individuals were excluded from further stable isotopic analysis (seven individuals from each millennium) because of poor sample integrity.

Stable isotopic results

Descriptive statistics for the $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ of bone collagen, $\delta^{13}C_{apatite}$ for bone apatite, and the spacing between $\delta^{13}C$ values for bone collagen and bone ($\Delta^{13}C_{apatite-collagen}$) are provided in Table 7.1. While the mean values for each of the variables indicates very little difference between the time periods, the ranges suggest there are a few outlier individuals (BC31, BC41, BCES03, and BCES23) with dietary patterns distinct from the whole sample within each time period (Figure 7.1). The range of $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values between the second and first millennium B.C. are similar (Figure 7.1). The overall $\delta^{13}C_{collagen}$ values range from -16.8‰ to -20.5‰ and the overall $\delta^{15}N_{collagen}$ values range from 8.5‰ to 11.2‰ (Table 7.3). Such values strongly suggest a predominately terrestrial food base supplemented with freshwater resources.

To further refine the degree of variation within a time period, the variance is calculated (Table 7.1). The variance is the average sum of squared deviations from the mean. The variances between the second and first millennium B.C. are very similar for all variables, although the greater variance in the $\delta^{13}C_{apatite}$ values suggests more variability in carbohydrate than protein sources within each of the time periods. Figure 7.2 also demonstrates a greater dispersion in $\delta^{13}C_{apatite}$ values than in $\delta^{15}N_{collagen}$ values, further illustrating more variety in carbohydrates than in protein foods.

The spacing between the $\delta^{13}C$ values for bone collagen and apatite are provided in order to make the comparison between the $\delta^{13}C$ for the two tissues (Figure 7.3). These values indicate a predominately C_3 based diet regime. Figure 7.3 also illustrates the

greater variability in $\delta^{13}C_{apatite}$ values than in $\delta^{13}C_{collagen}$ values indicating individuals from both time periods consumed a wide variety of carbohydrate sources.

$\Delta^{13}C_{apatite\text{-}collagen}$ values have their greatest variance also during the second millennium B.C., which is not surprising considering the larger variance in $\delta^{13}C_{apatite}$ values during this time period. The overall mean difference is 5.3±1.5 with a range of 2.1 to 8.9. The mean $\Delta^{13}C_{apatite\text{-}collagen}$ values between the two time periods suggest a temporal trend in which diet from protein is becoming more depleted in ^{13}C relative to the overall diet. This suggests a change over time in which protein ($\delta^{13}C_{collagen}$) is more negative than carbohydrates. A possible scenario for this could be an increased consumption of plants grown in open field agricultural system making the carbohydrates more positive along with an increased consumption of terrestrial protein.

In Figure 7.4, the wider dispersion of $\delta^{15}N_{collagen}$ values during the second millennium B.C. also indicates a wider range of protein sources. This suggests the first millennium people were consuming animals with less varied diets than the second millennium people, though individuals in both time periods supplemented their diets with freshwater fish. This greater variation in protein in the diet during the second millennium is also shown in Table 7.1 which indicates twice the amount of variance from the first millennium. The Mann Whitney U-test however shows this variation is not significantly different between time periods for any stable isotopic variable when sexes are combined.

Table 7.1. Summary statistics for Ban Chiang human remains.

	Millennium	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Second	46	-18.5	-19.5	-16.8	2.7	0.1	0.6	0.4
	First	20	-18.5	-20.5	-16.9	3.6	0.2	0.7	0.5
	Total	**66**	**-18.5**	**-20.5**	**-16.8**	**3.7**	**0.1**	**0.6**	**0.4**
$\delta^{15}N_{collagen}$	Second	46	10.1	8.5	11.2	2.7	0.1	0.6	0.4
	First	20	10.3	9.5	11.0	1.5	0.1	0.4	0.2
	Total	**66**	**10.1**	**8.5**	**11.2**	**2.7**	**0.1**	**0.6**	**0.3**
$\delta^{13}C_{apatite}$	Second	46	-13.3	-16.1	-9.9	6.2	0.2	1.1	1.3
	First	19	-12.9	-15.3	-10.9	4.4	0.3	1.3	1.7
	Total	**65**	**-13.2**	**-16.1**	**-9.9**	**6.2**	**0.1**	**1.2**	**1.4**
$\Delta^{13}C_{apatite-collagen}$	Second	46	5.2	2.1	8.9	6.8	0.2	1.5	2.1
	First	19	5.6	3.2	8.2	5.0	0.4	1.7	2.8
	Total	**65**	**5.3**	**2.1**	**8.9**	**6.8**	**0.2**	**1.5**	**2.3**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance.

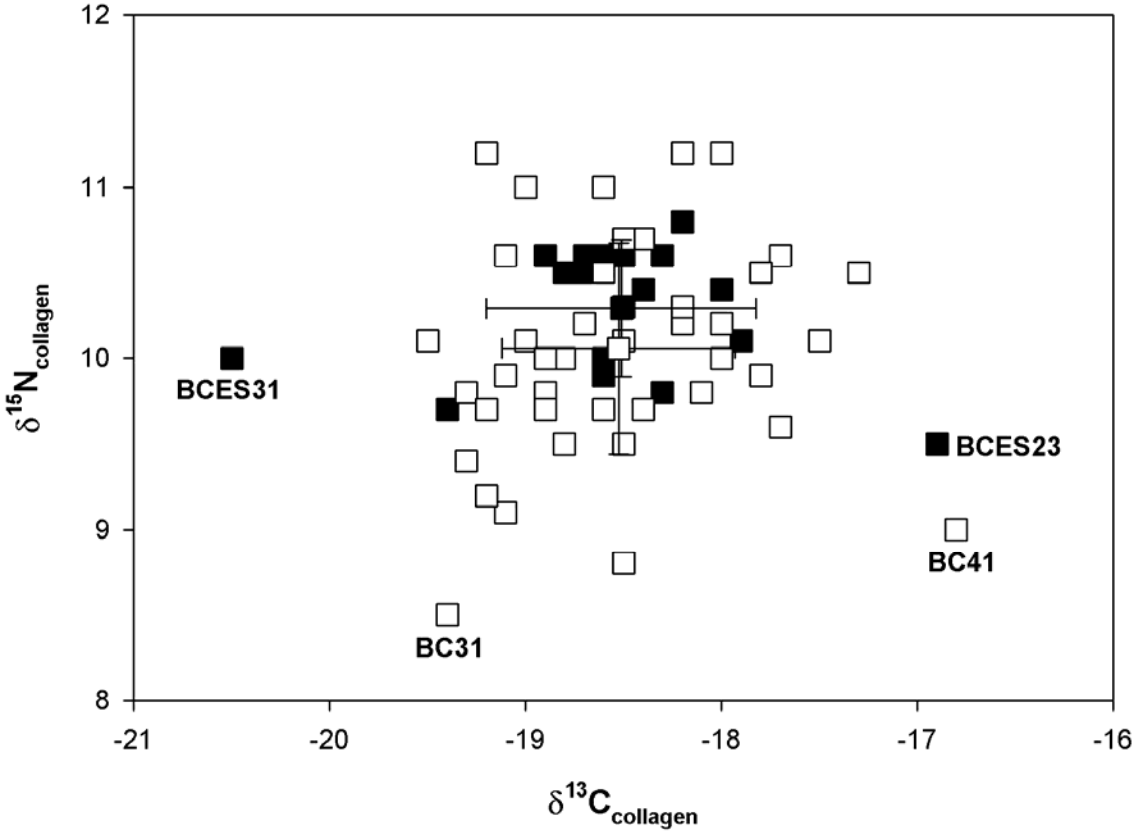

Figure 7.1. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang including mean range values with one standard deviation by time: □ Second Millennium B.C.; ■ First Millennium B.C.

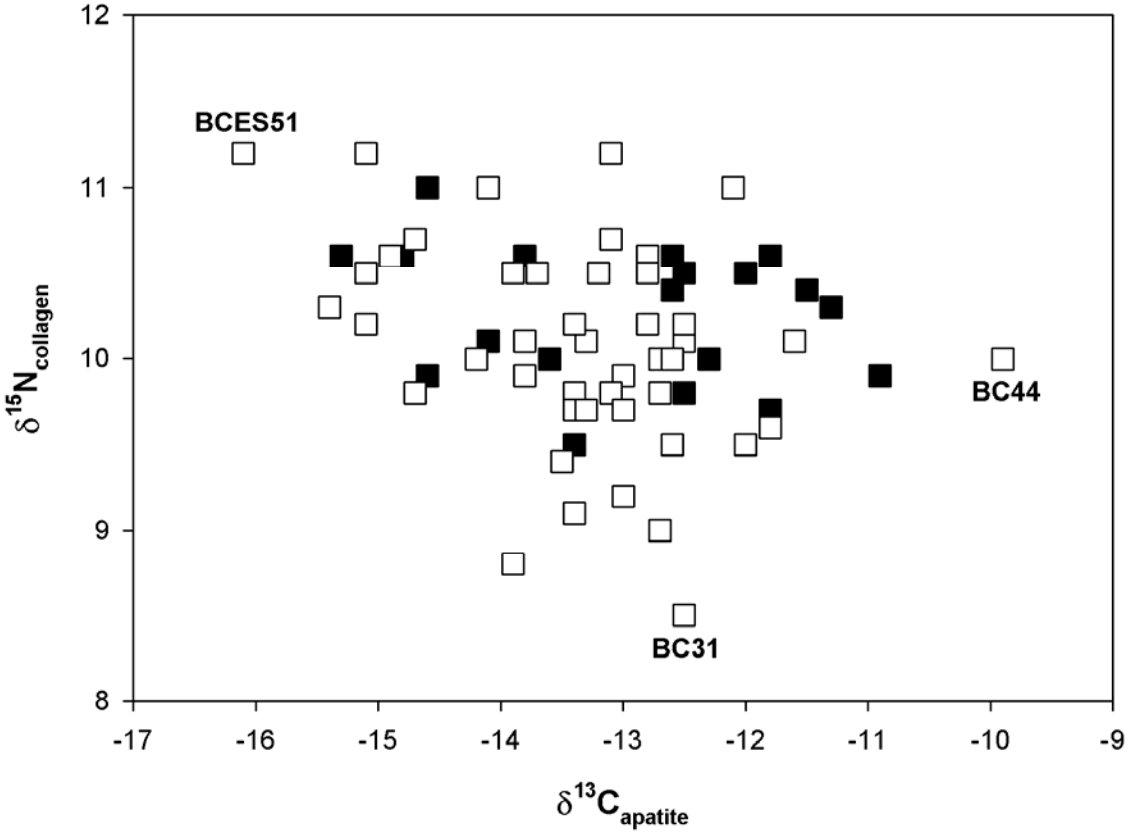

Figure 7.2. $\delta^{13}C_{apatite}$ versus $\delta^{15}N_{collagen}$ values from Ban Chiang by time: □ Second Millennium B.C.; ■ First Millennium B.C.

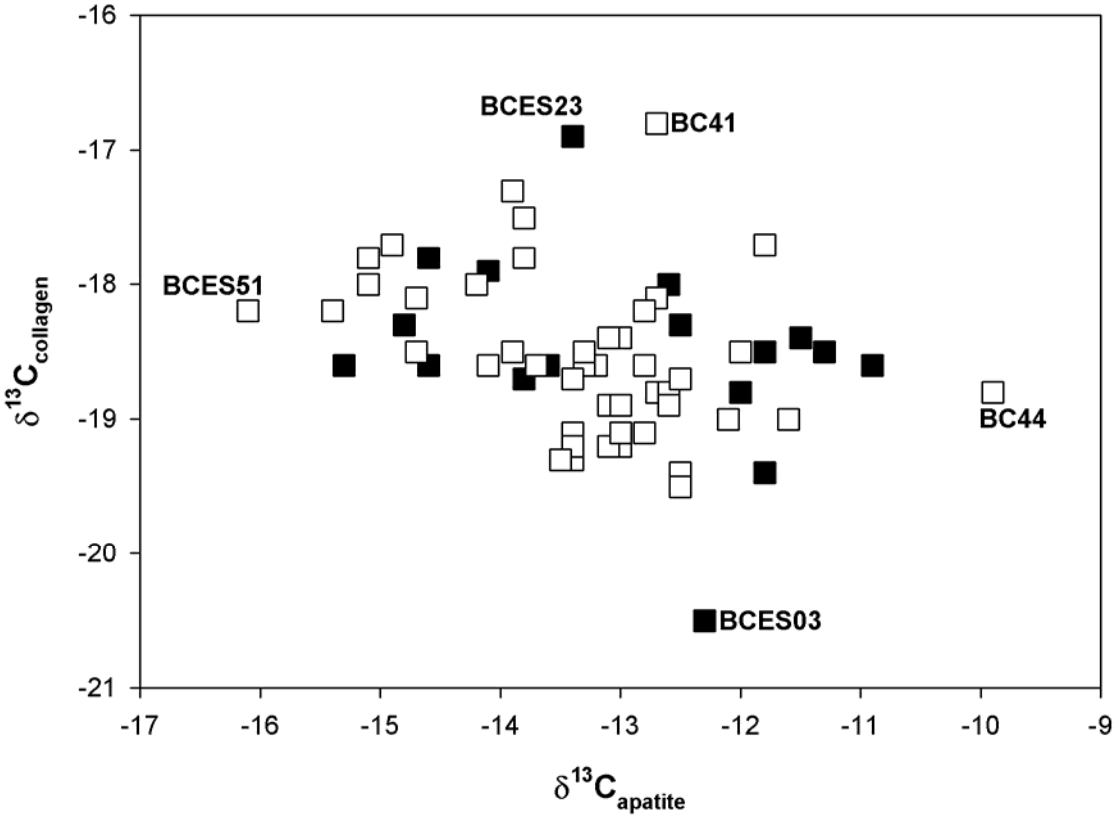

Figure 7.3. $\delta^{13}C_{apatite}$ spacing versus $\delta^{13}C_{collagen}$ values from Ban Chiang by time: □ Second Millennium B.C.; ■ First Millennium B.C.

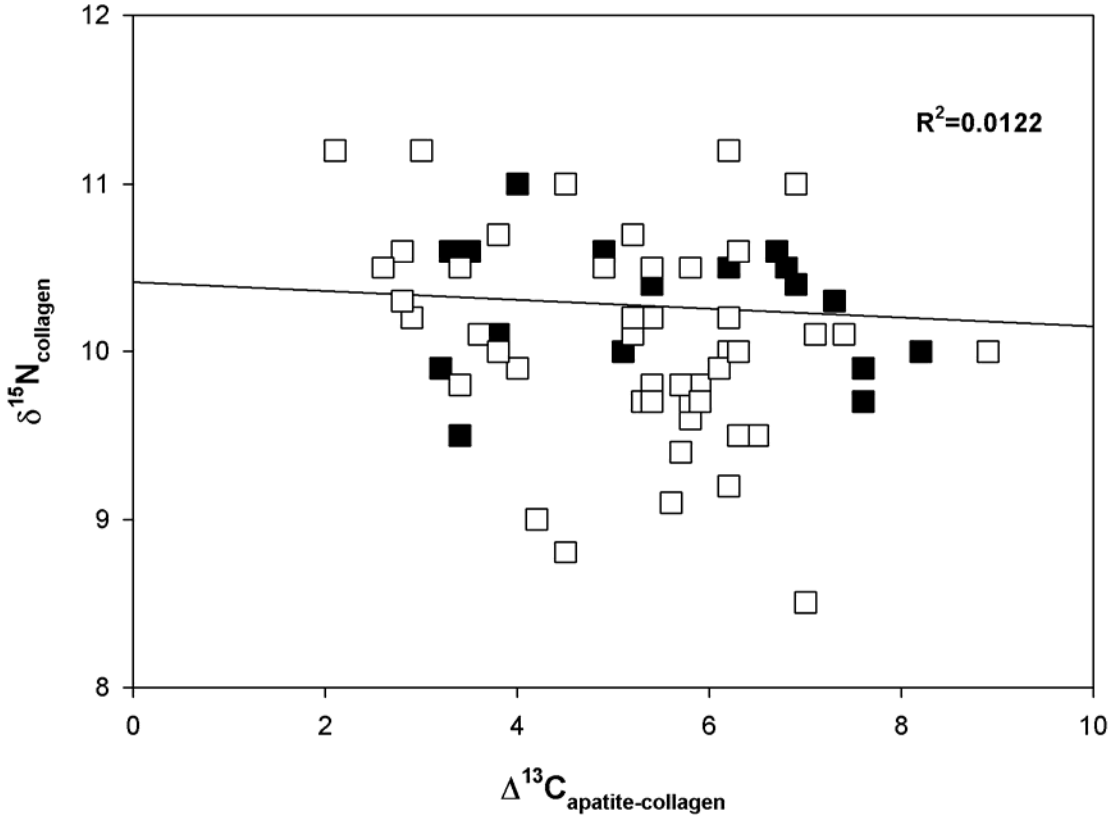

Figure 7.4. $\Delta^{13}C_{apatite-collagen}$ spacing versus $\delta^{15}N_{collagen}$ values from Ban Chiang by time: □ Second Millennium B.C.; ■ First Millennium B.C.

By sex

The previous section shows that there is no statistically significant temporal difference in Ban Chiang diets with the sexes combined. However, there are changes, as described above in reference to Table 7.1, and in the graphical analyses from Figures 7.1-7.4 to suggest wide individual dietary patterns within both time periods. In order to understand how diet may have changed over time, it is important to investigate the stable isotopic values between the sexes within each of the time periods. Tables 7.2 and 7.3 provide the descriptive statistics for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite-collagen}$ for females and males.

Females over time

There are 20 females from the second millennium B.C. and nine from the first millennium B.C. in the Ban Chiang sample (Table 7.2). Again, the smaller sample from the first millennium B.C. is the result of availability of adult individuals from this time period and not preservation. Mann-Whitney U-tests did not reveal any statistically significant differences for any stable isotopic variable in females between the second and first millennium B.C. Graphical analyses also suggest similar stable isotopic variability between these two time periods (Figures 7.5-7.8). There is a larger spread of individual variation for female $\delta^{15}N_{collagen}$ values in the second millennium B.C. than in the first millennium B.C. (Figure 7.5). This represents a slightly greater diversity in protein sources during the second millennium B.C. $\delta^{13}C_{apatite}$ values change very little over time, although two individuals (BCES28 and BCES31) suggest a greater variety of

carbohydrate sources were consumed during the second millennium B.C. than during the first millennium B.C. (Figures 7.6).

This diversity of plant food consumption is further illustrated in Figure 7.7. By comparing the relationship between $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ it is clear that females in both time periods have wide overall dietary ranges in protein and carbohydrate sources. First millennium females have the largest scattering for both $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ with individuals from the first millennium having the largest separation of values. This large dispersion is also reflected in the difference in variance between the two time periods. First millennium B.C. females have twice the variance (dietary variation) as during the previous time period (Table 7.2).

Lastly, the $\delta^{15}N_{collagen}$ comparison to $\Delta^{13}C_{apatite\text{-}collagen}$ values demonstrates that protein sources between time periods are very similar, though the trend over time seems to be towards a less varied protein diet (Figure 7.8). The mean value from the $\Delta^{13}C_{apatite\text{-}collagen}$ data is 5.2±1.5 with the first millennium having the largest degree of dispersion among individuals. Based on the graphical positioning of $\Delta^{13}C_{apatite\text{-}collagen}$ values in Figure 7.8, five out of nine (55.6%) of first millennium females are located outside the range of monoisotopic diets (<4 or >7). This is contrary to second millennium females among which no individual has a $\Delta^{13}C_{apatite\text{-}collagen}$ value above 7 and only five out of 15 (33.3%) are below 4. While the sample size for first millennium females is small, the placement of individuals above and below the monoisotopic range suggests more varied food sources than in the second millennium.

Males over time

There are 26 males from the second millennium B.C. and 11 males from the first millennium B.C. in the Ban Chiang sample (Table 7.3). The mean and variance indicate very little overall dietary differences in males between these time periods. There is however a greater range of variation for all three stable isotopic values ($\delta^{13}C_{collagen}$, $\delta^{13}C_{apatite}$, and $\delta^{15}N_{collagen}$) during the second millennium than during the later period. This indicates more diversity in diet during the second millennium relative to the first millennium, but Mann-Whitney U-tests did not reveal any statistically significant differences.

The greater range of individual diets between each time period is presented in Figures 7.5-7.8. An inspection of Figures 7.5 and 7.6 clearly shows the more varied range of $\delta^{13}C_{apatite}$ values compared to $\delta^{13}C_{collagen}$. This greater range of values in $\delta^{13}C_{apatite}$ suggests males of both time periods were consuming a wide variety of plant foods with the possibility that some individuals, e.g., BC44, consumed both C_3 and C_4 plants. The other outlier (BCES51), with the most depleted $\delta^{13}C_{apatite}$ value, was also identified by Bentley and colleagues (2005:875-876) as having the lowest strontium isotope ratio in their human sample from Ban Chiang. This suggests that this male may have been a relative newcomer to the Ban Chiang village and died not too long after his arrival.

When comparing the male variation in $\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$ values, Figure 7.7 indicates that $\delta^{13}C_{apatite}$ varies more than $\delta^{13}C_{collagen}$. The tight clustering of $\delta^{13}C_{collagen}$ values suggest less diversity in animal food consumption compared to a wide variety of plant foods. The smaller degree of separation in carbon from protein sources is further

supported by comparing the $\delta^{15}N_{collagen}$ values to $\Delta^{13}C_{apatite\text{-}collagen}$ values (Figure 7.8). It is evident that protein sources are very similar in each time period, though the trend over time seems to be toward a less varied protein diet.

The mean value from the $\Delta^{13}C_{apatite\text{-}collagen}$ data is 5.4±1.5 with the largest degree of dispersion among individuals in the second millennium (Table 7.3). While most of the individuals from both time periods demonstrate similar monoisotopic diets, there are a few individuals with $\Delta^{13}C_{apatite\text{-}collagen}$ values above 7 or below 4. During the second millennium B.C., nine out of 26 individuals (35%) were outside of the monoisotopic range, while during the first millennium B.C., the number of individuals outside this range stays essentially the same at 40% (4 out of 10) (Figure 7.8). The smaller sample size may contribute to this higher range during the first millennium. These results suggest that males within a time period have varied diets with little change over time.

Table 7.2. Summary statistics for Ban Chiang females by time period.

	Millennium B.C.	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Second	20	-18.4	-19.4	-16.8	2.6	0.2	0.7	0.5
	First	9	-18.6	-20.5	-16.9	3.6	0.3	1.0	1.0
	Total	**29**	**-18.5**	**-20.5**	**-16.8**	**3.7**	**0.1**	**0.8**	**0.6**
$\delta^{15}N_{collagen}$	Second	20	9.8	8.5	11.2	2.7	0.2	0.7	0.5
	First	9	10.1	9.5	10.6	1.1	0.1	0.4	0.2
	Total	**29**	**9.9**	**8.5**	**11.2**	**2.7**	**0.1**	**0.6**	**0.4**
$\delta^{13}C_{apatite}$	Second	20	-13.4	-15.1	-11.8	3.3	0.2	1.0	0.9
	First	9	-12.9	-15.3	-11.5	3.8	0.4	1.3	1.7
	Total	**29**	**-13.3**	**-15.3**	**-11.5**	**3.8**	**0.2**	**1.1**	**1.2**
$\Delta^{13}C_{apatite-collagen}$	Second	20	5.0	2.8	7.0	4.2	0.3	1.3	1.7
	First	9	5.7	3.2	8.2	5.0	0.6	1.9	3.8
	Total	**29**	**5.2**	**2.8**	**8.2**	**5.4**	**0.3**	**1.5**	**2.4**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

Table 7.3. Summary statistics for Ban Chiang males by time period.

	Millennium B.C.	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Second	26	-18.6	-19.5	-17.3	2.2	0.1	0.5	0.2
	First	11	-18.4	-18.7	-17.9	0.8	0.1	0.3	0.1
	Total	**37**	**-18.6**	**-19.5**	**-17.3**	**2.2**	**0.1**	**0.4**	**0.2**
$\delta^{15}N_{collagen}$	Second	26	10.2	9.4	11.2	1.8	0.1	0.5	0.3
	First	11	10.4	9.9	11.0	1.1	0.1	0.3	0.1
	Total	**37**	**10.3**	**9.4**	**11.2**	**1.8**	**0.1**	**0.5**	**0.2**
$\delta^{13}C_{apatite}$	Second	26	-13.3	-16.1	-9.9	6.2	0.2	1.2	1.5
	First	10	-13.0	-14.8	-10.9	3.9	0.4	1.4	1.9
	Total	**36**	**-13.2**	**-16.1**	**-9.9**	**6.2**	**0.2**	**1.3**	**1.6**
$\Delta^{13}C_{apatite-collagen}$	Second	26	5.4	2.1	8.9	6.8	0.3	1.6	2.4
	First	10	5.5	3.5	7.6	4.1	0.5	1.5	2.1
	Total	**36**	**5.4**	**2.1**	**8.9**	**6.8**	**0.3**	**1.5**	**2.3**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

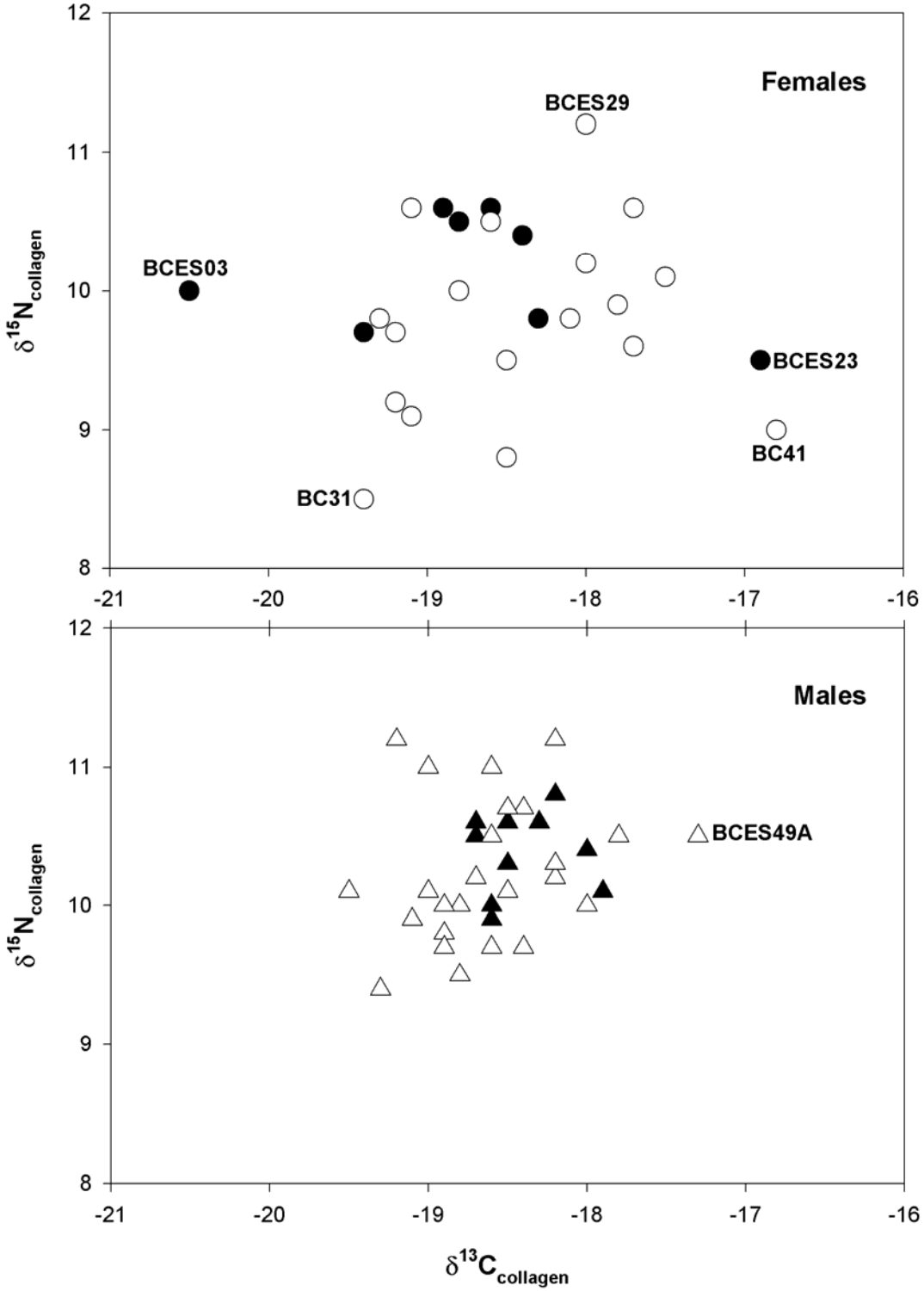

Figure 7.5. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

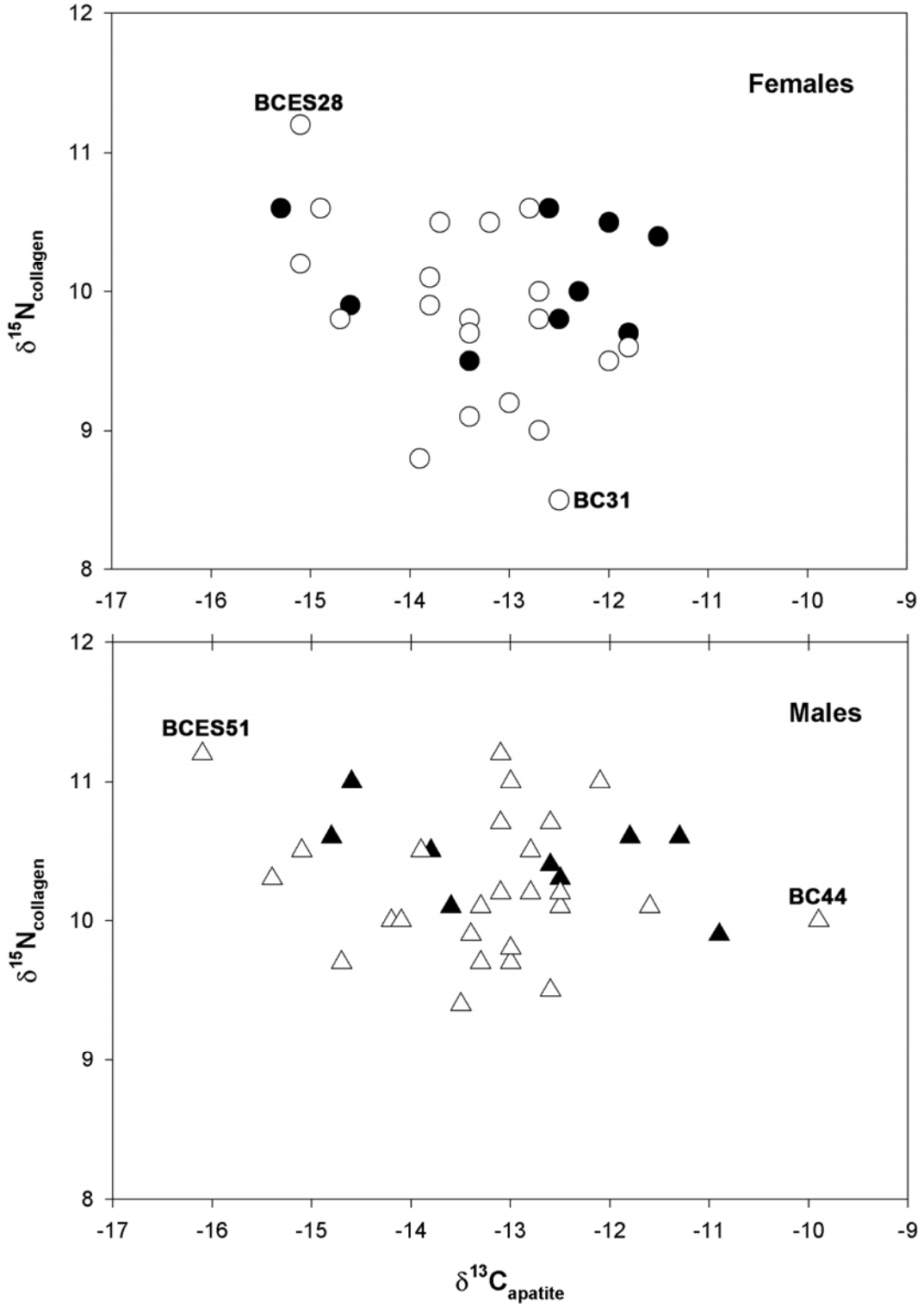

Figure 7.6. $\delta^{13}C_{apatite}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

