Stable Carbon and Nitrogen Isotope Analysis of Human Diet Change in Prehistoric and Historic Poland

DISSERTATION

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By

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Abstract

The medieval period in Europe was a time of unprecedented social, religious, political and economic change. In Poland, state formation, Christianization, transitions to market economies and urbanization occurred within a relatively restricted time period ca. AD 1000. Changes such as these influence food production and distribution, and may strongly impact human diet and health. Stable isotope analysis is a widely-used tool in anthropology that offers a sensitive and accurate measurement of diet that supplements and in some cases corrects previous historically- or archaeologically-based interpretations. I examine stable carbon and nitrogen isotopes from bone to assess changes in diet between the 2nd and 14th c. in North-Central Poland concurrent with sociopolitical upheavals.

Bone collagen and carbonate of 32 animals and 167 human skeletons are studied. The sites studied are from Rogowo (2nd c. AD), Kaldu (11th-13th c.) and Gruczno (12th-14th c.), along with four isolated skeletons from the Neolithic and the Iron Age. With this sample I investigate two primary predictions: 1) stable carbon and nitrogen isotope ratios increase significantly through time, reflecting an increase in consumption of marine fish concomitant with religious and economic change, and 2) stable isotope signatures from the medieval samples are more heterogeneous than those from pre-medieval samples and related to status (as estimated by grave goods) and sex. Change in
the medieval sample can be studied with a chronological resolution of approximately 100-150 years between samples and an effort was made to ascertain a rate of diet change.

Stable nitrogen isotope ratios of animals are higher than those usually reported for Europe, revealing a different isotopic baseline for North-Central Poland that may result from land management strategies such as manuring and/or burning fields. The human samples studied here show evidence for consumption of millet, a uniquely Slavic cultigen in Europe that may be useful in studying Slavic migrations. My stable isotope data track millet consumption in Poland back to the Neolithic period (approximately 2,000 BC).

During the Roman Era, diet was terrestrial-based and included millet and some fish. At the onset of the medieval period, more fish were eaten and diet was highly variable. Contrary to expectations, throughout the medieval period diet became less isotopically varied. Diet at Kaldus was more varied than diet at Gruczno, which likely reflects the different economic functions of the two sites. There are no consistent relationships between burial style and diet, suggesting that differences in diet may not have been drawn on the lines of religion or status. Sex-based differences in stable isotope ratios are observed only in the Roman Era and the latest medieval period, Gruczno site 2, which most closely represents a “true” medieval village.

Rather than agreeing with broad trends expected on the basis of other European populations, diet changes in the study area depended more on local socioeconomic and political circumstances. Local conditions shaping diet in the study area include the shaky foothold of Christianity including pagan revolts after state-wide conversion, the influence of the Teutonic Order starting in the 13th c., and the waxing and waning of the study
sites’ economic importance, independent of trends in Europe at large. These local particularities prevent assessment of a rate of change throughout the medieval period, although rate of diet change in small increments could be assessed at one site: Kaldus site 4 could be divided into five sub-phases, and over the course of 200 years the contribution of millet to diet decreased from 20% to 7%, an average of 2.6% per year.

The study samples were intended to isolate temporal diet change and control for regional and between-site variations. However, even in this very restricted geographic area, assessing temporal change in diet is not straightforward. Medieval settlements are socioeconomically diverse which complicates simple interpretations of diet change through time.
Dedication

Dedicated to my family
Acknowledgments

This dissertation would not have been possible without the support of many individuals and institutions. First I wish to thank my advisor Douglas Crews, whose approachability, academic rigor, and enthusiasm with all manner of troubleshooting were essential toward completing this research. Countless pages of earlier drafts of these chapters have been illustrated with his editorial remarks. Beyond his contributions to this thesis, I am grateful for all the advice and support he offered over the past six years, and for our easy rapport, without which I could never have proceeded as efficiently and confidently during my graduate career.

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I thank my committee member Clark Larsen not only for his contributions to the improvement of my dissertation research and thesis, but also for helping to advise my graduate career in general, and for working tirelessly to support and advance The Ohio...
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rigor, along with many friendly discussions about career development and stable isotopy. Yohei Matsui was one of the most important individuals I could have known at The Ohio State University, and is truly one of the University’s most vital human assets. Yohei worked tirelessly in the laboratory to assist student research and enforce impeccable standards from which the entire University community can learn and benefit. I thank and admire Yohei for his unwavering dedication to his work, his ability to explain things clearly, and his approachability. Yohei made my time in the lab fun and friendly, and is a living library of isotope biogeochemistry.

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Chapter 1: Introduction

1.1 Background

At the very foundation of human existence, diet influences diverse aspects of human behavior. Subsistence strategies, systems of exchange, symbolic cultural behaviors and health are all interlinked to the foods we eat, across all cultures and through time. Analysis of carbon and nitrogen stable isotopes in bone collagen is currently the most effective tool in archaeology for accurately assessing diet of past populations. As such, stable isotope analysis is a powerful window into past cultural dynamics. Relative reliance on plant, animal, and aquatic resources can be estimated by investigating stable carbon and nitrogen isotope ratios of consumer tissues because consumer ratios are representative of food source ratios. Stable isotope analysis has been applied in anthropology to study the dietary adaptations of our hominin ancestors, monitor the adoption and spread of agriculture, and to examine subtle sex- and status-based differences in diet in archaeological samples (e.g.: Linderholm et al. 2008; Pechenkina et al. 2005; Reitsema et al. 2010; Schoeninger 2009; Sponheimer et al. 2006; White et al. 2009).

Recently, stable isotopes have been used to identify variable dietary patterns in medieval Europe (e.g.: Garvie-Lok 2001; Jørkov et al. 2009; Kjellström et al. 2009;
Liden and Nelson 1994; Müldner et al. 2009; Müldner and Richards 2005; Polet and Katzenberg 2003; Reitsema et al. 2010; Richards et al. 2006; Schutkowski et al. 1999). Although historical records from the medieval period are extant, they typically underrepresent daily lives of individuals outside elite classes (Müldner and Richards 2005; Polet and Katzenberg 2003). Archaeozoology and archaeobotany greatly supplement records of diet by adding undocumented context to interpretations of the past, but provide bulk data without informing us how foods were distributed within the population. Stable isotope analyses have provided a valuable independent line of evidence for refining our interpretation of past human diet, because diets can be associated with individuals (e.g. Garvie-Lok 2001; Kjellstrom et al. 2009; Muldner and Richards 2005; Polet and Katzenberg 2003, Reitsema et al. 2010). In addition to reconstructing diet, stable isotope evidence provides insights into so-called “invisible behaviors,” such as differential access to foods across sex, age and status groups.

Stable isotope analyses were applied to a 11th-12th c. medieval sample in Poland to reconstruct diet and explore its variation within a single population (Reitsema et al. 2010). This dietary “snapshot” provided a nuanced interpretation of diet in Poland beyond that previously available using traditional archaeological and historical evidence. Elsewhere in Europe, stable isotope studies allowed researchers to track diet change over periods as long as 1,000 to 10,000 years (e.g.: Kosiba et al. 2007; Muldner and Richards 2007a; Richards et al. 2006). This study expands on previous research and examines diet change over the 2nd through 14th c. During this period, the Polish state formed, a common religion, Christianity, was introduced, and market economies developed. Due
to fundamental limitations in the historical and archaeological records, historians and archaeologists have been unable to precisely document diet in this shifting sociopolitical milieu. My purpose here is to reconstruct diet change in Poland using stable carbon and nitrogen signatures in human bone recovered from a period of extreme sociopolitical and economic change.

1.2 Theoretical Significance

This research contributes to three important issues in anthropology: 1) the relative roles of biology (sex, age, health) and culture (status, religion, gender) in structuring human diet, 2) how major demographic shifts affect human diet, and 3) how quickly human diet may respond to sociopolitical changes.

During the first millennium AD large numbers of people became increasingly divorced from local food production. Developing inter-regional exchange networks facilitated non-local menus. Human diets became free to “drift” beyond basic needs and resource availability to accommodate status-, religious-, and sex-specific food preferences. Elaboration of social differences within human societies contributes to diet change and its diversity through time. In egalitarian and ranked societies, sex and age are important in defining social roles. Cultural factors such as religion and status become increasingly important for structuring social relationships in stratified societies. Stable isotope research in Europe has been applied to study links between an individual’s diet during life and their inferred status (e.g.: Keenleyside et al. 2006) and their religion (e.g.: Rutgers et al. 2009; Salamon et al. 2008). One of my goals in this study is addressing
how important these cultural variables were in determining diet and health in past Polish populations.

Shifting demographic contexts associated with urbanization, state-formation and Christianization in Poland that impact diet also are investigated. Isotopic studies of ancient populations add specific data to our ethnographically-based understandings of how people mediate demographic and sociopolitical impacting health and behavior. Results from bioarchaeological research across a wide range of human populations demonstrate declining overall health as human populations begin living in increasingly large, agglomerated settlements (Larsen 1997; Storey 1992). Adverse health effects of urbanization are indicated by a variety of osseous marks on human skeletons suggesting physiological stress, growth interruption, disease, and malnutrition. Although interregional trade made a wider variety of foods accessible to medieval populations, members of the lower classes had reduced access to varied foods. For the general populace, dietary changes associated with urbanization include increased homogeneity in diet and a heavier reliance on mass-producible cereal crops which both can lead to malnutrition. Other dietary changes associated with urbanization are replacement of meat from cattle and wild animals with meat from pigs and chickens, both of which can be raised in confined spaces (Bartosiewicz 1995; Makowiecki 2006).

State formation is another major medieval demographic change that affected diet, primarily by facilitating interregional exchange. In the case of Europe, increased trade is indicated by a dramatic proliferation of the marine fish trade in inland zones (Barrett et al. 2008). Furthermore, political consolidation encouraged increased social stratification.
In the medieval period, certain foods were more expensive than others, and this increase in social stratification instigated an increase in dietary differences within the population (Bartosiewicz 1998; Dembińska 1999; Ervynck et al. 2003).

Christianity, introduced in Poland in the late 10th c., is another force of human diet change. The most fundamental change imparted by Christianization on diet is the introduction of fasts, during which consuming meat of terrestrial animals was proscribed. Fish were an alternative to meat on fast days, of which there were well over 200 per annum (Kloczowski 2000; Woolgar 2000). Archaeozoological and historical records document an increase in fish consumption among the social and religious elite during Christianization (Dembińska 1999; Makowiecki 2006). An outstanding question that these records do not resolve is whether these fasts were observed by the general populace as well. Stable isotope analysis, which may be applied to skeletons determined through mortuary analysis to be of high or low status with equal ease, may detect who actually conformed to these regulations during the medieval period (e.g.: Müldner et al. 2009). In addition to imposing dietary regulations in the form of fasts, Christianity may have impacted diet more subtly by altering interpersonal (and particularly, domestic) relationships and introducing a new social stratum based on religious prestige (Müldner et al. 2009; Polet and Katzenberg 2003; Rutgers et al. 2009; Stark 1996).

Finally, this research addresses the issue of how malleable humans are in restructuring diet in response to changing socioeconomic climates. Diet is among the most fundamental biocultural adaptations of human populations. In past human societies, diet reflects a balance between energy expenditure, environmental limitations
and food demands. Events such as imposed religious fasting restrictions disrupt this balance. Stable isotope research is in a unique position to identify and characterize subtle changes in diet through time that historical sources, archaeozoology and paleobotany do not detect (e.g.: Harrison and Katzenberg 2003). By examining a skeletal sample that encompasses a broad time span, I investigate the question of how long it takes humans to modify their food procurement and distribution routines when former systems are interrupted by new influences, regulations or limitations from governments, religions or environmental changes.

1.3 Study Sample

Stable carbon and nitrogen isotope ratios from human and animal skeletal materials are analyzed in order to address these issues. The use of stable isotopes in paleodietary studies derives from the fact that isotopic ratios of different types of food are preserved in the tissue chemistry of consumers (van der Merwe and Vogel 1978; Vogel and van der Merwe 1977). Stable carbon isotopes provide information about the ecosystem of a consumer, distinguishing between terrestrial versus marine niches, and between plants adapted for temperate versus arid environments. Stable nitrogen isotope ratios reveal information about an organism’s trophic position in the local food web, distinguishing between carnivores, omnivores and herbivores.

Five skeletal samples from North-Central Poland investigated in this study represent slightly different time periods within the same geographic region. Diets of these populations are reconstructed and interpreted, and a rate of diet change examined.
The five sites investigated include a pre-medieval outlier from the Roman Era (2nd c. AD) and four medieval cemeteries from approximately the same geographic area (dating to the 11th, 12th, 12th-13th, and 13th-14th c. AD).

1.4 Expected Outcomes and Hypotheses

Previous archaeological and historical research in Europe indicates significant changes in diet over the past 2,000 years (e.g.: Bonsall et al. 2004; Kjellström et al. 2009; Müldner and Richards 2007; Richards et al. 2006). However, little is known about the specific nature of these changes in Eastern Europe and in relation to intra-population differences. The following hypotheses are tested to examine the issue of diet change in Poland:

Hypothesis 1: Stable carbon and nitrogen isotope ratios increase significantly through time, reflecting an increase in consumption of marine fish (ANOVA, p < 0.05).

Fish consumption is expected to increase as inter-regional exchange networks increase the availability of marine species such as herring and cod (Barrett et al. 2008), and demand for these food items increases with Christian fasting regulations (Müldner and Richards 2005; Woolgar 2000) and increasing urbanization (Makowiecki 2001).

Hypothesis 2: Stable isotope signatures from the medieval samples are more variable than those from the Roman period samples (calculated using standard deviations).
Variability in diet is expected to increase as more foods become available to the population and social differentiation increases in the medieval period.

**Hypothesis 3:** Stable isotope differences between men and women are absent during the Roman period, but are significant during the medieval period (ANOVA, p < 0.05).

Social differentiation during the medieval period likely impacted the variety of foods available to various demographic groups because foods varied considerably in their availability and cost during the medieval period. Sex- and status-based differences in diet are a likely byproduct of increased social differentiation. Whereas a household economy had formerly governned food production and labor, men and women became increasingly separate in their daily labor during the medieval period. Bulk archaeobotanical data are incapable of determining sex-based differences in diet. For this, isotope analyses are well suited.

**Hypothesis 4:** Presence or absence of grave goods in the Roman period is not related to differences in stable isotope ratios (Kruskal-Wallis test, p ≥ 0.05).

In the Roman sample, high-status individuals are not expected to have consumed different foods than low-status individuals, as higher status in the tribal Roman period may reflect greater prestige without any accompanying differential resource access.
**Hypothesis 5:** During the medieval period, skeletons with grave goods will differ isotopically from skeletons without grave goods when treated as separate groups (ANOVA, p < 0.05).

The opportunity for specialized labor in the wake of a growing elite class and state bureaucracy in the medieval period fueled status differentiation. Individuals from high-status burials in the medieval sample are expected to have consumed a higher quality diet comprising more terrestrial animal or fish protein, reflecting a more pronounced social differentiation that affected resource access. Higher animal and fish protein consumption is associated with higher $\delta^{13}$C and $\delta^{15}$N values.

### 1.5 Organization of Dissertation

This dissertation is organized into seven chapters. In Chapter 2 I present the biocultural context of Poland during the Roman and medieval periods. This chapter provides the relevant background information for the questions addressed in this paper and describes the political and socioeconomic context of Poland in the medieval period, the process of Christianization, and changes in diet and subsistence strategies between AD 100 and 1400 as evidenced by archaeozoology, paleobotany, bioarchaeology and history. Chapter 3 provides a background to the method of stable isotope analysis for diet reconstruction. Chapter 4 describes the methods of sample preparation and analysis used in the study. Chapter 5 discusses the condition of the skeletal elements used in the study as determined from multiple collagen quality indicators and by Fourier transform
infrared spectroscopy measurements of apatite. Results of duplicate analyses also are discussed in Chapter 5, including their implications for sample quality, reliability of the methods used, and analytical accuracy. Chapter 6 presents the results of all stable isotope analyses and is divided into three parts: (1) a general overview of the major trends, (2) details from each site including status- and sex-based differences, and (3) comparisons between the sites. Chapter 7 is a discussion of the results in light of the biocultural context and other stable isotope studies from Europe. The first part of Chapter 6 includes diet reconstructions from all sites. The second part is a discussion of major trends in diet relevant to all the sites. Third, I return to the original hypotheses in light of stable isotope results and biocultural context presented in Chapter 2.
Chapter 2: Biocultural Context

In order to understand why and how diet changed in medieval Poland, a review of the biocultural context in which changes emerged is necessary. In this section, I discuss three topics. After a summary in section 2.1, sections 2.2 and 2.3 review Polish history between AD 100 and 1400, including political, demographic and socioeconomic changes. Section 2.4 reviews the Christianization of Poland by the Roman Catholic Church beginning at the end of the 10th c. Section 2.5 summarizes what is known about diet and changing subsistence behaviors in Poland from historical records, archaeozoology and paleobotany. Drawn from a variety of sources, this review synthesizes historical and archaeological data. The major emphasis is on changes throughout Poland’s history that impacted human diet variation.

2.1 An Overview of Poland between AD 100 and 1400

During the first centuries AD, the Wielbark and Przeworsk cultures occupied modern-day Poland (Barford 2001). After approximately AD 300, traces of their settlements disappear. During the 4th-6th c., referred to as the “Migration Period,” there is little archaeological evidence for human habitation in Poland. Beginning in the 7th c., tribes in Poland began to consolidate territory and build fortified stronghold complexes, the precursors of urban settlements (Hensel 1969). Agricultural exploitation of the land
intensified after the 7th c. and the rate of population growth increased (Barford 2001). A climatic optimum beginning in the 8th c. and lasting until the 13th c. facilitated agricultural productivity and demographic growth. The economic activities of the population diversified from household industries to specialized craft production at the newly forming stronghold sites. In the 10th c. incipient towns developed from these, a characteristic of which were marketplaces (Moźdioch 1994). As early as the 9th century, roads linked Poland with other European and Asian polities and interregional exchange grew in importance (Dzieduszycka and Dzieduszycki 1994). Coins were minted in Poland in the 10th century, which facilitated a shift toward a market economy (Gieysztor et al. 1979). Polish tribes were unified under a single leader in AD 963, and Poland was recognized officially as a state in AD 1000. In AD 966, Poland’s ruler was Christianized by the Roman Catholic Church, and the process of religious conversion among the general populace began (Gieysztor et al. 1979).

Following state-formation, Poland experienced cycles of centralization under the authority of a single king, and decentralization under the influence of powerful elite families (Gieysztor et al. 1979). In addition to this internal political instability, in the 13th c. the Duke of Mazovia invited the Teutonic Order into Poland to subdue neighboring pagan populations in Pomerania and Prussia (Knoll 2008). The Order remained a powerful influence in the North for centuries, introducing Germanic-style rule to these areas. The areas of Teutonic occupation included the study sites of Kaldus and Gruczno for approximately two centuries. Germanic law granted autonomy to many Polish cities
after the 13\textsuperscript{th} c., creating independent local markets (Gieysztor et al. 1979; Koter and Kulesza 1999).

Diet change followed these historical events. Differential access to food resources increased as society became socioeconomically stratified (Demińska 1999). Poultry and pigs became more common sources of meat compared to cattle and wild animals, as they could be more easily maintained by urban populations (Buko 2007:69; Makowiecki 2006: 79). Nevertheless, agriculture remained a primary activity of even urban-dwellers in medieval Poland. At the same time, market economies and interregional exchange facilitated importation of fish from the Baltic Sea to inland areas (Makowiecki 2001). Certain species of fish (e.g.: sturgeon) were considered luxury goods and reserved for political and religious elites. Other fish species, such as herring, were accessible to the general populace albeit more expensive than many other plant or animal foods. Fish consumption likely increased because the Catholic Church encouraged it on fasting days by prohibiting consuming terrestrial meat (Kloczowski 2000). Consequently, members of the general populace who observed these fasts had a cultural impetus to consume fish throughout the year.

2.2 Early Poland: The Wielbark Culture

The Roman Empire never managed to incorporate Poland. The period between the 1\textsuperscript{st} and 3\textsuperscript{rd} centuries is referred to in Poland as the period of Roman contact, or the Roman Era (Buko 2008). During this time, Poland was occupied by populations collectively referred to as the Wielbark culture in the North, and the Przeworsk culture in
the South. Rogowo is a 2nd c. Wielbark settlement from North-Central Poland included here as a pre-medieval outlier (Krenz-Niedbała and Kozłowski nd).

The ethnicity and origin of the Wielbark culture in Poland is widely debated. Either the Wielbark originated in modern-day Poland from several local ethnicities, or arrived through migration from another region (Heather 1996; Krenz-Niedbała and Kozłowski nd). Some researchers believe the Wielbark are one of several groups known in the Roman world as Goths (Heather 1996: 25). The earliest Wielbark settlements are found in Poland in the 1st – 3rd c. AD, after which there is a shift southeast, where they displace the Przeworsk culture in Southern Poland (Buko 2008; Heather 1996). Eventually, the Wielbark developed into the Černjachov culture of modern-day Ukraine and its surrounding areas. Archaeological trademarks of the Wielbark culture are bi-ritual cemeteries that include both inhumation and cremation burials, and a lack of weapons used as grave goods (Buko 2008; Heather 1996).
Wielbark tribes occupied open settlements suggesting an egalitarian way of life. Despite equal resource distribution, social structure was likely ranked with warriors and Dukes earning higher prestige (Buko 2007: 75). Several specialized industries existed during this period including iron metallurgy and ceramic production (Dabrowski 1962), but most craft production continued to occur at the household level. Status of higher ranked individuals (e.g.: chiefs, warriors) often is marked by burials with luxury items procured via trade routes running both north-south and east-west. Although Poland was never incorporated into the Roman Empire, Wielbark populations interacted with the Roman world via trade networks, particularly along the Vistula River that linked Southern Europe to the Baltic Sea (Kaczanowski 1998). Many luxury items excavated from Wielbark sites suggest Roman contact, including glassware, statuettes of Roman gods and amphorae (Gieysztor 1968).

The Wielbark economy was based on subsistence farming and animal husbandry. However, during the first centuries AD agricultural technologies could not have produced a surplus sufficient to sustain large populations or an idle elite. Evidence of early Wielbark land cultivation strategies comes from Odry (approximately 120 km northeast of the study area in North-Central Poland). There, excavation of a cemetery revealed bodies interred in a cultivated field. Analysis of the field itself demonstrated that “Ploughing took the form of narrow, criss-crossed scrapings, and the addition of ash – perhaps reflecting a slash and burn agriculture – the only form of fertilization.” (Heather 1996: 76). It was not until the 4th century that farming technologies such as intensive manuring and use of iron ploughshares began to significantly increase agricultural
productivity in northern Europe (White 1962). In Poland major deforestation events and population aggregation did not occur until approximately the 7th c. AD (Barford 2001).

2.3 Pre-State Poland in Late Antiquity

After the Wielbark culture moved southeast into the Ukraine, Poland was only sparsely occupied. The period between AD 400-700 is referred to in Poland as the “Migration Period” and is characterized by depopulation and high mobility. Little is know about populations in Poland during this period due to the scarcity of permanent settlements and cremation as the ubiquitous burial rite at this time. A major research issue in Polish archaeology remains the origin of the modern-day Poles, and whether they migrated into Poland during this enigmatic period, or if there was continuity in human occupation bridging the Migration Period that is invisible to archaeologists today. Following the Migration Period, the 7th-10th c. was a period of bricklaying for the Polish state. This period is characterized by development and expansion of agriculture and stockbreeding and a by a new settlement structure, the castellan, a type of fortified stronghold and its surrounding settlement (Gieysztor et al. 1979).

Elsewhere in Europe between the 7th and 10th c., centralized political bodies were forming, which affected Poland indirectly. Most importantly, the formation of neighboring states rekindled trade networks that ran through Poland. Goods including amber, salt and iron were increasingly exported from Polish lands.

Slaves were also important trade commodities in Poland at this time, leading to the sociopolitical elite’s self-aggrandizement. Military conquest provided slaves, and
those possessing the most slaves could productively work the most arable land, the wealth of which was accumulated and inherited, fueling status differentiation. Gradually tribal leaders began to control large territories, were legitimized in the eyes of their subordinates, and began to extract tribute and army service for wars that fueled more wealth (Gieysztor 1968).

Increased armed conflict is evidenced by the construction of fortified strongholds between the 7th and 10th centuries. There is a tendency for strongholds to be located near modern-day Poland’s borders with other polities (i.e. Bohemia and Germany), and “this picture strongly suggests that proximity to the imperial frontiers was able to promote local leaders to some importance and allow them to consolidate their power” (Barford 2001: 108).

Strongholds evolved from elite residences, which were fortified by wooden barricades to protect the high status families within. The needs of these elites provided opportunities for warriors and workers who settled around the elite residence, and eventually the strongholds or castellans could serve as larger refuges for the whole local population. The interior of the fortified areas might eventually be inhabited year-round, after which the overflow population settled in the suburbia surrounding the walls. Modern-day Kraków provides an example of this evolution: Kraków is a medieval city and palace secured within a wall, beyond which the city continues unfortified for many blocks.

During the pre-state period, elites presumably extracted tribute from throughout their territory in order to support their warrior class, investment in trade goods, and
stronghold-construction. Limited evidence for tribute extraction comes from the early medieval urban settlement of Wrocław, where inside the stronghold, a large quantity of cereals was stored. Each cache was contaminated by its own particular variety of weeds, suggesting the caches were derived systematically from different fields in the surrounding area (Moźdioch 1994: 142). Palynological analyses of lake cores confirm that in the 8th and 9th centuries there was an increase in the amount of forested land being converted to agriculture (Buko 2008). This new agricultural land sustained the tribute system as well as a larger population, which grew dramatically between the Migration period and the 9th c. (Barford 2001). The ard, a simple scratch plough of iron, was adopted in Poland in the period between the 7th and 10th c. AD (Gieysztor :43).

Human populations began to live in agglomerated settlements after the 7th century (e.g.: Dzieduszycka 1985; more). The number of such settlements in Poland increases prior to (and following) state formation. Generally, scattered settlements were dispersed surrounding a larger, principal settlement or a stronghold (Dzieduszycka 1985: 76). Proto-towns formed in Poland either as overflow from habitation in the castellans themselves, or by expansion of the surrounding settlements which eventually melded together into large complexes (Moźdioch 1994).

Prior to state-formation, tribal leaders (referred to as dukes or princes) were elected by a general assembly and were initially military commanders. It worked to their advantage to embark on military campaigns and thus this political situation was one of expansion. Dukes gained territories and power became concentrated by the 9th-10th centuries. By the mid-9th century, two tribes were particularly powerful: the Polanes and
the Vislanes, who together occupied nearly the entire modern-day country of Poland (Gieysztor et al. 1979). Poland’s dynasty of early rulers, the Piasts, descended from the Polanes tribe. Gallus Anonymous was the first to document the earliest beginnings of a Polish State, writing about these events in the 12th c. He records three generations of Piasts who consolidated large territories in Central Poland before a fourth-generation Piast, Prince Mieszko I, unified the entire State in AD 963. According to medieval archaeologist Andrzej Buko, “the history of Poland should be considered as beginning not so much with the pivotal year 966, that is the date of adopting Christianity, but at least three generations earlier” (Buko 2008: 176).

2.4 The Early Polish State: 10th c. – 14th c.

My discussion concerning the Polish medieval period is divided into four subsections: (1) political changes, (2) a shift to urban living, (3) social and demographic changes, and (4) economic changes. Christianization is introduced in this section and will be elaborated in section 2.5.

2.4.1 History

The merging of Poland’s territories under the direction of enterprising dukes culminated in AD 963. Prince Mieszko I, leader of the Polanes tribe, consolidated power and united the major territories in Poland, including Wielkopolska, Mazovia, Małopolska, Silesia and Pomerania (Fig. 2.2). In AD 966, Mieszko I and his court converted to
Christianity, thus making Christianity the official religion of Poland. This political maneuver permitted his marriage to the Czech princess Dobrava and strengthened Poland’s position with the Church in Rome and, subsequently, in the international community. Before his death in AD 992, Mieszko sought and received Papal protection for Poland, bringing it under the Apostolic See (Kloczowski 2000).

Mieszko I was succeeded in AD 992 by his son, Bolesław Chrobry. In AD 1000 Poland’s legitimacy as a nation was assured when Emperor Otto III visited Gniezno and acknowledged Boleslaw Chrobry as ruler of an independent polity. Bolesław Chrobry
continued to expand Poland’s borders, and in AD 1025 received the official title of King from the Pope, making him the first true king of Poland. Months after his coronation, Bolesław Chrobry died. Poland, under the influence of a handful of powerful families and a rebelling pagan population, dissolved into separate duchies in the 1030s (Dembieńska 1999; Gieysztor et al. 1979). This period is known as the “pagan reaction” in Polish history, a temporary collapse of Christianity and reversion to pagan customs (Dembieńska 1999). The tension between Christianity and paganism was greatest at the borders with Prussia and Pomerania. Pomerania, part of Poland until Boleslaw Chrobry’s death, reverted entirely to paganism and would not be reunited with the rest of Poland until much later. Kazimierz I reunited much of Poland in AD 1042 and unification would last for nearly 100 years. In 1138, Poland was divided again according to the mandate of King Boleslaw the Wrymouth before his death into 6 duchies ruled by Boleslaw’s children. Western Pomerania was again lost (Fig. 2.3).