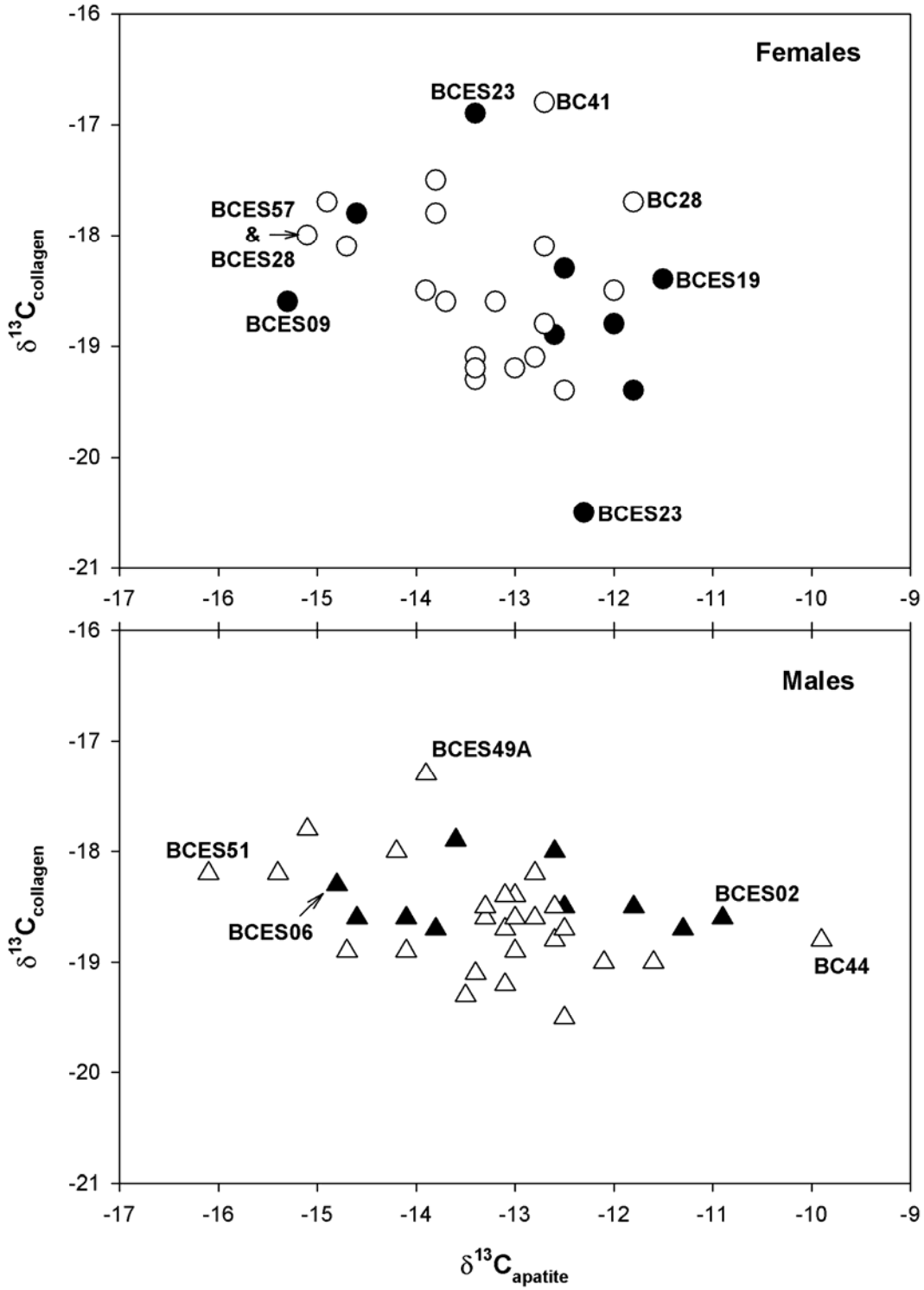

Figure 7.7. $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

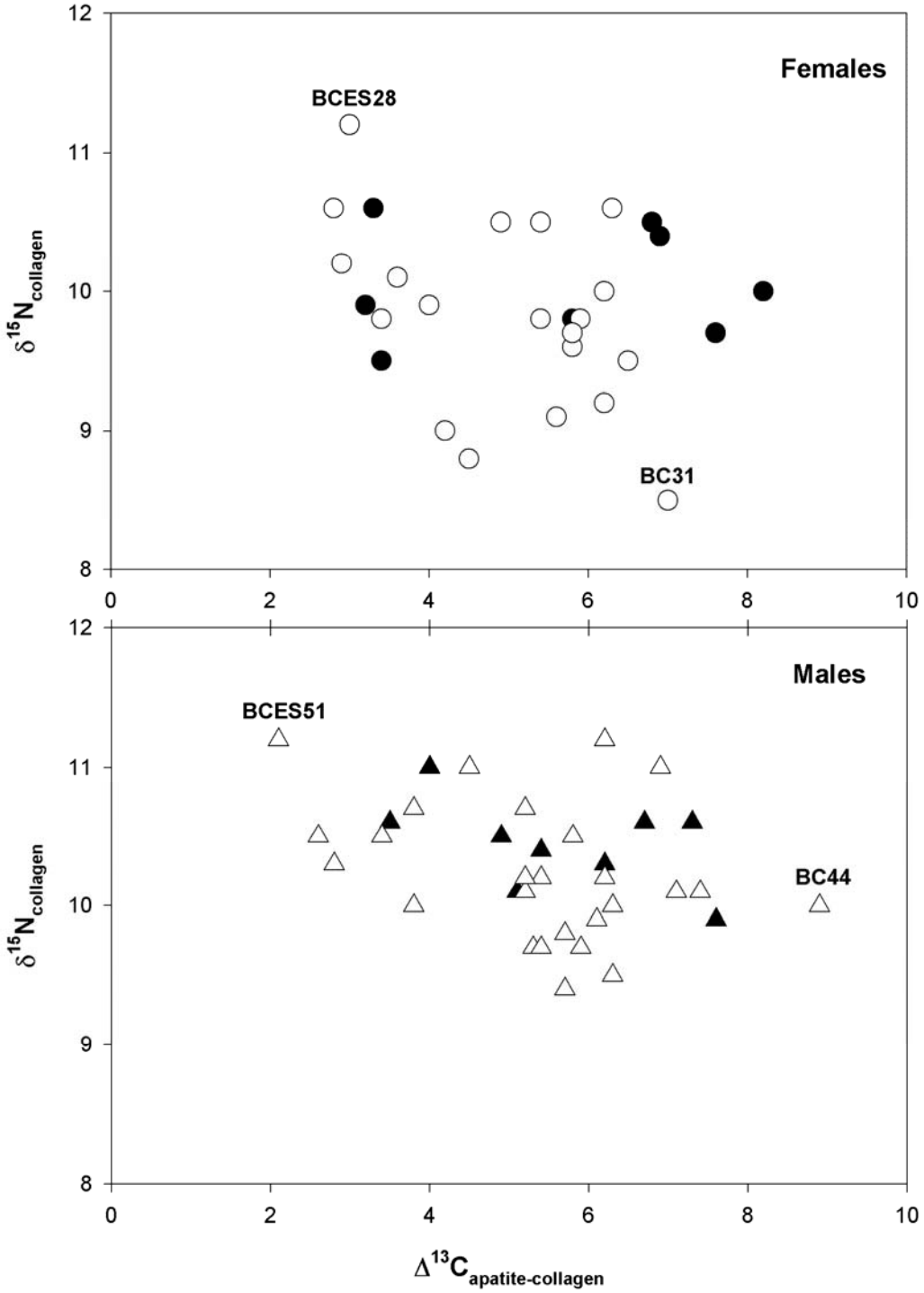

Figure 7.8. $\Delta^{13}C_{apatite\text{-}collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

Intra-Site Variation

As the only site investigated here with human individuals from both the second and first millennium B.C., Ban Chiang is used to examine the variation between these two time periods at one site. Tables 7.4 and 7.5 provide the descriptive statistics for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite\text{-}collagen}$ for each millennium, partitioned by sex.

Second millennium

The stable isotopic ranges shown in Table 7.4 for each of these variables demonstrate females (N=20) have a more varied diet than males (N=26). Mann-Whitney U-tests indicate there is a statistically significant difference between the sexes for $\delta^{15}N_{collagen}$ during this time period ($p \leq 0.038$). Graphical analyses also demonstrate greater variability for $\delta^{15}N_{collagen}$ in females relative to males (Figures 7.9 and 7.10). Carbon values from both $\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$ are also varied for both females and males, further indicating a diverse use of plant and animals resources (Figure 7.11).

The mean overall difference for $\Delta^{13}C_{apatite\text{-}collagen}$ values is 5.2±1.5 with values ranging from 2.1 to 8.9 (Table 7.4). While stable isotopic values for $\Delta^{13}C_{apatite\text{-}collagen}$ indicate both females and males had a monoisotopic diet, there is variation between the sexes (Figure 7.12). There were five out of 20 females with values below 4.0 and no females with values above 7.0. These five individuals have dietary protein enriched in ^{13}C relative to their overall diet. Males during this time period exhibit a slightly greater variation in $\Delta^{13}C_{apatite\text{-}collagen}$ values than females. There were six males with $\Delta^{13}C_{apatite\text{-}collagen}$ values less than 4.0 and three males with values greater than 7.0. Those individuals with values

above 7.0 have dietary protein depleted in ^{13}C, while those below 4.0 are enriched in ^{13}C relative to their overall diet (Ambrose and Norr 1993).

First millennium

Table 7.5 provides the descriptive statistics for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ with 20 individuals from the first millennium B.C. at Ban Chiang. From these 20 individuals, BCES40 failed to produce a $\delta^{13}C_{apatite}$ value, so only 19 individuals are available for $\delta^{13}C_{apatite}$ and $\Delta^{13}C_{apatite\text{-}collagen}$ analysis. These summary statistics indicate less variation between the sexes in the first millennium than in the prior millennium, which is also consistent with the reduced strontium variances observed by Bentley and colleagues (2005). This reduced variability may be related to smaller sample sizes. There is a large of variation among females in $\delta^{13}C_{collagen}$ values. This is evident in Figure 7.9 in which three females (BCES03, BCES75, and BCES23) are outside the main cluster of individuals. There is a clear consolidation of $\delta^{15}N_{collagen}$ values during this period for both sexes (Figure 7.10). The narrowing for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$, values with continued large variation in $\delta^{13}C_{apatite}$ values (Figures 7.10 and 7.11) suggests increased consumption of domesticated animals and less emphasis on wild game. The Mann-Whitney U-tests however do not indicate any significant difference in the variance of stable isotopic values between females and males during this time period.

The mean overall difference for $\Delta^{13}C_{apatite\text{-}collagen}$ values is 5.6±1.7 with values ranging from 3.2 to 8.2 (Table 7.5). While stable isotopic values for $\Delta^{13}C_{apatite\text{-}collagen}$ indicate both females and males had a monoisotopic diet, there is very little variation between the sexes (Figure 7.12). There are three females and two males with values below 4.0, and

two females and two males above 7.0. The overall diet between females and males remained diverse in plant consumption with a strong indication of increased domestic animal consumption during the first millennium B.C.

Table 7.4. Summary statistics for Ban Chiang human remains from the 2nd millennium B.C.

Millennium B.C.	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	20	-18.4	-19.4	-16.8	2.6	0.2	0.7	0.5
	Male	26	-18.6	-19.5	-17.3	2.2	0.1	0.5	0.2
	Total	**46**	**-18.5**	**-19.5**	**-16.8**	**2.7**	**0.1**	**0.6**	**0.4**
$\delta^{15}N_{collagen}$ ($p \leq 0.038$)	Female	20	9.8	8.5	11.2	2.7	0.2	0.7	0.5
	Male	26	10.2	9.4	11.2	1.8	0.1	0.5	0.3
	Total	**46**	**10.1**	**8.5**	**11.2**	**2.7**	**0.1**	**0.6**	**0.4**
$\delta^{13}C_{apatite}$	Female	20	-13.4	-15.1	-11.8	3.3	0.2	1.0	.9
	Male	26	-13.3	-16.1	-9.9	6.2	0.2	1.2	1.5
	Total	**46**	**-13.3**	**-16.1**	**-9.9**	**6.2**	**0.2**	**1.1**	**1.3**
$\Delta^{13}C_{apatite-collagen}$	Female	20	5.0	2.8	7.0	4.2	0.3	1.3	1.7
	Male	26	5.4	2.1	8.9	6.8	0.3	1.6	2.4
	Total	**46**	**5.2**	**2.1**	**8.9**	**6.8**	**0.2**	**1.5**	**2.1**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

Table 7.5. Summary statistics for Ban Chiang human remains from the 1st millennium B.C.

Millennium B.C.	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	9	-18.6	-20.5	-16.9	3.6	0.3	1.0	1.0
	Male	11	-18.4	-18.7	-17.9	0.8	0.1	0.3	0.1
	Total	**20**	**-18.5**	**-20.5**	**-16.9**	**3.6**	**0.2**	**0.7**	**0.5**
$\delta^{15}N_{collagen}$	Female	9	10.1	9.5	10.6	1.1	0.1	0.4	0.2
	Male	11	10.4	9.9	11.0	1.1	0.1	0.3	0.1
	Total	**20**	**10.3**	**9.5**	**11.0**	**1.5**	**0.1**	**0.4**	**0.2**
$\delta^{13}C_{apatite}$	Female	9	-12.9	-15.3	-11.5	3.8	0.4	1.3	1.7
	Male	10	-13.0	-14.8	-10.9	3.9	0.4	1.4	1.9
	Total	**19**	**-12.9**	**-15.3**	**-10.9**	**4.4**	**0.3**	**1.3**	**1.7**
$\Delta^{13}C_{apatite-collagen}$	Female	9	5.7	3.2	8.2	5.0	0.6	1.9	3.8
	Male	10	5.5	3.5	7.6	4.1	0.5	1.5	2.1
	Total	**19**	**5.6**	**3.2**	**8.2**	**5.0**	**0.4**	**1.7**	**2.8**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

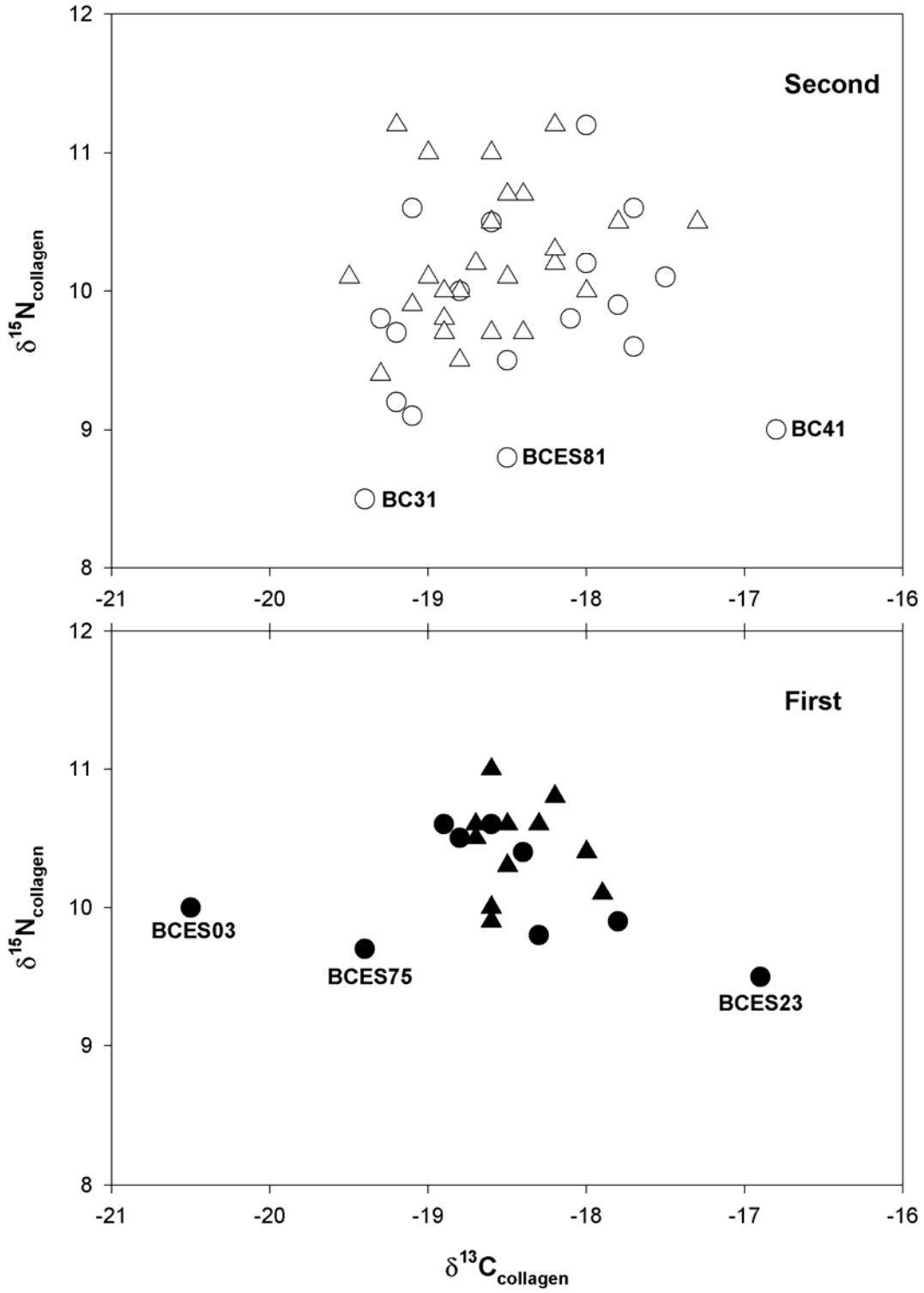

Figure 7.9. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

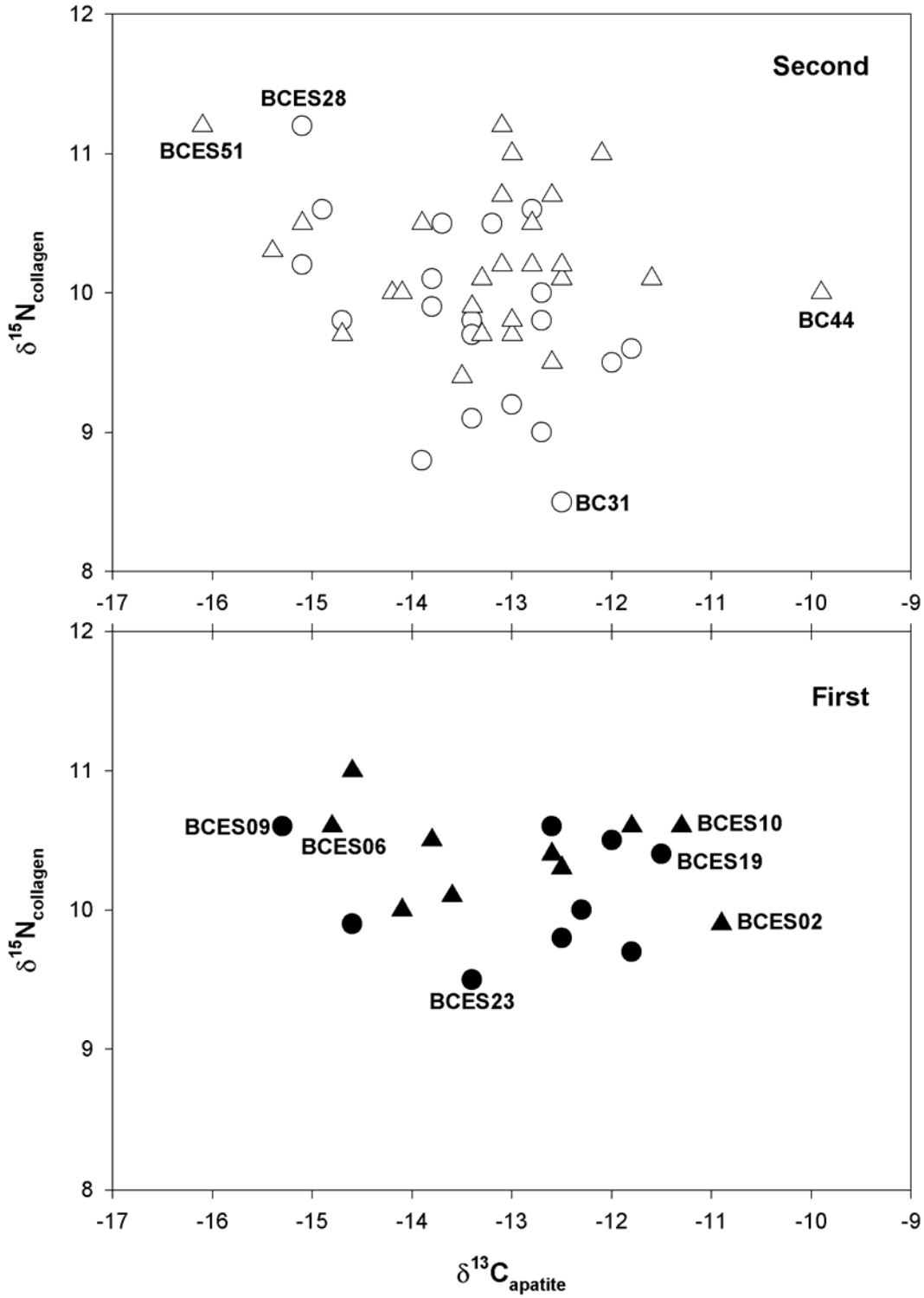

Figure 7.10. $\delta^{13}C_{apatite}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

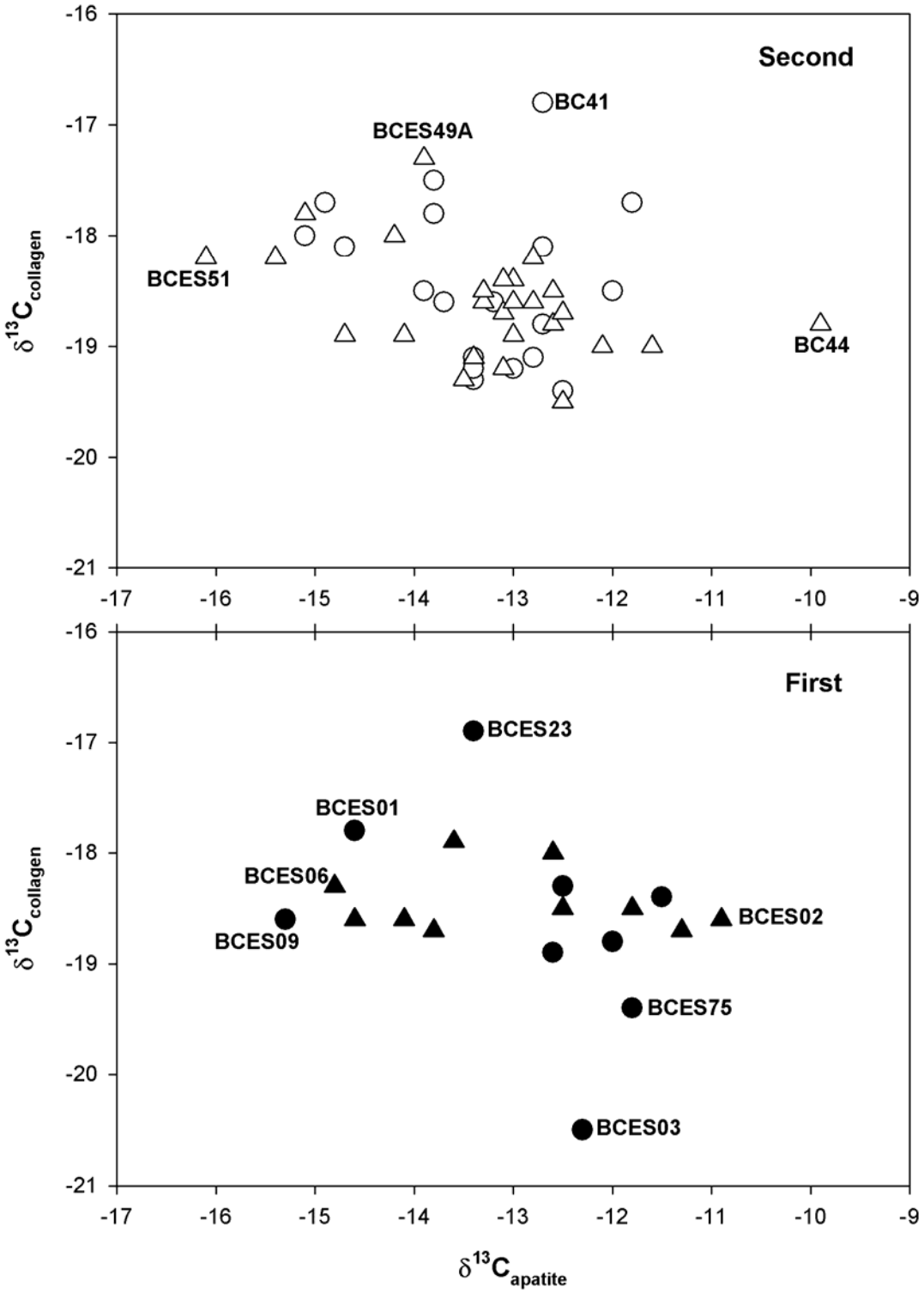

Figure 7.11. $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

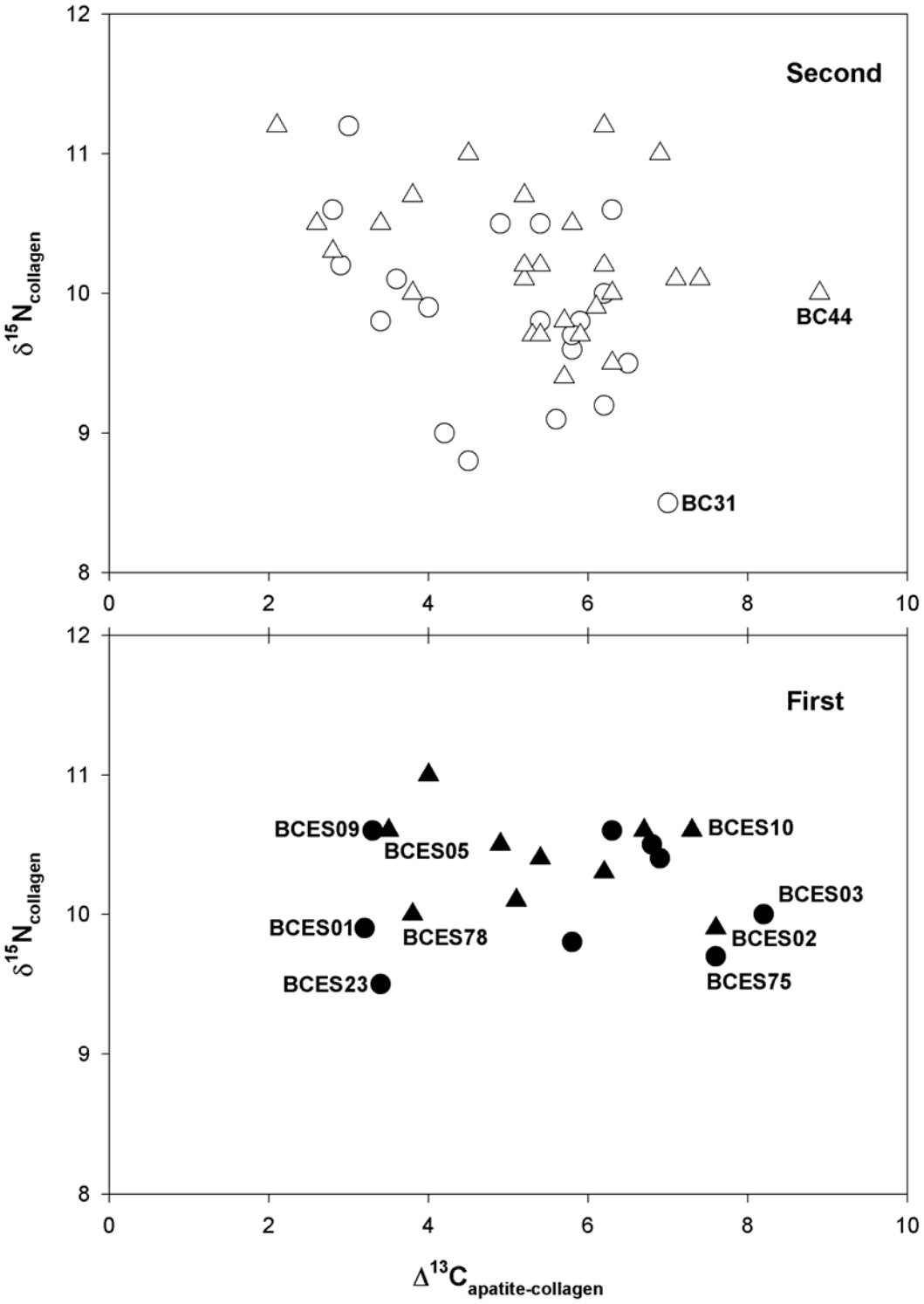

Figure 7.12. $\Delta^{13}C_{apatite\text{-}collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

Ban Na Di Human Samples

Sample integrity

The human remains from the Ban Na Di archaeological site appeared to be well preserved with 25/35 individuals (71.4%) producing viable stable isotope data for analysis. Of these 25 individuals, there are 12 females and 13 males. Ten samples were excluded from further paleodietary interpretations (Appendix C, Tables C.2). Of these ten excluded individuals, four (BND42, BND49, BNDT05, BNDT12) have poor carbon and nitrogen percent values for collagen, and four (BND35, BND37, BND39, BND47) have C/N ratios below the minimum value of 2.9. Lastly, two individuals (BND16, BND 32) yielded acceptable collagen data but were excluded from further analysis because the samples failed to produce a $\delta^{13}C_{apatite}$ values.

Stable isotopic results

Females have greater ranges of isotopic variation for $\delta^{13}C_{collagen}$ while males demonstrate greater variability in $\delta^{15}N_{collagen}$ values. $\Delta^{13}C_{apatite\text{-}collagen}$ values are used to investigate stable isotopic differences in protein and carbohydrates in the diet. From Table 7.6, the overall mean difference is 5.4 ± 0.3 for $\Delta^{13}C_{apatite\text{-}collagen}$ with values ranging from 2.3 to 9.2. $\Delta^{13}C_{apatite\text{-}collagen}$ values indicate that most of the individual values are between 4.0 and 7.0 indicating the consumption of protein and carbohydrates that are isotopically similar, and that C_3 plants were the dominant plant group consumed by both humans and animals. There are a few individuals with outlier values. One individual (BND01) has a larger $\Delta^{13}C_{apatite\text{-}collagen}$ value, while two individuals (BND15, BNDT20) have smaller $\Delta^{13}C_{apatite\text{-}collagen}$ values. Individuals with $\Delta^{13}C_{apatite\text{-}collagen}$ values less than 4

consumed dietary protein enriched in ^{13}C relative to their overall diet, while individuals with values greater than 7 have dietary protein depleted in ^{13}C relative to their overall diet. No statistically significant differences between the sexes are found for any of the isotope data (Table 7.6).