Poland’s history is characterized by these cycles of unification and deunification. Throughout centuries of political turmoil, Poland also faced the additional problem of a tenuous hold on its borderlands. Prussia and Pomerania, located in the north of modern-day Poland and encompassing the major Baltic ports of Gdańsk and Kołobrzeg, were particularly difficult to Christianize and bring under Polish authority. This frontier likely was a zone of intense political and religious conflict for centuries after Poland’s state formation and Christianization. In the period of deunification after 1138 Poland lost control over several of its territories in Pomerania and Prussia (Gieysztor et al. 1979).
In AD 1226, during a period of decentralization, one of the Polish dukes invited the Teutonic Order of Knights into Poland to help eradicate pagans in Prussia and Lithuania. The Order was given a region known as the “Chełmno Land,” in which Kałdus, Gruczno and the major economic center Toruń are located (Gieysztor et al. 1979). Teutonic castles were constructed along Poland’s then northern-most border throughout the 13th-14th c. and populations there experienced Germanic-style rule for centuries. The Order encouraged German immigration to replace the decimated populations in Prussia and Pomerania (Piskorski 2008).
Kałdus and Gruczno were located just north of the border between Poland and Prussia during the Teutonic Order’s rule, and were thus outside the Poland’s decentralized, ducal borders. Just south of these settlements in the nearby urban center of Toruń an impressive Teutonic castle was constructed in the mid-13\textsuperscript{th} c (Gieysztor et al. 1979).

The Teutonic Knights converted or eradicated pagan populations in Prussia and established a monastic state in the lands south of the Baltic Sea (Knoll 2008). By AD 1283 the original “Crusade” to Christianize Prussia and Pomerania was complete. The Order then initiated expansionist conflicts with Lithuania, which in the 14\textsuperscript{th} c. was the last remaining pagan state in Europe. After the Lithuanian King willingly and peacefully converted to Catholicism in order to marry the Queen Jadwiga, the Order was obliged to doubt the legitimacy of his conversion in order to continue expanding. During the 14\textsuperscript{th} c., the relationship between Poland and the Teutonic Order became increasingly strained and turned to war as both polities claimed many of the same territories in the vicinity of Prussia. Throughout this conflict, Kałdus and Gruczno in the Chelmno Lands remained part of the Teutonic Order, outside Poland’s borders.

In 1409 Poland and Lithuania formed an alliance to counter growing Teutonic aggression (Knoll 2008). Their army defeated the Teutonic Knights at the decisive Battle of Grunwald in 1410. Poland-Lithuania and the Teutonic Order signed the First Peace of Toruń in 1411, ending the war, but barely diminishing the land holdings of the Order. For decades, conflicts continued, gradually reducing the power of the Order (Knoll 2008). By the mid-1400s the expansionist Teutonic Order was substantially diminished.
when it signed the Second Peace of Toruń with Poland. With this treaty, Kałdus, Gruczno and Toruń in the Chelmno Lands along with several other territories returned to Poland after approximately 150 years of Teutonic rule. The Teutonic Order persisted as a polity in Prussia until 1525 AD, albeit with substantially reduced power and less international support (Knoll 2008).

2.4.2 Urban changes

By the 10th and 11th centuries, castellans in Poland had developed into “incipient towns.” Incipient towns are distinguished from conventional villages by archaeological evidence for craft specialization and trade (Hensel 1969). The most important of these were the sedes reini principales, the capitals of local provinces (Dzieduszycka and Dzieduszycki 1994). These incipient towns comprised the local ruler’s residence, areas of craft production and a market place (Hensel 1969; Koter and Kulesza 1999). They differed from the towns of later eras in that they lacked one or more of the following characteristics: economic self-sufficiency, a planned and systematic infrastructure, a means of defense, a role in the country’s military or administrative system and legal recognition as an independent political and economic unit. Populations of incipient towns often exceeded the capacity of the early fortified area and spilled into the suburbia flanking the original settlement. “In densely populated areas, the radius of influence of the centre did not exceed 14 km (c. 9 miles)…” (Gieysztor 1979: 68-69).

In the 12th century, towns in Poland had “reached their peak,” and are considered to be early urban centers (Gieysztor 1979; Buko 2008: 223). The largest early urban
centers in the 12th c. sustained populations of 3,000—5,000 inhabitants (Hensel 1969: 384-5). About 50 modern-day Polish towns have a history of 1,000 years or more (Buko 2008). Among them is Kałdus (relocated slightly and known today as Chełmno), one of the three medieval settlements which I investigate here.

Unlike many other Western European towns, even urban areas in Poland remained fairly dependent on agriculture and animal husbandry (Koter and Kulesza 1999: 66-67). Non-agricultural functions of urban sites in Poland were not as well-developed as in contemporary cities elsewhere in Europe (Koter and Kulesza 1999), and agriculture, stock-breeding or fishing remained “major concerns” of even the city-dwellers (Gieysztor et al. 1979). Settlements were flanked by urban tracts of land used for crops or livestock, including fields, meadows and forests. The 3-field system of agriculture was in place during the medieval period, facilitating the efficient use of smaller land areas. Each town still retained large tracts of land: “Whereas the built-up areas of the towns ranged in size from 8.5 to 54 ha, the surrounding tracts, even in small towns, were of at least 340 ha and sometimes over 1700 ha” (Koter and Kulesza 1999: 76). As populations in urban contexts grew, tracts of additional land were established in a meandering fashion around the settlement nexus. These narrow plots later posed problems for growth because they were unsuitable for conversion to urban city planning (Koter and Kulesza 1999: 76). By the 13th century, charters were granted to a number of Polish towns enabling self-governance including regulation of taxes and trade (Koter and Kulesza 1999).
2.4.3 Socio-demographic changes

Social differentiation increased during the medieval period. Pre-medicieval subsistence farmers lived as tribal units working communally-owned land. When military leaders consolidated power, as Mieszko I did in the 10th c., tribute systems developed in which agricultural products or services were paid by the general populace to the military elite. By the 12th c., this tribute-paying peasantry became differentiated into two groups. Some peasants remained “free” farmers working land for their own subsistence and profit while other peasants “experienced some type of restraint on their existence, whether freedom of movement, use of resources, or limitations on the types of activities they could engage in. Some had become outright serfs to their princely rulers; nearly all were required to pay heavy duties” (Dembińska 1999: 32).

Kings and dukes rewarded loyalty and service by gifting large tracts of land and the peasants who occupied them to the social and religious elite. Land and people thus became consolidated under increasingly wealthy landowners. The opportunity for landowners to increase their incomes in Poland attracted foreign settlers, especially from Germany. In some areas, German immigrants were absorbed into the local culture. In others, “German peasant colonists squeezed out the Slavs and Pruthenians and restricted their development” (Gieysztor et al. 1979: 98). At Toruń, the largest settlement in the vicinity of Kaldus and Gruczno, German immigrants “preserved their language within the framework of the then multinational Polish State” rather than being absorbed in the 13th c. (Gieysztor et al. 1979: 98). German traditions likely influenced culture, including diet, at Kaldus and Gruczno.
In Western Europe, the custom of feudal relations had for centuries imposed a system of land rental on peasants. This system was introduced in Poland in the 13th c. and by the 14th c. renting was widespread among the “non-free” peasantry. “The economic benefit to the landowners lay in the fact that agricultural risk was shifted to the peasant while guaranteeing a steady annual flow of rents in cash. The peasants acquired cash by selling their produce in the market towns which were developing during this same period” (Dembińska 1999: 33).

The “free” peasantry in Poland in the 13th c. represented a middle class whose prestige and power derived from military service, either as fighters or pages and stewards. In the 14th c. this loosely recognized class became the “lesser nobility” or szlachta that in 1374 was granted legal status by the King (Dembińska 1999:34). Clans of knights also developed as a type of lesser nobility in the 13th-15th c., sharing “real or imagined genetic relationships with a common ancestor” (Dembińska 1999: 35). The szlachta and clans in Poland constantly acted to decentralize political control throughout Poland’s medieval period. This sets Poland apart from, and often at a disadvantage to, other European polities where centralization went uninterrupted for many centuries.

2.4.4 Economic changes

Road systems were in place in the 10th c. and possibly as early as the 9th century. Transport by way of rivers would certainly have been possible regardless of the state of roads in Poland (Wasowiczowna 1959). Development of roads reflects an increase in consumer demand for non-local goods while facilitating interregional communication and
awareness of sociopolitical situations in other European territories. It would not be until
the 13th c. that roads in Poland would have a truly permanent character. Archaeological
evidence of which is road reinforcement with wood planks, road pillars carved from stone
and artwork depicting especially the travel of papal legates over Polish roads
(Wasowiczowna 1959: 130-134). Control over intersections of important roads provided
an economic opportunity because tolls and trade taxes could be levied from travelers
and tradesmen (Wasowiczowna 1959: 136). Indeed, roads often intersect at the locations
of markets or at major river crossings (W 1959: 134).

At least as early as the 12th century a major road linked the Baltic Sea at Gdańsk
with Central Poland and Russia and passed through Gruczno on the West bank of the
Vistula River (Fig. 2.4). Regional roads likely connected Kałdus, an important local
economic center on the East bank, to this network. The most important trade goods that
passed North-South on this roadway were amber, salt and fish (especially herring) from
the Baltic Sea. Herring were imported inland from the Baltic as early as the 8th c. AD
and were the principal commercial fish in Poland (Makowiecki 2001). Remains of this
and other marine fish are a proxy indicator for long-distance exchange (Barrett et al.
2008). The increase in demand for herring began during the 8th-10th c. when proto-towns
developed and fishing technologies improved (Makowiecki 2003). After the 10th century,
Christianity provided an impetus for fish consumption: fish, unlike all other meats, were
permitted on fasting days, which numbered well over 200 per annum (Kloczowski 2000;
Woolgar 2000).
During the 12\textsuperscript{th} and 13\textsuperscript{th} centuries, the wheeled mouldboard plough was adopted in Germany and surrounding areas which allowed more rapid turning of Northern Europe’s thick sod (Gieysztor et al. 1979; Rösch et al. 1992). Also, the 3-field system was spreading in which a winter and a summer crop could be planted in two fields while a third lay fallow (Gieysztor et al. 1979; Rösch et al. 1992). As a result, populations increased dramatically in the 12\textsuperscript{th} c. and an agricultural surplus was produced, facilitating socioeconomic differentiation.

Markets became common in the 11\textsuperscript{th} century; by the end of the 12\textsuperscript{th} century, more than 250 existed in Poland (Gieysztor et al. 1979; Moźdioch 1994). Specialized industries included butchers, blacksmiths, potters and carpenters. There is evidence in
some incipient towns of “middle men,” for example, butcher stalls that intervened between production and consumption (Hensel 1969: 385). Markets were under the protection of ducal law, meaning taxes were levied on goods traded therein. This changed when Germanic law granted autonomy to many Polish cities after the 13th c., creating independent markets. With the demise of ducal law, elites could no longer derive power by extracting tribute and redistributing it amongst their land-workers. Power and wealth became linked to land-ownership rather than redistribution.

Subsequently, the political strength of strongholds declined in the 13th-14th c. (Mozdioch: 143-148)

As early as AD 1070, coins were minted in Poland (Barford 2001). “With this came changes in the stronghold-towns (and especially in their extramural settlements) which seem to have led to the creation of something more recognizable as urban sites functioning as market centres in the expanding early state economic system” (Barford 2001: 185). Coin hordes throughout Poland track the increasing reliance on currency: whereas in ca. AD 1000 it appears to have taken 50 years for coins of English origin to have diffused via circulation from Central to Southern Poland, by AD 1100 this transfer took only 25 years (Mozdzioch 1994: 148).

2.5 Christianity in Poland

Because Christianity is credited as having been a major catalyst for the rise of medieval nation-states, it is important to understand the nature and magnitude of its spread through Europe. In this section, I provide three subsections reviewing the
Christianization of Poland: (1) pagan religious beliefs preceding Christianity, (2) important events in Poland’s official Christianization, and (3) Christianization as experienced by the general populace, as distinct from the sociopolitical elite. This includes new diet restrictions imposed by the Church; namely, fasting most days of the year when meat and dairy products from terrestrial animals were prohibited.

If we can detect diet changes associated with Christianity, then we also may monitor rates of diet change and thereby ascertain the rate of Christianization in medieval Poland. Historical explanations of how Slavic states came to be powerful entities in medieval European assume Christianity was an important driving force (Barford 2001; Kloczowski 2000; Steward and Shaw 1994). Christianity advantaged leaders of nascent European states. The Roman Catholic Church protected and legitimized a Christian King’s authority and promoted official recognition by other Christian kingdoms. Historical records provide ample evidence that social changes followed conversion of monarchs to Catholicism.

Christianity initiated social changes across the general populace influencing Europe’s political successes during the medieval period. If Christianity was merely an official religion declared by the state but observed by few outside the social elite, its role in Europe’s rise to power during the medieval period needs to be re-examined. However, neither spiritual nor moral conversion of peasantry are detectable using traditional archaeological and historical approaches (Brown 1997; Fogelin 2007; Renfrew 1994). Mortuary analyses have been useful tools because graves of pagan Slavs differ from Christian burials (Barber 1988; Barford 2001; Daniell 1998). Documenting religiously-
based diet changes with stable isotopes may be an even more powerful tool (Müldner and Richards 2005; Polet and Katzenberg 2003).

2.5.1 Paganism

Prior to Christianization, Poland’s tribal groups practiced regionally diverse forms of paganism. Little is known about these belief systems. Due to the paucity of written information from the first millennium A.D., what is known comes from archaeological evidence, comparative studies of Indo-European religions, and the limited historical record. The Slavs worshipped a pantheon of deities. A sun god, Swaróžyc, was of major importance (Dembińska 1999), and “The names and some effigies of particular Slav gods, such as Perun (the God of Thunder), Swietowit (the God of War and Harvest), Swarog (the Sunmaker), or Trzyglow (the Three-headed One), date back to the last centuries of Slav paganism” (Kloczowski 2000: 8). Other gods and spirits were associated with objects, animals, elements and rituals such as phases of the life cycle or calendrical events (Kloczowski 2000). Slavic paganism met the needs of rural communities by addressing two primary concerns: “…weather, for one, which ruled their lives. Care of animals was another.” (MacMullen 64). Because pagan gods were closely allied to daily concerns the process of Christianization took centuries in Poland, as paganism was difficult for the Church to eliminate.