The range of $\delta^{13}C$ variation for $\delta^{13}C_{collagen}$ values compared to $\delta^{15}N_{collagen}$ values is displayed in Figure 7.13. Both females and males tend to have a wide range of variation in nitrogen values. Females appear to have a wider range of carbon values, mostly the result of one individual (BND48) who has a $\delta^{13}C_{collagen}$ value of -15.7‰. If this individual is eliminated, the range of variation for females $\delta^{13}C_{collagen}$ values drops from 3.2‰ to 1.4‰, nearly identical to the range of variation in males. In Figure 7.14, a broader range of $\delta^{13}C_{apatite}$ variation than $\delta^{15}N_{collagen}$ is demonstrated for both sexes, indicating a larger diversity of carbohydrates consumed than proteins consumed.

Figure 7.15 shows how much variation in carbon isotope values exist between $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values. The range of variation of $\delta^{13}C_{apatite}$ values is much greater than $\delta^{13}C_{collagen}$ values, though BND48 is clearly outside the $\delta^{13}C_{collagen}$ range for this sample. BND01, BNDT20, and BNDT15 are outside the main cluster for $\delta^{13}C_{apatite}$ values. Most of the variation in carbon values is attributable to diversity in carbohydrate consumption.

This conclusion is further supported in Figure 7.16. If isotopic values from protein sources contributed significantly to the $\Delta^{13}C_{apatite\text{-}collagen}$ variation then a correlation to $\delta^{15}N_{collagen}$ and $\Delta^{13}C_{apatite\text{-}collagen}$ would be apparent. The lack of correlation (R^2=0.0111) suggests females and males were consuming proteins from similar sources.

Table 7.6. Summary statistics for Ban Na Di human remains as a whole sample and partitioned by sex.

	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	12	-18.1	-18.9	-15.7	3.2	0.2	0.8	0.7
	Male	13	-18.2	-18.7	-17.5	1.3	0.1	0.4	0.2
	Total	**25**	**-18.1**	**-18.9**	**-15.7**	**3.2**	**0.1**	**0.6**	**0.4**
$\delta^{15}N_{collagen}$	Female	12	10.3	9.5	11.0	1.5	0.1	0.4	0.2
	Male	13	10.4	9.3	11.5	2.2	0.2	0.6	0.3
	Total	**25**	**10.3**	**9.3**	**11.5**	**2.2**	**0.1**	**0.5**	**0.3**
$\delta^{13}C_{apatite}$	Female	11	-12.1	-13.8	-9.8	4.0	0.4	1.3	1.7
	Male	13	-13.2	-15.9	-11.8	4.0	0.3	1.1	1.3
	Total	**24**	**-12.7**	**-15.9**	**-9.8**	**6.1**	**0.3**	**1.3**	**1.7**
$\Delta^{13}C_{apatite\text{-}collagen}$	Female	11	5.8	4.5	9.2	4.6	0.4	1.3	1.6
	Male	13	5.0	2.3	6.9	4.6	0.3	1.2	1.4
	Total	**24**	**5.4**	**2.3**	**9.2**	**6.8**	**0.3**	**1.2**	**1.5**

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

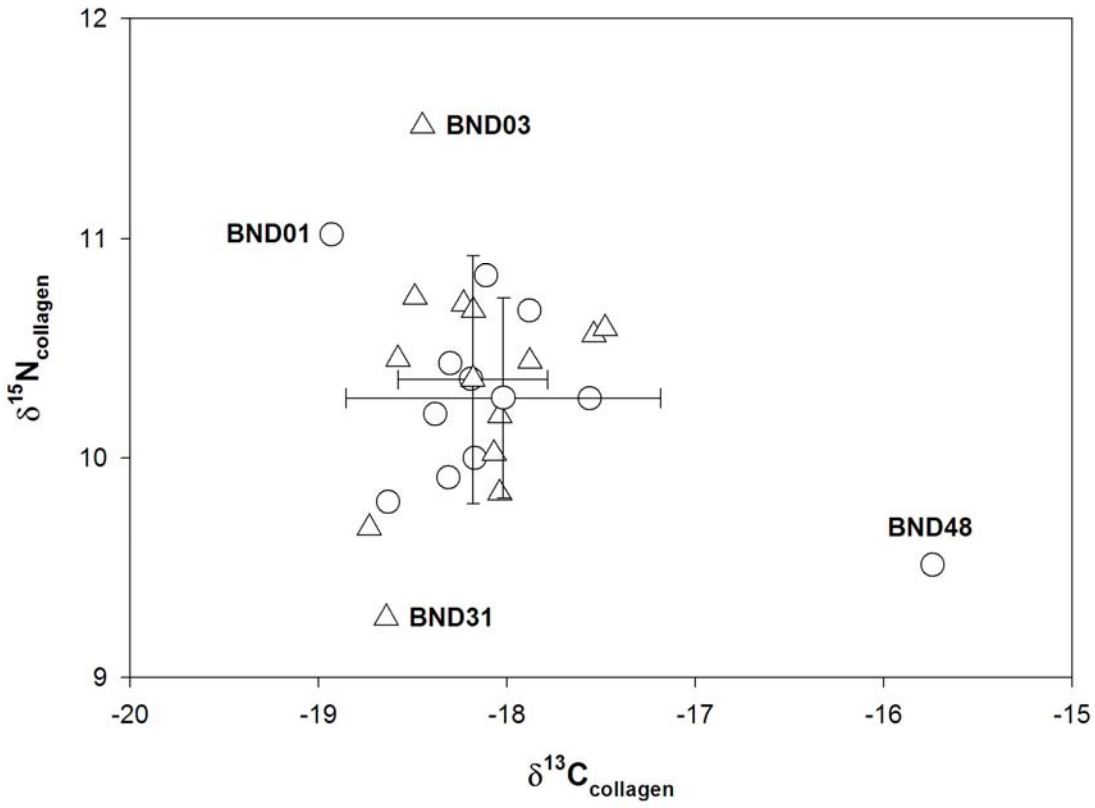

Figure 7.13. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Na Di by sex including mean values with one standard deviation: ○ Females; △ Males.

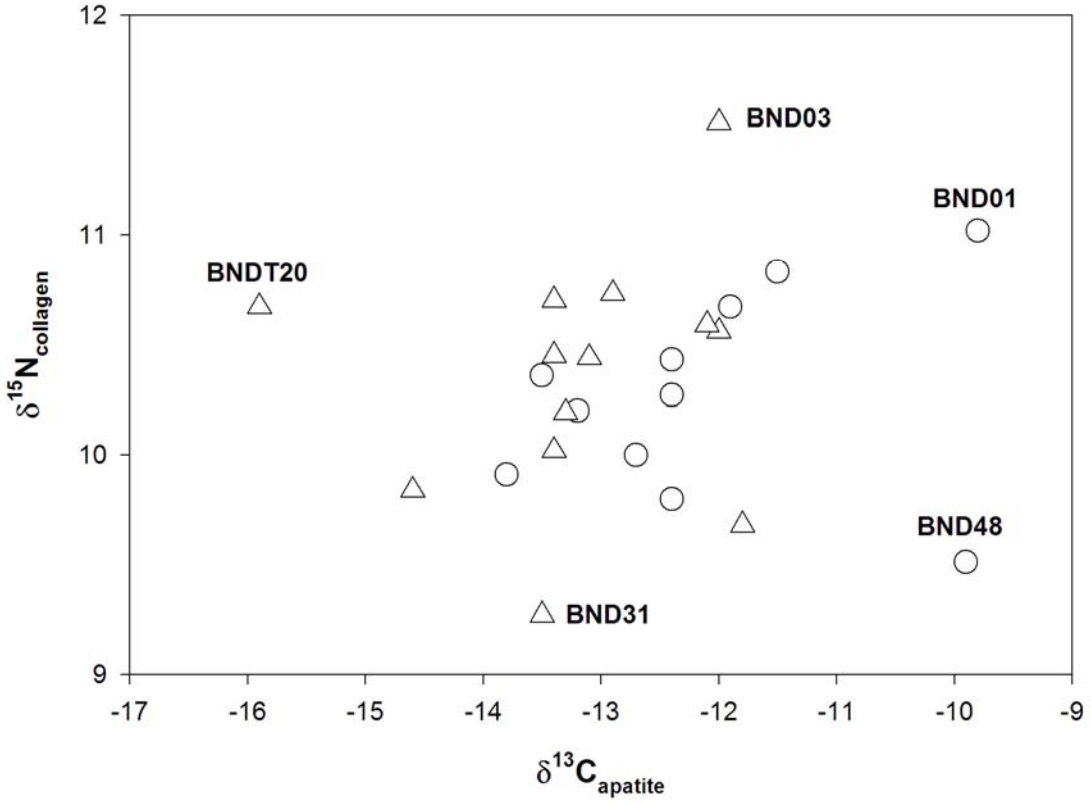

Figure 7.14. $\delta^{13}C_{apatite}$ versus $\delta^{15}N_{collagen}$ values from Ban Na Di by sex: ○ Females; △ Males.

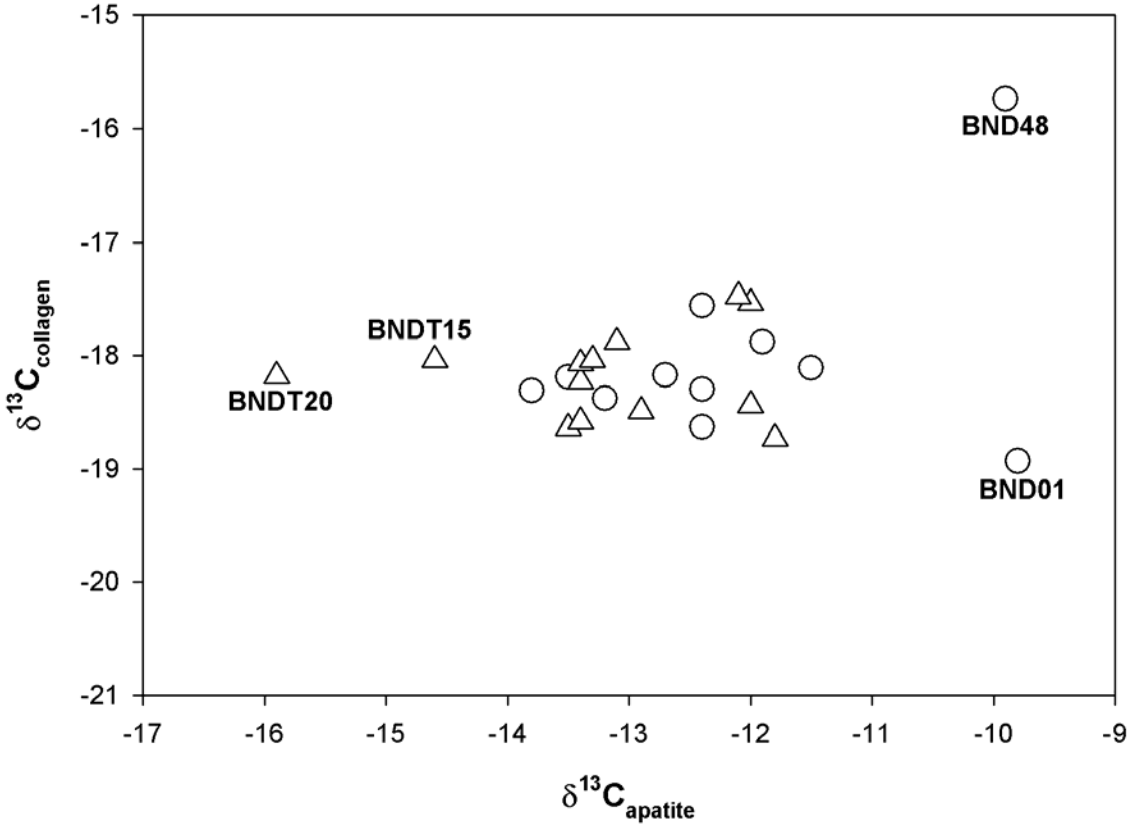

Figure 7.15. $\delta^{13}C_{apatite}$ spacing versus $\delta^{13}C_{collagen}$ values from Ban Na Di by sex: ○ Females; △ Males.

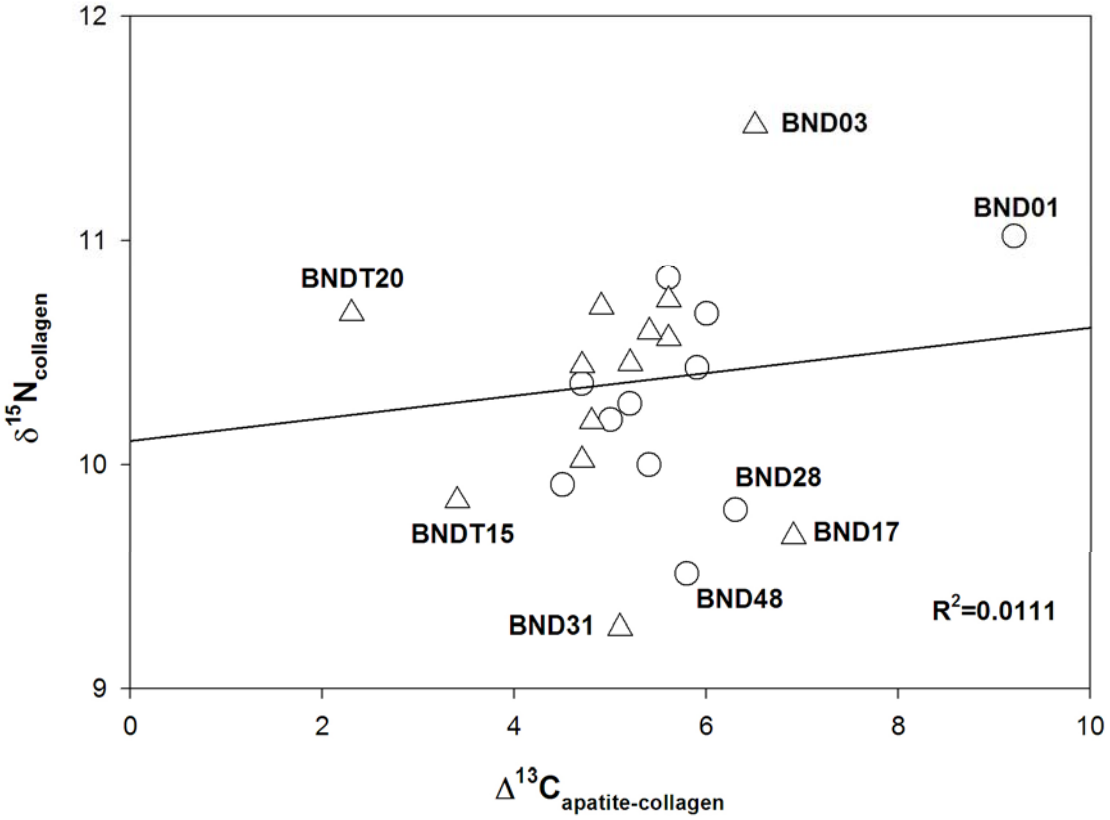

Figure 7.16. $\Delta^{13}C_{apatite\text{-}collagen}$ spacing versus $\delta^{15}N_{collagen}$ values from Ban Na Di by sex: ○ Females; △ Males.

Ban Lum Khao Human Samples

Sample integrity

The human remains from the Ban Lum Khao were poorly preserved for stable isotopic analysis. Burial conditions are the most likely explanation for the poor isotopic results. Many of the burials closer to the surface were at least partially mineralized and had concretions on the surface of the bones. Deeper burials did not contain these concretions.

Bone samples for chemical analysis were taken from 22 individuals (14 females, eight males). Most of the bone samples from Ban Lum Khao failed to yield data suitable for paleodietary reconstruction based on tests for sample integrity. From these 22 individuals, only two females (BLK49 and BLK 95) yielded suitable data (Table 7.7). Table C.3 in Appendix C provides a list of samples that were excluded from further analysis. Reasons for exclusion were either poor carbon and nitrogen percent values for collagen (BLK 39, BLK59, BLK 82) or failure to produce a $\delta^{13}C_{apatite}$ value (BLK21, BLK28, BLK34, BLK36, BLK37, BLK38, BLK42, BLK47, BLK48, BLK55, BLK61, BLK64, BLK67, BLK75, BLK80, BLK85, BLK98).

Stable isotopic results

Summary descriptive statistics for the $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite-collagen}$ are provided in Table 7.7. Since no male samples yielded usable stable isotope data, comparison between the sexes for this site is not possible. Sample size and the availability of only female individuals greatly limit potential for interpretation. As a result, the stable isotope values are interpreted with some caution.

The degree of variation between these two individuals is greatest for $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ suggesting dietary differences in protein consumption for females at Ban Lum Khao. Stable isotopic values for $\delta^{13}C_{apatite}$ are more depleted in ^{12}C and higher $\Delta^{13}C_{apatite-collagen}$ values indicate C_3-type plant foods and primarily terrestrial animal proteins are being eaten by these two individuals. Interestingly, both individuals have $\Delta^{13}C_{apatite-collagen}$ values which are >7 indicating the $\delta^{13}C$ value of the whole diet is higher (more positive) than that of the dietary protein. This suggests these individuals were consuming a mixture of C_3 and C_4 plants in their diet.

Table 7.7. Summary statistics for Ban Lum Khao human remains.

	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	2	-18.6	-19.3	-17.9	1.4	0.7	1.0	1.0
$\delta^{15}N_{collagen}$	Female	2	10.3	9.8	10.9	1.2	0.6	0.8	0.7
$\delta^{13}C_{apatite}$	Female	2	-9.8	-10.1	-9.5	0.6	0.3	0.4	0.2
$\Delta^{13}C_{apatite-collagen}$	Female	2	8.8	7.8	9.8	2.0	1.0	1.4	2.0

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

Noen U-Loke Human Samples

Sample integrity

The human remains from the Noen U-Loke archaeological site were poorly preserved. Forty-two individuals (19 females and 23 males) were selected for chemical extraction of bone collagen and bone apatite. From these 42 individuals only one female (NUL108) and one male (NUL42) yielded sufficient data for further paleodietary analysis (Appendix C.4). While it is not known why so many specimens failed to produce stable isotope data, one possibility is the manner in which the individuals were buried. The inhabitants of Noen U-Loke followed a mortuary ritual that involved filling the grave

with large quantities of white, silicified rice on top of the deceased. These rice grains eventually adhered to the bone, making cleaning very difficult and most likely causing an increased rate of bone diagenesis. Reasons for exclusion were either poor collagen yield (n=3), poor carbon and nitrogen percent values for collagen (n=22), poor C/N ratio values for collagen (n=14), and failure to produce both collagen and apatite values (n=1).

Stable isotopic results

Table 7.8 includes the summary descriptive statistics for $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite\text{-}collagen}$. With only one individual of each sex represented, sample size greatly limits the interpretive potential. As a result, the stable isotope values are interpreted with some caution.

The degree of variation between these two individuals is greatest for $\delta^{15}N_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite\text{-}collagen}$. $\delta^{15}N_{collagen}$ values are more enriched in the male suggesting this individual was consuming more fish or more terrestrial carnivores. While $\delta^{13}C_{apatite}$ values for both the female and the male indicate primarily C_3 plant foods, the more positive value in the female suggests a greater mix of plant food sources in the diet. The higher $\Delta^{13}C_{apatite\text{-}collagen}$ value in the female most likely reflects a whole diet that includes a mixture of both C_3 and C_4 starches and protein that is predominately C_3 terrestrial based. While these two individuals have different diets the isotopic values are not much different from first millennium individuals from Ban Chiang or Ban Na Di.

Table 7.8. Summary statistics for Noen U-Loke human remains.

	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	1	-18.3	---	---	---	---	---	---
	Male	1	-17.8	---	---	---	---	---	---
	Total	2	-18.1	-18.3	-17.8	0.5	0.3	0.4	0.1
$\delta^{15}N_{collagen}$	Female	1	10.5	---	---	---	---	---	---
	Male	1	12.4	---	---	---	---	---	---
	Total	2	11.5	10.5	12.4	1.9	1.0	1.3	1.8
$\delta^{13}C_{apatite}$	Female	1	-10.4	---	---	---	---	---	---
	Male	1	-12.5	---	---	---	---	---	---
	Total	2	-11.5	-12.5	-10.4	2.1	1.1	1.5	2.2
$\Delta^{13}C_{apatite-collagen}$	Female	1	7.9	---	---	---	---	---	---
	Male	1	5.3	---	---	---	---	---	---
	Total	2	6.6	5.3	7.9	2.6	1.3	1.8	3.4

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance; --- = cannot be computed.

Northeast Thailand Human Samples

In this section, all of the different samples are combined to examine the questions of temporal variation and sex differences in diet. The combined data are presented in Tables 7.9-7.13 and Figures 7.21-7.35.

Temporal variation

Sexes combined

The combined northeast Thailand series has 48 individuals from the second millennium B.C. and 47 individuals from the first millennium B.C. (Table 7.9). Two individuals from this total (BCES40 and BNDT08) failed to produce $\delta^{13}C_{apatite}$ values so only 45 individuals from the first millennium B.C. are available for analysis. Due to poor preservation in the Ban Lum Khao series (n=2), the second millennium B.C. data is comprised mostly of individuals from Ban Chiang (n=46). The first millennium B.C. series includes individuals from Ban Chiang (n=20), Ban Na Di (n=24), and Noen U-Loke (n=2).

Stable isotopic results

The mean values, and variance of the isotopes, indicate very little difference between each time period for all stable isotope values (Table 7.9). However, the range of values suggests individual differences in overall diets over time. Mann-Whitney U-tests indicate there are statistically significant differences in the means for $\delta^{13}C_{collagen}$ ($p \leq 0.025$), $\delta^{15}N_{collagen}$ ($p \leq 0.030$), and $\delta^{13}C_{apatite}$ ($p \leq 0.048$) stable isotopic values. These significant levels though can be misleading. As shown in Figure 7.17, most of the samples form a fairly distinct cluster. This is also apparent in Table 7.9 in which mean and standard

deviations for each variable are very similar. There are however, a number of individuals which scatter outside the main grouping. Based on the given set of isotope values, it would be impossible to guess much better than 50/50 from which millennium an individual was derived.

Graphical analyses by time period are presented in Figures 7.17-7.20. The range of $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values between second and first millennium B.C. are very similar (Figure 7.17). While the graph illustrates the close proximity in isotopic values over time, there are a few individuals from both time periods outside the central grouping (BCES03, BC31, BCES23, BC41, BND48, and NUL42). These individuals are mostly different in $\delta^{13}C_{collagen}$ values though NUL42 is enriched and BC31 is more depleted in $\delta^{15}N_{collagen}$ compared to the other individuals. Like $\delta^{13}C_{collagen}$, $\delta^{13}C_{apatite}$ values also show a great range of variation (Figure 7.18). Mean values for $\delta^{13}C_{apatite}$ indicate a more positive mean in the first millennium.

$\Delta^{13}C_{apatite\text{-}collagen}$ values demonstrate the greatest variance and range during the second millennium B.C. though differences between the time periods are not statistically significant. Figure 7.20 illustrates a larger number of individuals above and below the monoisotopic value range of 4.0-7.0, with a very weak correlation, indicating the carbohydrates of the diet contribute most of the correlation with $\Delta^{13}C_{apatite\text{-}collagen}$ values. In all, both time periods have individuals with varying diets of primarily terrestrial animals consuming C_3-type plants along with freshwater fish. Dietary carbohydrates showed the most variation compared to protein sources though stable isotopic values suggest the carbohydrates come from primarily C_3-plants.

Table 7.9. Summary statistics for northeast Thailand human remains.

	Millennium	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$ $p \leq 0.025$	Second	48	-18.5	-19.5	-16.8	2.7	0.1	0.6	0.4
	First	47	-18.3	-20.5	-15.7	4.8	0.1	0.7	0.4
	Total	95	-18.4	-20.5	-15.7	4.8	0.1	0.6	0.4
$\delta^{15}N_{collagen}$ $p \leq 0.030$	Second	48	10.1	8.5	11.2	2.7	0.1	0.6	0.4
	First	47	10.3	9.3	12.4	3.1	0.1	0.5	0.3
	Total	95	10.2	8.5	12.4	3.9	0.1	0.6	0.4
$\delta^{13}C_{apatite}$ $p \leq 0.048$	Second	48	-13.2	-16.1	-9.5	6.6	0.2	1.3	1.7
	First	45	-12.8	-15.9	-9.8	6.1	0.2	1.3	1.7
	Total	93	-13.0	-16.1	-9.5	6.6	0.1	1.3	1.8
$\Delta^{13}C_{apatite\text{-}collagen}$	Second	48	5.3	2.1	9.8	7.7	0.2	1.6	2.6
	First	45	5.5	2.3	9.2	6.9	0.2	1.5	2.1
	Total	93	5.4	2.1	9.8	7.7	0.2	1.5	2.3

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

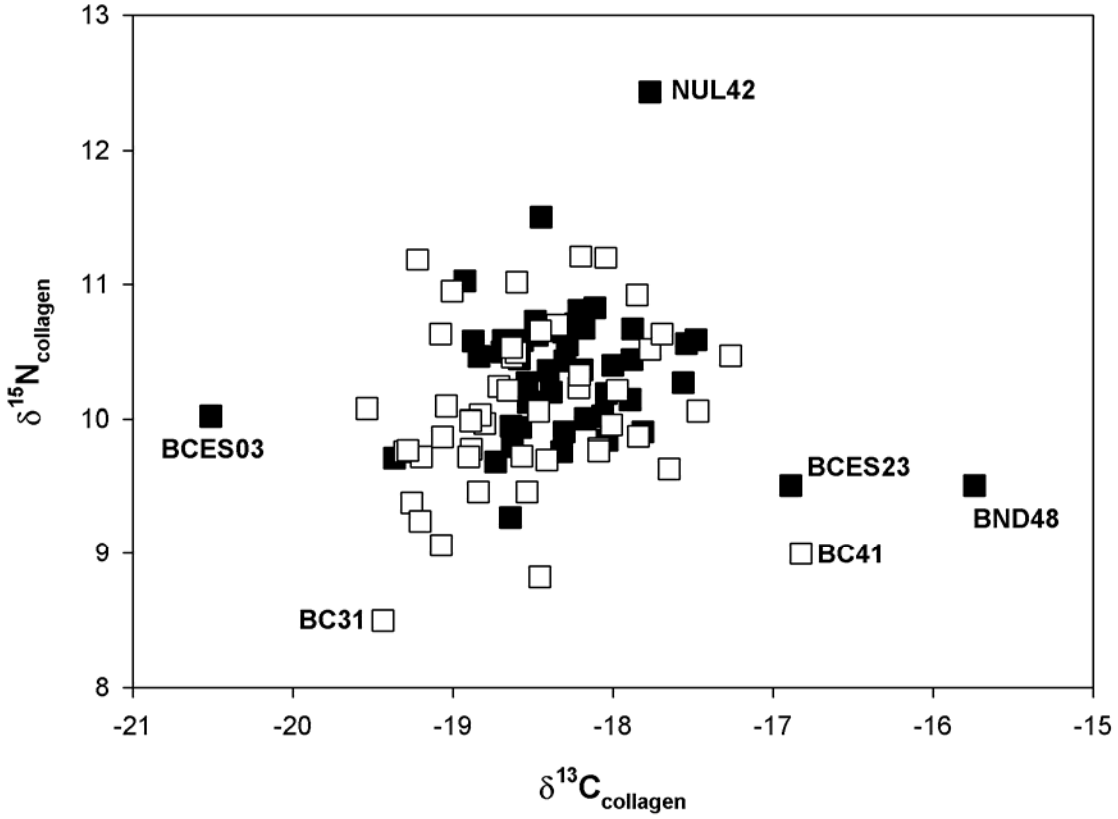

Figure 7.17. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period: □ Second Millennium B.C.; ■ First Millennium B.C.

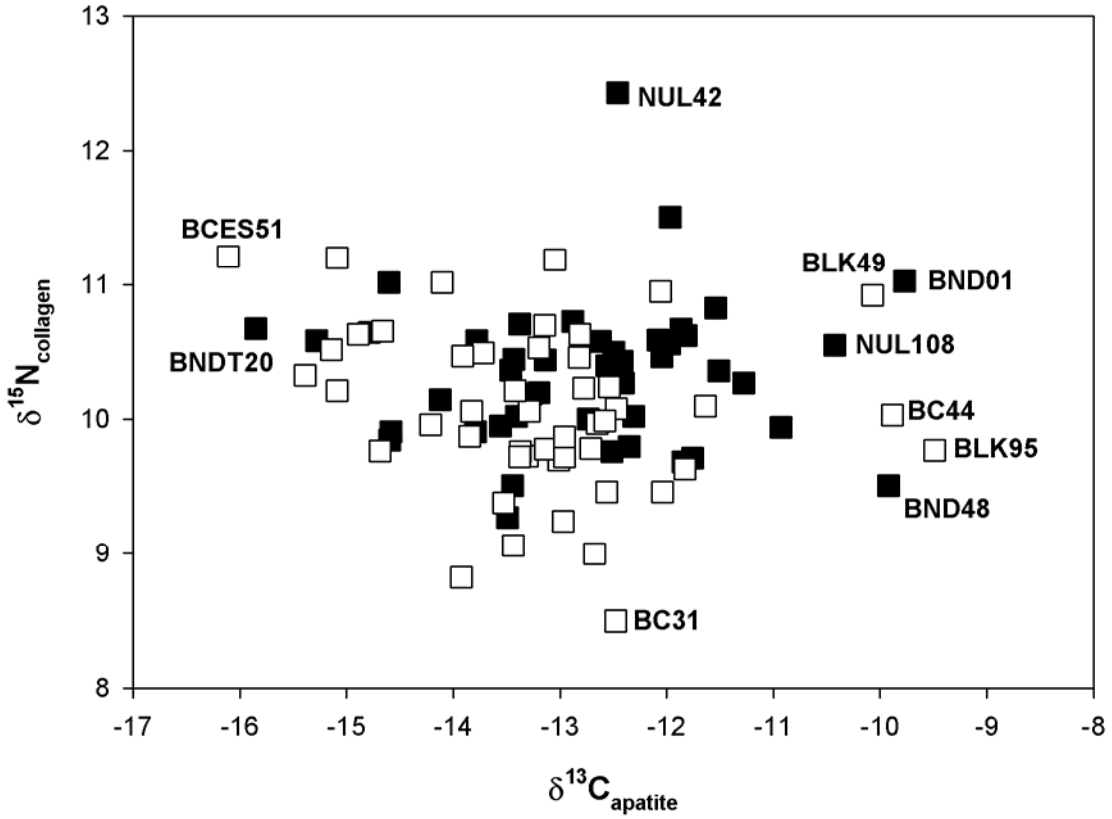

Figure 7.18. $\delta^{13}C_{apatite}$ versus $\delta^{15}N_{collagen}$ values from northeast Thailand by time period: □ Second Millennium B.C.; ■ First Millennium B.C.

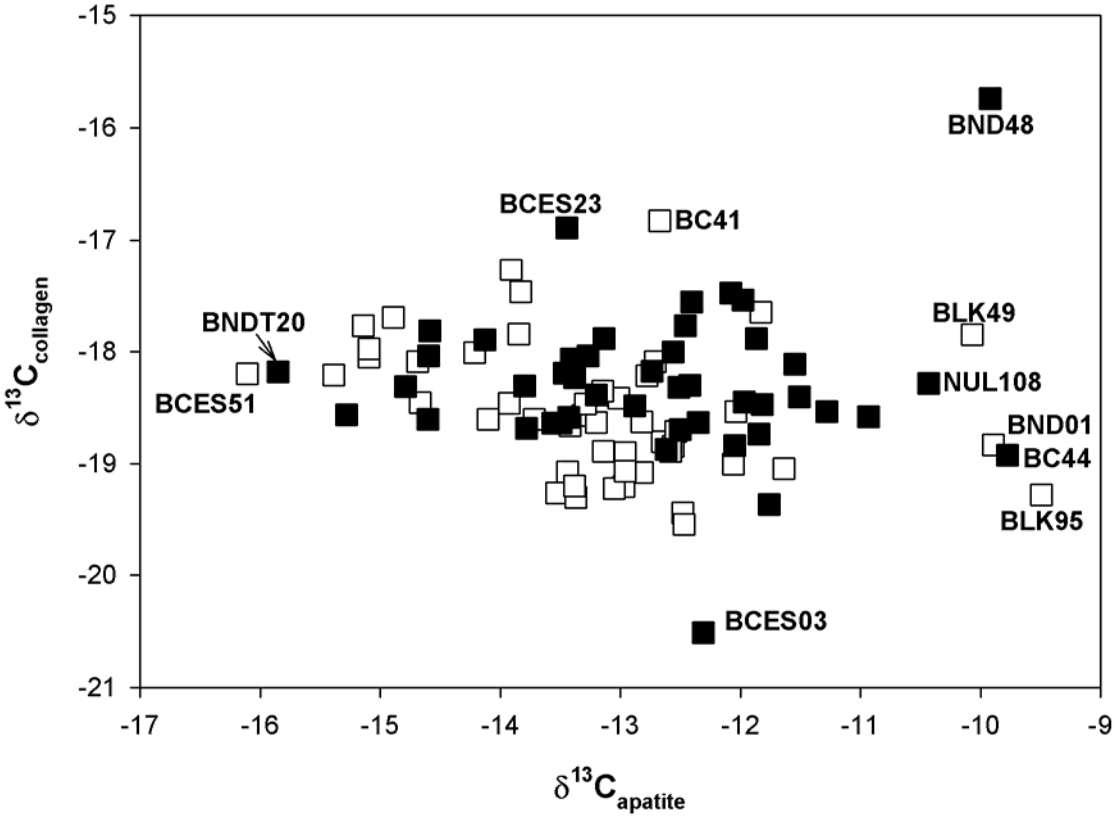

Figure 7.19. $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values from northeast Thailand by time period: □ Second Millennium B.C.; ■ First Millennium B.C.

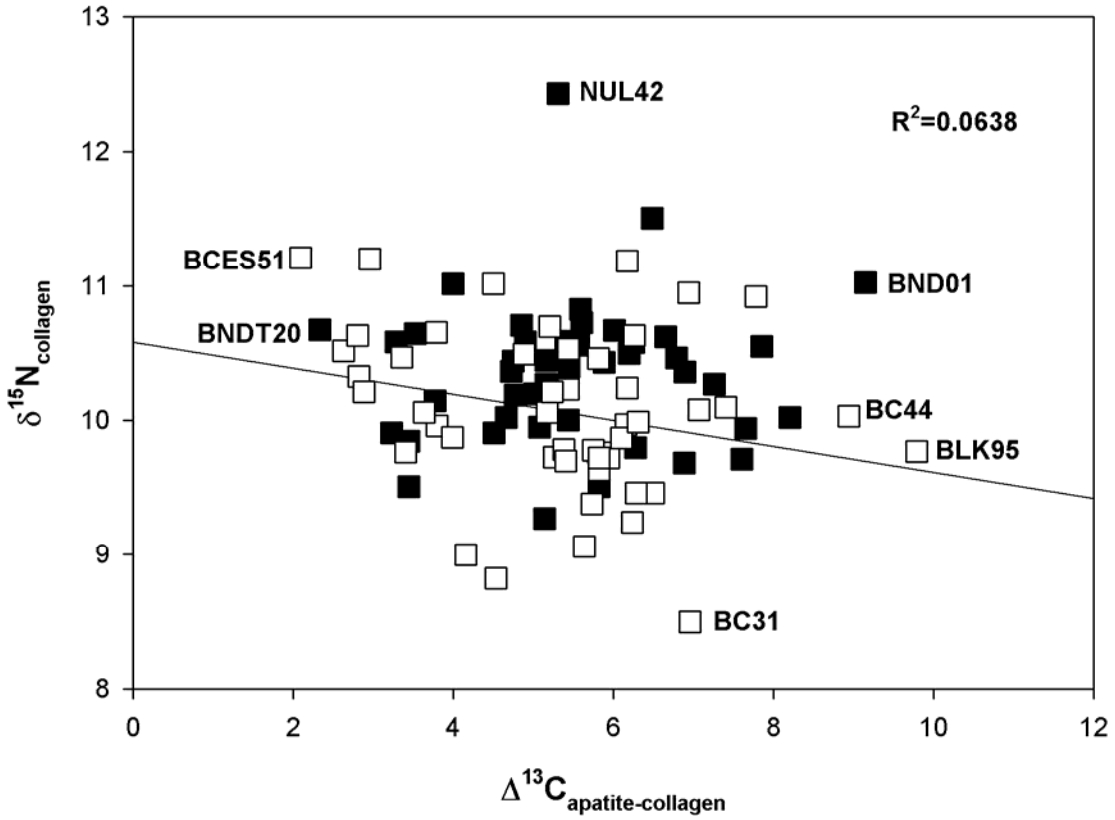

Figure 7.20. $\Delta^{13}C_{apatite\text{-}collagen}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period: ☐ Second Millennium B.C.; ■ First Millennium B.C.

By sex

Tables 7.10 and 7.11 provide the descriptive statistics for $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$, $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite\text{-}collagen}$ for females and males.

Females over time

Table 7.10 provides the summary statistics for isotope values in females from northeast Thailand over time. There are a total of 44 females, 22 from the second millennium B.C. and 22 from the first millennium B.C. Second millennium B.C. females are mostly from Ban Chiang (n=20) with two individuals from Ban Lum Khao. First millennium B.C. females include individuals from Ban Chiang (n=9), Ban Na Di (n=12), and Noen U-Loke (n=1). These descriptive statistics suggest similarity in female food patterns over time based on stable isotopic values.

However, there are statistically significant differences in female $\delta^{13}C_{apatite}$ ($p \leq 0.030$) values and $\delta^{15}N_{collagen}$ values ($p \leq 0.076$) between the two time periods. Significance in both $\delta^{13}C$ from bone apatite and $\delta^{15}N$ from bone collagen suggests a greater range of diversity in the type of carbohydrates and proteins consumed during the second millennium than in the first millennium, which coincide with the reduction in the range of strontium isotope signatures found in Bentley and associates (2005). Figures 7.21 and 7.22 also suggest similar stable isotopic variability between the two time periods. $\delta^{15}N_{collagen}$ values for each time period show only slight variation over time, though second millennium females have a much wider range of variation, most likely contributing to the statistical significance. Figure 7.23 demonstrates overall more positive $\delta^{13}C_{apatite}$ values during the first millennium, suggest either the addition of more

C_4 cereal plants in the first millennium diet and/or increased consumption of plant foods grown in open fields.

Mean values for $\Delta^{13}C_{apatite\text{-}collagen}$ are 5.3 (second millennium B.C.) and 5.9 (first millennium B.C.) indicating monoisotopic diets for females in both time periods. The $\Delta^{13}C_{apatite\text{-}collagen}$ values show 4/6 (66.7%) females with values greater than 7.0 are from the first millennium, while only 3/8 (37.8%) females have values greater than 7.0 in the second millennium. The very weak relationship between $\delta^{15}N_{collagen}$ and $\Delta^{13}C_{apatite\text{-}collagen}$ (R^2=0.0440) shown in Figure 7.24 further substantiates the overall similarity in female protein resource consumption over time.

Males over time

Summary statistics for isotope values in males from northeast Thailand are presented in Table 7.11. There are a total of 51 males, 26 from the second millennium B.C. and 25 from the first millennium B.C. The second millennium B.C. series is represented only by individuals from Ban Chiang (N=26), whereas, the first millennium B.C. series includes individuals from Ban Chiang (n=11), Ban Na Di (n=13), and Noen U-Loke (n=1). Mean and variance values for each time period suggest very few differences over time. There are however some individuals during each time period who had distinctive signatures relative to the rest of the population.

A large range of variation for all stable isotopic values is found in both time periods, though only the two mean $\delta^{13}C_{collagen}$ values are statistically significant ($p \leq 0.004$), suggesting a slight change in mean protein consumption for males over time. However, given that the standard deviations $\delta^{13}C_{collagen}$ values for males overlap considerably

between the second and first millennia, it is not surprising that the $\delta^{15}N_{collagen}$ values also overlap each other squarely (Figure 7.21). Figures 7.22 and 7.23 show a broad range in $\delta^{13}C_{apatite}$ values for both time periods, though neither seems to demonstrate any specific trends for any one period over another. Both graphs demonstrate a tight clustering of $\delta^{15}N_{collagen}$ and $\delta^{13}C_{collagen}$ values indicating a broad range of carbohydrate sources during both time periods.

Of the 51 males, there are 14 outside the 4-7 range of monoisotopic diets (Figure 7.24). There is no apparent temporal relationship between these individuals. There are nine individuals with $\Delta^{13}C_{apatite\text{-}collagen}$ values less than four. Of these, five are from the second millennium and four from the first millennium B.C. The five individuals with $\Delta^{13}C_{apatite\text{-}collagen}$ values greater than seven are also fairly evenly distributed between the time periods. These $\Delta^{13}C_{apatite\text{-}collagen}$ values suggest that carbohydrate and protein differences in males are not significantly different. Moreover, the $\delta^{15}N_{collagen}$ values compared to $\Delta^{13}C_{apatite\text{-}collagen}$ over time are very similar with no substantive change in protein in the diet for males over time (Figure 7.24).

Table 7.10. Summary statistics for northeast Thailand females by time period.

	Millennium B.C.	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Second	22	-18.4	-19.4	-16.8	2.6	0.2	0.7	0.5
	First	22	-18.3	-20.5	-15.7	4.8	0.2	0.9	0.8
	Total	44	-18.4	-20.5	-15.7	4.8	0.1	0.8	0.6
$\delta^{15}N_{collagen}$ $p \leq 0.076$	Second	22	9.9	8.5	11.2	2.7	0.1	0.7	0.5
	First	22	10.2	9.5	11.0	1.5	0.1	0.4	0.2
	Total	44	10.0	8.5	11.2	2.7	0.1	0.6	0.3
$\delta^{13}C_{apatite}$ $p \leq 0.030$	Second	22	-13.1	-15.1	-9.5	5.6	0.3	1.4	2.0
	First	21	-12.4	-15.3	-9.8	5.5	0.3	1.4	1.9
	Total	43	-12.7	-15.3	-9.5	5.8	0.2	1.4	2.0
$\Delta^{13}C_{apatite-collagen}$	Second	22	5.3	2.8	9.8	7.0	0.4	1.7	2.9
	First	21	5.9	3.2	9.2	6.0	0.3	1.6	2.5
	Total	43	5.6	2.8	9.8	7.0	0.3	1.7	2.8

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

Table 7.11. Summary statistics for northeast Thailand males by time period.

	Millennium B.C.	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$ $p \leq 0.004$	Second	26	-18.6	-19.5	-17.3	2.2	0.1	0.5	0.2
	First	25	-18.3	-18.7	-17.5	1.2	0.1	0.4	0.1
	Total	51	-18.4	-19.5	-17.3	2.2	0.1	0.5	0.2
$\delta^{15}N_{collagen}$	Second	26	10.2	9.4	11.2	1.8	0.1	0.5	0.3
	First	25	10.5	9.3	12.4	3.1	0.1	0.6	0.4
	Total	51	10.4	9.3	12.4	3.1	0.1	0.6	0.3
$\delta^{13}C_{apatite}$	Second	26	-13.3	-16.1	-9.9	6.2	0.2	1.2	1.5
	First	24	-13.1	-15.9	-10.9	5.0	0.2	1.2	1.4
	Total	50	-13.2	-16.1	-9.9	6.2	0.2	1.2	1.5
$\Delta^{13}C_{apatite-collagen}$	Second	26	5.4	2.1	8.9	6.8	0.3	1.6	2.4
	First	24	5.2	2.3	7.6	5.3	0.3	1.3	1.6
	Total	50	5.3	2.1	8.9	6.8	0.2	1.4	2.0

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

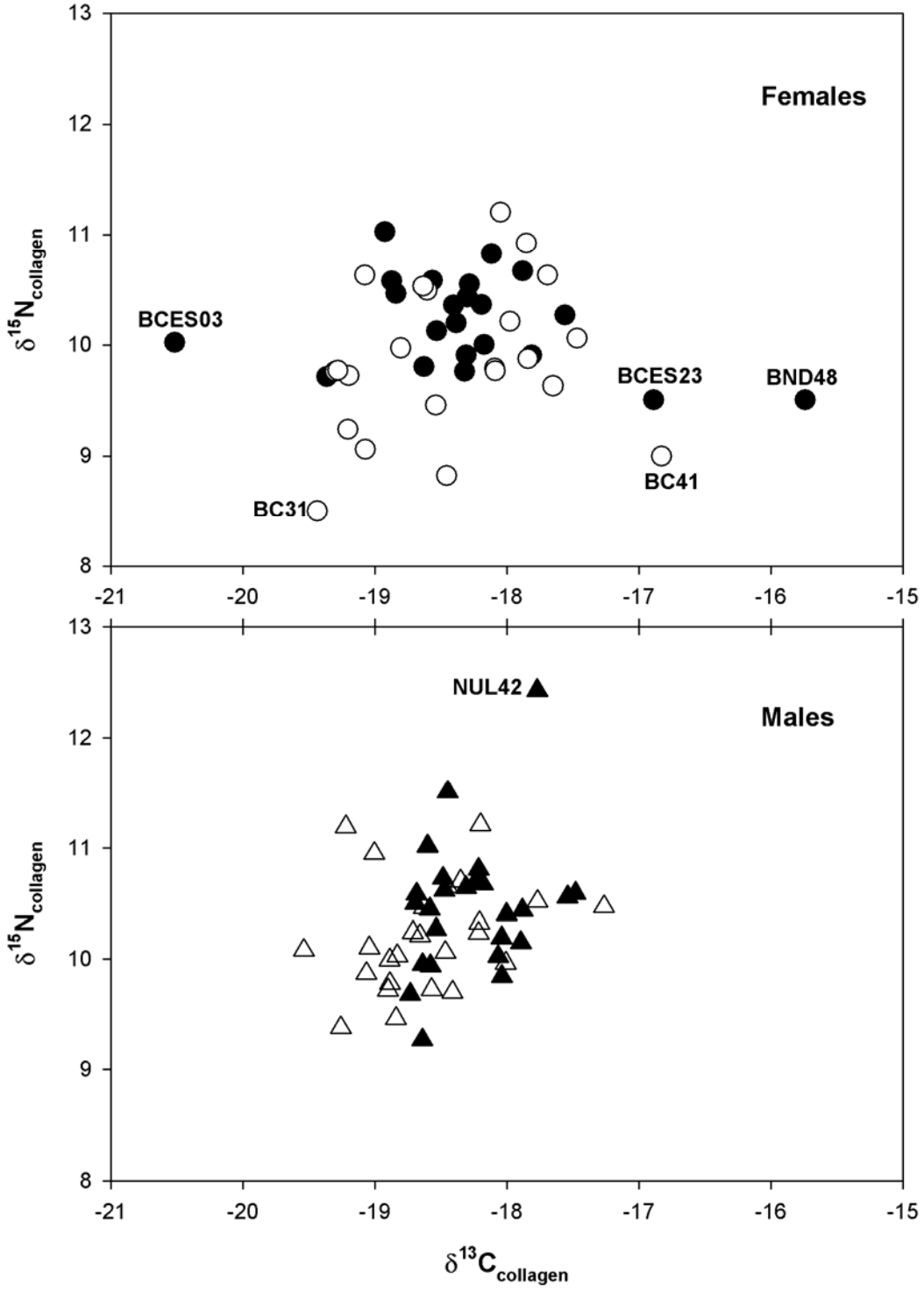

Figure 7.21. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

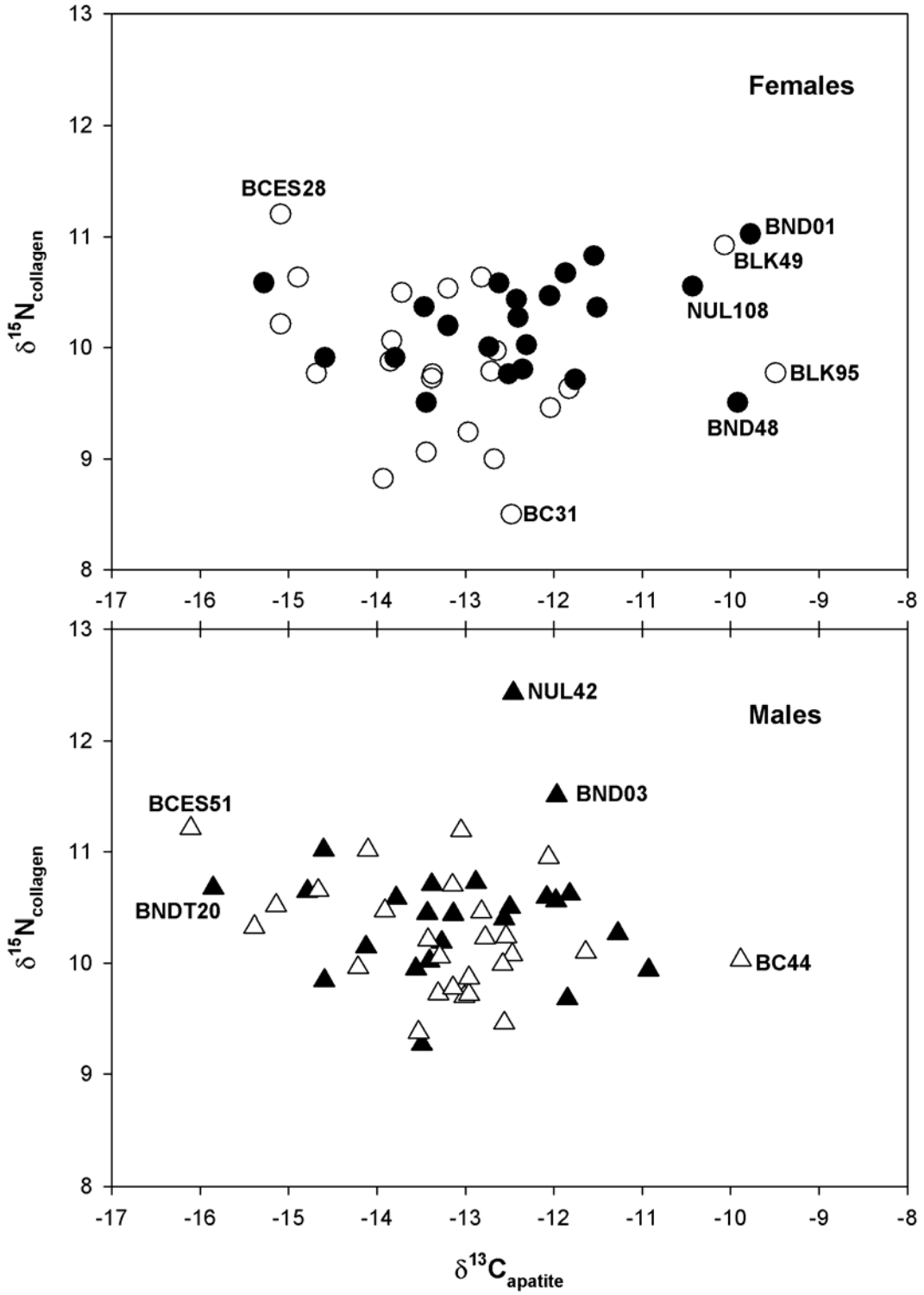

Figure 7.22. $\delta^{13}C_{apatite}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

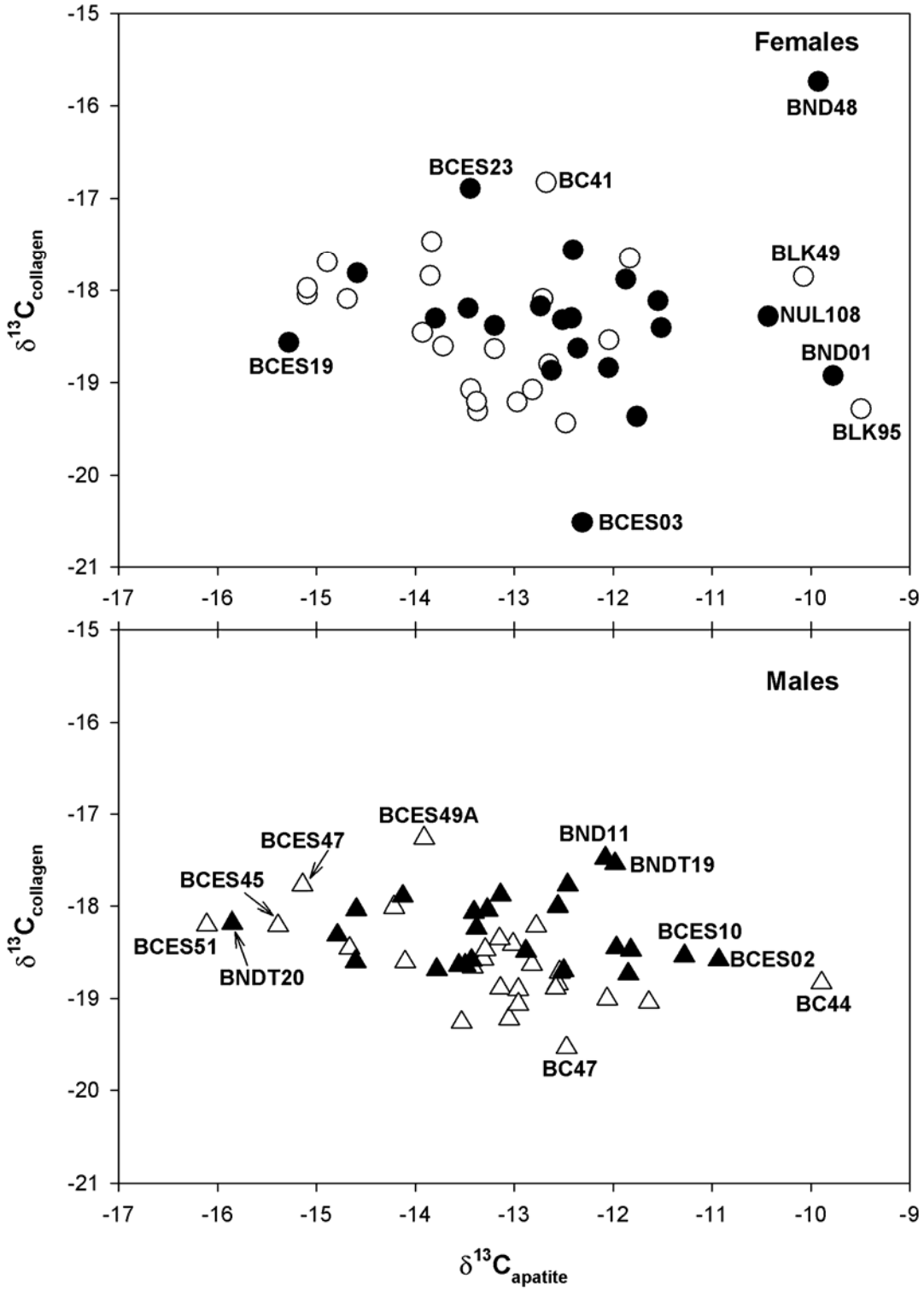

Figure 7.23. $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

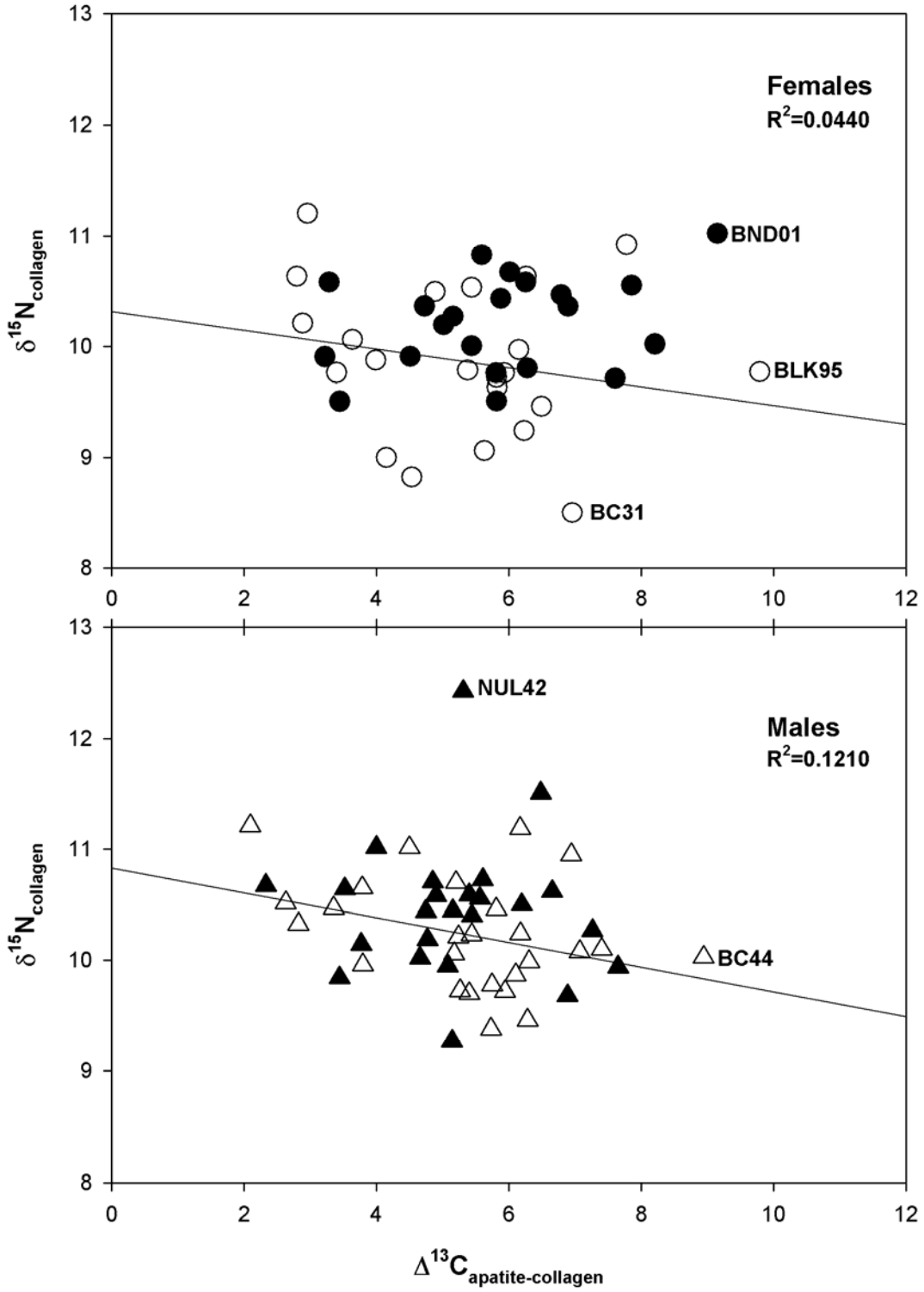

Figure 7.24. $\Delta^{13}C_{apatite\text{-}collagen}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

Northeast Thailand Intra-Regional Variation

The previous section documents statistically significant differences in mean stable isotopic values over time in both females ($\delta^{15}N_{collagen}$ and $\delta^{13}C_{apatite}$) and males ($\delta^{13}C_{collagen}$), although the standard deviations overlapped considerably in each case. To further understand these shifts in mean isotopic values, this section investigates differences between females and males within a given time period.

Second millennium

Table 7.12 provides the descriptive summary statistics for females and males from the second millennium B.C. There are a total of 48 individuals, 22 females and 26 males. Females are represented by Ban Chiang (n=20) and Ban Lum Khao (n=2) while males are solely represented by Ban Chiang (N=26). Mann-Whitney U-tests indicate there are statistically significant differences for $\delta^{15}N_{collagen}$ ($p \leq 0.056$) values at the $p<0.1$ level. Graphical analyses further support differing dietary patterns for females and males during this time period, particularly for $\delta^{15}N_{collagen}$ (Figures 7.31-7.35) to suggest a wide dietary during this period.

The means for each of the isotope values suggest very little dietary difference between the sexes during the second millennium B.C. The ranges of values, however, are large for $\delta^{15}N_{collagen}$ and $\delta^{13}C_{apatite}$ for each sex indicating a wide variety of protein and carbohydrate sources. The variance for $\delta^{13}C_{apatite}$ is also large relative to other stable isotopic values, indicating a lot variation within each group (females and males) for starchy food consumption.

Figures 7.25-7.27 display a large central clustering of females and males with $\delta^{13}C_{apatite}$ having more individuals with dietary patterns outside the norm of this sample. Mean values for $\Delta^{13}C_{apatite\text{-}collagen}$ indicate a primarily monoisotopic diet, though the ranges indicate wide variety in dietary patterns for both females and males (Figures 7.28). The similar range of variation for both $\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$ suggest carbon sources of bone collagen and bone apatite are very similar during this time period (Figures 7.27). Figure 7.28 displays the correlation of $\delta^{15}N_{collagen}$ (R^2=0.1193) to $\Delta^{13}C_{apatite\text{-}collagen}$, and though not significant, there is an indication that females consumed a wider variety of protein sources than males.

First millennium

This time period is represented by 47 individuals, 22 females and 25 males. Female samples include individuals from Ban Chiang (n=9), Ban Na Di (n=12), and Noen U-Loke (n=1). Male samples include individuals from Ban Chiang (n=11), Ban Na Di (n=13), and Noen U-Loke (n=1). Dietary patterns between females and males during the first millennium B.C. are varied. Mann-Whitney U-tests indicate that $\delta^{13}C_{apatite}$ ($p \leq 0.088$) values are significantly different between females and males during this time period though only at the $p<0.1$ level. During this time period there is a tighter clustering of individuals than during the second millennium suggesting a less diverse dietary regime. Several individuals however (BCES03, BCES75, BCES23, BND31, BND03, BND48, and NUL42) have $\delta^{13}C_{collagen}$ values outside the main grouping (Figure 7.25-7.27).

Stable isotopic values for $\delta^{15}N_{collagen}$ are also more closely grouped than during the previous time period (Figure 7.22). Conversely, individual stable isotopic values for

$\delta^{13}C_{apatite}$ are not closely clustered suggesting the potential for a wide variety of carbohydrate sources (Figure 7.27). There is a very weak relationship between $\delta^{15}N_{collagen}$ (R^2=0.0983) and $\Delta^{13}C_{apatite\text{-}collagen}$ scores. Some of this lack of correlation however, can be attributed to a few individuals with higher $\delta^{15}N_{collagen}$ than the rest of the sample (Figure 7.28).