Paganism was an integral part of tribal egalitarian social structures. According to Premysław Urbańczyk, “Pagan religions were polytheistic and decentralized, locally changing and difficult to control. They took shape during the evolution of societies that
were comprised of relatively autonomous rural populations. They were part of a system of keeping the balance between unavoidable centralizing tendencies and the tradition of relatively egalitarian organization in these societies” (Urbańczyk 2003).

The physical landscape had sacred importance in Slavic paganism. Groves of certain trees appear to have been considered holy (Buko 2008: 133-141). In the Świętokrzyskie Mountains of South Central Poland a 1,300 meter circle of stones was constructed in the in the 9th c. which attracted pagan pilgrims throughout the early periods of Christianization. Hills could assume sacred importance and may have been visited as pilgrimage sites. Mount Saint Laurence, located at Kaldus, is one of these. A natural hill at Kaldus was artificially enlarged by local tribal populations. In one of the depressions created around its base, an altar with sacral function was constructed. Offerings of plants, animals, and a human were deposited in the late 10th c. near this altar. Construction of a basilica began on the site of the altar shortly after Poland’s Christianization, evidently in an attempt by the Catholic Church to stamp out pagan rituals. Despite these efforts, construction halted after the pagan reaction in the 1030s (Buko 2008; Chudziak 1997).

2.5.2 Important Events in Poland’s Christianization

The foundations of Slavic-Christian culture were laid when the brothers Cyril and Methodius commenced a mission to Northern Europe in AD 863 (Fletcher 1999). Educated in theology in Constantinople, they were sent to evangelize Slavic populations in Great Moravia, a historical geographic area comprising parts of modern-day Slovakia,
The Czech Republic, and other neighboring countries. Cyril and Methodius invented the Glagolitic script, the precursor of the Cyrillic alphabet, in their efforts to translate the Bible into Slavic dialects. Their mission to the Slavs was friendly and successful, and the ability to deliver Christian liturgy in Slavic languages was pivotal in forming Slavic-Christian culture. The Cyrillic alphabet is still used in Slavic countries affiliated with the Eastern Orthodox Church, which Cyril and Methodius represented. Later, in the 10th c. Poland’s ties with Western Catholicism and its Latin alphabet were forged by its first ruler, Mieszko I.

Christianity likely percolated throughout Poland in the 9th and 10th c. at a level essentially invisible in archaeological and historical records (Kloczowski 2000: 10). Christian contact also may have come through Benedictines entering Poland during the 9th c. or simply through interactions with neighboring populations. Poland’s most powerful neighbors, Germany and Bohemia, were Christianized long before Poland. Germany had retained vestiges of Roman Christianity throughout Antiquity, and the first Christian ruler of Bohemia was baptised by Methodius in the late 9th c. (Table 2.1; Graham-Campbell 2007). Missionary activity “could only hope for permanent success only where new forms of political organization (i.e. the state) had already emerged” (Graham-Campbell 2007: 67).

In the mid-10th c. a unified state was forming in Poland under the consolidating efforts of Mieszko I, leader of the Polanes tribe. Mieszko I became Poland’s first ruler around AD 960. Poland’s “official” Christianization followed in AD 966 when Mieszko and his court were baptised in Greater Poland (Kloczowski 2000). This was a political
Table 2.1: Dates of Christian Conversion by European Polities

<table>
<thead>
<tr>
<th>Polity</th>
<th>Date of Christian Conversion (A.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bohemia (Czech Republic)</td>
<td>883</td>
</tr>
<tr>
<td>Denmark</td>
<td>960</td>
</tr>
<tr>
<td>Poland</td>
<td>966</td>
</tr>
<tr>
<td>Hungary</td>
<td>973</td>
</tr>
<tr>
<td>Russia</td>
<td>988</td>
</tr>
<tr>
<td>Iceland</td>
<td>ca. 1000</td>
</tr>
</tbody>
</table>

*After Graham-Campbell (2007)*

maneuver. It strengthened his strategic marriage to the Bohemian princess Dobrava and reinforced Poland’s legitimacy as an autonomous polity in the eyes of the Church and the increasingly Christian European community. State formation and conversion to Christianity often went hand-in-hand which was likely no coincidence.

“Paganism, with its characteristic particularism, was absolutely impossible to use as a means of unifying the scattered elements of these societies in this way… but time and time again it was found that the imported and monotheistic Christianity was a useful tool in promoting social unity and aiding the authorities of the early state in their struggles with decentralizing tendencies in a way that no pagan religion could have done” (Barford 2001: 212-3)

In this light, Christianization of Poland by Mieszko I is seen as a political maneuver rather than a spiritual conversion. Mieszko I took advantage of Christianity as a unifying force standardizing allegiance of his growing bureaucracy and fellow
aristocracy to the state. The earliest Christian converts were these elite individuals who were the most important element of social unity in the early Polish state. Christianity spread to incipient towns (aka castellans or in Polish, gróds) from Poznań and Gniezno. These elite-governed castellans were the backbone of Poland’s social structure in the 10th c. Castellans originated as fortified elite residences during the tribal period, but over time grew into socioeconomic hubs governed by elite landowning Lords. Christianized landowners were thus scattered throughout the new Polish state in strongholds and were instrumental in converting the general populace. Although the earliest churches in Poland were constructed on the orders of Mieszko I or the Church, many churches eventually were built by landowners. Landowners also enforced state laws, which, after official Christianization in AD 992, directly interfered with pagan practices. The “instruments of persecution” in Poland during the process of Christianization were “laws, monks, and landowners” (MacMullen 1997: 67).

After the baptism of Mieszko I, “Overall responsibility for the Polish mission was undoubtedly taken by Rome” (Kloczowski 2000: 11). Bishop Jordan was appointed by the Pope to head this mission that operated out of Poznań. Churches were built in both Poznań and Gniezno, the first cities to receive missionary attention. Early church officials were relatives of the royal family, “so the web of dynastic power during this period was tightly woven” (Dembińska 1999:30). Mission activity spread from these hubs such that by the 11th c. churches were constructed in the hinterlands. The basilica at Kaldus is one of these.
Boleslaw Chrobry inherited the Polish crown after the death of his father, Mieszko I. His reign over a unified Poland lasted 33 years. In 1025 Boleslaw died and Poland was divided into separate duchies and a “full-scale reversion to the old pagan religion” occurred in the Polish regions of Prussia and Pomerania (Dembińska 1999: 30). The state was unified again in 1042 by Kazimierz I.

In the late 11th and early 12th c. Christian Poland was divided into distinct dioceses (Kloczowski 2000). A diocese is land supervised by one bishop that can be further subdivided into parishes. A hierarchy of clergy and a network of local churches developed within this diocesan structure. Initially, churches were located in cities and founded by bishops or princes, but eventually, nobles and knights founded churches in more rural areas (Kloczowski 2000). Thus, the influence of Christianity began to trickle down to the general populace in a more influential way approximately 100 years after Poland’s official Christianization. The Church collected tithes from the surrounding population and also received endowments from the nobility.

Religious orders (monasteries, convents) were founded in Poland following Christianization. These include the Benedictines (11th c.), Cistercians (12th c.) and Dominicans (13th c.) (Gieysztor et al. 1979; Kloczowski 2000). Between AD 1200 and 1300 the number of orders in modern-day Poland grew from approximately 150 to 750 (Kloczowski 2000: 39). For women during this period in Poland “The convent life was so attractive…that for a long time the main problem was to limit the number of candidates” (Kloczowski 2000: 40). Religious orders served as a model for Christian values and behaviors, helping solidify the Church’s presence in Poland. They also
stimulated economic growth, many orders were endowed with land and peasant workers by the nobility, that facilitated trade, particularly of fish from the Baltic Sea (Makowiecki 2001).

2.5.3 Christianity in Poland after State Conversion

Compared with events affecting the nobility and elite classes, the chronology of the spread of Christianity to the peasantry is more difficult to detect. Kloczowski (2000) locates the most important spiritual changes during the 13th c. Paganism was firmly rooted in the family unit with blood ties functioning as the most important social bond. However, by the 13th c. populations were increasingly mobile, moving from rural areas to incipient towns and colonizing new rural settlements. Such social migrations dissolved the foundations of pagan Polish society. Religious orders and local churches became more numerous, and new generations of Poles were immersed in a different social climate than previous. Infant baptism became widespread for the first time in the 13th c. (Kloczowski 2000). At the same time, the Church assumed control over the legitimization of marriages. According to Kloczowski (2000: 49), “religious rites and practices, the churchyard and various religious experiences challenging the drabness of everyday living, were a source of gradual integration: they provided a sense of identity for all the parishioners.”

“Official” Christianization played a critical role in unifying and legitimizing the European states, but the smaller repercussions felt by the general populace are also important to consider. By instilling ideas of social equality, brotherly love, and charity
beyond one’s own social network, interpersonal stresses implicit in urbanization such as class conflict and disease were ameliorated (Stark 1996). Christian attitudes regarding the immorality of slavery motivated exploration of technologies such as wind and water power that could replace human labor in energy production (White 1962). Additionally, Christianity introduced the ritual of a work schedule into the daily lives of peasants with Sunday as a day of rest (Brundage 1995; Kloczowski 2000). Regarding Christianity’s rise from early foundations in Rome, Stark (1996) argues that Christianity favored population growth by condemning abortion and infanticide. This accelerated its spread through social landscapes. Christianity’s “linking of a highly social ethical code with religion” (Stark 1996: 86) meant that Christianization of the peasantry – and not just of the elite – engendered large-scale but less-well documented social change during the medieval period.

To understand Christianity’s role in restructuring European society, it is important to know whether early “Christians” actually adhered to Catholic values and customs or if conversion was ostentatious and more for political reasons. Kloczowski writes that “…for the majority of Slav tribes and communities, the adoption of Christianity was primarily a political act that changed the form of their public worship rather than their domestic or communal customs or attitudes” (Kloczowski 2000: 9). The evangelization of Poland was difficult: “…old religion suited most people very well. They loved it, trusted it, found fulfillment in it, and so resisted change however eloquently, or ferociously, pressed upon them” (MacMullen 1997: 69).
Attempts to convert the Polish countryside to Christianity were met with resistance, but for how many years and to what extent, we cannot know from historical records alone. Such records often overestimate Christianity’s success: in the early medieval period in Europe, the only individuals who were literate were themselves Christians. Regarding the rate of Christianization, MacMullen estimates that it took approximately 200 years to curtail pagan practices, and writes that “… in the process of eradicating paganism, the most provoking, accessible, vulnerable aspects were attacked in sequence…. Persecution that first focused on acts sponsored by community leaders only later turned to those involving no-account people, the poor and the rural” (MacMullen 1997: 72).

Studying the Christianization of burial customs helps elucidate changes in religiosity. Polish populations up to the 10th century exclusively practiced cremation. All other burial styles before this time can be attributed to immigration of foreigners. After the 10th century, changes gradually occurred: first, burials were oriented on an East-West axis. Then, “during the 12th century, both the location and form of Early Medieval cemeteries underwent a change. This was connected with the appearance of churches in towns” (Buko 2008: 398). In the 13th century parish priests assumed more responsibility in supervising burial rites, and presence of grave goods declined. By the end of the medieval period burials were almost entirely devoid of grave goods. Based upon changes in burial practices, it appears the transition from pagan to Christian burial rites took at least the larger part of 500 years. Questions remain: Are the behaviors interpreted as
pagan survivals really indicative of paganism? Or were they subsumed by the Church, becoming Polish Catholic idiosyncrasies, without implications for pagan beliefs?

The medieval Christian Church imposed nearly 200 days of fasting during which meat, dairy and eggs of land mammals were proscribed (Woolgar 2000). In Poland, the number of fasting days may have been even greater due in part to a longer Lent season, and historical records note that fasting days were vigorously enforced (Kloczowski 2000). It is generally assumed that terrestrial protein sources were replaced by fish (Dembńska 1999; Kloczowski 2000; Woolgar 2000). Medieval historical records and archaeo-ichthyological remains document a general increase in fish consumption from AD 1000-1500 (Barrett et al. 2004; Dembińska 1999). However, these methods do not account for differences among the elite and peasantry, nor between men and women. The incorporation of fish into peasant diets can best be studied with stable isotopes in human bone, which reveal individual consumption patterns. A primary goal of this research is to determine whether fish consumption increased during the medieval period in response to Christianization, and if so, to determine the rate of increase.

2.6 An Archaeological and Historical Perspective on Polish Diet

In this section, I review historical and archaeological evidence regarding diet in Poland between AD 100 and 1400. This information lays a foundation for building a richer interpretation of diet from isotope data. Whereas historical and archaeological sources provide a menu of foods, stable isotope data illustrate how foods were distributed.
within the population. Stable Isotopes more precisely document actual human consumption through time and across regions.

This chapter is divided into two sections: diet in the Roman Era and diet in the medieval period. How sociopolitical developments influenced dietary changes are highlighted for major food groups – grains, fish and meat. In some cases, it is possible to discuss why specific foods were consumed: for example, increased consumption of pigs during the medieval period as a consequence of urbanization, or a Slavic cultural tradition of cultivating millet. Little stable isotopic or trace element data are available for this review of prehistoric Polish diet; when possible, these data are reviewed.

2.6.1 Diet in the Roman Era

During the first centuries A.D., Wielbark populations in North-Central Poland were engaging in agriculture and animal husbandry. Written accounts from the Roman Era document large amounts of animal products – particularly beef and dairy – in early Polish diet (Smrćka et al. 2000). Discussing the “Old Germanic diet” north of the Danube River in Europe, Caesar wrote “they are not particularly interested in farming the land and that their diet consisted mostly of milk, cheese and meat” (Gladykowska-Rzeczycka et al. 1997: 94). Trace element analysis of strontium and zinc, considered relatively reliable paleodiet indicators (Lambert et al. 1984; Price et al. 1985), support this interpretation of a diet high in animal protein (Gladykowska-Rzeczycka et al. 1997; Smrćka et al. 2000).
Although subsistence economies were based on animal husbandry and agriculture in the Roman period, “There were regional differences of lesser importance, resulting from the abundance of wildlife or bees; nests in the forests, or from an abundance of freshwater fish” (Gieysztor 1968: 43). Land was tilled on a household level but was collectively owned during the pre-state period. For this reason, little intra-population diet differentiation may be expected at this time (Gieysztor 1968).