Table 7.12. Summary statistics for northeast Thailand human remains from the second millennium B.C.

Millennium B.C.	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	22	-18.4	-19.4	-16.8	2.6	0.2	0.7	0.5
	Male	26	-18.6	-19.5	-17.3	2.2	0.1	0.5	0.2
	Total	48	-18.5	-19.5	-16.8	2.7	0.1	0.6	0.4
$\delta^{15}N_{collagen}$ $p \leq 0.056$	Female	22	9.9	8.5	11.2	2.7	0.1	0.7	0.5
	Male	26	10.2	9.4	11.2	1.8	0.1	0.5	0.3
	Total	48	10.1	8.5	11.2	2.7	0.1	0.6	0.4
$\delta^{13}C_{apatite}$	Female	22	-13.1	-15.1	-9.5	5.6	0.3	1.4	2.0
	Male	26	-13.3	-16.1	-9.9	6.2	0.2	1.2	1.5
	Total	48	-13.2	-16.1	-9.5	6.6	0.2	1.3	1.7
$\Delta^{13}C_{apatite-collagen}$	Female	22	5.3	2.8	9.8	7.0	0.4	1.7	2.9
	Male	26	5.4	2.1	8.9	6.8	0.3	1.6	2.4
	Total	48	5.3	2.1	9.8	7.7	0.2	1.6	2.6

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

Table 7.13. Summary statistics for northeast Thailand human remains from the first millennium B.C.

Millennium B.C.	Sex	N	Mean	Min[a]	Max	Range	Std. Error	Std. Dev	Var
$\delta^{13}C_{collagen}$	Female	22	-18.3	-20.5	-15.7	4.8	0.2	0.9	0.8
	Male	25	-18.3	-18.7	-17.5	1.2	0.1	0.4	0.1
	Total	47	-18.3	-20.5	-15.7	4.8	0.1	0.7	0.4
$\delta^{15}N_{collagen}$	Female	22	10.2	9.5	11.0	1.5	0.1	0.4	0.2
	Male	25	10.5	9.3	12.4	3.1	0.1	0.6	0.4
	Total	47	10.3	9.3	12.4	3.1	0.1	0.5	0.3
$\delta^{13}C_{apatite}$ $p \leq 0.088$	Female	21	-12.4	-15.3	-9.8	5.5	0.3	1.4	1.9
	Male	24	-13.1	-15.9	-10.9	5.0	0.2	1.2	1.4
	Total	45	-12.8	-15.9	-9.8	6.1	0.2	1.3	1.7
$\Delta^{13}C_{apatite-collagen}$	Female	21	5.9	3.2	9.2	6.0	0.3	1.6	2.5
	Male	24	5.2	2.3	7.6	5.3	0.3	1.3	1.6
	Total	45	5.5	2.3	9.2	6.9	0.2	1.5	2.1

[a] Min = minimum value; Max = maximum value; Std. Error = standard error from the mean; Std Dev = standard deviation; Var = variance

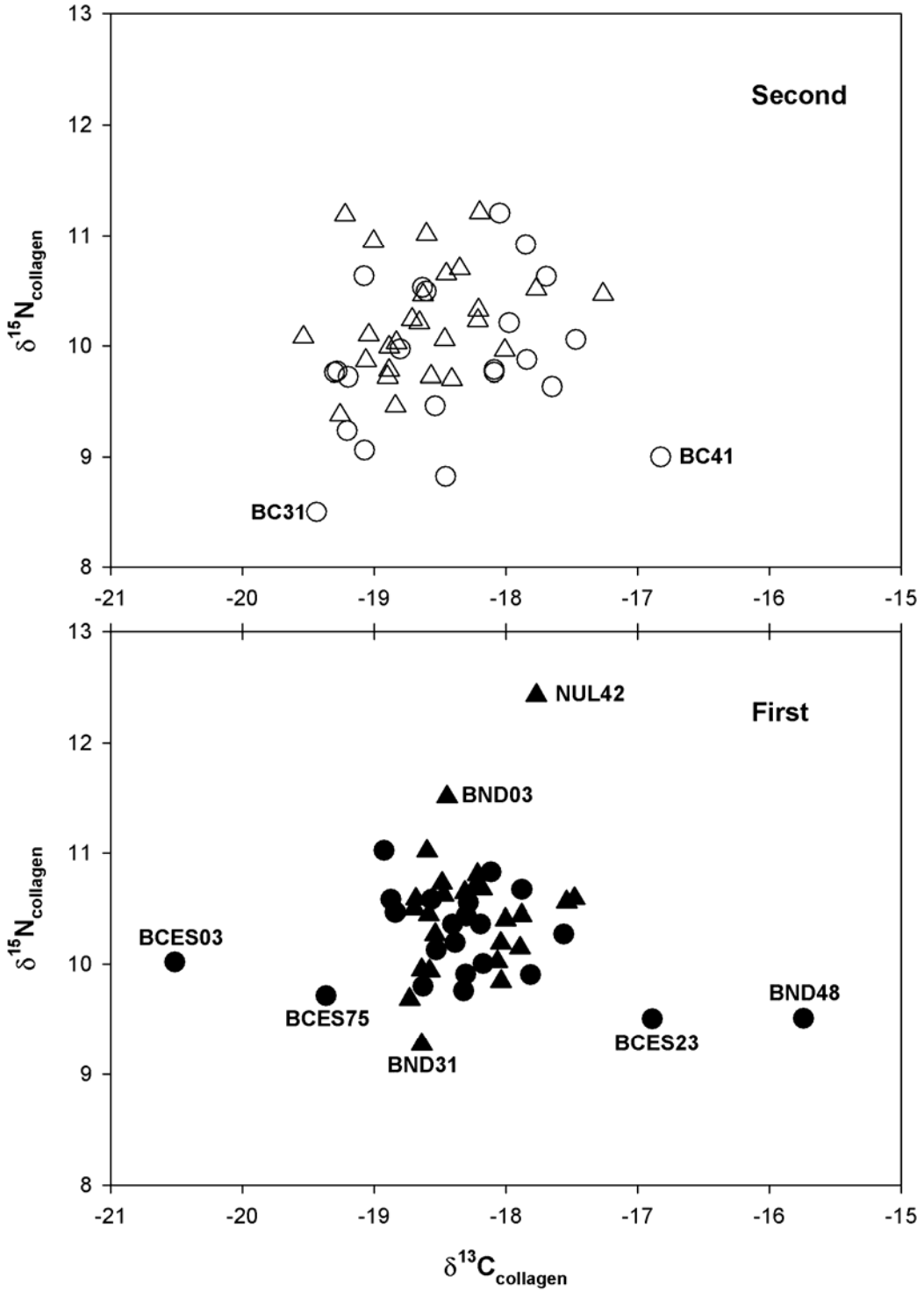

Figure 7.25. $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

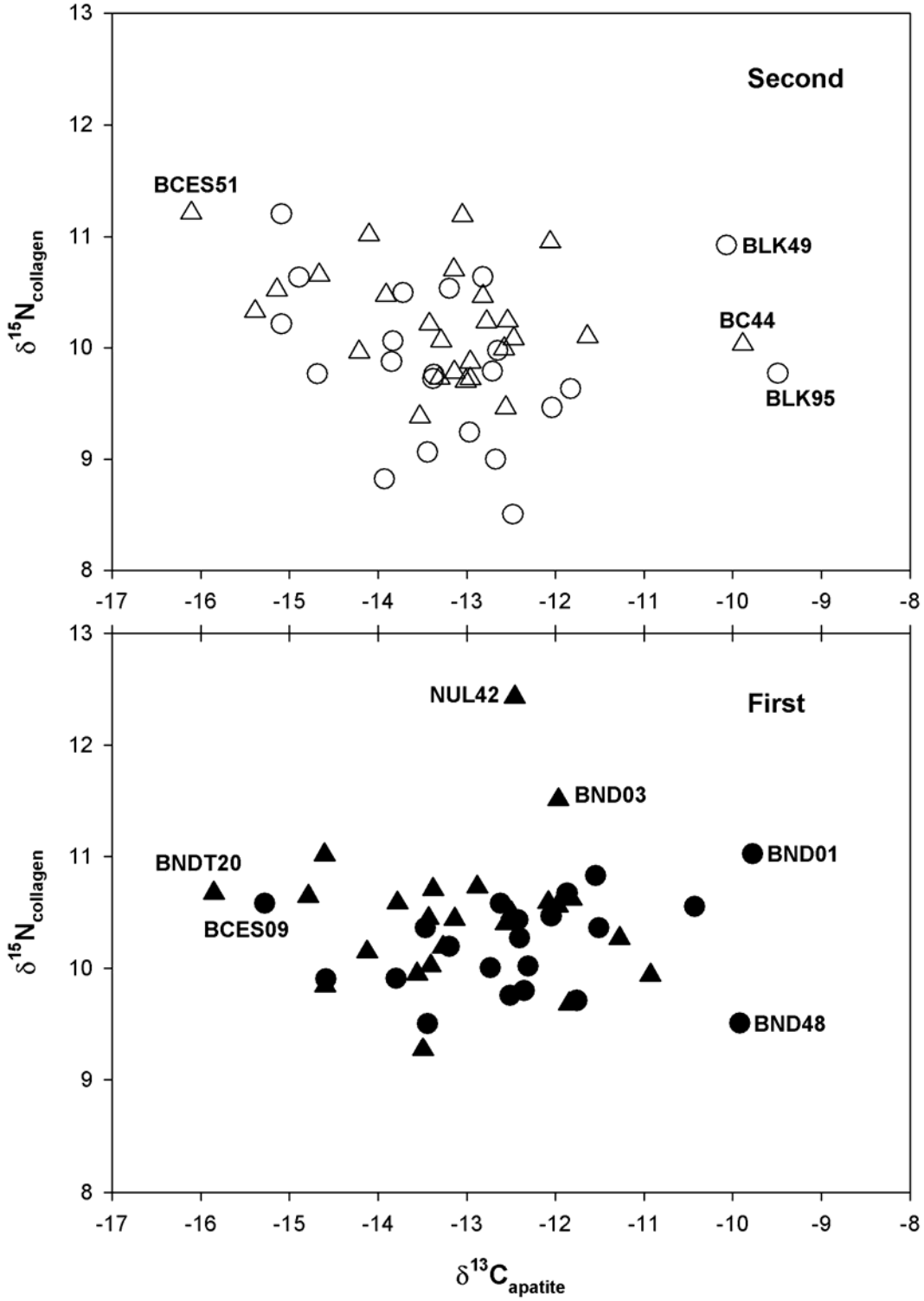

Figure 7.26. $\delta^{13}C_{apatite}$ and $\delta^{15}N_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

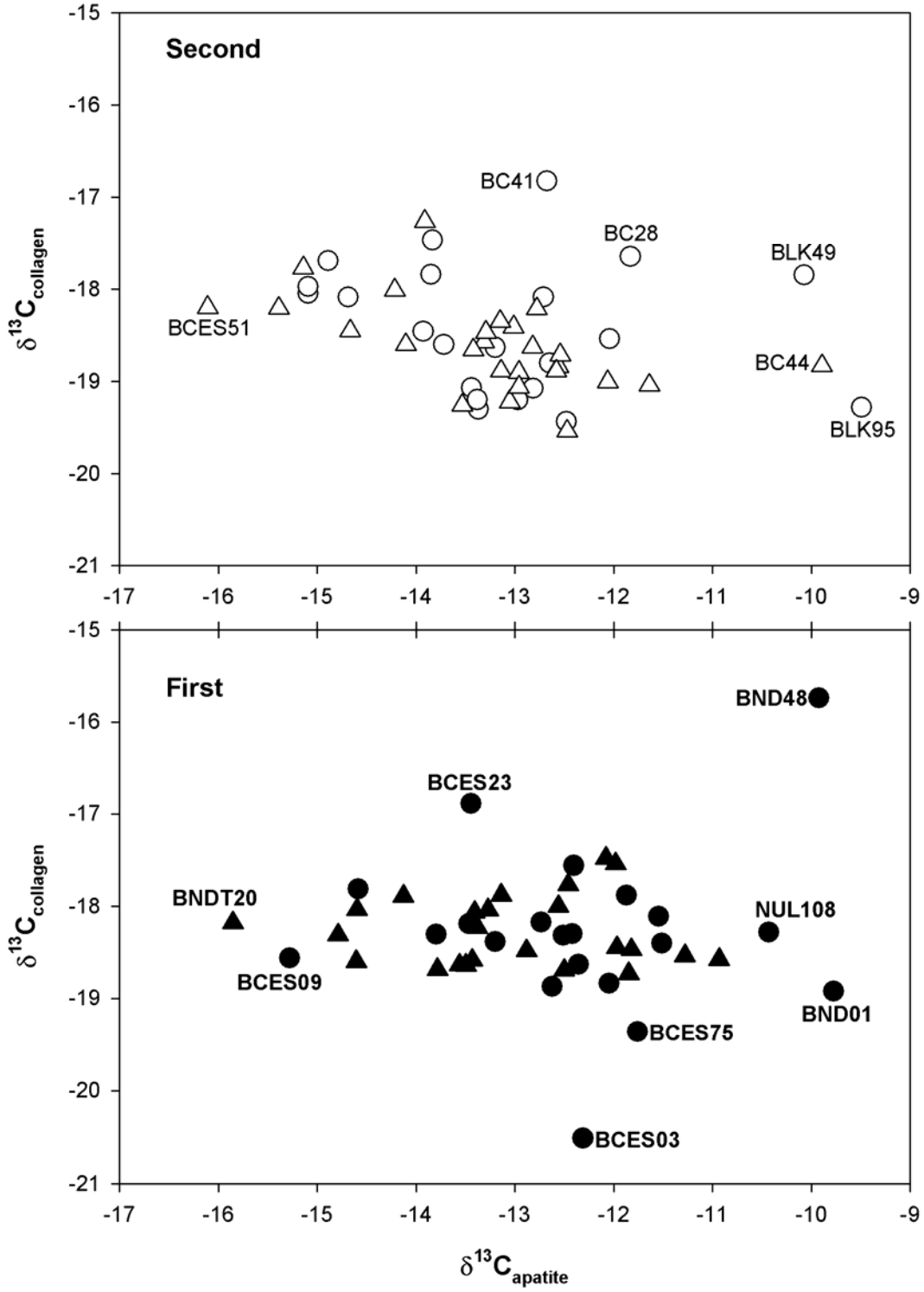

Figure 7.27. $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$ values from northeast Thailand by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

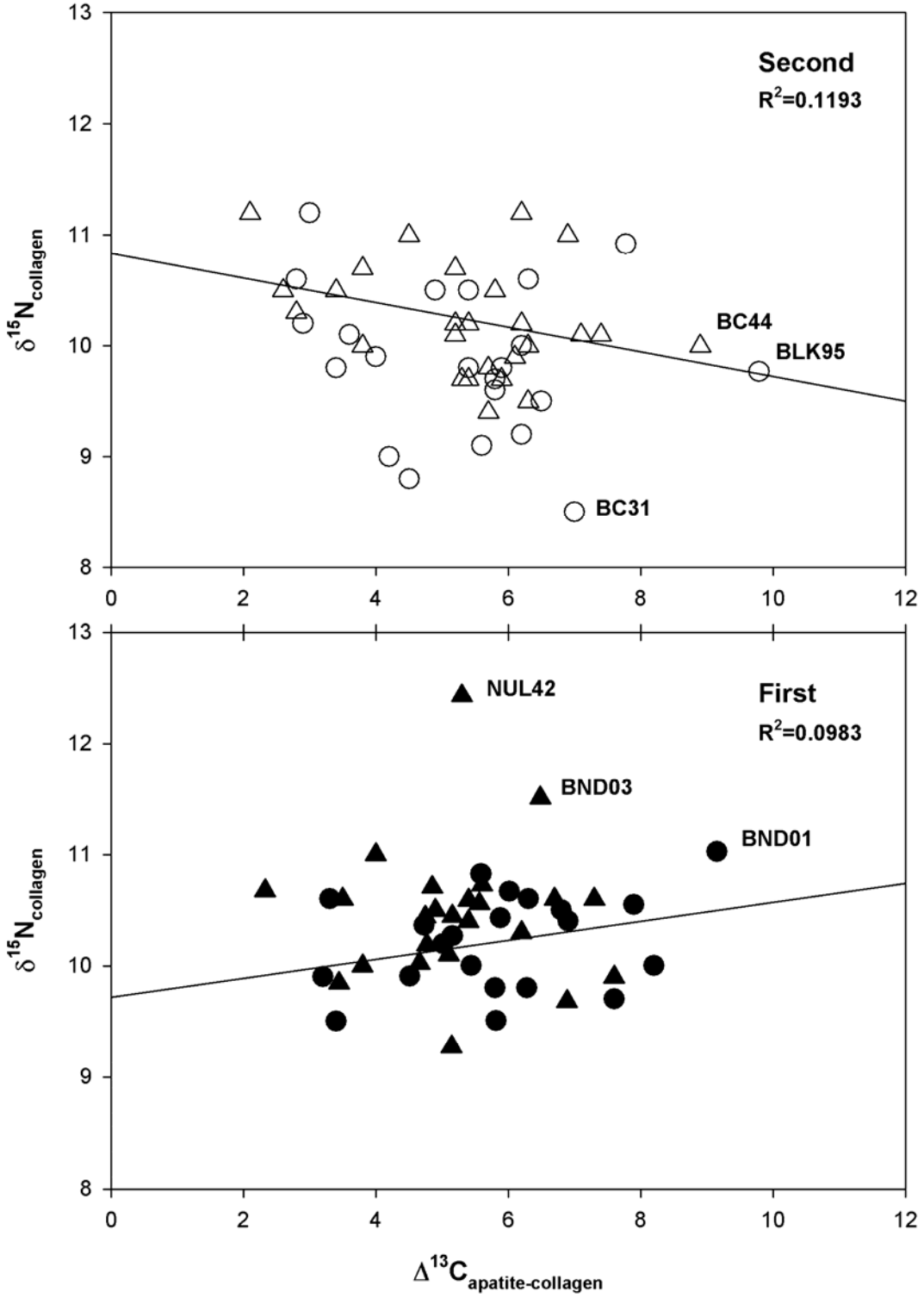

Figure 7.28. $\Delta^{13}C_{apatite\text{-}collagen}$ and $\delta^{15}N_{collagen}$ values from Ban Chiang by time period and sex: ○ 2nd Millennium Females, △ 2nd Millennium Males, ● 1st Millennium Females, ▲ 1st Millennium Males.

Summary

The purpose of this chapter was to present the isotope data from the analyses of human bone samples from four archaeological sites from northeast Thailand spanning two millennia. These archaeological sites are Ban Chiang and Ban Na Di in Sakon Nakhon Basin and Ban Lum Khao and Noen U-Loke in the Khorat Basin. Ban Chiang and Ban Lum Khao are second millennium B.C. sites. Ban Chiang, Ban Na Di, and Noen U-Loke are first millennium B.C. sites.

The Ban Chiang cemetery is the only site that covers both millennia. As such, the individuals can be analyzed for temporal variation, sex variation, and intra-site variation. With sexes combined, no statistically significant relationship for any stable isotopic variable is observed. The range of $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values strongly suggests a predominately terrestrial food base supplemented with freshwater protein resources. C_3 plant foods predominate, though the $\Delta^{13}C_{apatite\text{-}collagen}$ results suggest a shift in stable isotopic values that suggest an increased dependence on open-field agriculture over time.

No statistically significant temporal isotopic differences were found for either sex. Females during the second millennium demonstrate slightly more diversity in protein sources than females during the first millennium. A slight change in female $\Delta^{13}C_{apatite\text{-}collagen}$ values over time suggests intensification of open field agricultural practices with the possible supplementation of C_4 plants during the first millennium. In males, dietary diversity does not change much over time with the stable isotope data suggesting that the diet of males at Ban Chiang remained predominately C_3 plant and animal foods. The only trend over time among Ban Chiang males was in the decrease in standard deviation

of $\delta^{15}N$ values (from 0.5 to 0.3 from second to first millennium), suggesting protein sources were becoming slightly less varied over time.

The final analysis of remains from Ban Chiang investigated differences between females and males within a given millennium. During the second millennium, the mean $\delta^{15}N_{collagen}$ values for females was statistically ($p \leq 0.015$) more variable (and lower) than for males, suggesting females had more diverse protein in their diet than males. Males have more individuals who supplemented their diets with C_4 plant foods and/or plants grown in open fields. This pattern changed over time as both protein and carbohydrate sources became less varied between the sexes, a pattern consistent with the results of Bentley and colleagues (2005). The changing $\Delta^{13}C_{apatite\text{-}collagen}$ data does hint at the possibility of more open environments enabling intensified open field agricultural production at Ban Chiang during the first millennium B.C.

Individuals from the Ban Na Di cemetery all date from the first millennium B.C. Isotopic values from these individuals suggest very slight differences in diets between the females and males. Females have greater variability in protein in their diet. Both sexes demonstrate a diet predominately based on C_3 plants with protein sources from terrestrial animals eating C_3 plant foods. No statistically significant differences between the sexes for any stable isotopic variable were observed from Ban Na Di.

Only two female individuals yielded usable stable isotope data from the second millennium site of Ban Lum Khao. The data from these two individuals suggest a diet of C_3 plants and terrestrial animals eating C_3 plants. Interestingly, data from $\Delta^{13}C_{apatite\text{-}collagen}$

indicate similar overall diets to individuals from the other site (Ban Chiang) during the second millennium.

Noen U-Loke was another poorly preserved site with only two individuals, one male and one female, who yielded viable stable isotope data. The male individual expressed a higher $\delta^{15}N_{collagen}$ value suggesting more fish and/or carnivorous terrestrial animals in his diet than in the female's diet. The more positive $\delta^{13}C_{apatite}$ and higher $\Delta^{13}C_{apatite\text{-}collagen}$ values imply the female was consuming a greater mix of plant food sources including C_4 plant food resources than the male was.

Data from these four sites were combined to make general evaluations about dietary change in northeast Thailand. Due to the poor preservation from cemeteries at Ban Lum Khao and Noen U-Loke, these interpretations were comprised mostly from Ban Chiang for the second millennium, and Ban Chiang and Ban Na Di for the first millennium.

With the sexes combined, temporal variation between the mean values is statistically significant in the means for $\delta^{13}C_{collagen}$ ($p \leq 0.025$), $\delta^{15}N_{collagen}$ ($p \leq 0.030$), and $\delta^{13}C_{apatite}$ ($p \leq 0.048$) stable isotopic values, despite the fact that the standard deviations in all isotopes overlap greatly between millennia. Individuals from the second millennium expressed greater diversity in food choices than individuals from the first millennium, particularly among females, who have a larger variation than males for each isotope in the second millennium. Even though the diet choices appear to narrow over time, the $\Delta^{13}C_{apatite\text{-}collagen}$ results suggest diets in both time periods include primarily terrestrial animals consuming C_3-type plants, along with supplementation with freshwater fish. Plant foods consumed were also predominately C_3 plants though some individuals appear

to have supplemented their diets with plant foods which were C_4 or C_3 plants grown in open fields.

When each sex was analyzed separately for temporal variation some distinct differences became apparent. For females, decreasing variance for $\delta^{13}C_{apatite}$ ($p \leq 0.030$) and $\delta^{15}N_{collagen}$ ($p \leq 0.076$) were statistically significant, demonstrating the lower overall variation in diet among first millennium females. Both time periods indicate at least some individuals were consuming plants derived from open environments, suggesting an oscillation in agricultural practices over time. The increased number of first millennium individuals with more positive $\delta^{13}C_{apatite}$ values (particularly among females) implies an increased utilization of plants grown in open field environments. There was less difference between the millennia among males, with the only difference being a slightly more negative mean $\delta^{13}C_{collagen}$ value ($p \leq 0.004$) during the second millennium. Otherwise, the $\delta^{15}N_{collagen}$ $\delta^{13}C_{apatite}$, and $\Delta^{13}C_{apatite\text{-}collagen}$ results suggest that carbohydrate and protein sources in males are not significantly different over time.

Comparisons within each time period reveal very few dietary differences between females and males during the second millennium. Mean $\delta^{15}N_{collagen}$ values are statistically significant at the $p<0.1$ level though this could be related to a couple of female individuals with low values. Both females and males appear to have maintained a diverse diet of C_3 plants as well as the consumption of animals consuming C_3 resources. During the first millennium statistically significant differences in females and males are observed for the $\delta^{13}C_{apatite}$ values. As with $\delta^{15}N_{collagen}$ values from the previous time period, this too is only at the $p<0.1$ level and can be explained by a few female

individuals with more positive values. Overall, both females and males are slightly more tightly clustered in $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ during the first millennium (Figure 7.26), with a few outlier females. The data thus suggest less diversity in diet during the first millennium than the second millennium.

The results found in this chapter are discussed in Chapter VIII in the context of bringing together the plant, animal, and human data to provide a fuller picture of dietary patterns during the last two millennia B.C. in northeast Thailand.

Chapter VIII. Discussion and Conclusions

This body of data represents one of the largest paleodietary studies of prehistoric human subsistence using stable isotope analysis in northeast Thailand. The goal of this study was to develop an understanding of dietary change between the second and first millennia B.C. and between females and males within each time period. Individuals selected for this study represent the second and first millennium B.C. from two different regions in northeast Thailand. A secondary, though very important, aspect of this study is the establishment of baseline stable isotope data from plants and animals to interpret the human data assayed. These include a study of endemic plant foods (fruits and vegetables) and an analysis of modern and prehistoric faunal remains.

Plant Samples

Plant samples were chosen to explore the isotopic values of some of the plants that may have been available to prehistoric human and animal inhabitants of northeast Thailand. Modern plant samples had $\delta^{13}C$ values that span the ranges of both C_3 and C_4 plants (Appendix A and Figure 8.1). C_3 plants have a very high variance in $\delta^{13}C$ values while C_4 plants demonstrate very little within group variation in $\delta^{13}C$ values. This wide variation is most likely the result of the greater degree of sampling from a broader range of plants utilizing the C_3 photosynthetic pathway. The mean $\delta^{13}C$ values of the C_3 and C_4 plant groups are very similar to those from other areas reported in the literature (O'Leary 1981, 1988; Tieszen 1991).

$\delta^{15}N$ values for plant samples also show a larger variance for C_3 plants than for C_4 plants. The majority of nitrogen values fall between 0‰ and 10‰. Since modern plants

were used for this study, this high variance in $\delta^{15}N$ has two possibilities. First, modern inhabitants of northeast Thailand could be using artificial fertilizers that came in contact with the plants either directly or indirectly through run-off. Or, the more plausible scenario is the influence of animal dung on or within proximity to the plant. In modern-day northeast Thailand it is common practice to lead water buffalo or cattle to areas of dense vegetation growth. Free-ranging populations of these animals are frequently observed grazing in ditches or near ponds and streams. Spreading natural manure is known to increase the $\delta^{15}N$ values of both soil and plants (DeNiro and Epstein 1981; Hoefs 1987; Schwarcz et al. 1999).

Pinpointing the arrival and domestication of rice in different parts of the world has been of interest to prehistorians for a long time. This study analyzes a large number of wild and domesticated (glutinous and non-glutinous) rice varieties to test if the use of stable isotopes could distinguish differences (Table 6.2 and Figure 6.3). Although wild rice varieties average lower $\delta^{15}N$ values than domesticated varieties, the overlap in $\delta^{13}C$ values is considerable. Neither $\delta^{13}C$ nor $\delta^{15}N$ can be used to statistically differentiate wild and domesticated rice nor could glutinous versus non-glutinous domesticated varieties be reliably distinguished.

Faunal Samples

The large number of faunal samples (Appendix B) demonstrates a considerable amount of variation in both $\delta^{13}C$ and $\delta^{15}N$ values. Figure 8.1 is a graphic representation of the faunal stable isotope results. The mean range values for each archaeological site are also included for comparison, and to allow inference regarding human diet.

Most of the animal species subsist on known diets and so have expected stable carbon and nitrogen isotope results. Thus the diversity in faunal stable isotopic values is the product of differing dietary regimes. Based on the prevalence of faunal species recovered from archaeological cemeteries in the region, animal protein in the human diet primarily included deer, pig, fish, shellfish, chicken, cattle, water buffalo, and rat.

For larger terrestrial omnivores and herbivores recovered from archaeological sites in northeast Thailand there is marked variation in both $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values. The stable isotopic results for the water buffalo are interesting as they indicate a free-ranging diet of primarily open field grasses that may have included C_4 grasses. Today in northeast Thailand, open field wet rice agriculture is the dominant land use with a strong focus on feeding water buffalo rice stubble and straw (Joyce White, personal communication 2005). If it is assumed that rice, a C_3 plant, was one of the primary crops grown by prehistoric inhabitants in this region then farmers would likely have fed their buffalo primarily rice stubble and straw.

As listed in Appendix B.2, four out of six water buffalo were from the first millennium B.C. AFB16 and AFB31 were from Ban Chiang and AFB45 and AFB51 were from Ban Na Di. The stable isotope data from these indicate a diet of mixed C_3 but mostly C_4 open field grasses. A plausible inference would be that rice stubble and straw were less important as animal feed and water buffalo roamed more freely.

The results for the deer species sampled were also not all as expected. The small browsers like the *Muntiacus muntjak* demonstrated typical isotopic values for an animal eating fruits, leafy shrubbery, and bark (Figure 6.4) with little change over time

(Appendix B.2). Larger browsers (*Cervus unicolor*) were clearly consuming predominately open field C_4 grass types. *Cervus unicolor* is a mixed browser/grazer so when in areas of jungle clearance they can easily adjust to open plains grass (Kurt 1990). Archaeological samples from both time periods for *Cervus unicolor* indicate similar dietary patterns of primarily open field C_4 grass consumption.

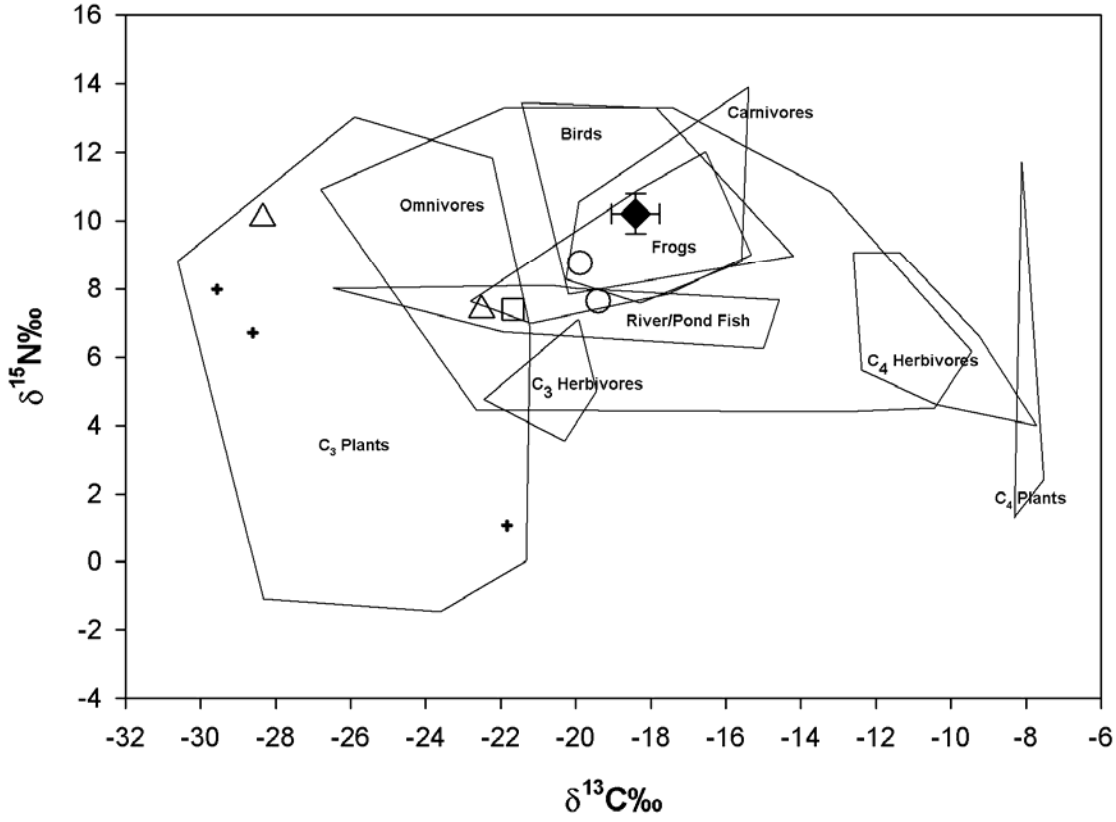

Figure 8.1. $\delta^{13}C$ and $\delta^{15}N$ values of possible foodstuffs in prehistoric northeast Thailand: ○ Bats, □ Land Crab, △ Insects; ✚ Snails; shapes are drawn for groupings of plants and animals that numbered more than two and data points are shown for cases with less than two individuals. Human samples ◆ including mean range values with one standard deviation.