Barley, millet, rye and wheat are the most common cultigens in Poland during the Roman Era. These vary by region in relative importance. According to paleobotanical evidence, in Northern and East-Central Poland barley was the most common grain cultivated. In North-Eastern Poland, rye is most common. In Southern Poland, millet is most common in the 1st-2nd c., whereas rye becomes most common in the 3rd-4th c. (Gładykowska-Rzeczycka et al. 1997).

Millet was cultivated in Poland since the Neolithic, but increased significantly in the Roman Era (Wasylikowka et al. 1991: 227). Millet is common among Slavic populations and has been documented in Southern and Eastern Europe by numerous paleobotanical (Poleyn 2002; Pyrgala 1970; Rösch et al. 1992; Wasylikowa et al. 1991; Zohary and Hopf 1988) and stable isotope investigations (Le Huray and Schutkowski 2005; Murray and Schoeninger 1988; Reitsema et al. 2010). Stable isotope studies in Western Europe (e.g.: Netherlands and Britain) indicate an absence of millet in human diet during and preceding the medieval period (Randsborg 1985; Richards et al. 2006; Schutkowski et al. 1999). This East-West dichotomy suggests Slavs had a cultural
preference for millet (Dembińska 1999). Legumes also were prevalent in the Roman Era, according to the paleobotanical record (Wasylikowa et al. 1991).

Cattle were the most common domesticated animals in the Roman period and account for between 45% and 81% of Roman Era assemblages, depending on the site (Makowiecki et al. 2007). Cattle were valued in the Roman period for meat as evidenced by butchery patterns, milk and cheese as evidenced by domestic remains of storage devices, and hides as evidenced by abundant tanneries (Pyrgała 1975). Whether dung was an important secondary product is not well-established. Historic accounts of Poland indicate that Roman-era populations were reputedly great consumers of beef (Gladykowska-Rzeczycka et al. 1997; Smrčka et al. 2000). In the Kalduś region of North-Central Poland in the Roman period, the four most common taxa are cattle (53% of assemblage), sheep/goat (22%), pig (19%) and horse (5%). Horse is typically found at low frequencies throughout Poland in both the Roman and medieval periods, as are wild animals. Also uncommon are remains of birds, such as domestic chickens. From two sites in East-Central Poland, only one yielded remains of birds, which comprised only 0.1% of the total faunal assemblage (Pyrgała 1975).

Bones of wild animals are rare compared to those of domesticated animals and account for approximately 6% of faunal remains in the Roman period. The most common hunted animals as assessed archaeozoologically were roe deer, wild boar and beaver (Pyrgała 1975).
2.6.2 Diet during the Medieval Period

Population growth and a demographic shift to living in agglomerated settings strongly shaped changes in diet during the medieval period. Whereas formerly human populations were largely self-sufficient and farmed their own land, urbanization divorced much of the population from food production. This trend instigated a settlement structure in which *suburbia* supplied towns and strongholds with agricultural produce. Urban settings with their markets and trade links provided more variety in available foods (Herrschler et al. 2001). Despite variation in foods at a site, some foods may nevertheless have been restricted to the social elite (Dembińska 1999).

2.6.2.i Domesticated animals

Beginning in the 6th c., pig remains become increasingly common in Polish faunal assemblages (Pyrgała 1975). Between the Roman and medieval periods in Poland, the percentage of pigs increases dramatically, from approximately 20% to approximately 50% of the total faunal assemblages (Makowiecki 2006). Pork is more commonly mentioned than beef in historical records as well (Dembińska 1999). At Kaldus between the 7th/8th and 13th c. AD, domestic animals include cattle (42.2%), pig (38.5%), sheep/goat (14.4%) and horse (4.9%), very similar to other medieval sites in Poland. At Wolin, the breakdown was cattle (31.5%), pig (63.4%), and sheep/goat (5%). Medieval prices of meat from various animals reveal their relative availability: the cheapest foods, such as chicken, were likely ubiquitous (Table 2.2). Cattle were valued by the peasantry for traction (ploughing, pulling carts), and “one only ate beef, generally, when the draft
Table 2.2: Medieval Prices of Polish Foods, after Dembińska (1999)

<table>
<thead>
<tr>
<th>Food/animal</th>
<th>Price (in Polish grosze)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken</td>
<td>1</td>
</tr>
<tr>
<td>Pig</td>
<td>21</td>
</tr>
<tr>
<td>Cow</td>
<td>44</td>
</tr>
<tr>
<td>Ox</td>
<td>54</td>
</tr>
<tr>
<td>Elk</td>
<td>90</td>
</tr>
<tr>
<td>Salmon (whole)</td>
<td>20</td>
</tr>
<tr>
<td>Sturgeon (one piece)</td>
<td>70</td>
</tr>
<tr>
<td>Cod (three pieces)</td>
<td>8-11</td>
</tr>
<tr>
<td>Herring (100 pieces)</td>
<td>8</td>
</tr>
<tr>
<td>Eel (“per barrel”)</td>
<td>1½ - 2</td>
</tr>
</tbody>
</table>

animal died, or when the most important son was married off in a favorable land deal” (Demińska 1999).

2.6.2.ii Wild animals

Hunting was regulated by the nobility during the medieval period: only the King and his nobles could hunt larger animals such as elk, deer and aurochs in forests. Correspondingly, archaeozoological assemblages show a shift in how wild animals were exploited. In Poland during the 7th-10th centuries, prior to state formation, wild animals comprise approximately 4-6% of animal assemblages (rarely exceeding 10%). After state
formation ca. AD 1000, the contributions of wild animals falls at rural sites to a mere 1-3% of total faunal remains (Makowiecki 2006), but remains constant or increases at stronghold sites (Barford 2001). Most likely, elites inhabiting the stronghold sites are responsible for this trend. Dembińska (1999) notes that game may be underrepresented in faunal assemblages in all types of settlement site, as butchering of larger animals likely took place in the forests. For example, bones of bear paws are found most often at settlements in Poland, suggesting the carcass was left behind after removal of paws, skin and edible flesh (Buko 2008; Dembińska 1999).

Bones of wild animals recovered from medieval sites include elk, hare, aurochs (which survived in Poland until the 17th c.), red and roe deer, bear, and a number of wild bird species. Hare are the most common wild animal at medieval sites, accounting for 20% of the total wild animal remains (Makowiecki 2006).

2.6.2.iii Avifauna

Bones of birds account for 0.5 – 8.0% of total archaeozoological remains in early medieval Polish sites. Of these, 85% are domestic birds. The most common bird is the domestic chicken which contributes 70% of the total bird remains. Bones of roosters are relatively common suggesting they were selectively culled. 25-30% of the domestic fowl are juveniles, also culled for consumption (Waluszewska-Bubién 1979). Hens were kept as egg-layers: Makowiecki (2006) identified calcium crystals in chicken bones that indicate they were regularly laying eggs (Makowiecki 2006).
Dembińska (1999) records the average price of a single chicken in Poland to be very low – only 1 grosze, in contrast to a pig which cost 21 grosze (Table 3.1). Chicken was the most affordable type of animal protein in medieval Poland, although herring and eel were inexpensive fish. Goose remains are next most common bird at an average of 11.3% of the total bird remains in Poland. Ducks contribute 0.4-5% to overall bird remains. Generally, wild birds are found in low frequencies. Swans, pigeons, grouse, cranes, crows and ravens are among the wild birds found at medieval Polish sites (Makowiecki et al. 2007). Some wild birds at these sites are hawks, used by the social elite for hunting. An exception is the medieval settlement complex at Opole, where wild birds comprise one-third of the total bird remains (Waluszewska-Bubién 1979).

Makowiecki et al. (2007) illustrate very clearly the relationship between certain birds and a high-status lifestyle in the medieval period. They examined a settlement and a stronghold from Kalduś, one of the study areas investigated in this dissertation, in North-Central Poland. Roughly a dozen wild species of bird were represented between the two sites, in addition to domestic birds such as chicken and goose. Wild bird remains in the stronghold greatly outnumbered those in the settlement (30% versus 10%). These birds were likely considered a delicacy, and were probably hunted for sport by the elite. Wild species recovered from the castle included grey heron, white stork, partridge and great cormorant (Makowiecki et al. 2007). It has been noted that some of these animals may have been valued for their feathers (Bartosiewicz 1995; Waluszewska-Bubién 1979). In the settlement, domestic fowl are the most common bird represented, accounting for 76% of the total bird remains. In the stronghold, only 57% of the bird remains were of
domestic chickens (Makowiecki 2010: 60). Geese were equally common in both the stronghold and the settlement at 13.8% each (Makowiecki 2010: 60). Makowiecki and G (2002) noted that through time, the average size of domestic fowl increases.

2.6.2.iv Secondary products

Secondary products include milk, wool, traction and fertilizer provided by animals (Koepke and Baten 2008; Sherratt 1983). Human’s widespread harnessing of these resources in the Old World may have occurred several thousand years after domestication of plants and animals for primary food sources. Most often, secondary products do not leave direct traces in the archaeological record. Recovery of milk fats from ceramics, well preserved textiles, ancient plough marks and isotope analysis of manured fields are exceptions (Bakels 1997; Bethell et al. 1994; Bull et al. 1999; Greenfield 2010). By examining age, size, sex and stature profiles of animals, the importance of meat vs. secondary products can be evaluated.

A preponderance of adult female animals is evidence for dairying, as is overall size of the animals. During the medieval period, withers height of cattle in Poland remained relatively stable and small at 104 cm on average (Makowiecki 2006). From this measurement, it has been estimated that the average amount of milk these cows could have produced per year was 400-600 kg, their lactation period was 305 days, and a nursing calf would consume 250-350 kg. A relatively small amount remained for human consumption (an estimated 150-200 kg annual surplus). Long-term storage was impossible due to lack of refrigeration; consequently, milk and cheese from cattle in Poland may have been a product reserved for the social elite and not consumed by the general populace. Slaughter age of cattle from Poland show a uniform pattern from the 10th-13th c. with two culling peaks: at
approximately age 2 and at age 4 (unlike pigs, which exhibit one culling peak at age 3, and were exclusively used for meat). This may illustrate use of animals for more than just meat. Makowiecki (2006) concludes that cattle were more likely used for traction force or dung in the medieval period. An increase in the average height of cattle to 112 cm in the early modern period (ca. AD 1400-1700) suggests that milk may have become more important in later centuries. In Hungary, highly commercialized dairying did not commence until this time (Bartosiewicz 1995).

Age profiles can detect the use of sheep for wool rather than meat. Younger adults would have been selected for culling for meat, whereas older individuals would have been retained for secondary products. Bartosiewicz (1998) noted many older sheep/goats in the castle site of Váralja Castle. Additionally, the bones recovered from the castle represented the more desirable cuts of meat, leading the author to conclude they may have been used for wool in the surrounding settlement until death, at which point they were butchered and brought, partially processed, into the castle for consumption. Makowiecki reports three culling ages for sheep/goat in medieval Poland: 4-8 months, 10-17 months and 3-4 years, the latter age group being the most common (Makowiecki n.d.). These older animals were retained for secondary products. Sheep and goat were fairly small in medieval Poland, suggesting wool was the major impetus for keeping them (Dembińska 1999).

Chickens were certainly kept for eggs as well as meat. Males were selectively culled (Waluszewska-Bubién 1979) and bones of females suggest they were egg-layers (Makowiecki 2006). Żabiński (1959) considered economics and the buying power of money during the medieval period to calculate that on average, an individual living in medieval Poland consumed 242 eggs annually. Historical records suggest that elite
households consumed 266,450 eggs per year, or 730 eggs per day (Dembińska 1999:73). Chicken, which could live within medieval settlements in close quarters with humans, were clearly important for feeding urban populations.

2.6.2.v Grains, vegetables and fruit

During the medieval period, the main crops cultivated were still wheat, barley, millet and rye. However, the subsistence economy became more narrowly focused on fewer crops. According to Wasylikowa (1991: 228-229), “The most striking feature of the Early Medieval period, as far as cereals are concerned, is the increased importance of Triticum aestivum s.l. [common/bread wheat]…followed later (after the 10th century) by the spread of rye. Barley and hulled wheats became less common than in the Roman period.” Millet, along with oats, peas, lentil, flax and hemp, remained an important cultigen in Poland during the medieval period (Wasylikowa et al. 1991). According to Dembińska (1999: 103), “…porridge made with finely ground millet or millet grits was the staff of life for all Poles, princes and commoners alike. Millet was also one of the distinctive features of medieval Polish cookery that differentiated it from cookery in Western Europe.”

Dembińska compiled a list of 25 vegetable species mentioned in historic Polish texts. Peas and cabbage are the most commonly mentioned, although broad (fava) beans and onion are also common. Peas and beans could be dried and consumed during the winter, and cabbage could be pickled for storage and winter consumption as well. Kale and lentil could even be harvested in the winter. Many tubers were grown and consumed, including parsnips, beets, rutabagas, turnips, radishes, alexanders and skirrets. Many of
these vegetables’ greens were also eaten. Cucumbers were grown throughout the medieval period (Dembińska 1999; Wasylikowa et al. 1991).

Fruits, such as peaches and cherries, become more common in the medieval period in Poland. These were grown in orchards or in household trees as is still common in rural Poland. According to Wasylikowa et al. (1991: 229), increased use of fruits in the medieval period “reflects the development of fruit-growing and horticulture which took place in the whole of Europe at that time.” It should be noted that refuse pits associated with newly-forming urban centers would provide better opportunities for archaeological preservation of fruits in the medieval period than earlier. Foreign-grown foods such as almonds, oranges, figs and rice were reserved for the sociopolitical elite (Dembińska 1999) and typically do not appear in records until the 14th-15th c.

2.6.2. vi Fish

Fish are more commonly found in medieval sites than in Roman Era sites, an increase that begins in the 8th c. (Makowiecki 2001). The most common varieties of fish in medieval archaeozoological assemblages are freshwater bream, tench and roach (Makowiecki 2001). The next most common freshwater fish are pike and perch. Less common fish were the anadromous salmon and sturgeon, which were reserved for elite social classes (see prices in Table 2.2). Herring are the most common marine fish found at medieval sites. Herring were relatively inexpensive and could be preserved for long-distance transport by smoking or salting. Kołobrzeg and Gdańsk were major Baltic Sea hubs for the herring trade, and a trace element analysis of diet in medieval Gdańsk
demonstrates large amounts of marine fish in the diet (Szostek et al. 2009). Other fish excavated from medieval sites are eel (anadromous), flounder (marine), catfish, rudd and carp (freshwater).

A useful way to monitor the spread of market economies in the medieval period is to identify a “low-value staple” that could be easily exchanged, and monitor its dissemination throughout Europe. Barrett et al. (2004) identified cod and herring as such a staple, the spread of which was not likely to represent gift-exchange. The authors conducted a comprehensive archaeozoological survey of 127 archaeoichthyological assemblages from England that spanned the 7th-16th centuries. Their results indicated marked differences between assemblages before and after the 11th century. In the earlier periods, freshwater and migratory species were most prevalent. After AD 1000, bones of herring and cod were much more common.

This pattern is also observed in Poland, Germany, Belgium and France (Barrett et al. 2004). The authors refer to this pronounced and widespread intensification of herring and cod ca. AD 1000 as a ‘fish event horizon’. The trend is corroborated in the stable isotope record of human populations from the medieval period (Kosiba et al. 2007; Müldner and Richards 2007a; Salamon et al. 2008), and by the prevalence of middens in some regions associated with cod processing for export (Barrett et al. 2004). The intercontinental linkages and intensive exploitation of marine fish revealed by their study lead Barrett et al. (2004) to conclude that cod and herring were informative proxy indicators of the shift to market economies.
Despite the characterization of this as a “fish event,” in Poland there was a gradual increase of herring beginning in the 8th c., reaching a peak intensity in the 9th-11th c. (Makowiecki 2001). This gradual change occurred hand-in-hand with the development of strongholds. The prevalence of herring bones within the stronghold at Kołobrzeg as opposed to outside in surrounding areas supports the idea that intensified fishing of herring was at least partially driven by urbanization, a conclusion also reached by Barrett et al. (2004) to explain the English evidence.

During the medieval period in Poland, fish bone evidence supports a picture of increasing social differentiation. Limited finds of salmon are restricted to urban settings, which may be in line with written records indicating salmon was reserved for elite classes (Makowiecki 2001). Sturgeon remains are most common near sacred buildings, and become increasingly rare after the 11th c. (likely due to environmental degradation), causing their price to increase through time (Dembińska 1999). Bones of freshwater fish (bream, roach) which could be fished locally are common at rural sites in Poland both before and after AD 1000 (Makowiecki 2001).

Social differentiation in diet was drawn along religious lines as the medieval period progressed. Religious orders (e.g.: monasteries) imported large amounts of fish to feed their members and to sell within their communities (Dembińska 1999; Makowiecki 2001). Stable isotope evidence from Europe also suggests that within a population, more fish were consumed by the “religious” individuals buried in the monastic cemetery (Müldner et al. 2009; Polet and Katzenberg 2003).
Whereas herring and cod are both part of the ‘fish event horizon’ in Western Europe, cod remains do not increase alongside herring in Poland. Rather, cod becomes more prevalent only after the Teutonic Knights occupied Poland in the 14th c. (Makowiecki 2001). Prior to this, Slavic populations appear not to have consumed cod in any significant amount. While this is perhaps more linked to different cultural traditions than to status-based resource access, it is an interesting example of the links between social groups and food.

2.6.3 Archaeozoology and Paleobotany at Kaldus

In this last subsection I report detailed information about subsistence behaviors at one of the main study sites, Kaldus. The settlement complex at Kaldus will be discussed in greater detail in Chapter 4. For now, archaeozoological research in the area is presented as a case-study providing archaeological context for medieval diet. Kaldus comprises four archaeological sites of interest: a medieval settlement (site 2), an associated stronghold (site 3), and two cemeteries (sites 1 and 4). All four sites have yielded faunal remains, despite the fact that two are cemeteries. Comparisons between the roughly contemporary settlement and stronghold site illuminate status differences in diet at Kaldus, whereas comparisons between the earlier (site 4) and later (site 1) cemeteries provide preliminary information on changes in animal exploitation through time, although it should be remembered that these are cemeteries, and may not offer as complete a window into past diet as would the analysis of habitation sites.
Health and diet have been well-studied at Kałdus, including archaeozoological, paleobotanical and paleopathological examinations (Kozłowski and Drozd 2006). Figures depicting archaeozoological information are based on data reported by Makowiecki (2010) and are based on number of specimens identified (NISP).

Polcyn and Abramów (2007) investigated plant remains excavated from the settlement (site 2) associated with the early medieval stronghold at Kałdus. The most common are cereals, accounting for 62% of the total plant remains. Of these, the most common cereal is rye at 30% of total assemblage, followed by millet (17%), wheat (9%) and barley (3%). 25% of total plants recovered are legumes. 91% of these legumes are peas, whereas vetch and lentils account for 9%. Finally, trees, including hazel and hornbeam, contribute 2% of the total plant remains. 1% of plant remains are herbs. Isotope reconstructions of human diet at Kałdus may thus be interpreted as a high-plant diet based on both C3 and C4 cereals and with large input from legumes.

Archaeological animal remains from Kałdus are displayed in Figure 2.5. Interestingly, significantly different categories of animals are found at Kałdus sites 4 and 1. Domestic animals in general are less common at site 4 than they are at site 1. Wild animals, birds and especially fish are more common at Kałdus site 4.

Frequencies of domestic animals at Kałdus (sites 1 and 4) are displayed in Figure 2.6. As with other medieval sites, the most common domestic animal (excluding poultry) is pig, followed by cow, sheep/goat and horse. Sheep/goat and horse are more common at Kałdus site 4 and cattle and pig are more common at Kałdus site 1.
Figure 2.5: Classes of Animal Found at Kaldus (Sites 1 and 4)

(Data from Makowiecki [2010])

(Makowiecki 2010a). Recall that at Kaldus site 1, domestic animals are more common in general than they are at Kaldus site 4 (Fig. 2.5).

Stronghold (site 3) and settlement (site 2) also show different frequencies of domestic animals (not pictured). Cattle and pig are more commonly found in the stronghold than in the settlement. Sheep/goat and domestic fowl (chicken) are more commonly found in the settlement (Makowiecki 2010: 60; 67).

Makowiecki (2006) has argued that dairy productivity for domestic animals in the medieval period was low. In agreement with historical records (Dembinska 1999),
chicken were probably the most common source of protein for the general populace at Kaldu. At Kaldu, chicken are by far the most common bird species excavated. A breakdown of bird remains from the Kaldu stronghold (site 3) and settlement (site 2) is presented in Figure 2.7. Makowiecki (2010) compares wild animal bones excavated from the stronghold at Kaldu (site 3) and its associated settlement (site 2). By comparing a stronghold and a settlement, possible “status” foods can be identified. Wild animals more commonly found in the stronghold include hare, red deer and roe deer. The sole
Figure 2.7: Birds at Kaldus (Sites 2 and 3)

![Bar graph showing bird species frequencies at Kaldus sites 2 and 3.](image)

(Data from Makowiecki [2007])

The wild animal found more commonly in the settlement is wild boar (Makowiecki 2010: 69-70). Frequencies of large game (excluding smaller animals like hare and beaver, which were hunted) are presented in Figure 2.8. Not pictured are buffalo, which comprise just 0.1% of the faunal assemblage at site 3.

The four most common fish species found at Kaldus (all sites) are carp (40% of total fish assemblage), sturgeon (11%), pike (9%) and catfish (4%) (Makowiecki 2010b). All four varieties inhabited the Vistula River during the medieval period. All are freshwater species, except sturgeon which is anadromous. Surprisingly, eel are represented by a single find at Kaldus. When the Kaldus settlement (site 2), stronghold (site 3) and cemetery (site 4) are considered separately, proportions of fish vary from the overall frequencies. This breakdown is pictured in Figure 2.9. Perch are also pictured...
because they were relatively common at Kalduś site 4, one of the sites of particular interest here. Herring are displayed in addition to the three most common fish species in Figure 2.9 because they are believed to have been so widespread in the medieval period (Makowiecki 2001; Woolgar 2000). Cod is another marine fish common during the
Figure 2.9: Fish at Kaldus (Sites 2, 3 and 4)

(Data from Makowiecki [2010])
medieval period in Western Europe but absent at Kałdus. During earlier periods at Kałdus, a wider variety of fish species were evidently consumed. At Kałdus site 4 (11th c.), nine different taxa are identified; the six most common are displayed in Figure 2.9 (after Makowiecki 2010). At Kałdus site 1 (12th-13th c.) only three species are present (asp, carp and sturgeon). It should be remembered that these are cemeteries and not settlements.

A closer look at Figure 2.9 demonstrates that some of these fish were “high status” varieties. Site 3 at Kałdus is an elite stronghold, unlike the site 2 settlement or site 4 cemetery. Most notably, sturgeon appear to be an elite commodity as they are considerably more common in the stronghold than in the settlement or cemetery. Carp were a fish for the general populace, as evidenced by their high frequency in the settlement and cemetery areas. Herring are absent at Kałdus site 4, but found in very low frequencies at other sites. Thus, the only fish expected to have an enriched-\(^{13}\)C signal at Kałdus are anadromous sturgeon.

### 2.7 Summary of Biocultural Context

In this chapter, I have outlined major events in Polish prehistory and history relevant to this study. The two most important sociopolitical changes of interest are state formation and Christianization, which both occurred ca. AD 1000. However, the first 1000 years AD involved many other gradual changes such as the formation of road and trade networks, urbanization and improvements in agricultural techniques. The
establishment of the Teutonic Order of Knights in North-Central Poland was a third major event that dramatically influenced Polish history beginning in the 13th c.

Also in this chapter, I have described the process and impact of Christianization in Poland during the medieval period. After reviewing major events in the history of the Polish Church, I discussed impacts of Catholicism on daily lives of the general populace. Multiple lines of evidence suggest the process of conversion was gradual and patchy in Poland due to persistent pagan traditions. The process of conversion remains poorly understood. Because Catholicism imposed fasts most of the year prohibiting meat and dairy consumption, religion may have profoundly impacted diet and health in the past.

Finally, I have summarized archaeobotanical, archaeozoological and historical evidence for Polish diet, highlighting changes that occurred in tandem with the aforementioned sociopolitical events. Diet changes are of interest in this study because they may be detected isotopically, thereby providing a window into past demographic, economic and religious change. By taking advantage of links between human diet and human behavior, stable isotope analyses may be used to study complex human interactions in the past.
3.1 Introduction

Over the last forty years, stable isotope analyses of human and animal bone have become instrumental for archaeological reconstructions and interpretations of past human diets. The utility of isotope analyses in paleodiet studies derives from the fact that isotopic ratios of different foods are preserved in the tissue chemistry of consumers (van der Merwe and Vogel 1978; Vogel and van der Merwe 1977). Stable carbon isotope ratios provide information about the ecosystem of a consumer, distinguishing between terrestrial versus marine niches and between plants adapted for temperate and arid environments. Stable nitrogen isotope ratios reflect an organism’s trophic position in the local food web, distinguishing between carnivores, omnivores and herbivores. Stable isotopes are also sensitive to non-dietary variables, rendering their interpretation complex.

My purpose in this section is to review how stable carbon and nitrogen isotope analyses are used to reconstruct diet of past populations. In addition, a consideration of non-dietary sources of isotope variation is included, including diagenesis (contamination, alteration or degradation of bone following death and deposition). Using case-studies I illustrate how stable isotope analyses reveal information regarding sex-differences, status-differences and differences in subsistence economies of past populations. Finally,
I compare the uses of bone collagen and bone apatite as sources of isotopes for diet reconstruction.

3.2 Background

Isotopes are atoms of the same element with the same number of protons in their nuclei, but different numbers of neutrons. This difference in atomic weight is measurable through mass spectrometry. Some isotopes are radioactive, and decay at a known rate (e.g.: carbon-14, notated as $^{14}$C). Other isotopes are stable and do not change over time (e.g: $^{12}$C and $^{13}$C) (Hoefs 2004). Plants and animals exhibit systematic stable isotopic variation due to differences in their environments, physiologies and diets. Stable isotope signatures in our tissues, including our bones, represent a composite of the stable isotope signatures of all the foods we eat. By measuring the stable isotope ratios of ancient bones and comparing the signatures to ratios of various food types, a person’s life-long “menu” can be estimated. Although stable isotopes do not decay, stable isotope relative abundances of an element may change as the element is transferred from foods to consumer tissues through a process known as fractionation. Fractionation occurs because bonds incorporating lighter isotopes are weaker than bonds incorporating heavier isotopes and break more readily during such events as diffusion and evaporation (Hoefs 2004). During some chemical reactions, fractionation changes the overall isotope signatures of an initial material and its byproduct(s) (Hoefs 2004).

Stable isotope values are expressed as a permil ($\delta$) ratio of one of an element’s isotopes to another in relation to a standard of known abundance. The original standard
for carbon isotopes in laboratories was *Belemnitella americana*, a Cretaceous fossil from the Pee Dee formation in South Carolina (Hoefs 2004). In terms of its absolute value, Pee Dee Belemnite is relatively high in $^{13}$C, but as a laboratory standard it was assigned the baseline value of 0‰. Consequently, carbon isotope ratios are usually reported as negative values. Stable carbon, nitrogen and oxygen stable isotope ratios are reported according to the equation \[ \delta = \frac{(R_{sample} - R_{standard})}{R_{standard}} \times 1000. \]

### 3.3 Stable Carbon Isotopes

#### 3.3.1 Carbon Isotopes in Terrestrial Foodwebs

Beginning with early assays of the isotope $^{14}$C for radiocarbon dating, carbon isotopes were the first to be used by anthropologists (Libby 1955). It was recognized that certain classes of plants differed in their carbon isotope ratios (Park and Epstein 1961). These are referred to as C$_3$ and C$_4$ plants because the product of photosynthesis in each is either a 3- or a 4-carbon molecule (Park and Epstein 1960; Park and Epstein 1961). C$_3$ plants include most vegetables and human cultigens such as wheat, barley and rye. C$_4$ plants include millet, maize, and other tropical grasses (Bender 1968; Smith and Epstein 1971).

The source of carbon for terrestrial ecosystems is atmospheric CO$_2$, with a $\delta^{13}$C ratio of about $-7\%$. The photosynthetic pathway of C$_3$ plants, the Calvin-Benson cycle, fixes carbon dissolved in leaf cytoplasm through ribulose biphosphate carboxylation. Carbon is ultimately fixed as the three-carbon molecule, phosphoglycerate (Hoefs 2004).
This reaction preferentially incorporates the lighter isotope $^{12}$C and discriminates heavily against $^{13}$C. Resulting stable carbon isotope ratios in plant tissue are approximately $-17.0\%$ lower than atmospheric CO$_2$ (Park and Epstein 1960), and C$_3$ plants exhibit values of $-20.0\%$ to $-35.0\%$ (Katzenberg 2000). Trees, shrubs, vegetables, and many cultigens (wheat, barley, rye) follow the Calvin-Benson pathway.