Human Samples

Four human skeletal samples from northeast Thailand, Ban Chiang, Ban Na Di, Ban Lum Khao, and Noen U-Loke are used to investigate patterns of dietary intake and dietary change during the second and first millennium B.C. As described in Chapter II, archaeological evidence indicates these periods represent the transition from pre-metal, to bronze, to iron metallurgy along with substantive other changes in the material culture (Higham 2002). These changes in material culture, particularly the transitions from bronze to iron metallurgical skills, also coincide with the appearance of domesticated water buffalo, which is still commonly used today for traction. Paleoenvironmental research has also discerned that evidence of forest recovery during the beginning of the first millennium B.C. supports an interpretation of a shift from unmanaged burning of forests to controlled burns of ground cover (White et al. 2004:129).

Bioarchaeological analysis of individuals from these periods indicates the inhabitants of northeast Thailand are relatively healthy (Domett 2001; Domett and Tayles 2006; Douglas 2006; Pietrusewsky and Douglas 2002a). Osteological data suggest the subsistence for second and first millennium B.C. people was broadly based in both wild and domestic plants and animals consumed from upland/lowland and forest/open plains areas. Furthermore, osteological evidence from teeth, discussed in Chapter III, indicates possible dietary differences between females and males within these sites and within each time period.

Through the use of stable isotope analysis of $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$ and $\delta^{13}C_{apatite}$ this study has hypothesized that human induced changes to the surrounding landscape as well

as innovations in material cultural, resulted in distinct dietary differences among the populations of these time periods in northeast Thailand. In order to test these assumptions of dietary change in northeast Thailand, two hypotheses are addressed. Hypothesis 1: There are distinct dietary differences among the populations of different time periods in northeast Thailand. Hypothesis 2: That female and male diet changed over time.

Sample size and potential biases

Before this discussion begins, a brief remark on the available dataset is warranted. A total of 95 out of 179 (53%) human bone samples produced viable stable isotope data. While this is an adequate sample for stable isotopic analysis, there were two sampling issues. First, Ban Lum Khao and Noen U-Loke series yielded only two samples each. This meant that only cursory interpretive information could be provided for these sites. As a result, intra-regional differences between the Sakon Nakon and Khorat Basins could not be examined since these two sites were both from the Khorat Basin. Poor preservation is the most likely explanation for the inadequate samples. At each of these sites, concretions adhering to the bone either from the surrounding soil and/or from funerary practices resulted in poor preservation of bone collagen. Also many of the Ban Lum Khao samples were highly mineralized, also resulting in little or no bone collagen yield.

Second, the lack of adequate samples from Ban Lum Khao and Noen U-Loke means that most of the second millennium individuals come from Ban Chiang and the bulk of the first millennium samples are from Ban Chiang and Ban Na Di. As a result,

interpretations of temporal variation are principally from only two sites. A caveat to this however is that the values from the four individuals from Ban Lum Khao and Noen U-Loke did not differ greatly from the individuals from Ban Chiang and Ban Na Di. This suggests similar dietary patterns between the two regions though greater sampling of the Khorat Basin is needed.

Inter-Site Variation

To answer questions about dietary change for northeast Thailand during the second and first millennium B.C. skeletal series from four archaeological sites were selected. These samples are analyzed separately to investigate inter-site variation between females and males. In addition, Ban Chiang's long temporal span and large sample size has allowed for additional analyses of dietary change over time.

The results from the Ban Chiang analysis indicate only slight shifts in dietary variation over time. The stable isotope data suggest an increased dependence on intensified open field agriculture over time. For both females and males, protein sources became less diverse over time. While it is more apparent in females than males, carbon isotope values shift more positively over time suggesting an increased consumption of plants grown in, and animals who consumed plants derived from, non-forested, open fields.

Differences between females and males within a time period are observed. During the second millennium females consumed a greater variety of protein sources than males which may be related to the consumption of more fish. Males, on the other hand, appear

to have consumed a wider variety of plant foods, which may have included C_4 and/or more plants grown in open fields to account for the more positive carbon isotope values.

An investigation of first millennium individuals indicates both protein and carbohydrate sources are more homogenous for both females and males. These results confirm those reported in a previous stable isotope study from Ban Chiang (Bentley et al. 2005). During this period most of the variation in carbon isotopic values was explained by diversity in carbohydrate consumption with more similar stable isotopic values in protein sources between females and males.

The skeletal sample from Ban Na Di also yielded similar information concerning dietary differences between females and males during the first millennium B.C. Most of the variability in carbon values between females and males comes from $\delta^{13}C_{apatite}$ values. In addition the broader range of $\delta^{13}C_{apatite}$ to $\delta^{15}N_{collagen}$ variation for both sexes indicates a larger range of carbohydrates consumed than proteins consumed. This would support the implication that individuals during the first millennium B.C. were consuming mostly domesticated animals while plant food sources remained more diverse. $\delta^{13}C_{apatite}$ values from Ban Na Di and first millennium Ban Chiang are similar (compare Tables 7.5 and 7.6) and this suggests that most of the plant foods consumed at these locations were C_3-derived crops from open field agricultural systems.

Due to poor preservation, detailed analysis to investigate inter-site variation for Ban Lum Khao and Noen U-Loke could not be undertaken. However, these samples are combined with the datasets from Ban Chiang and Ban Na Di to test the hypotheses of

dietary change over time as well as dietary differences between females and males within a time period.

Hypothesis 1: Diet Changed over Time in Northeast Thailand

The first hypothesis states that there is a detectable shift in the isotopic signature for $\delta^{13}C_{collagen}$, $\delta^{15}N_{collagen}$ and/or $\delta^{13}C_{apatite}$ between the second and first millennium B.C. in northeast Thailand. This change results from agricultural intensification near the middle of the first millennium B.C. To test this hypothesis the samples from the four archaeological sites were separated by time period.

Statistically significant differences are observed for $\delta^{13}C_{collagen}$ ($p \leq 0.025$), $\delta^{15}N_{collagen}$ ($p \leq 0.030$), and $\delta^{13}C_{apatite}$ ($p \leq 0.048$) values suggesting change over time in dietary patterns. Overall, $\delta^{13}C_{collagen}$ ranges from -20.5‰ to -18.4‰ reflecting dietary protein sources predominately of C_3 terrestrial protein (terrestrial animals consuming terrestrial C_3 plants). The less varied $\delta^{15}N_{collagen}$ values that occur during the first millennium suggest an increased reliance on domesticated animals consuming C_3 plants than in the second millennium. Two first millennium individuals (BCES03 and BND48) on either end of the $\delta^{13}C_{collagen}$ range are the most likely explanation for the significant difference in this value (Figure 8.2). There is a trend for more positive $\delta^{15}N_{collagen}$ values over time.

Based on $\delta^{13}C_{apatite}$ values the overall diets from the second to the first millennium B.C. have changed significantly over time (Figure 8.3). Also of interest is an apparent separation of isotope values of first millennium Ban Chiang individuals into two clusters. There is a 0.8‰ division between -13.4‰ and -12.6‰. The three most negative individuals (furthest left) are from Ban Chiang LP X. While these negative values may

suggest increased rice consumption late in the first millennium B.C., the individuals with the most positive $\delta^{13}C_{apatite}$ values (furthest right) are also from LP X. This may suggest that some late first millennium B.C. and early A.D. period individuals at Ban Chiang were not completely reliant on open field agriculture. These individuals may also have been recent immigrants to Ban Chiang (see Bentley et al. 2005).

Individuals from the second millennium have more negative $\Delta^{13}C_{apatite\text{-}collagen}$ mean values than individuals from the first millennium. This suggests that dietary intake during the first millennium was more enriched in ^{13}C than the diet consumed by second millennium individuals. Further, individual diets are becoming more monoisotopic, that is, more similar over time. The more positive ^{13}C values suggest a combination of possible changes to the subsistence pattern over time. An increased reliance on domesticated animals consuming primarily C_3 plant foods could explain the differences. Or a trend towards increased open field agriculture, as well as possible supplementation with C_4 plant foods such as millet or Job's Tears.

These shifts in the dietary regime may have also played a role in demography as well as dental health as related to diet over time. Paleodemographic analysis indicates that from the second to first millennium B.C. there is an increase in the birth rate, but also a higher mortality rate (Table 3.2). These paleodemographic indicators are all consequences of a shift in agricultural practices towards intensified open field agriculture. Dental health also indicates a shift in diet over time. There is a significant decrease in dental caries but no appreciable difference in dental attrition or antemortem tooth loss. The significant decrease in carious lesions from 7.6% to 4.7% is contrary to what is

expected with a subsistence shift to intensified agriculture (Cohen and Armelagos 1984). This suggests the diet remained varied and not completely reliant on a single starchy field crop (Pietrusewsky and Douglas 2002a:201).

The increased homogeneity from the second to the first millennium B.C. supports the archaeological evidence which implies first millennium B.C. settlements were full-time sedentary villages relying principally on domesticated plants and animals in northeast Thailand (Higham and Thosarat 1998a). While there is a trend towards homogeneity over time, prehistoric people during the first millennium B.C. still maintained a broad subsistence regime. Based on the available stable isotope data, Hypothesis 1 is accepted.

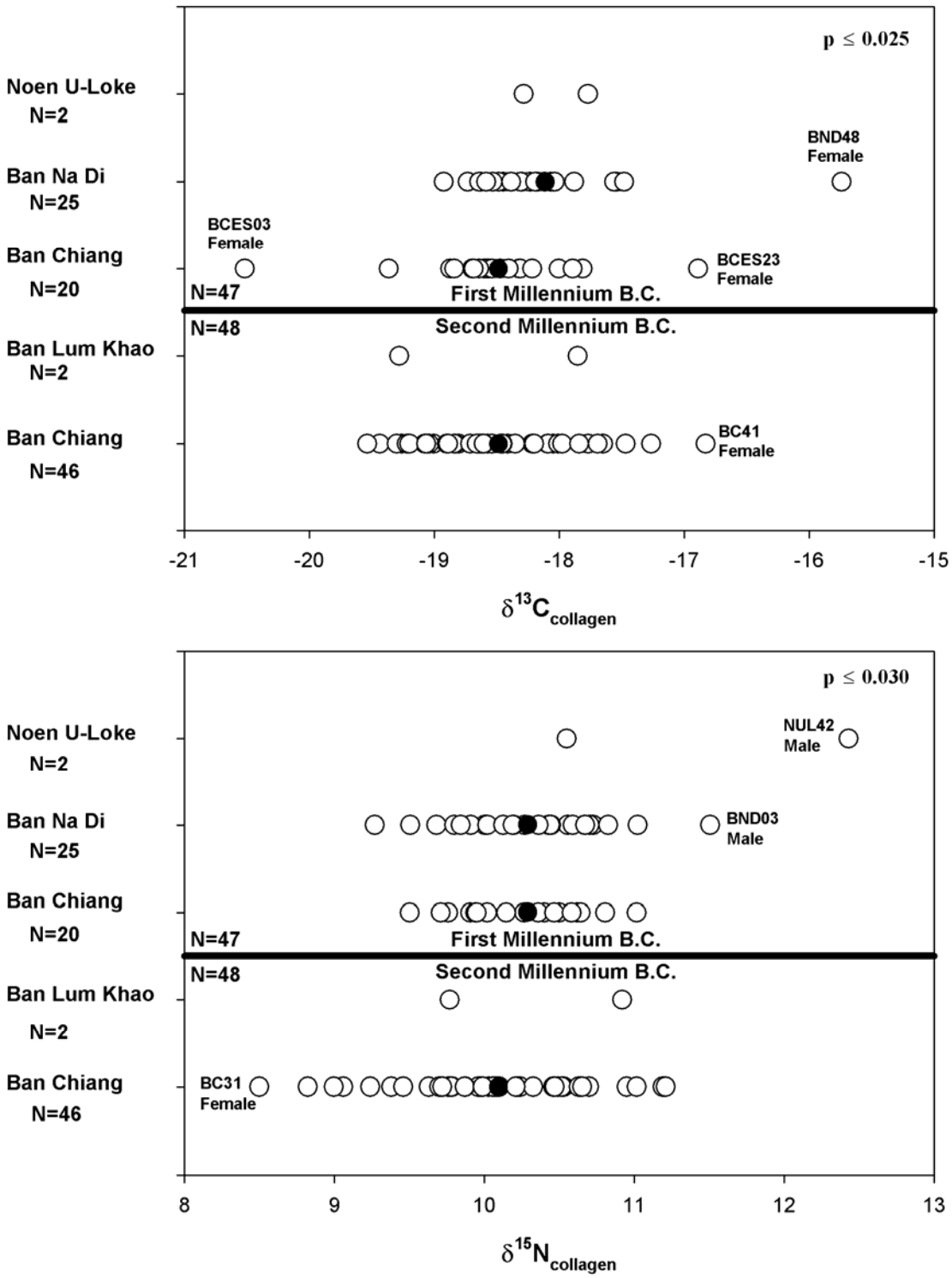

Figure 8.2. Trends in $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values in human remains from northeast Thailand by site: ○ represent individuals; ● represent the mean value.

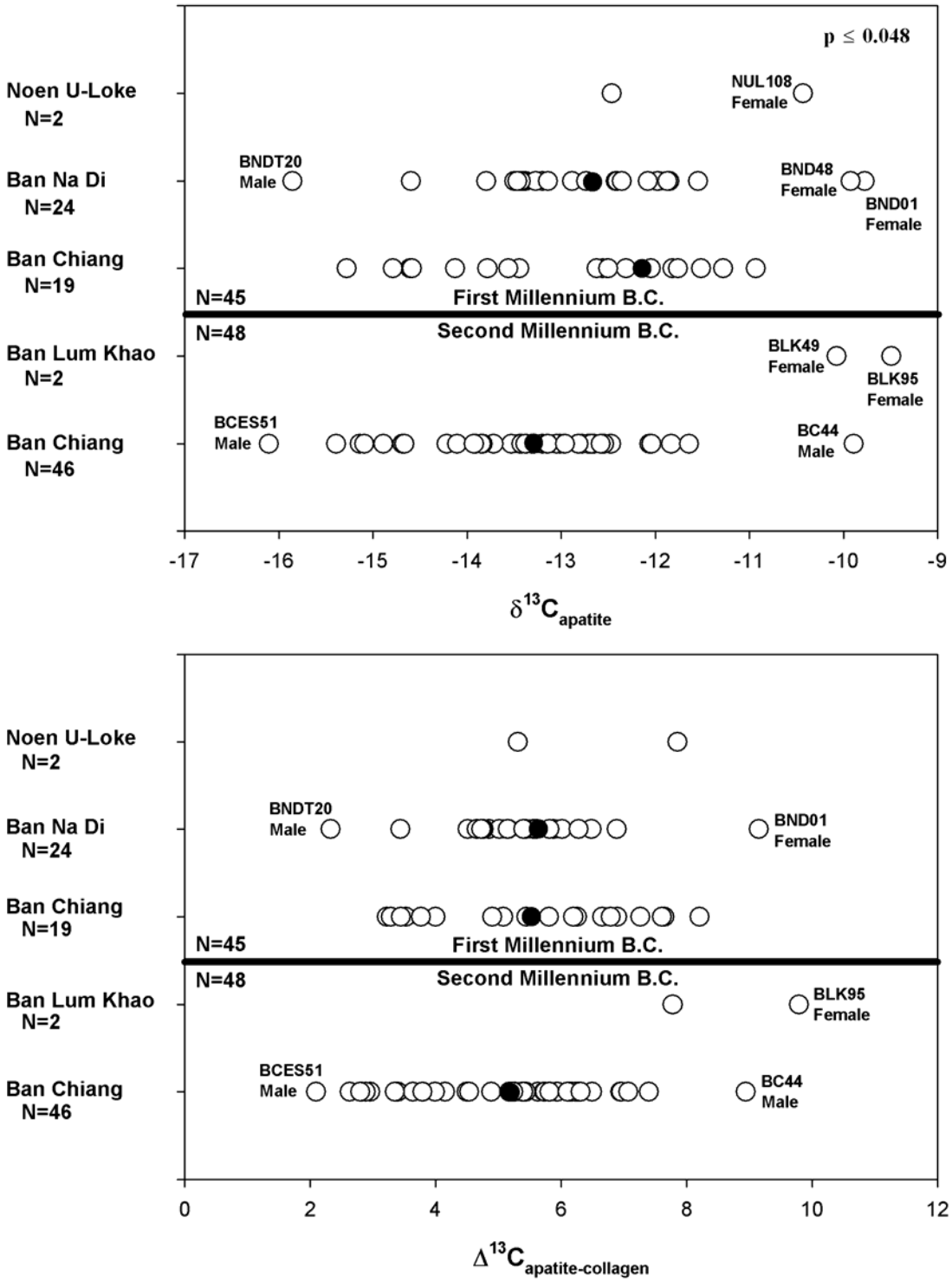

Figure 8.3. Trends in $\delta^{13}C_{apatite}$ and $\Delta^{13}C_{apatite\text{-}collagen}$ values in human remains from northeast Thailand by site: ○ represent individuals; ● represent the mean value.

Hypothesis 2: Differences Exist in Dietary Intakes over Time for Females and Males.

Inter-site variation between females and males from Ban Chiang and Ban Na Di demonstrate that variation exists with each time period. The first hypothesis investigated broad changes in diet over time regardless of the sex of the individuals. Significant temporal differences in diet are evident. A second hypothesis seeks to identify dietary patterns by sex over time.

In northeast Thailand, analyses of dental pathological conditions indicate inter- and intra-site differences between females and males (Domett 2001; Douglas 1996; Pietrusewsky and Douglas 2002b; White 1982c; Wiriyaromp 1984a,b). Analysis of dental remains indicate statistically significant differences between females and males within and between time periods for carious lesions, advanced attrition, and antemortem tooth loss (Table 3.10). These differences result from factors such as environmental differences, a sexual division in food resources, or inter-site variation (Domett 1999; Douglas 1996; Tayles 1992). The test implications for Hypothesis 2 include a difference in the isotopic signatures in females and males between time periods.

Statistically significant temporal differences in isotope values are found for both females and males. For females, the Mann-Whitney U-test indicates there are significant differences in $\delta^{15}N_{collagen}$ ($p \leq 0.076$) and $\delta^{13}C_{apatite}$ ($p \leq 0.030$) stable isotopes (Table 7.10). For males, only $\delta^{13}C_{collagen}$ ($p \leq 0.004$) values change significantly over time (Tables 7.11).

These isotopic differences suggest the dietary regime of females in northeast Thailand changed over time more than the dietary regime of males. Significant changes in both

$\delta^{15}N_{collagen}$ and $\delta^{13}C_{apatite}$ in females indicate both the protein and carbohydrate components of the diet were affected. The mean $\delta^{15}N_{collagen}$ value for females increased from 9.9‰ to 10.2‰. This more positive shift over time suggests an increased consumption of animals at higher trophic levels which may result from the consumption of more fish and/or carnivorous animals than their predecessors. The second millennium range for $\delta^{15}N_{collagen}$ values (2.7) is almost double that of the first millennium range (1.5) (Table 7.10, page 184). This wider spread of $\delta^{15}N_{collagen}$ values means, a greater variety of animals were being consumed by females during the second millennium B.C. (Figure 8.4) with decreasing variability over time.

The more positive shift in $\delta^{13}C_{apatite}$ values ($p \leq 0.030$) for females suggests the carbohydrate component of the diet also changed over time (Figure 8.5). From the second to first millennium B.C., $\delta^{13}C_{apatite}$ values in females become more positive with the mean shifting from -13.1‰ to -12.4‰. This increased enrichment implies that first millennium females were consuming a greater quantity of plants from open field agriculture. If the archaeological data for intensification of wet rice agriculture during the first millennium B.C. in northeast Thailand are accepted, this would concur with evidence from dental carious lesions which indicate females have a significantly higher rate of dental caries during the first millennium B.C. than males (Table 3.10). Females also have a significant increase in antemortem tooth loss over time and significantly greater antemortem tooth loss than males during the first millennium B.C. This increase suggests an increase in carbohydrate consumption that led to an increased likelihood of tooth loss.

The evidence for dietary change over time in males includes a significant difference in the variance for $\delta^{13}C_{collagen}$ ($p \leq 0.004$) (Figure 8.4). The mean $\delta^{13}C_{collagen}$ value for the first millennium males (-18.3‰) is virtually the same as during the second millennium (-18.6‰). The $\delta^{13}C_{collagen}$ range during the first millennium (1.2) however is half as large as the range in the second millennium (2.2) indicating a more homogenous pattern over time (Table 7.11, page 184). First millennium males were consuming fauna with a narrower dietary carbon range than the fauna consumed by males during the second millennium. This suggests the consumption of more domesticated animals with less of an emphasis on wild game, perhaps reflecting a more sedentary lifestyle. Even though there are no significant differences when the whole diet ($\Delta^{13}C_{apatite\text{-}collagen}$) is evaluated, there are indications that some dietary elements changed over time for both females and males (Figure 8.5). Hypothesis 2 is accepted.

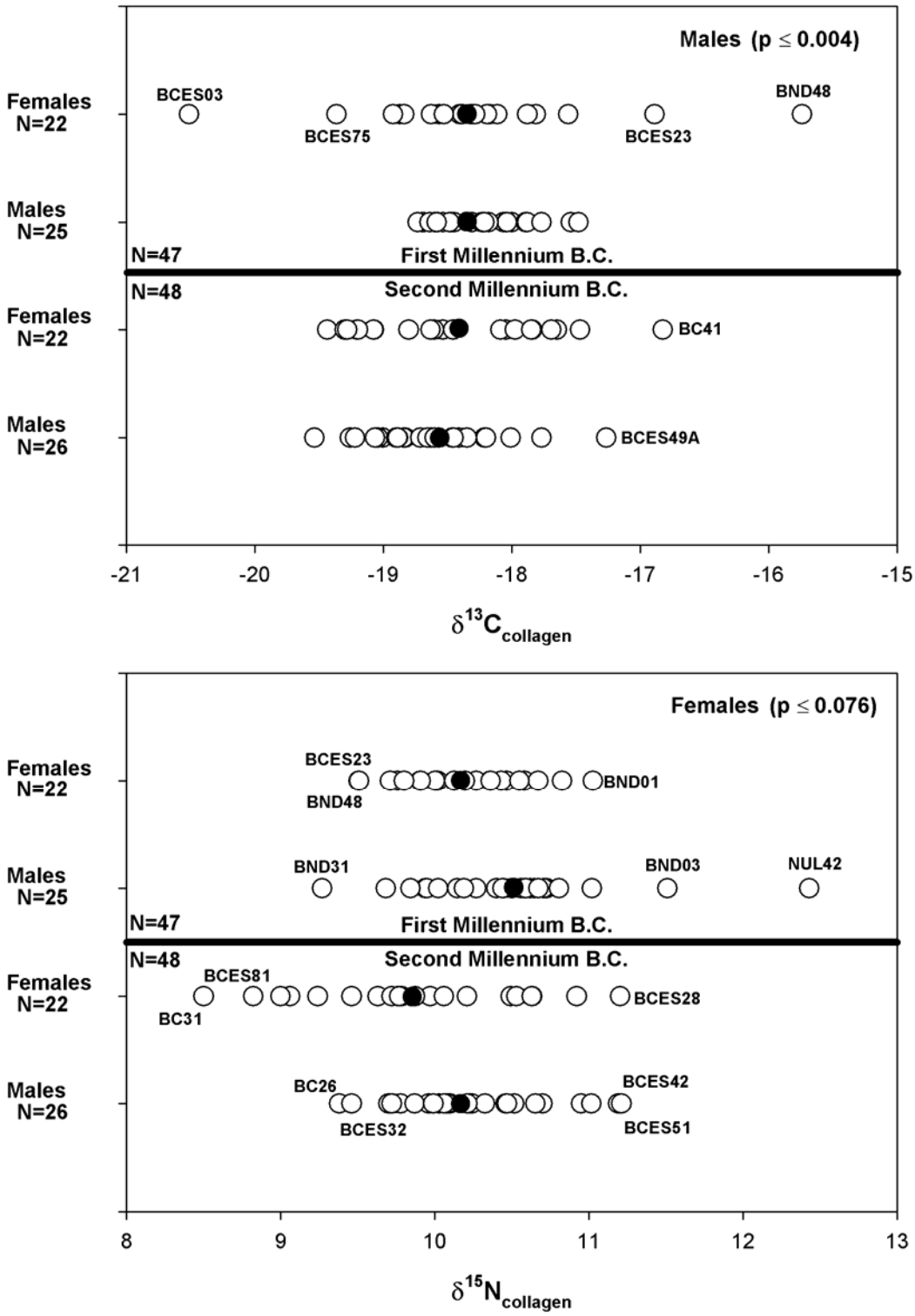

Figure 8.4. Trends in $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values in human remains from northeast Thailand by sex: ○ represent individuals; ● represent the mean value.

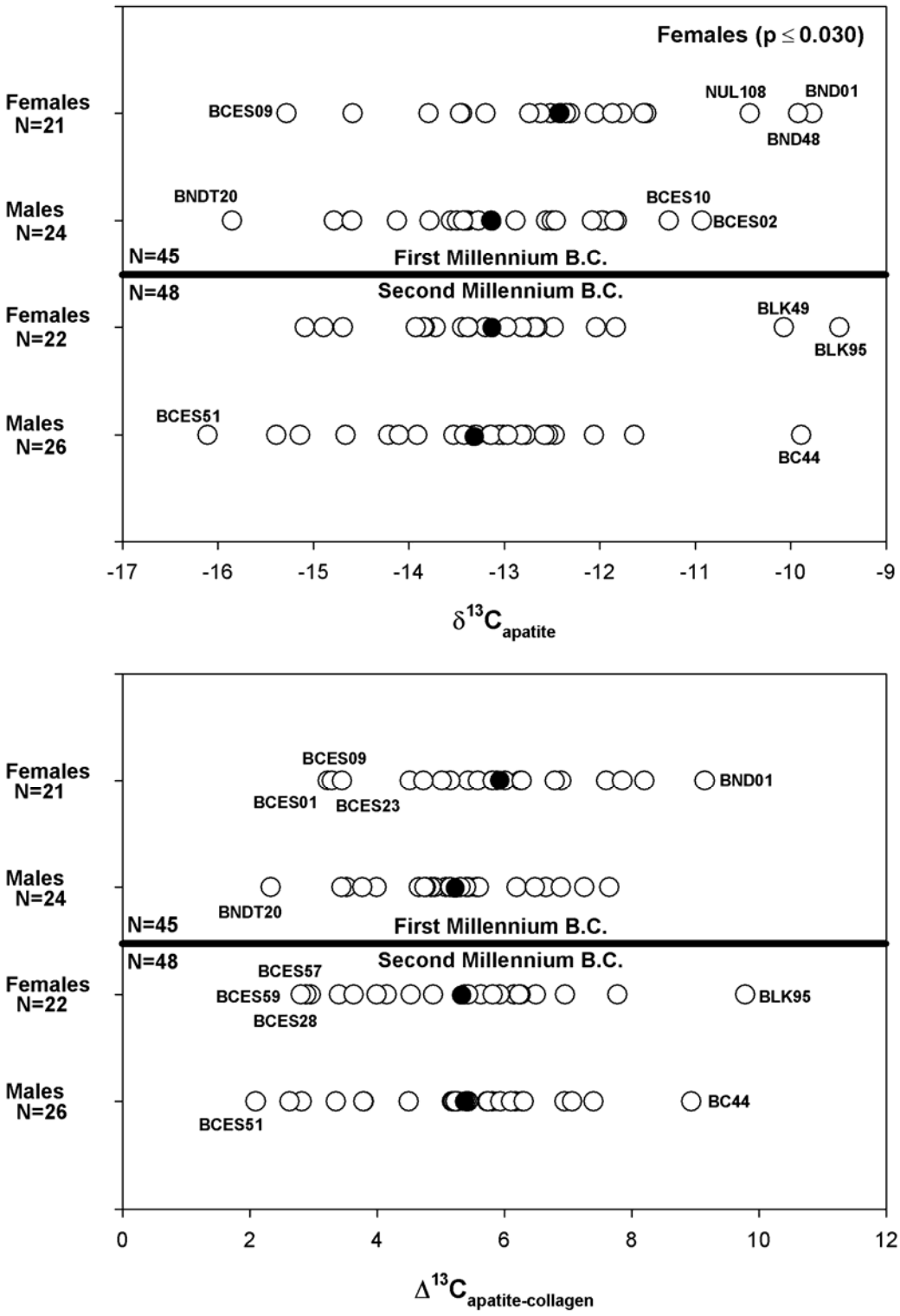

Figure 8.5. Trends in $\delta^{13}C_{apatite}$ and $\Delta^{13}C_{apatite\text{-}collagen}$ values in human remains from northeast Thailand by sex: ○ represent individuals; ● represent the mean value.

Synopsis of Dietary Change in Northeast Thailand

An understanding of dietary patterns in a prehistoric population from any region must take into account the surrounding environment as well as cultural practices. Cultural change in northeast Thailand is typically classified under the heading of general periods (GP) with GP B and C of particular interest since they represent the cultural developments approximately equivalent to a Bronze Age (second millennium B.C.) and Iron Age (first millennium B.C.).

Paleoenvironmental data from the Sakon Nakhon and the Khorat Basins both indicate that during the second millennium B.C. the landscape was mostly clear of any major forests but pockets of forest clearance are apparent (Boyd et al. 1999b; Penny 1999a,b; White et al. 2004). The stable isotope data suggest that forests were still being exploited with forest products consumed, presumably in remnant forests. Concurrently, extensive open areas were being experimented with for open field cereal production, presumably wet rice.

The overall food procurement pattern in northeast Thailand has a wide dietary breadth, that is, a mixture of pure foraging supplemented by systematic tending of plants through swiddening or another form of horticulture (Harris 1989). Archaeological evidence suggests a hunting-based economy which included the exploitation of riverine/pond fish and shellfish (Higham 2002). This wide dietary breadth is further supported through bioarchaeological data. Stable isotope data from the second millennium B.C. support a dietary pattern based on wild plant foraging, cultivation of plant foods, and the consumption of wild and domestic animals.