The Hatch-Slack pathway, which C$_4$ plants follow to fix carbon, uses a different enzyme to incorporate CO$_2$: phosphoenolpyruvate carboxylase. The product of this reaction is oxaloacetate, a four-carbon molecule (Hoefs 2004). This reaction does not discriminate as stringently against the heavier stable isotope, causing a fractionation of approximately $-3\%$ compared to atmospheric CO$_2$. Grasses adapted to warm climates are C$_4$ plants, including four important cultigens: maize, millet, sorghum and sugarcane. C$_4$ plants are relatively $^{13}$C-enriched compared to C$_3$ plants, ranging from $-6.0\%$ to $-19.0\%$ (Smith and Epstein 1971). The $\delta^{13}$C ranges of C$_3$ and C$_4$ plants do not overlap (Katzenberg 2000).

A third class of plants use crassulacean acid metabolism (CAM) to fix carbon (Hoefs 2004). This photosynthetic strategy is not a separate chemical reaction but rather an ability some plants have to use both the C$_3$ and the C$_4$ carbon fixing pathways in response to climate shifts. CAM plants are found in very hot and dry environments. In mild conditions, the C$_3$ pathway is used, but the C$_4$ pathway is used as a more conservative carbon fixation strategy when temperatures are high or humidity is low. Shifting between the two pathways causes CAM plants to exhibit $\delta^{13}$C values intermediate to the C$_3$ and C$_4$ plant ranges. Cactii and pineapple are among the CAM
plants that have played a role in human diet.

After metabolic fractionation, the $\delta^{13}C$ ratio of bone collagen from consumers is approximately 5‰ higher than that of their total diet. Enrichment of approximately +1‰ occurs between flesh and bone collagen from the animal consuming it (Schoeninger 1989). By subtracting these known diet-collagen spacing factors from the $\delta^{13}C$ signatures in human bone, an average $\delta^{13}C$ ratio for total diet can be obtained. Using this bulk value, an accurate interpretation of which of many potential foods were consumed depends on knowledge of the local subsistence economy and environment.

The distinction between C$_3$ and C$_4$ plants enabled groundbreaking research into the pattern of maize adoption in the Americas (van der Merwe and Vogel 1978; Vogel and van der Merwe 1977). By isotopically monitoring the addition of C$_4$ foods against a background of traditionally exploited C$_3$ plants and C$_3$ feeding animals, estimates for maize cultivation and intensification based on paleobotanical data were substantially refined. Schoeninger (2009) and Hutchinson et al. (1998) emphasized the importance of stable isotope data in providing more precise regional accounts of how maize agriculture was received that consider the social as well as the physical environments. The same principles are now being applied to track millet consumption in Europe (Le Huray and Schutkowski 2005; Murray and Schoeninger 1988; Reitsema et al. 2010; Tafuri et al. 2009).
3.3.2 *Stable Carbon isotopes in aquatic foodwebs*

The major source of carbon in marine ecosystems is dissolved inorganic carbon (including carbonic acid and \( \text{CO}_2 \)), which in oceans worldwide exhibits an average \( \delta^{13}\text{C} \) value of approximately 1.5‰ (Hoefs 2004). Particulate organic matter (including algae and detritus) is another source of carbon with \( \delta^{13}\text{C} \) values generally ranging from −18.5‰ to −22.0‰ (Hoefs 2004). The \( \delta^{13}\text{C} \) ratios of plants and animals occupying marine niches fall between these values, and marine fish \( \delta^{13}\text{C} \) values can range from approximately −11.0‰ to −19.0‰ (Barrett et al. 2008). The \( \delta^{13}\text{C} \) differences between marine and terrestrial ecosystems are reflected in the tissues of humans relying to a greater or lesser extent on each (Chisholm et al. 1982).

Tauber (1981) and Chisolm et al. (1982) were among the first to demonstrate the utility of stable carbon isotopes in identifying marine resource consumption. Tauber (1981) compared stable carbon isotopes from bones of 28 skeletons from the Mesolithic, Neolithic, Bronze Age, Iron Age and historic periods in Denmark. High \( \delta^{13}\text{C} \) values demonstrated a diet based on marine resources during the Mesolithic (contrary to archaeozoological evidence) which changed dramatically in the Neolithic to a terrestrial-based diet (low \( \delta^{13}\text{C} \) values). It was not until the medieval period that fish resumed importance as a dietary resource, underscoring the importance of agriculture in the Neolithic and Iron Age.

Tauber (1981) could assume that stable carbon isotope enrichment was indicative of marine resource consumption because \( \text{C}_4 \) plants, another source of \( ^{13}\text{C} \) enrichment, are demonstrably absent in Northern Europe in that time period (Burleigh et al. 1984). In
regions where C₄ plants may have been present, δ¹³C ratios should be supplemented with historical or archaeobotanical evidence and/or δ¹⁵N ratios to identify marine fish in diet.

In their study of Iron Age skeletons from Slovenia, Murray and Schoeninger (1988) discovered ¹³C enrichment among a land-locked population. Low δ¹⁵N values from the same individuals permitted the authors to rule out marine fish consumption as a source of ¹³C enrichment. By considering this in tandem with the region’s archaeobotanical record, they concluded instead that the isotopic enrichment was due to consumption of the C₄ plant millet, the first isotopic indication of millet consumption by humans in Europe.

The δ¹³C composition of plants in freshwater ecosystems is highly variable. Unlike terrestrial carbon that derives primarily from atmospheric CO₂ or marine carbon that derives primarily from dissolved carbonate, carbon composition in freshwater environments is influenced by many factors. Important among these are equilibration with the atmosphere and decomposing organic matter. The relative contribution of each to the overall isotopic value of freshwater depends largely on lake size and water turbulence (Dufour et al. 1999). Freshwater fish consequently exhibit a broad range of δ¹³C values (Katzenberg and Weber 1999). Many studies report very low δ¹³C values for freshwater fish because of the low δ¹³C of freshwater plants (Dufour et al. 1999; Pazdur et al. 1999; Reitsema et al. 2010), but a few studies of freshwater fish report values that mimic those of marine fish (e.g.: Hecky and Hesslein 1995; Katzenberg and Weber 2009; Katzenberg et al. 2009; Katzenberg et al. 2010).
Linderholm et al. (2008) investigated a Swedish skeletal sample from the Viking Period (AD 800–1050) and identified a “high status” individual exhibiting high $\delta^{15}N$ but low $\delta^{13}C$ values. Although his $\delta^{15}N$ value indicated fish consumption, the low $\delta^{13}C$ values allowed researchers to conclude the fish were of *freshwater* origin. Through this reconstruction of diet, a link could be made between freshwater fish consumption and high status, revealing aspects of the past social hierarchy.

3.3.3 **Non-dietary sources of variation in carbon isotope ratios**

Non-dietary effects on $\delta^{13}C$ ratios include the “canopy-effect” in which admixture between CO$_2$ in forests and in the atmosphere is prevented by tree-canopies. The decay of organic matter emits isotopically depleted CO$_2$ that impact the $\delta^{13}C$ ratios of plants. Animals living in forested environments exhibit lower $\delta^{13}C$ ratios as a result (van Klinken et al. 2000). Isotope research on herbivorous animals in European forests indicate that taxa occupying densely forested areas (e.g.: red deer, aurochs) exhibit significantly lower $\delta^{13}C$ ratios than do animals occupying forest fringes or open fields (e.g.: cattle, hare) (Lynch et al. 2008; Noe-Nygaard et al. 2005; Rodiere et al. 1996).

Isotopically light fossil fuel emissions in the last century have caused overall atmospheric CO$_2$ to differ in $\delta^{13}C$ from pre-modern times (Marino and McElroy 1991). Comparisons between modern and archaeological plants and animals must factor in a -1.5‰ shift. $\delta^{13}C$ ratios also vary with latitude due to the effects of temperature and humidity on photosynthesis. Using ratios from wood carbon, a 2-4‰ range has been demonstrated in northern Europe attributable purely to latitude (van Klinken et al. 2000).
3.4 Stable Nitrogen Isotopes

3.4.1 Terrestrial foodwebs

Stable nitrogen isotope values in plant and animal tissues are expressed as a ratio of nitrogen’s two stable isotopes, $^{15}$N and $^{14}$N, in relation to the accepted standard (atmospheric nitrogen). Bone collagen is the main source of $\delta^{15}$N ratios in archaeological diet reconstructions, although stable nitrogen isotopes can also be assayed from soft tissues such as hair and fingernails. An organism’s $\delta^{15}$N ratio is related to its trophic position in the local food web: as nitrogen from food sources is ingested and incorporated into consumer tissues, the lighter isotope $^{14}$N breaks down more readily than $^{15}$N and is excreted with urea (Minawaga and Wada 1984; Schoeninger and DeNiro 1984). This leaves consumers’ tissues enriched by approximately 3-5‰ compared to their diets throughout the food chain (Drucker and Bocherens 2004).

Within terrestrial systems, many plants exhibit $\delta^{15}$N values of approximately 3‰ after fractionation from atmospheric air via photosynthesis. After trophic enrichment, herbivorous animals eating these plants exhibit $\delta^{15}$N values of 6-8‰ and carnivores exhibit values around 9‰. Omnivores such as humans typically exhibit intermediate values (Schoeninger and Moore 1992). Although $\delta^{15}$N ratios evaluate the importance of animal protein in an organism’s diet, they do not distinguish between meat from different parts of an animal or between meat and dairy from the same animal, as these tissues exhibit similar $\delta^{15}$N ratios (Garvie-Lok 2001; Steele and Daniel 1978). For this more specific information, archaeozoological data are indispensable.
Legumes are capable of fixing atmospheric nitrogen without fractionation via bacteria on their root nodules; therefore the $\delta^{15}N$ values of legumes are similar to air (~0‰) (Klepinger 1984). DeNiro and Epstein (1981) have suggested that the increasing consumption of large amounts of legumes in the Tehuacán valley caused a gradual decrease in $\delta^{15}N$ values of humans from approximately 10.5‰ in 6000 BC to 8‰ in AD 1000. The effect legumes may have on $\delta^{15}N$ values of populations that consume only small amounts relative to overall diet is uncertain. It is not well-understood if legumes are capable of “cancelling out” any or all of the higher $\delta^{15}N$ values of animal consumption.

Meat is generally considered a higher quality food resource than are plants (Harris 1987). This has led to the use of $\delta^{15}N$ ratios for identifying sex-based (Richards et al. 2006) and status-based (Richards et al. 1998) differential access to animal protein. $\delta^{15}N$ ratios are also informative of ancient weaning practices (Dupras et al. 2001; Fogel et al. 1989; Katzenberg 1993; Richards et al. 2002; Schurr 1998; Waters-Rist et al. 2010)(Waters-Rist and Katzenberg 2010). When an infant nurses, it is elevated a trophic position, causing its bone to be enriched in $^{15}N$. Weaning ages vary widely between human societies and, due to post-partum amenorrhea, are inextricably linked to population growth.

3.4.2 Nitrogen isotopes in aquatic foodwebs

Due to fractionation associated with denitrification in ocean water (Price et al. 1985) and the relatively great length of aquatic food webs, freshwater and marine
organisms typically exhibit elevated $\delta^{15}$N ratios (Barrett et al. 2008; DeNiro and Epstein 1981; Katzenberg and Weber 1999). After trophic enrichment, consumers of fish are expected to exhibit $\delta^{15}$N enrichment beyond what could be expected from a terrestrial diet – i.e., above approximately 11.0‰. Many researchers have investigated more than just diet of past populations by taking advantage of the fact that fish consumption (or lack thereof) is associated with broader social processes such as the shift from hunting and gathering to agriculture (Bonsall et al. 1997; Lubell et al. 1994; Tauber 1981), the expansion of market economies (Barrett et al. 2008), and the adoption of Christian fasting restrictions (Müldner and Richards 2005; Müldner and Richards 2007a; Salamon et al. 2008).

3.4.3 Non-dietary sources of variation in consumer $\delta^{15}$N

Despite these general trends, $\delta^{15}$N values of plants and animals are not identical across regions (DeNiro and Epstein 1981). Non-dietary factors influence $\delta^{15}$N of plants and animals such as climate, nutrition stress, and agricultural techniques, generating inter-regional differences in human $\delta^{15}$N values unrelated to diet. This complicates isotopic comparisons across populations. It is important to establish local baselines for humans’ stable isotope values which can be used as a point of comparison for estimating human diet free of cultural influences. A local baseline should include associated plant and animal resources. Ideally, the baseline also includes animals not consumed by humans, such as carnivores, to ascertain the end-member ratio of a truly carnivorous diet in that particular environment.
3.4.3.i Climate

Although a diet-collagen space of + 3‰ is typically posited in hypothetical stable isotope models, a range as wide as 1.3 to 5.7‰ has been observed (Ambrose 2000). Hot, arid climates may augment isotopic fractionation between trophic positions due to animals’ physiological responses to heat stress. In order to conserve water, many animals are capable of concentrating urea, enabling greater discrimination against $^{14}N$ during this process and leaving tissues more enriched than normal. Perhaps due to the unsuitability of rodent models, experimental studies have not yet validated this hypothesis (Ambrose 2000).

3.4.3.ii Nutritional stress

Hobson et al. (1993) were among the first to describe the relationship between $\delta^{15}N$ values and nutrition stress (negative nitrogen balance) in their investigation of quail tissues. Birds on a maintenance diet exhibited higher $\delta^{15}N$ ratios than birds on a growth diet, likely due to the fact that the former were catabolizing their own tissues (and were thus elevated a trophic position). Katzenberg and Lovell (1999) observed a similar effect in the bone collagen of an osteomyelitic bone from an AIDS sufferer, also attributable to catabolism of proteins. Alternately, during growth (positive nitrogen balance), relatively more nitrogen is used to build tissues, and relatively less undergoes the fractionating processes of transamination and deamination (Fuller et al. 2004; Macko et al. 1986;
Waters-Rist and Katzenberg 2010). Animals in positive nitrogen balance should have lower $\delta^{15}$N ratios as a result.