Using the GP scheme, the transition from GP B to GP C took place around 500 B.C. with the archaeological appearance of iron technology (Bayard 1984; Higham 1989). Paleoenvironmental studies provide evidence for gradual and persistent modification of the landscape by humans during the second millennium that peaked around 890 B.C., cal. (White et al. 2004:123). This paleoenvironmental transition supports archaeological observations of a gradual increase in settlement sizes, increased human modification of the environment, increased metallurgical sophistication, and significant changes in ceramic and mortuary differentiation during the first millennium B.C. (Boyd et al. 2001b; O'Reilly 2001; White and Pigott 1996).

The increase in human modification of the surrounding landscape suggests a greater reliance on low lying wetland cultivation. Moreover, the introduction of the iron plow and increase in domesticated cattle, water buffalo, and pig in the faunal record suggest an increasing reliance on domestic resources. The analysis of dietary change using stable isotopes corroborates a trend toward more homogenous diets from the second to the first millennium B.C. (Figure 8.3, $\Delta^{13}C_{apatite\text{-}collagen}$).

Archaeological, paleoenvironmental, and stable isotopic evidence supports pattern for an increase in cereal-focused food production during the first millennium B.C. as suggested by paleoenvironmental research (Boyd et al. 2001b; White et al. 2004). Low burning combined with a re-establishment of secondary forests (Penny 1999) during the first millennium B.C. is consistent with agriculture less reliant on active clearing and more focused on intensification (more food produced per unit of land), most likely wet rice cultivation of some sort. This intensification of open field cereal crop production is

also supported by the appearance of iron and water buffalo in excavations of first millennium sites (Higham 2002).

The stable isotope data suggest that individual diets in both time periods were widely varied in both the types of plants and kinds of animals consumed. The variation in stable isotope values among individuals during the first millennium B.C. indicates there is not a complete conversion of the group to intensive open field agriculture and domestic animal consumption. Stable isotopic variation from the second to the first millennium B.C. indicates farming and raising of domestic animals were not uniform throughout northeast Thailand.

An increased use of aquatic resources over time would entail enrichment in both ^{13}C and ^{15}N making $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ both more positive (Chisholm et al. 1982; Schoeninger et al. 1983; Tauber 1981). Fish and shellfish consumption occurs during both the second and first millennium B.C. periods. There are significant differences observed over time for both $\delta^{13}C_{collagen}$ and $\delta^{15}N_{collagen}$ values (Table 8.2). First millennium females are significantly more positive in $\delta^{15}N_{collagen}$, while males are more significantly positive in $\delta^{13}C_{collagen}$ (Table 8.4). This suggests that the more positive $\delta^{13}C$ values during the first millennium B.C. can be attributed to an increase use of aquatic resources for females but not necessarily for males.

The degree of utilization of C_4 cultigens in northeast Thailand, or any other part of mainland Southeast Asia is an unanswerable question at this time. C_4 plants found in Thailand today include Job's Tears, millet, and sugar cane. Due to poor preservation of botanical remains, the utilization of certain edible grasses and even tubers are difficult to

assess through paleobotanical analysis alone. However, since C_4 plants are significantly enriched in ^{13}C they are easily distinguishable from C_3 plants when consumed in large quantities for long periods of time (Katzenberg 2000). C_4 plants are also more typical of seasonal open field areas rather than humid closed forest conditions since they require a dry season to mature (Lu 1999). This makes C_4 plants a potentially useful crop for northeast Thailand, particularly during long dry seasons which would result in poor rice (C_3) yields. However, paleobotanical and ethnographic evidence do not provide overwhelming evidence for long-term or large-scale use of C_4 cereal crops in northeast Thailand. Further, ceramic analysis of pottery has only yielded evidence for rice being used as a tempering agent. As a result, the conclusion can be made that if millet or other C_4 cereal crops were available in prehistory they were only utilized minimally and never transformed into a major food crop in northeast Thailand.

A reconstruction of the isotopic composition of the human paleodiet is compared to the isotopic composition of the food resources in northeast Thailand (Figure 8.6). To begin this process isotopic determination of potential food resources need to be presented. For modern plants and flesh samples from modern animals, $\delta^{13}C$ values were adjusted by +1.5‰ to compensate for increased ^{12}C in the atmosphere from the burning of fossil fuels (Keeling et al 1979; Tieszen 1991). For faunal bone samples from modern and archaeological specimens were utilized. The $\delta^{15}N_{collagen}$ were adjusted by +0.6‰ to represent the isotopic composition of flesh (DeNiro and Epstein 1978, 1981). Due to financial constraints, only 24 out of 104 faunal bones samples were able to be analyzed for $\delta^{13}C_{apatite}$ values. The average $\Delta^{13}C_{apatite\text{-}collagen}$ value for these specimens was 5.0.

Using the 5.0 difference as a proxy indicator of the stable isotopic difference between $\delta^{13}C_{apatite}$ and $\delta^{13}C_{collagen}$, the $\delta^{13}C_{apatite}$ values for the remaining faunal samples were computed by subtracting 5.0 from the individual $\delta^{13}C_{collagen}$ value. The archaeological and modern terrestrial faunal bone samples were then converted to a flesh value by adjusting the $\delta^{13}C_{apatite}$ values by -3.7‰.

The second step is to reconstruct the isotopic composition of the human diet using bone isotope values. There is a linear relationship between the whole diet carbon isotopic composition and that of the food source. This relationship is demonstrated in bone apatite carbonate. Bone apatite carbonate is derived from CO_2 produced from food metabolism, and because all dietary macronutrient fractions (fats, protein, and carbohydrates) are used for energy metabolism, the $\delta^{13}C_{apatite}$ value reflects that of the total caloric base (Ambrose and Norr 1993; Ambrose et al. 1997). Regardless of the isotopic composition of the dietary components in the human diet, there is a consistent 9.5‰ diet-to-tissue fractionation factor (Ambrose and Norr 1993; Tieszen and Fagre 1993). Therefore, it can be said that for $\delta^{13}C_{apatite}$, 'you are what you eat' +9.5‰. In order to obtain the $\delta^{13}C$ dietary values ($\delta^{13}C_{apatite\text{-}diet}$) from bone samples of humans, the $\delta^{13}C_{apatite}$ values were adjusted by -9.5‰. An additional adjustment of -2.5‰ diet-to-tissue spacing was used for $\delta^{15}N_{collagen}$ values to determine diet $\delta^{15}N_{diet}$ (DeNiro and Epstein 1981).

Figure 8.6 demonstrates the complexity of understanding human paleodietary change in a sub-tropical monsoon region in which the food web is predominately C_3 food resources. There is considerable overlap in $\delta^{13}C$ and $\delta^{15}N$ values in meat resources,

particularly between aquatic and terrestrial food resources. The mean $\delta^{13}C_{apatite\text{-}diet}$ values for second and first millennium B.C. individuals are -22.7‰ and -22.3‰ respectively. For $\delta^{15}N_{diet}$, the mean values are 7.6 and 7.9 for second and first millennium B.C. individuals respectively. These dietary values indicate an overall diet that is strongly based on C_3 plants and animals along with the utilization of aquatic resources (river and pond fish) in the area. There is no $\delta^{13}C$ signature from any of the human samples to suggest the regular consumption of C_4 cereals such as millet or Job's Tears.

The most likely explanation then for the enrichment in carbon ^{13}C over time in humans is a decrease in the consumption of forest products vis-à-vis an increase in open field animal and plant food consumption. While the breadth of food choice remains wide for both time periods, there is clear indication that during the first millennium B.C. people were choosing to eat open field resources even though the forest was recovering. This supports the argument that agriculture was intensifying during the first millennium B.C.

The reduction in the consumption of forest derived food products occurs when the forests are regenerating in the environment during the first millennium B.C. (White et al. 2004). This increase in forest recovery is consistent with agricultural intensification as it implies a decreased reliance on swiddening, and probably increased dependence on wet rice cultivation which promotes forest retention. While this study only sampled modern plants commonly consumed by humans, there is a significant range of variation among C_3 plants (Figure 8.1). Therefore it can be argued that since humans and animals consume plant foods enriched in ^{13}C, this is reflected in the carbon stable isotopic values observed

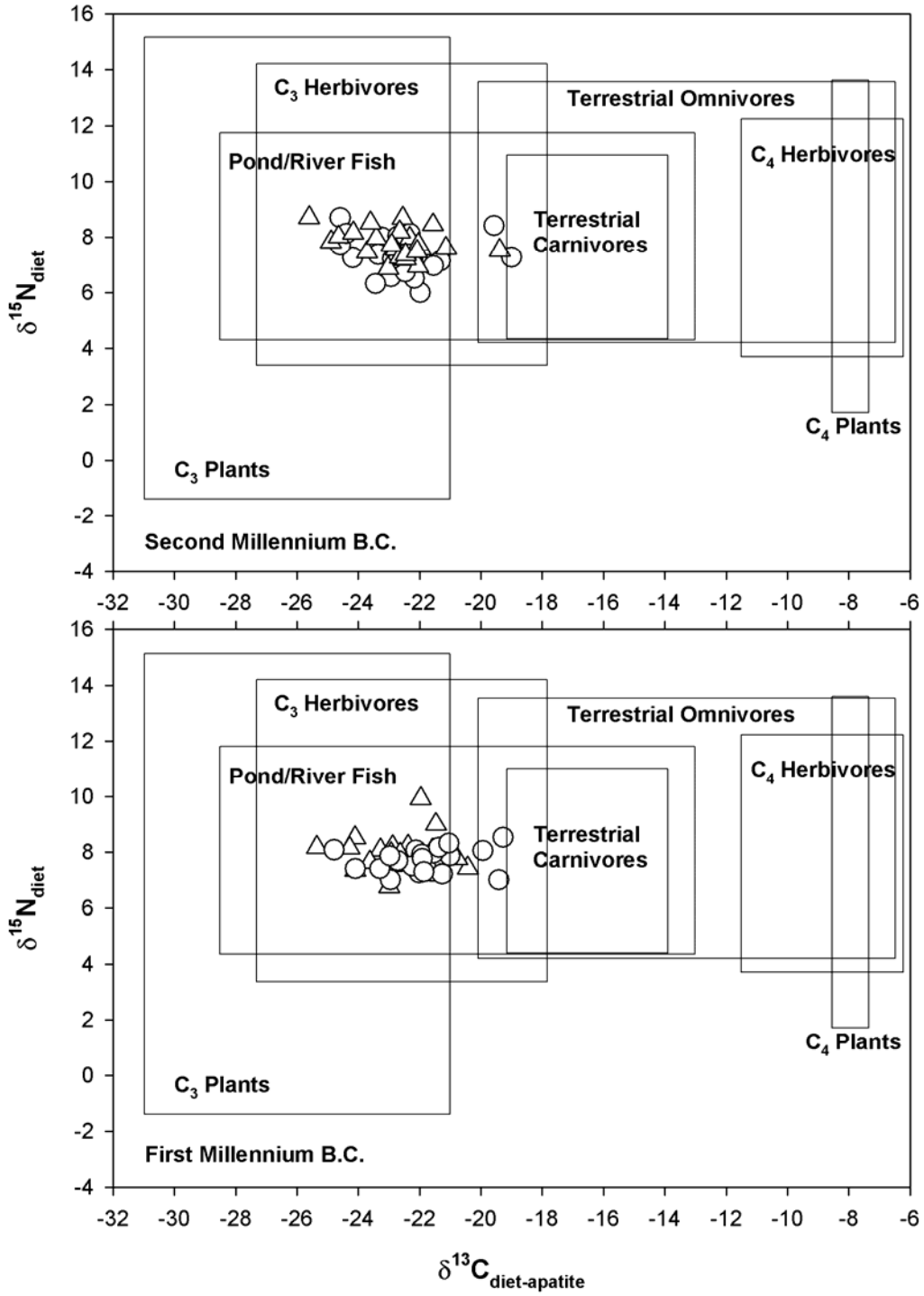

Figure 8.6. Isotopic composition of individual diets from second and first millennium B.C. compared to isotopic composition of local food resources: ○ Females, △ Males.

in humans. As a result there are detectable changes in dietary patterns over time and between females and males. The use of stable isotopes from human remains from northeast Thailand has provided unequivocal indications for diet change in northeast Thailand during the second and first millennium B.C.

This dissertation provides a foundation for future paleodietary research in mainland Southeast Asia and for understanding other subtropical monsoon regions of Asia. The stable isotopic data presented here provides an indication for dietary change over time though more work needs to done provide a more refined interpretation for this change. Increased sampling of human remains as well as increased data from faunal remains, namely fish, cows, pigs, and chicken, will help refine this approach. Through stable isotope analysis, along with continued archaeological and bioarchaeological research, a greater understanding of the complexities of cultural change can have on subsistence, settlement, diet be achieved.

Directions for Future Research

The present study provides additional interpretative power to our understanding of prehistoric dietary changes in subtropical monsoon Asia. Advances made in both archaeological and skeletal biological research indicate subsistence change in prehistoric production systems of northeast Thailand points to both spatial and temporal differences. Local production systems are affected by both resource availability and cultural food preferences. Food choice and subsistence patterns in turn are affected by simultaneous developments in demography and socio-political organization.

This dissertation research used stable isotope analyses of bone collagen ($\delta^{13}C_{collagen}$ $\delta^{15}N_{collagen}$) and bone apatite ($\delta^{13}C_{apatite}$). The stable isotope analysis of human samples from a sub-tropical monsoon region that is dominated by an abundance of C_3 resources is very rare in the paleodietary literature. As such, this dissertation has laid a biogeographical foundation for future studies into paleodietary reconstruction. Northeast Thailand was chosen as the test region for this study because of the substantial existing body of archaeological and skeletal data. The region also provides a relatively confined geographic area from which changes in diet through time and between the sexes could be evaluated. Although the isotope data presented here do not portray a radical change in diet over time, these data do portray a gradual transition that coincides with skeletal and archaeological data suggesting gradual cultural change (Higham 2002).

The main weakness in this analysis is that the human edible plants in the region are predominately C_3 plants. This makes it difficult to mark clear changes in carbohydrates in the diet like those that occur when corn or maize is introduced. If a population was to change from rice to millet or Job's Tears like some did in northern China (see Pechenkina 2005) then the change in consumption would be visible using this method. Increased sampling of plants as well as animals, particularly cows, pigs, chicken, and fish in the region may help improve our interpretive power.

The next step in understanding dietary changes in subtropical monsoon Asia is to widen the sample range to include inter-regional differences. Isotopic analysis on human skeletal remains from Central Thailand, particularly sites near the coast (e.g., Khok Phanom Di and Nong Nor) would be a terrific addition.

Further stable isotopic studies should focus on expanding the composition of the human skeletal samples to include not only a large number of individuals from the first millennium B.C. but also to include more individuals that died during childhood, and to include representatives spanning the age range from birth to adulthood. Through study of $\delta^{15}N_{collagen}$ values questions concerning the age of weaning and whether the weaning food was C_3 or C_4-plant based can be addressed (Katzenberg and Pfeiffer 1995; Wright and Schwarcz 1998). Finally, it would be useful to expand on other stable isotopes such as oxygen and strontium recently reported by Bentley and colleagues (2005). This could be used to further elaborate on migration and even marriage systems in prehistoric northeast Thailand.

Appendix A

Species identification and stable isotope values for modern plant samples from Thailand.

Common Name	Scientific Name	Sample ID	$\delta^{13}C$‰	$\delta^{13}C$‰ Corrected[a]	$\delta^{15}N$‰
Plants using the C_3 photosynthetic pathway					
Angola Pea; Congo Pea; Pigeon Pea	*Cajanus indicus*	37F	-23.5	-22.0	0.8
Balsam Pear; Bitter Melon	*Momordica charantia L.*	51L	-25.1	-23.6	4.4
Bamboo	*Bambusa sp.*	JW386	-25.5	-24.0	8.6
Bamboo - Wild	*Bambusa sp.*	48L	-26.9	-25.4	4.3
Banana	*Musa sp.*	45L	-22.8	-21.3	0.0
		46L	-22.7	-21.2	6.8
Bean-not cultivated	*Vigna sinensis*	JW568	-23.5	-22.0	3.1
Bitter gourd; Bitter cucumber; creeping cucumber; Balsam Pear	*Momordica charantia L.*	07F	-29.7	-28.2	6.3
Black-Eye Pea	*Vigna sinensis*	JW471	-25.8	-24.3	-0.2
Bottle Gourd	*Lagenaria sp.*	JW387	-28.5	-27.0	-0.6
Bottle Gourd, Calabash	*Lagenaria siceraria Standl.*	32F	-24.7	-23.2	8.7
Ceylon Oak	*Schleichera oleosa Merr.*	02L	-29.3	-27.8	9.0
Chestnut	*Castanopsis sp.*	JW178	-26.3	-24.8	6.6
Chinese Lizard Tail; Fishwort; Heartleaf	*Houttuynia cordata Thunb.*	40L	-28.2	-26.7	7.6
Cowpea	*Vigna sinensis*	23F	-25.1	-23.6	-1.5
Custard Apple; Sugar Apple	*Annona squamosa*	13F	-27.4	-25.9	13.0
Ear Mushroom	*Auricularia auricula*	20L	-22.9	-21.4	1.5
Greater Yam	*Dioscorea alata*	19R	-25.3	-23.8	8.3
Horse-Tamarind	*Leucaena leucocephala de Wit*	09F	-27.2	-25.7	7.2
Indian Borage; Broadleaf Thyme	*Coleus amboinicus Lour.*	35L	-28.7	-27.2	11.4
Ivy Gourd	*Coccinia grandis Voight*	26L	-28.7	-27.2	8.4
Jackfruit	*Artocarpus heterophylla*	03F	-23.7	-22.2	11.8
Leech Lime	*Citrus hystrix*	JW389	-28.5	-27.0	8.0

Common Name	Scientific Name	Sample ID	$\delta^{13}C$‰	$\delta^{13}C$‰ Corrected[a]	$\delta^{15}N$‰
		JW403	-29.0	-27.5	11.7
Loofah	*Luffa cylindrica*	14L	-23.8	-22.3	9.8
		21L	-28.3	-26.8	6.2
		47L	-25.7	-24.2	5.4
		JW470	-27.4	-25.9	5.7
Morning Glory; Swamp Cabbage	*Ipomoea aquatica Forsk.*	22L	-28.7	-27.2	0.4
Nut-Not Cultivated	*Canarium venosum*	JW177	-25.2	-23.7	3.8
Otaheite Gooseberry, Star Gooseberry	*Phyllanthus acidus*	05F	-27.5	-26.0	11.8
Pomegranate, Punic apple	*Punica granatum*	08F	-27.1	-25.6	0.0
Pomelo	*Citrus grandis*	36F	-27.4	-25.9	10.4
		JW411	-32.1	-30.6	8.8
Rice-Glutinous	*Oryza sativa*	JW001	-26.2	-24.7	7.7
		JW002	-27.7	-26.2	10.7
		JW003	-26.5	-25.0	8.3
		JW005	-25.9	-24.4	9.5
		JW006	-26.3	-24.8	8.1
		JW007	-26.8	-25.3	6.4
		JW008	-26.6	-25.1	7.9
		JW012	-26.6	-25.1	8.5
		JW013	-24.9	-23.4	1.6
		JW014	-26.2	-24.7	2.9
		JW019	-26.3	-24.8	6.4
		JW020	-26.7	-25.2	3.7
		JW024	-25.6	-24.1	6.4
		JW027	-25.7	-24.2	5.4
		JW028	-26.4	-24.9	5.3
		JW034	-26.6	-25.1	5.7

Common Name	Scientific Name	Sample ID	$\delta^{13}C$‰	$\delta^{13}C$‰ Corrected[a]	$\delta^{15}N$‰
		JW035	-26.6	-25.1	6.6
		JW037	-26.1	-24.6	6.4
		JW038	-26.0	-24.5	7.0
		JW039	-25.1	-23.6	6.0
		JW040	-26.4	-24.9	5.9
		JW042	-25.7	-24.2	6.9
Rice-Non-glutinous	*Oryza sativa*	JW015	-25.6	-24.1	8.8
		JW018	-26.8	-25.3	6.5
		JW021	-26.7	-25.2	4.3
		JW030	-25.6	-24.1	6.2
		JW032	-26.0	-24.5	7.1
		JW041	-27.0	-25.5	6.5
		PIR	-26.4	-24.9	6.7
Rice-Unknown	*Oryza sativa*	JW025	-27.4	-25.1	6.4
Rice-Wild	*Oryza nivara*	JW010	-26.1	-25.9	4.0
		JW011	-27.1	-24.6	5.3
	Oryza rufipogon	JW016	-25.1	-25.6	6.8
	Oryza sp.	JW026	-26.6	-23.6	4.5
Starfruit	*Averrhoa carambola*	16L	-27.4	-25.9	11.9
		JW071	-27.8	-26.3	7.5
Straw Mushroom	*Volvariella volvacea*	33L	-24.5	-23.0	0.0
Sugar Palm	*Borassus flabellifer*	44L	-26.3	-24.8	0.0
Swamp pea	*Sesbania grandiflora*	11F	-25.5	-24.0	0.0
Tamarind	*Tamarandus indica*	28F	-29.7	-28.2	0.0
Taro	*Colocasia esculenta*	15L	-30.1	-28.6	8.9
		18R	-30.8	-29.3	7.2
Taro-cultivated	*Colocasia esculenta*	JW496	-25.9	-24.4	10.1

Common Name	Scientific Name	Sample ID	$\delta^{13}C$‰	$\delta^{13}C$‰ Corrected[a]	$\delta^{15}N$‰
Wax Gourd; White Gourd	*Benicasa hispida*	30F	-26.0	-24.5	7.3
White Gourd Melon	*Benicasa cerifera Saya*	49L	-24.8	-23.3	6.5
Yam	*Dioscorea hispida*	29R	-29.2	-27.7	3.6
Yam-Cultivated	*Dioscorea alata*	JW489	-26.3	-24.8	10.0
Yam-not cultivated	*Dioscorea hispida*	JW022	-24.8	-23.3	3.9
	Dioscorea sp.	JW443	-29.8	-28.3	-1.1
Plants using the C_4 photosynthetic pathway					
Brown Millet	Panicum sp.	YEN011	-9.7	-8.2	3.1
Job's Tears	Coix lachyma-jobi	JW493	-9.6	-8.1	11.7
		YEN002	-9.8	-8.3	1.3
Sorghum	Sorghum bicolor Moench	YEN006	-9.0	-7.5	2.4
White Millet	Panicum sp.	YEN016	-9.6	-8.1	2.3
		YEN017	-9.6	-8.1	6.3

[a] $\delta^{13}C$‰ values corrected (+1.5‰) for the atmospheric changes in carbon composition according to Marino and McElroy (1991) and Tieszen and Fagre (1993).

Appendix B

B.1. Collagen sample integrity and stable isotope values for modern faunal bone samples from Thailand (N=57).

Common Name	ID	Yield (%)	Carbon (%)	Nitrogen (%)	C/N Ratio	δ^{13}C‰	δ^{15}N‰
Bat	MFB01	12.4	45.4	16.3	3.2	-19.4	7.6
	MFB02	14.4	38.1	13.5	3.3	-19.9	8.8
Bird, Cat Owl	MFB03	4.2	25.1	9.4	3.1	-20.2	7.9
Bird, Dove (*Macropygia ruficeps*)	MFB04	17.2	36.5	13.5	3.1	-20.0	8.6
Bird, Grey Hawk	MFB05	7.6	34.2	12.7	3.2	-17.5	8.4
Bird, Kingfish	MFB06	12.3	36.7	13.6	3.1	-21.4	13.4
Bird, Mynah	MFB07	18.1	35.3	13.0	3.2	-19.9	8.4
Bird, Owl	MFB08	10.6	38.2	14.3	3.1	-18.3	9.4
Bird, Owl?	MFB09	20.6	39.6	14.5	3.2	-17.8	13.3
Bird, Peacock (*Pavo cristatus*)	MFB10	21.5	36.3	12.8	3.3	-14.2	9.0
Bird, Quail	MFB11	18.2	33.4	12.3	3.2	-16.7	9.4
Bird, Unidentified	MFB12	14.2	33.6	12.5	3.1	-20.7	10.5
Bos sp.	MFB16	20.3	43.6	15.2	3.3	-11.3	9.0
Bos, Buffalo, Water (*Bubalus bubalis*)	MFB17	17.0	41.0	14.6	3.3	-12.6	9.1
Cat, Asian Golden (Fire cat) (*Felis temmincki*)	MFB18	19.6	40.3	14.4	3.3	-19.1	9.9
Cat, Jungle (*Felis chaus*)	MFB19	20.9	39.8	14.3	3.2	-19.6	8.0
Cat, Modern	MFB20	21.9	42.1	15.3	3.2	-18.3	7.5
Chicken, Domestic (*Gallus sp.*)	MFB13	14.2	32.8	12.2	3.1	-21.3	6.7
	MFB14	19.4	39.2	13.7	3.3	-21.5	7.3
Chicken, Wild (*Gallus sp.*)	MFB15	16.0	37.4	13.4	3.3	-21.6	6.9
Civet sp.	MFB21	19.7	41.3	14.7	3.3	-20.2	8.3
	MFB23	25.0	33.4	12.0	3.2	-19.2	9.0
Civet, Common Palm (Toddy cat) (*Paradoxrus hermaphroditus*)	MFB22	25.5	39.8	14.4	3.2	-19.9	10.5
Civet sp. (Striped)	MFB24	15.0	39.4	13.9	3.3	-15.6	8.8

Common Name	ID	Yield (%)	Carbon (%)	Nitrogen (%)	C/N Ratio	$\delta^{13}C$‰	$\delta^{15}N$‰
Deer, Barking (*Muntiacus muntjak*)	MFB25	17.7	39.5	14.3	3.2	-22.4	4.8
Dog (*Canis sp.*)	MFB27	21.3	41.1	15.0	3.2	-18.6	11.9
	MFB28	20.3	43.2	15.0	3.3	-21.0	8.2
Frog (*Glyphoglossus molossus*)	MFB30	12.3	31.6	11.0	3.3	-21.2	7.0
Frog (*Rana sp.*)	MFB61	14.5	40.1	13.8	3.4	-17.5	7.8
Frog (*Rana tigrina*)	MFB31	9.8	33.5	12.0	3.2	-15.3	9.0
Frog	MFB29	15.4	38.9	12.9	3.5	-18.3	10.9
Frog, Asian Painted (*Kaloula pulchra*)	MFB32	16.8	34.5	12.5	3.2	-17.7	9.4
Monkey, Slow Loris (*Nycticebus coucang*)	MFB34	20.0	41.6	15.2	3.2	-19.1	6.4
Monkey, Langur (*Presbytis sp.*)	MFB36	19.2	40.3	14.6	3.2	-20.5	6.8
Monkey, Langur, Silver Leaf (*Presbytis cristata*)	MFB37	18.6	42.6	15.5	3.2	-20.7	7.6
Monkey, Pig-tailed Macaque (*Macaca nemestrina*)	MFB38	19.7	43.4	15.7	3.2	-20.7	4.7
	MFB59	19.3	40.2	15.0	3.1	-20.5	4.5
Pig (*Sus sp.*)	MFB39	21.0	40.2	14.7	3.2	-22.7	4.4
	MFB60	18.6	41.3	14.9	3.2	-9.4	6.2
Pig, Domestic (*Sus sp.*)	MFB40	21.3	41.8	14.8	3.3	-17.3	7.0
	MFB41	19.6	43.7	14.7	3.5	-17.3	6.4
Pig, Wild (*Sus sp.*)	MFB42	18.7	41.8	14.9	3.3	-21.2	5.4
Rat, Sladen's (*Rattus rattus koratensis*)	MFB44	17.5	40.2	14.4	3.3	-19.1	10.0
Rodentia sp. (*Rattus rattus*)	MFB58	17.3	39.3	14.3	3.2	-18.3	10.7
Rodentia sp. (*Rattus sp.*)	MFB45	11.5	38.9	14.0	3.2	-20.8	5.4
Rodentia sp.	MFB46	15.4	39.9	14.4	3.2	-21.3	6.4
Snake, Lion	MFB47	11.9	36.7	13.6	3.2	-15.4	13.9

Common Name	ID	Yield (%)	Carbon (%)	Nitrogen (%)	C/N Ratio	$\delta^{13}C$‰	$\delta^{15}N$‰
Squirrel, Black Giant (*Ratufa bicolor*)	MFB48	17.6	39.0	14.3	3.2	-20.5	5.9
Squirrel, Flying, Phayre's (*Hylopetes phayrei*)	MFB49	13.9	40.2	14.7	3.2	-19.9	7.1
Squirrel, Flying, Red Giant (*Petaurista petaurista*)	MFB50	16.9	44.2	14.3	3.6	-20.3	3.6
Squirrel, Indochinese Ground/Multi-Striped Palm (*Menetes berdmore*)	MFB51	16.9	39.2	14.3	3.2	-20.5	5.6
Squirrel, Red	MFB52	15.9	36.2	13.0	3.2	-20.7	6.1
Toad, Black Spined (*Bufo melanostictus*)	MFB53	13.0	35.1	12.9	3.2	-16.5	12.0
Turtle, Field	MFB54	13.5	40.1	14.7	3.2	-26.8	10.9
Turtle, Grass	MFB55	15.7	39.6	14.5	3.2	-21.9	13.3
Turtle, Hawksbill (*Eretmochelys imbricata*)	MFB56	17.5	40.9	15.0	3.2	-13.2	10.8
Turtle, Water	MFB57	13.6	40.0	14.9	3.1	-20.6	11.5

B.2. Collagen sample integrity and stable isotope values for archaeological faunal bone samples from Thailand (N=90).

Common Name	Millennium	Site	Sample	% Yield	%C	%N	C/N	δ^{13}C‰	δ^{15}N‰
Buffalo, Water (*Bubalus bubalis*)	Second	Ban Chiang	AFB15	7.3	37.9	13.7	3.2	-9.2	6.6
			AFB17	7.8	39.7	14.2	3.3	-9.3	6.3
	First	Ban Chiang	AFB16	8.0	31.9	11.3	3.3	-10.8	6.2
			AFB31	5.1	32.5	11.8	3.2	-11.2	8.3
		Ban Na Di	AFB45	4.5	36.8	13.6	3.2	-10.1	5.9
			AFB51	5.6	35.9	13.3	3.2	-9.9	6.0
Chicken (Red Jungle Fowl) (*Gallus gallus*)	First	Noen U-Loke	AFB91	2.2	26.3	9.3	3.3	-16.3	10.7
Deer (*Cervus sp*)	Second	Ban Chiang	AFB11	2.6	9.9	3.5	3.3	-11.6	5.2
			AFB33	5.3	28.8	10.3	3.3	-7.7	4.0
	First	Ban Chiang	AFB02	2.6	14.9	5.3	3.3	-11.9	6.1
Deer, Brow-antlered/Eld's/Thamin (*Cervus eldi*)	First	Ban Na Di	AFB42	7.5	33.8	12.5	3.2	-10.1	6.0
			AFB48	2.0	7.2	2.6	3.2	-12.4	5.6
Deer, Common Barking (*Muntiacus muntjak*)	Second	Ban Chiang	AFB08	2.6	7.4	2.6	3.3	-10.7	5.3
			AFB09	4.0	23.5	8.4	3.3	-19.4	5.0
	First	Ban Chiang	AFB10	6.5	32.8	11.8	3.2	-20.4	4.8
			AFB30	2.1	12.3	4.5	3.2	-11.4	5.2
		Ban Lum Khao	AFB61	2.3	9.8	3.4	3.3	-10.4	4.6
		Ban Na Di	AFB39	1.7	5.9	2.2	3.1	-19.6	5.5
Deer, Sambar (*Cervus unicolor*)	Second	Ban Chiang	AFB18	8.1	40.2	14.4	3.3	-8.7	4.7
	First	Ban Chiang	AFB28	3.3	25.7	9.3	3.2	-10.1	5.0
		Ban Na Di	AFB47	4.3	26.7	9.8	3.2	-8.6	4.5
			AFB49	4.5	27.2	10.0	3.2	-9.5	4.6
Dog (*Canis sp.*)	Second	Ban Chiang	AFB03	4.6	16.1	5.8	3.3	-16.9	8.3
			AFB04	3.1	6.5	2.3	3.3	-18.5	8.1
	First	Ban Lum Khao	AFB69	1.1	17.8	6.6	3.2	-17.3	9.2
			AFB71	1.3	13.7	5.0	3.2	-17.4	13.3
		Ban Na Di	AFB40	6.4	34.4	12.6	3.2	-17.0	7.6
			AFB41	3.8	16.0	5.9	3.2	-17.3	9.2
		Noen U-Loke	AFB70	1.1	4.7	1.6	3.4	-20.2	9.9

Common Name	Millennium	Site	Sample	% Yield	%C	%N	C/N	$\delta^{13}C$‰	$\delta^{15}N$‰
Fish, Air-breathing Catfish (*Clarias sp.*)	First	Ban Na Di	AFB75	1.5	10.7	3.7	3.4	-17.2	6.8
			AFB89	2.0	8.1	2.8	3.4	-14.6	7.6
Fish, Climbing Perch (*Anabas testudineus*)	First	Ban Na Di	AFB90	1.9	10.4	3.8	3.2	-15.0	6.2
Pig (*Sus scrofa*)	Second	Ban Chiang	AFB12	4.4	27.4	9.9	3.2	-19.7	8.6
			AFB14	5.7	22.2	8.0	3.2	-19.3	8.0
			AFB32	6.3	36.9	13.4	3.2	-10.4	4.5
	First	Ban Chiang	AFB05	6.5	28.6	10.2	3.3	-19.8	8.3
			AFB06	2.9	9.6	3.4	3.3	-19.7	10.4
		Ban Lum Khao	AFB81	1.4	13.6	4.6	3.4	-18.8	8.4
Pig (*Sus sp.*)	First	Ban Na Di	AFB43	3.9	24.3	8.9	3.2	-19.5	8.4
			AFB53	5.1	34.6	12.7	3.2	-12.2	5.3
Rat (*Rattus sp.*)	Second	Ban Chiang	AFB36	3.5	16.2	5.8	3.2	-18.5	7.1
			AFB38	4.2	19.1	6.9	3.2	-17.6	8.4
	First	Ban Chiang	AFB37	3.6	17.3	6.2	3.3	-16.7	7.9
Turtle, Soft-Shelled (*Trionyx/Chitra sp.*)	Second	Ban Chiang	AFB07	4.1	7.7	2.7	3.3	-19.8	10.0
	First	Ban Lum Khao	AFB78	1.2	4.9	1.6	3.6	-12.9	4.4
		Ban Na Di	AFB46	2.3	5.0	1.9	3.0	-20.5	12.0
			AFB52	3.4	25.4	9.5	3.1	-16.7	9.3
Excluded due to failure to produce both $\delta^{13}C_{collagen}$ values									
Bos sp. (*Bos sp.*)	First	Ban Lum Khao	AFB66	0.9	0.8	0.1	16.0	---[1]	---
Buffalo, Water	First	Ban Lum Khao	AFB72	1.0	1.0	0.1	9.6	---	---
(*Bubalus bubalis*)			AFB73	1.9	0.5	0.0	26.6	---	---
Cow (*Ungulate sp*)	First	Ban Chiang	AFB13	2.4	1.3	0.4	3.5	---	---
Deer, Brow-antlered/Eld's/Thamin (*Cervus eldi*)	First	Ban Lum Khao	AFB56	1.0	1.2	0.1	12.7	---	---
			AFB57	0.9	1.1	0.1	10.3	---	---
			AFB60	1.5	0.7	0.1	12.2	---	---
Deer, Common Barking (*Muntiacus muntjak*)	First	Ban Lum Khao	AFB65	2.0	0.6	0.1	11.4	---	---
			AFB76	2.7	0.4	0.0	---	---	---
Deer, Sambar	First	Ban Chiang	AFB29	2.4	4.5	1.6	3.3	---	---

Common Name	Millennium	Site	Sample	% Yield	%C	%N	C/N	$\delta^{13}C$‰	$\delta^{15}N$‰
(*Cervus unicolor*)		Ban Lum Khao	AFB55	0.8	1.0	0.2	7.5	---	---
			AFB63	2.0	0.7	0.0	124.0	---	---
		Noen U-Loke	AFB74	0.8	0.0	0.0	---	---	---
Eel, Swamp Eel (*Monopterus (Fluta) alba*)	First	Ban Lum Khao	AFB24	1.2	0.6	0.1	6.6	---	---
			AFB25	0.9	0.8	0.2	4.3	---	---
			AFB26	1.2	0.8	0.2	4.3	---	---
			AFB27	1.9	0.6	0.1	5.2	---	---
			AFB64	2.7	0.4	0.0	52.4	---	---
Fish, Air-breathing Catfish (*Clarias sp.*)	First	Ban Lum Khao	AFB01	2.1	0.4	0.0	9.9	---	---
			AFB19	1.2	0.7	0.2	4.0	---	---
Fish, Asian Red-tailed Catfish (*HemiBagrus (Mystus) nemurus*)	First	Ban Lum Khao	AFB35	1.9	0.5	0.1	4.2	---	---
			AFB67	1.5	0.8	0.0	18.3	---	---
			AFB68	1.1	1.6	0.2	9.7	---	---
		Ban Na Di	AFB77	1.4	1.5	0.5	3.6	---	---
Fish, Butter Catfish (*Ompok bimaculatus*)	First	Ban Lum Khao	AFB21	1.0	0.8	0.2	4.5	---	---
			AFB22	1.9	0.4	0.1	4.2	---	---
Fish, Climbing Perch (*Anabas testudineus*)	First	Ban Lum Khao	AFB20	1.0	0.8	0.2	4.4	---	---
Fish, Giant Snakehead (*Ophicephalus micropeltes*)	First	Ban Lum Khao	AFB23	0.8	0.5	0.2	3.1	---	---
Fish, Snakehead murrel (*Ophicephalus striatus*)	First	Ban Lum Khao	AFB62	1.2	1.9	0.3	7.3	---	---
			AFB82	1.3	0.8	0.1	7.1	---	---
			AFB83	1.2	1.1	0.2	6.3	---	---
			AFB84	1.2	1.4	0.4	4.2	---	---
			AFB85	0.9	1.3	0.3	4.8	---	---
			AFB86	1.1	1.0	0.2	7.5	---	---
			AFB87	0.9	1.1	0.3	5.2	---	---
			AFB88	1.3	0.9	0.1	9.0	---	---
Fish, Wallago Catfish (*Wallagonia attu*)	First	Ban Lum Khao	AFB54	1.3	0.6	0.0	77.2	---	---
Pig (*Sus scrofa*)	First	Ban Lum Khao	AFB58	0.9	1.0	0.2	7.3	---	---
			AFB59	2.8	0.7	0.1	11.0	---	---

Common Name	Millennium	Site	Sample	% Yield	%C	%N	C/N	δ^{13}C‰	δ^{15}N‰
		Ban Na Di	AFB44	2.5	0.4	0.1	3.5	---	---
			AFB50	1.1	0.5	0.2	3.6	---	---
Turtle, Soft-Shelled (*Trionyx/Chitra sp*)	First	Ban Lum Khao	AFB79	1.0	0.6	0.1	9.7	---	---
		Noen U-Loke	AFB80	1.1	2.4	0.7	4.3	---	---

--- = No Data

Appendix C

C.1. Sample integrity and stable isotope data for human bone collagen and bone apatite samples from Ban Chiang.

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
Female Average (n=29)		4.4	31.0	11.1	3.3	-18.5	9.9	51.8	1.3	-13.3	22.7	5.2
Male Average (n=36)		4.6	29.2	10.2	3.3	-18.6	10.3	48.2	1.3	-13.2	22.6	5.4
Overall Average (N=65)		4.5	30.0	10.6	3.3	-18.5	10.1	49.8	1.3	-13.2	22.6	5.3
Female	BC11	3.1	27.8	10.2	3.2	-18.3	9.8	61.0	1.0	-12.5	25.4	5.8
	BC21	4.6	36.2	13.2	3.2	-18.1	9.8	53.0	1.1	-12.7	24.6	5.4
	BC24	6.2	34.6	12.3	3.3	-19.1	9.1	45.3	1.2	-13.4	23.5	5.6
	BC28	1.3	7.7	2.7	3.4	-17.7	9.6	54.9	1.1	-11.8	24.2	5.8
	BC31	6.3	29.3	10.4	3.3	-19.4	8.5	50.9	1.1	-12.5	23.6	7.0
	BC33	3.9	29.6	10.1	3.4	-18.5	9.5	50.4	1.7	-12.0	22.8	6.5
	BC34	3.7	15.0	5.4	3.3	-18.8	10.0	55.7	1.0	-12.7	23.0	6.2
	BC41	2.0	22.2	8.0	3.2	-16.8	9.0	61.4	1.1	-12.7	23.2	4.2
	BC45	3.8	32.7	11.1	3.5	-19.3	9.8	49.5	1.0	-13.4	22.2	5.9
	BCES01	3.3	31.0	11.3	3.2	-17.8	9.9	61.9	1.2	-14.6	20.2	3.2
	BCES03	2.7	28.2	9.5	3.5	-20.5	10.0	48.7	1.1	-12.3	21.9	8.2
	BCES09	5.2	33.0	12.0	3.2	-18.6	10.6	63.8	1.2	-15.3	20.8	3.3
	BCES19	4.9	34.7	12.6	3.2	-18.4	10.4	52.5	1.6	-11.5	22.9	6.9
	BCES20	5.5	34.4	11.8	3.4	-18.9	10.6	51.1	2.6	-12.6	22.8	6.3
	BCES23	3.3	28.4	10.3	3.2	-16.9	9.5	56.1	1.2	-13.4	22.3	3.4
	BCES27	3.2	58.3	21.1	3.2	-18.6	10.5	50.9	1.2	-13.7	20.6	4.9
	BCES28	2.2	17.2	6.2	3.2	-18.0	11.2	62.1	1.3	-15.1	22.2	3.0
	BCES29	5.1	31.6	11.6	3.2	-19.1	10.6	52.5	1.7	-12.8	22.4	6.3
	BCES30	4.9	28.6	10.4	3.2	-18.6	10.5	48.4	1.7	-13.2	21.1	5.4
	BCES33	6.3	36.1	13.1	3.2	-18.1	9.8	41.4	1.2	-14.7	22.9	3.4
	BCES34	4.9	34.8	12.4	3.3	-19.2	9.2	31.5	1.2	-13.0	25.4	6.2
	BCES41	5.9	34.5	12.3	3.3	-18.8	10.5	51.4	1.5	-12.0	23.0	6.8
	BCES46	5.9	39.4	14.4	3.2	-17.5	10.1	56.4	1.5	-13.8	22.8	3.6
	BCES57	2.7	16.9	6.1	3.2	-18.0	10.2	61.8	1.3	-15.1	22.0	2.9
	BCES59	6.3	38.7	14.1	3.2	-17.7	10.6	58.1	1.3	-14.9	22.5	2.8
	BCES61	4.9	37.4	13.6	3.2	-17.8	9.9	46.3	1.6	-13.8	23.1	4.0

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
	BCES69	7.8	34.9	12.5	3.3	-19.2	9.7	35.8	1.1	-13.4	24.0	5.8
	BCES75	4.6	33.3	11.4	3.4	-19.4	9.7	42.5	1.4	-11.8	23.0	7.6
	BCES81	3.1	32.3	11.7	3.2	-18.5	8.8	47.0	1.4	-13.9	22.3	4.5
	Excluded due to poor collagen yield (<1%)											
	BC08	0.7	0.4	0.1	3.6	-19.2	9.3	61.5	1.0	-14.0	24.0	5.2
	BC19	0.7	1.3	0.5	2.8	---[1]	---	55.9	---	-12.5	22.4	---
	Excluded due to Poor Carbon and Nitrogen Percent Values for Collagen (<3% Carbon or <1% Nitrogen											
	BC01	1.6	1.8	0.4	5.9	---	---	51.9	0.9	-10.8	24.3	---
	BC02	1.1	0.0	0.0	---	---	---	48.1	---	-12.2	25.8	---
	BC17	1.5	1.4	0.5	3.2	---	---	55.6	---	-13.6	23.1	---
	BC27	1.1	2.1	0.4	6.1	---	---	45.4	1.0	-12.5	22.9	---
	BC30	1.1	3.2	0.7	5.2	---	---	49.5	0.9	-12.3	23.1	---
	Excluded as Outlier											
	BC16	1.3	9.5	3.3	3.3	-11.0	7.2	61.9	1.2	-8.2	23.5	2.8
Male	BC12	3.0	32.7	11.2	3.4	-19.0	11.0	50.4	1.2	-12.1	22.7	6.9
	BC13	2.4	23.1	8.2	3.3	-18.6	9.7	61.9	1.3	-13.3	21.7	5.3
	BC18	2.4	24.2	8.6	3.3	-18.6	11.0	62.4	1.0	-14.6	21.2	4.0
	BC20	2.0	20.1	7.3	3.2	-18.5	10.6	37.3	1.1	-11.8	23.4	6.7
	BC23	2.4	22.1	8.1	3.2	-18.2	10.2	45.2	1.4	-12.8	21.3	5.4
	BC26	5.2	31.0	11.1	3.3	-19.3	9.4	44.5	1.0	-13.5	23.3	5.7
	BC39	3.0	27.2	9.1	3.5	-18.6	10.5	60.7	1.0	-12.8	21.7	5.8
	BC43	3.3	27.8	9.4	3.5	-19.0	10.1	52.5	1.1	-11.6	22.6	7.4
	BC44	4.5	25.1	8.9	3.3	-18.8	10.0	54.4	1.4	-9.9	22.2	8.9
	BC47	2.2	20.9	6.9	3.5	-19.5	10.1	63.7	1.1	-12.5	22.3	7.1
	BCES02	3.4	30.0	10.2	3.4	-18.6	9.9	47.2	1.6	-10.9	23.0	7.6
	BCES06	5.4	32.4	11.6	3.3	-18.3	10.6	60.4	1.2	-14.8	21.9	3.5
	BCES07	4.5	33.7	11.5	3.4	-18.0	10.4	51.8	1.1	-12.6	23.0	5.4
	BCES10	3.2	25.1	9.0	3.2	-18.5	10.3	66.4	1.3	-11.3	22.9	7.3
	BCES24	6.8	37.9	12.9	3.4	-18.7	10.5	41.1	1.4	-12.5	22.7	6.2
	BCES25	11.4	39.3	14.0	3.3	-18.6	10.0	30.1	2.3	-13.6	23.5	5.1
	BCES31	4.2	28.8	9.6	3.5	-18.4	9.7	43.5	1.2	-13.0	22.6	5.4
	BCES32	8.3	36.5	12.4	3.4	-18.8	9.5	37.4	1.3	-12.6	22.9	6.3
	BCES35	5.5	33.8	12.4	3.2	-18.0	10.0	48.5	1.2	-14.2	22.1	3.8

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
	BCES36	3.1	30.4	10.3	3.4	-18.7	10.2	45.8	1.4	-12.5	23.0	6.2
	BCES40	5.3	25.2	9.3	3.2	-18.2	10.8	50.5	---	---	---	
	BCES42	8.8	40.4	13.9	3.4	-19.2	11.2	33.8	3.2	-13.1	23.5	6.2
	BCES45	6.0	31.5	11.6	3.2	-18.2	10.3	48.1	1.5	-15.4	22.6	2.8
	BCES47	3.8	23.8	8.7	3.2	-17.8	10.5	48.6	1.4	-15.1	21.5	2.6
	BCES49	6.3	34.5	12.3	3.3	-18.5	10.1	36.5	1.5	-13.3	22.8	5.2
	BCES49A	5.9	35.6	13.2	3.1	-17.3	10.5	42.9	1.2	-13.9	25.0	3.4
	BCES50	1.6	13.4	4.7	3.4	-18.4	10.7	40.6	1.7	-13.1	21.0	5.2
	BCES51	3.0	23.0	8.0	3.4	-18.2	11.2	42.5	1.5	-16.1	21.2	2.1
	BCES53	8.5	31.2	11.2	3.3	-18.9	9.8	45.9	1.2	-13.1	23.9	5.7
	BCES55	5.3	35.3	12.1	3.4	-18.9	9.7	42.0	1.0	-13.0	23.7	5.9
	BCES56	4.0	28.8	9.7	3.5	-18.7	10.2	39.8	1.1	-13.4	23.6	5.2
	BCES65	3.1	29.7	10.6	3.3	-18.6	11.0	58.9	1.1	-14.1	23.4	4.5
	BCES72	7.2	31.9	11.4	3.3	-19.1	9.9	38.4	1.3	-13.0	22.6	6.1
	BCES73	2.4	26.0	9.5	3.2	-18.7	10.6	55.1	1.1	-13.8	21.6	4.9
	BCES74	1.8	18.4	6.4	3.4	-18.5	10.7	70.4	1.0	-14.7	23.1	3.8
	BCES76	3.1	30.4	10.3	3.5	-18.9	10.0	42.2	1.2	-12.6	22.3	6.3
	BCES78	7.0	35.0	12.9	3.2	-17.9	10.1	43.1	1.4	-14.1	23.6	3.8
	Excluded due to Poor Carbon and Nitrogen Percent Values for Collagen (<3% Carbon or <1% Nitrogen											
	BC06	1.1	1.3	0.6	2.6	---	---	59.7	---	-12.6	24.8	---
	BC07	1.1	0.7	0.1	6.6	---	---	49.5	---	-10.4	25.6	---
	BC09	1.2	0.0	0.6	---	---	---	47.2	---	---	---	
	BC22	1.1	2.4	0.7	3.8	---	---	61.8	---	-12.8	23.4	---
	BC35	1.0	1.3	0.6	2.6	---	---	55.9	---	-12.1	23.6	---

[1] --- = No Data

C.2. Sample integrity and stable isotope data for human bone collagen and bone apatite samples from Ban Na Di.

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
Female Average (n=12)		3.0	17.9	6.5	3.2	-18.1	10.3	61.9	1.2	-12.1	23.7	5.8
Male Average (n=13)		3.2	18.3	6.5	3.3	-18.2	10.4	61.4	1.3	-13.2	23.3	5.0
Overall Average (N=25)		3.1	18.1	6.5	3.3	-18.1	10.3	61.6	1.3	-12.7	23.5	5.4
Female	BND01	4.1	17.2	6.2	3.2	-18.9	11.0	62.3	1.0	-9.8	23.2	9.2
	BND10	2.9	19.5	7.1	3.2	-18.3	10.4	52.2	1.1	-12.4	24.2	5.9
	BND18	4.7	28.0	10.3	3.2	-18.2	10.0	58.5	1.0	-12.7	23.8	5.4
	BND20.2	6.5	33.2	12.0	3.2	-18.3	9.9	63.6	1.0	-13.8	24.8	4.5
	BND22	1.9	8.4	3.0	3.3	-17.6	10.3	68.3	1.2	-12.4	23.2	5.2
	BND26	2.0	7.1	2.5	3.3	-17.9	10.7	77.6	1.1	-11.9	22.7	6.0
	BND28	1.8	5.0	1.8	3.3	-18.6	9.8	66.4	1.2	-12.4	23.1	6.3
	BND36	4.3	32.1	11.7	3.2	-18.4	10.2	53.5	1.1	-13.2	24.1	18.4
	BND40	2.3	19.3	7.0	3.2	-18.1	10.8	62.0	1.5	-11.5	23.7	18.1
	BND48	2.4	13.4	4.8	3.3	-15.7	9.5	54.3	1.2	-9.9	25.0	5.8
	BNDT08	1.5	21.8	7.8	3.3	-18.5	10.1	57.0	---[1]	---	---	---
	BNDT21	1.8	10.2	3.6	3.3	-18.2	10.4	66.4	1.5	-13.5	23.0	4.7
	Excluded due to poor carbon and nitrogen percent values for collagen (<3% carbon or <1% nitrogen)											
	BND49	2.1	1.7	0.7	3.0	-18.8	9.7	75.0	1.4	-14.9	21.6	3.9
	BNDT12	2.0	2.5	0.9	3.2	-18.1	10.0	63.6	1.5	-14.9	22.0	3.2
Male	BND03	3.6	20.6	7.4	3.3	-18.4	11.5	71.7	1.0	-12.0	23.4	6.5
	BND11	2.6	22.9	8.3	3.2	-17.5	10.6	50.8	1.1	-12.0	24.1	5.6
	BND12	3.8	24.3	8.8	3.2	-18.5	10.7	72.1	1.0	-12.9	23.4	5.6
	BND13	4.1	23.2	8.3	3.3	-18.2	10.7	61.0	1.0	-13.4	23.3	4.9
	BND17	4.5	29.9	10.8	3.2	-18.7	9.7	40.1	1.1	-11.8	23.7	6.9
	BND23	6.3	34.4	12.2	3.3	-18.1	10.0	65.0	1.1	-13.4	24.5	4.7
	BND31	1.2	5.1	1.7	3.5	-18.6	9.3	58.5	1.1	-13.5	23.5	5.1
	BNDT08.1	1.0	3.4	1.2	3.4	-18.0	10.2	64.1	2.5	-13.3	23.7	4.8
	BNDT09	3.8	23.7	8.6	3.2	-18.6	10.4	54.8	1.2	-13.4	23.8	5.2
	BNDT15	2.7	19.9	7.0	3.3	-18.0	9.8	69.0	1.6	-14.6	22.1	3.4
	BNDT17	2.9	10.3	3.7	3.2	-17.9	10.4	68.6	1.7	-13.1	22.1	4.7
	BNDT19	3.9	5.1	1.8	3.3	-17.5	10.6	66.7	1.8	-12.1	24.2	5.4

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
	BNDT20	1.8	14.6	5.2	3.3	-18.2	10.7	56.3	1.4	-15.9	21.4	2.3
	Excluded due to poor collagen yield (<1%)											
	BND42	0.9	2.4	0.9	3.2	-18.3	10.1	60.5	1.4	-13.3	23.7	8.4
	BNDT05	0.9	1.0	0.4	3.3	-18.4	10.2	69.7	1.4	-12.6	23.2	5.8
	Excluded due poor carbon and nitrogen percent values for collagen (<3% carbon or <1% nitrogen)											
	BND16	1.4	---	---	---	---	---	56.7	---	---	---	---
	BND32	2.3	0.5	0.1	4.5	---	---	68.5	---	---	---	---
	BND35	1.7	1.0	0.3	3.4	-18.7	9.6	78.2	1.2	-12.7	23.7	6.0
	BND37	1.5	0.2	0.1	2.1	---	---	68.0	---	---	---	---
	BND39	1.5	0.1	0.1	1.2	---	---	67.7	1.4	-13.4	21.4	---
	BND47	1.8	0.1	0.1	1.5	---	---	68.8	---	-12.5	22.2	---

[1] --- = No Data

C.3. Sample integrity and stable isotope data for human bone collagen and bone apatite samples from Ban Lum Khao.

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
Female Average (N=2)		1.6	17.8	6.4	3.2	-18.6	10.3	58.4	1.5	-9.8	22.8	8.8
Female	BLK49	2.2	24.5	8.8	3.2	-17.9	10.9	65.7	1.1	-10.1	23.6	7.8
	BLK95	1.1	11.0	4.0	3.2	-19.3	9.8	51.1	1.8	-9.5	22.1	9.8
	Excluded due to poor collagen yield (<1%)											
	BLK21	0.7	2.1	0.5	4.7	---[1]	---	73.6	---	---	---	---
	BLK36	0.6	1.9	0.5	4.7	---	---	76.4	---	---	---	---
	BLK38	0.5	1.2	0.4	3.4	---	---	66.1	---	---	---	---
	BLK42	0.8	1.7	0.3	7.9	---	---	73.7	---	---	---	---
	BLK61	0.9	1.5	0.4	4.3	-20.3	7.3	72.0	---	---	---	---
	Excluded due to Poor Carbon and Nitrogen Percent Values for Collagen (<3% Carbon or <1% Nitrogen											
	BLK34	1.0	0.6	0.2	3.6	---	---	72.8	---	---	---	---
	BLK39	1.2	2.3	0.8	3.2	-18.0	9.7	81.6	1.0	-12.0	23.7	6.0
	BLK64	2.0	0.3	0.1	4.9	-20.3	---	72.4	---	---	---	---
	BLK75	2.1	0.3	0.1	6.4	-23.5	---	71.8	---	---	---	---
	BLK80	1.1	0.6	0.2	4.0	---	---	78.7	---	---	---	---
	BLK85	1.0	1.0	0.2	5.2	---	---	86.1	---	---	---	---
	BLK98	2.6	0.4	0.1	4.5	-21.5	8.4	88.8	---	---	---	---
Male	**Excluded due to poor collagen yield (<1%)**											
	BLK47	0.9	1.2	0.4	3.5	---	---	74.4	---	---	---	---
	BLK48	0.9	2.6	0.9	3.3	---	---	74.0	---	---	---	---
	BLK55	0.7	1.6	0.4	5.4	---	---	70.1	---	---	---	---
	BLK67	0.6	4.2	1.4	3.6	---	---	62.7	---	---	---	---
	Excluded due to Poor Carbon and Nitrogen Percent Values for Collagen (<3% Carbon or <1% Nitrogen											
	BLK28	3.0	0.1	0.0	3.2	---	---	75.2	---	---	---	---
	BLK37	1.2	0.6	0.2	3.5	---	---	70.3	---	---	---	---
	BLK59	2.1	1.8	0.7	3.2	-18.1	10.0	69.4	5.4	-9.4	21.5	8.7
	BLK82	2.5	1.1	0.4	3.3	-19.4	8.9	57.0	2.2	-10.7	21.7	8.7

[1] --- = No Data

C.4. Sample integrity and stable isotope data for human bone collagen and bone apatite samples from Noen U-Loke.

		Collagen						Apatite				$\Delta^{13}C_{apatite-collagen}$
Sex	**Burial no.**	**Yield (%)**	**Carbon (%)**	**Nitrogen (%)**	**C/N Ratio**	**$\delta^{13}C$ (‰)**	**$\delta^{15}N$ ‰**	**Yield (%)**	**Carbon (%)**	**$\delta^{13}C$ ‰**	**$\delta^{18}O$ ‰**	
Female Average (n=1)		2.0	9.7	3.7	3.1	-18.3	10.5	63.4	2.1	-10.4	22.6	7.9
Male Average (n=1)		1.2	5.7	2.0	3.4	-17.8	12.4	59.7	1.2	-12.5	23.5	5.3
Overall Average (N=2)		1.6	7.7	2.8	3.2	-18.0	11.5	61.5	1.7	-11.4	23.1	6.6
Female	NUL108	2.0	9.7	3.7	3.1	-18.3	10.5	63.4	2.1	-10.4	22.6	7.9
	Excluded due to poor collagen yield (<1%)											
	NUL104	0.8	0.6	0.1	5.4	---[1]	---	68.4	---	---	---	---
	NUL113	0.8	0.9	0.1	11.3	---	---	41.7	---	---	---	---
	Excluded due to Poor Carbon and Nitrogen Percent Values for Collagen (<3% Carbon or <1% Nitrogen											
	NUL12	1.8	2.7	0.9	3.4	-19.0	12.1	95.3	3.4	-9.9	23.4	9.1
	NUL64	1.2	1.4	0.5	3.2	-20.4	11.9	60.7	1.1	-11.1	23.3	9.3
		Excluded due to Poor C/N Ratio Values for Collagen (<2.9 or >3.6)										
	NUL16	2.2	0.2	0.1	2.3	---	---	77.6	---	---	---	---
	NUL30	1.5	0.2	0.1	3.7	---	---	80.3	---	---	---	---
	NUL35	2.1	0.4	0.1	4.3	---	---	60.1	---	---	---	---
	NUL37	7.4	34.2	10.3	3.9	---	---	55.2	---	---	---	---
	NUL40	2.1	0.2	0.1	2.9	---	---	64.1	---	---	---	---
	NUL48	1.3	0.3	0.1	4.7	---	---	63.5	---	---	---	---
	NUL49	2.3	0.1	0.1	2.1	---	---	67.3	---	---	---	---
	NUL52	2.1	0.2	0.1	---	---	---	80.0	---	---	---	---
	NUL62	1.2	0.3	0.1	2.7	---	---	57.8	---	---	---	---
	NUL82	1.2	0.2	0.1	2.8	---	---	74.8	---	---	---	---
	NUL99	2.2	0.1	0.1	2.2	---	---	33.6	---	---	---	---
	NUL110	1.9	0.3	0.1	2.4	---	---	78.6	---	---	---	---
	NUL114	1.8	0.3	0.1	3.2	---	---	56.1	---	---	---	---
	Excluded due to failure to produce both $\delta^{13}C_{collagen}$ and $\delta^{13}C_{apatite}$ values											
	NUL36	2.9	22.8	8.1	3.3	---	---	69.1	---	---	---	---
Male	NUL42	1.2	5.7	2.0	3.4	-17.8	12.4	59.7	1.2	-12.5	23.5	5.3
	Excluded due to poor collagen yield (<1%)											
	NUL39	0.7	0.2	0.3	0.8	---	---	68.8	---	---	---	---

	Excluded due to Poor Carbon and Nitrogen Percent Values for Collagen (<3% Carbon or <1% Nitrogen											
	NUL01	1.3	0.4	0.1	5.1	---	---	61.7	---	---	---	---
	NUL05	1.8	7.3	0.1	116.0	---	---	54.9	---	---	---	---
	NUL14	1.5	0.2	0.1	2.8	---	---	65.0	---	---	---	---
	NUL27	2.0	0.5	0.1	6.3	---	---	64.0	---	---	---	---
	NUL32	3.2	0.3	0.1	3.1	---	---	64.9	---	---	---	---
	NUL33	1.5	0.2	0.3	0.6	---	---	76.6	---	---	---	---
	NUL44	1.5	1.1	0.4	3.4	---	---	59.2	---	---	---	---
	NUL45	1.7	0.1	0.1	1.7	---	---	74.4	---	---	---	---
	NUL50	1.6	0.3	0.1	3.2	---	---	71.2	---	---	---	---
	NUL60	1.5	0.4	0.1	5.9	---	---	65.0	---	---	---	---
	NUL61	1.6	0.1	0.1	2.0	---	---	66.2	---	---	---	---
	NUL66	1.4	---	0.2	---	---	---	65.3	---	---	---	---
	NUL69	1.3	0.9	0.2	5.6	---	---	58.1	---	---	---	---
	NUL74	1.3	0.2	0.1	2.8	---	---	68.2	---	---	---	---
	NUL84	1.3	0.3	0.1	3.4	---	---	53.0	---	---	---	---
	NUL86	1.5	0.4	0.1	5.0	---	---	66.7	---	---	---	---
	NUL94	2.5	0.1	0.1	2.1	---	---	82.6	---	---	---	---
	NUL98	1.2	0.4	0.1	2.9	---	---	68.7	---	---	---	---
	NUL107	1.3	0.7	0.2	4.0	---	---	66.4	---	---	---	---
	NUL111	1.8	0.1	0.1	1.3	---	---	63.1	---	---	---	---
	Excluded to Poor C/N Ratio Values for Collagen (<2.9 or <3.6)											
	NUL26	1.1	10.8	3.4	3.7	-18.4	11.5	61.2	2.0	-13.5	20.7	4.9

[1] --- = No Data

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