It has been generally assumed that stable isotope ratios of men and women do not differ for physiological reasons (DeNiro and Schoeninger 1983; Lovell et al. 1986). A number of studies nevertheless have found small but significant $^{15}$N enrichments among men (Fuller et al. 2006b and citations therein). Recently, Fuller et al. (2004) proposed a non-dietary explanation for lower $\delta^{15}$N values among women. Pregnancy causes $\delta^{15}$N in hair of modern pregnant women to be depleted by 0.5 – 1.0‰. Bone, which remodels at an increased rate during gestation and lactation, may demonstrate a similar effect. According to Fuller et al. (2006b: 51), “the resorption of the bone matrix and subsequent remineralization after weaning during a lifetime of pregnancies and periods of lactation could potentially result in changes to the $\delta^{15}$N values of the skeleton whereby women could have lower $\delta^{15}$N results.” This physiologically-based and sex-dependent explanation has been posited to account for different $\delta^{15}$N ratios among men and women in a Roman period cemetery from the Britain (Fuller et al. 2006b). However, Müldner and Richards (2007b) suggest that the remodeling rate of bone may not be high enough during pregnancy for this 9 month period to leave an isotopic trace in bone collagen. The fact that this trend is not universal (see for example Keenleyside et al. 2009; Kjellström et al. 2009) also cautions against physiology as an explanation per se.

3.4.3.iii Agricultural and animal husbandry techniques

Although there is a well-established relationship between $\delta^{15}$N ratios in
plants/animals and in humans, several human subsistence activities and landscape
modifications can alter this relationship. Manuring is a relatively simple strategy that
dramatically increases agricultural productivity. In its simplest form, animals are left to
graze on fields during a fallow period, their dung replenishes nitrogen in soil, and the
field can be farmed in subsequent seasons. It is safe to assume that manuring could have
been widespread in past human societies. Because manuring changes the source of
nitrogen for plants to one with more $^{15}\text{N}$, plants growing on manured lands exhibit
elevated $\delta^{15}\text{N}$ ratios, occasionally of great magnitude (Bogaard et al. 2007). Commissio
and Nelson (2008) demonstrated that land used as a barn in a medieval Norse farm
produced plants with $\delta^{15}\text{N}$ values of 10-16‰ (as opposed to the usual 2-3‰). As far as
stable isotope analyses are concerned, plants grown on manured fields are
indistinguishable as components of human diet from the animals producing the manure.
Sampling of archaeological sites similar to the study by Commissio and Nelson (2008)
can identify potentially manured fields, as can chemical analysis of the soil itself (Bull et
al. 1999). Stable isotope analyses of animal bones also can reveal manuring if primarily
herbivorous animals such as cattle exhibit unexpectedly high $^{15}\text{N}$ that cannot reasonably
be attributed to fish or meat consumption.

Another strategy used to increase soil productivity is clearing land with fire.
Burning is shown to increase $\delta^{15}\text{N}$ values of plants grown on burnt soil (Grogan et al.
2000). The surface layers of soil in which most plants are rooted become gradually
depleted in $^{15}\text{N}$ due to generations of selective uptake by plants. Fires facilitate the
removal of the upper layers of soil, exposing the more $^{15}\text{N}$-rich lower layers for future
plant growth. Additionally, plants recovering in burned areas take up less nitrate (which is isotopically depleted) than do plants in unburned areas, which also contributes to higher $\delta^{15}N$ values in plants on burned land (Grogan et al. 2000). Grogan et al. (2000) demonstrated that leaf $\delta^{15}N$ of herbs grown in a mature forest were approximately 8‰ lower than leaf values from recently burned soils (approximately -2‰ vs. +5-7‰, respectively). Swidden agriculture could dramatically affect $\delta^{15}N$ values of plants at the base of human food chains.

Plants exposed to sea spray can become $^{15}N$-enriched (Cloern et al. 2002; Heaton 1987). In some regions of prehistoric Europe, salt-marsh grazing was a deliberate animal husbandry strategy (Britton et al. 2008). Indeed, bones from ancient animals suspected of salt-marsh grazing in the UK during the Bronze Age exhibit significantly higher $\delta^{15}N$ than an inland control sample. Without a faunal baseline, the $\delta^{15}N$ of humans consuming these herbivores might not be accurately interpreted.

### 3.5 Diagenesis

Bone is a composite of organic and inorganic constituents. The organic fraction of bone is primarily Type I collagen, a large protein molecule that gives bone its elasticity. Bone also contains a number of non-collagenous proteins (Tuross 1993). The inorganic fraction is a hydroxyapatite mineral that, interwoven with collagen fibers, gives bone its strength. Hydroxyapatite is a heavily-, substituted, poorly crystalline mineral with the chemical formula $\text{Ca}_{10} (\text{PO}_4)_6 (\text{OH})_2$ (Biltz and Pellegrino 1977; Kay et al. 1964). Carbonate exists in apatite through substitutions at the $\text{OH}^-$ (Type A substitutions) and
PO$_4^{3-}$ (Type B substitutions) sites in the crystal structure. These are referred to as structural carbonates. Carbonate can also be adsorbed onto crystal surfaces. This adsorbed carbonate is more labile than structural carbonate, making it more susceptible to post-deposition alteration and to alteration during chemical treatment of bone. Apatite consists of many small unstable crystals that are prone to adsorption and recrystallization. Post-depositional processes may cause collagen to be degraded or lost, or may add additional material, ostensibly affecting the isotope ratio obtained when attempting to isolate and analyze bulk collagen. Stable isotope research must involve rigorous screening of bone samples to ensure diagenesis has not obscured the dietary signal from collagen and mineral.

Collagen can be degraded by hydrolization of the bonds amongst its constituent amino acids in acidic burial environments (Collins et al. 1995). These non-collagenous protein fragments may be leached from the bone during deposition or during chemical preparation methods, or they may remain with bone. Collagen may also be digested by tunneling microbes from the surrounding soil. This may be independently investigated by examining bone porosity and histology (Nielsen-Marsh and Hedges 2000a). Younger collagen is more soluble than older collagen (Bell et al. 2001), and degradation affects this fraction more readily. Additionally, lipids may remain in bone after collagen decays. Lipids are relatively depleted in $^{13}$C and their differential preservation can cause $\delta^{13}$C ratios from the non-mineral fraction of bone to be misleadingly low (Ambrose 1990). Humic contaminants such as bacteria and fungii can also affect bulk isotope ratios in bone oranic matter. Ultrafiltration or treating with methanol are strategies for removing lipids.
and humic contaminants from bone; and soaking in sodium hydroxide removes some lipids as well as humic contaminants (Ambrose 1990).

Criteria exist for determining the preservation quality of bone collagen. These include overall carbon content in collagen (\%carbon), overall nitrogen content (\%nitrogen), the atomic ratio of carbon to nitrogen (C:N), the percent collagen yield of a sample (\%collagen), and the intact structure of a collagen model after chemical treatment of bone (Ambrose 1990; DeNiro 1985; Garvie-Lok 2001). Acceptable ranges for these parameters reported by Ambrose (1990), DeNiro (1985) and van Klinken (1999) are presented in Table 3.1.

<table>
<thead>
<tr>
<th>Collagen Quality Indicator</th>
<th>Acceptable Range in Bone Collagen*</th>
</tr>
</thead>
<tbody>
<tr>
<td>%Carbon</td>
<td>13-47%</td>
</tr>
<tr>
<td>%Nitrogen</td>
<td>5-17%</td>
</tr>
<tr>
<td>Atomic C:N Ratio</td>
<td>2.9-3.6</td>
</tr>
<tr>
<td>%Collagen</td>
<td>5-28%</td>
</tr>
</tbody>
</table>

*Based on the work of DeNiro (1985), van Klinken (1999), and Ambrose (1990)
processes include alteration of chemical signatures by interaction with surrounding soils (through isotope exchange or recrystallization of carbonates), microbial contamination, and other sources of degradation and disintegration (Ambrose 1990; Nielsen-Mash and Hedges 2000a). Isotopic alteration can also occur during sample preparation. For example, more concentrated solutions of acetic acids used to purify bone mineral encourage recrystallization (Garvie-Lok et al. 2004). Enamel is much denser than bone with fewer crystal surfaces exposed to the depositional environment, and is therefore resistant to diagenesis. Carbon isotope signatures in enamel have been shown to remain reliable indicators of diet for millions of years (Lee-Thorp and van der Merwe 1991).

A number of methods have been developed to identify the effects of diagenesis among inorganic samples including X-ray diffraction, Fourier transform infrared spectroscopy, histological analysis of bone microstructure, mineral content in bone, and oxygen isotope analysis (Ambrose 1990; Garvie-Lok 2001; Garvie-Lok et al. 2004; Nielsen-Mash and Hedges 2000a; Nielsen-Mash and Hedges 2000b; Wright and Schwarcz 1996). One of these, Fourier transform infrared (FTIR) spectroscopy, is discussed in greater detail later in this chapter. If it is not possible to correct diagenetic effects, altered samples can at least be removed from analysis.

3.6 Sources of Stable Isotopes in Bone: The Issue of Collagen versus Apatite

During the 1970s, collagen became a popular part of the tool kit for diet reconstruction from archaeological samples. The utility of apatite for diet reconstruction was less well-known. In 1981, Sullivan and Krueger reported stable carbon isotopes
from bone collagen and apatite of the same bones, including 2 humans and 24 animals with known diets. Although $\delta^{13}C_{ap}$ values were approximately 8‰ higher than $\delta^{13}C_{coll}$ values, the two measurements showed a near perfect correlation ($r=0.99$). Given their nearly identical dietary signals, it was implied that isotopes from carbonate and collagen could be sampled interchangably. The value of this discovery was that whereas collagen degrades, carbonate can be studied even in fossil remains.

The conclusion that collagen and carbonate are interchangable substrates for isotopic paleodiet reconstructions was soon countered. Schoeninger and DeNiro (1982) reported results from a larger sample of human bones which did not show a similarly significant relationship between collagen and apatite isotope values. One of the sampled populations, from the Tehuacán Valley, plotted far to the right of the collagen-apatite regression line. This anomaly was ascribed to diagenetic alteration of apatite samples, suggesting bone apatite is more susceptible to diagenetic processes and less reliable for diet reconstructions.

Since then, sample preparation methods have been developed using dilute acetic acid to successfully remove most contaminants from carbonate samples (Lee-Thorp and van der Merwe 1987). Isotope analysis of the inorganic phase of bone now is accepted as a technique for diet reconstructions, so long as diagenetic alteration is addressed and as much as possible eliminated with acid treatment and cleaning. Part of the reason for the discrepancy between the results of Sullivan and Krueger (1981) and Schoeninger and DeNiro (1982) had to do with sample preparation methods. Schoeninger and DeNiro (1982) employed a soak in 50:50 glacial acetic acid:water whereas Sullivan and Krueger...
(1981) used 1 M acetic acid. Since then, this difference in sample preparation methods has been shown to significantly alter isotope results from the same samples (Lee-Thorp and van der Merwe 1991).

The strong correlation between collagen and carbonate $\delta^{13}C$ ratios observed by Sullivan and Krueger (1981) and the poor correlation observed by Schoeninger and DeNiro (1982) support suggestions that collagen and apatite provide information about different dietary macronutrients (Krueger and Sullivan 1984). Controlled feeding experiments with small rodents demonstrate that collagen primarily reflects dietary protein sources, whereas apatite represents whole diet including protein, lipids, and carbohydrates (Ambrose and Norr 1993; Tieszen and Fagre 1993). In cases where the isotope ratios of protein sources differ from the isotope ratios of energy sources or a wide variety of trophic positions are represented in diet, as with maize-consuming populations of the Tehuacán valley (DeNiro and Epstein 1981), the isotopic signal of energy sources will be underrepresented in collagen at best, but will factor prominently into isotope ratios from carbonate. In other words, “You are not what you eat plus 5‰ when protein and non-protein macronutrients have different isotope ratios” (Ambrose et al. 2003: 220). Rather than a linear correlation, collagen-carbonate data points from the Tehuacán valley formed a scatter that reflected the relative amounts of maize consumption and omnivory of the individuals sampled. Sullivan and Krueger (1981) studied herbivorous animals, which obtain both protein and carbohydrates from vegetal foods, explaining why the collagen and carbonate isotope ratios were related. This discovery that protein is routed
to collagen casts doubt on the reliability of using collagen alone in stable isotope reconstructions of diet when potential food sources are isotopically heterogeneous.

3.7 Collagen vs. Carbonate in Bone: Macronutrient Routing

There are two models accounting for how macronutrients are routed to tissues such as collagen (Krueger and Sullivan 1984). The linear mixing model assumes that all macronutrients contribute equally to the bulk isotopic signal in a consumer’s tissue. The routing model assumes that certain macronutrients are routed to certain tissues, and become over-represented in the bulk isotopic signal of those tissues.

Ratios of $\delta^{13}C$ can be measured in bone collagen (reported as $\delta^{13}C_{\text{coll}}$), bone apatite ($\delta^{13}C_{\text{ap}}$), and tooth enamel. This discussion focuses on collagen and bone apatite carbon values. Experimental evidence from controlled feeding experiments with rodents suggests that isotopes in bone collagen primarily represent a consumer’s protein sources (Ambrose and Norr 1993; Tieszen and Fagre 1993). This is because bone collagen is formed from amino acids, many of which are essential and derive from ingested protein (Schoeller 1999). However, 78% of the carbon in bone derives from non-essential amino acids. Typically, these are also obtained directly from dietary protein, although in protein-deficient diets they may be assembled from other macronutrients (primarily carbohydrates) (Schwarcz 2000). Isotopes in collagen therefore primarily, though not exclusively, represent dietary protein sources. Krueger and Sullivan (1984) emphasize that only 1% protein (dry weight) in diet is needed to maintain net protein growth; according to them, organisms with even a small amount of animal protein in their diet are
capable of obtaining all their amino acids without requiring transamination from carbohydrates.

Carbon is formed in apatite in equilibrium with carbon in the bloodstream, which derives from all three dietary macronutrients (Schwarcz 2000). $\delta^{13}C_{\text{coll}}$ values are lower than $\delta^{13}C_{\text{ap}}$ values of the same animal. Relative enrichment in $\delta^{13}C_{\text{ap}}$ is because $^{13}C$-depleted CO$_2$ from blood is expired in breath CO$_2$, leaving tissues with $\delta^{13}C_{\text{ap}}$ values approximately 12‰ higher than bulk diet (Krueger and Sullivan 1984; Tieszen and Fagre 1993). In their initial study of animal bone, Sullivan and Krueger (1981) reported a consistent offset between of $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ of approximately $+8‰$. Lee-Thorp et al. (1989) report $\Delta^{13}C_{\text{coll}-\text{ap}}$ values of 6.8‰ for herbivores and 4.3‰ for carnivores among South African fauna. Lower $\Delta^{13}C_{\text{coll}-\text{ap}}$ values among carnivores result from the fact that carnivores obtain relatively more dietary energy from lipids, a $^{13}C$-depleted macronutrient, causing their $\delta^{13}C_{\text{ap}}$ values to be relatively depleted (with little effect on $\delta^{13}C_{\text{coll}}$).

The isotope chemistry of bioapatites is not as well understood as that of collagen. Studies report unexplained offsets between diet, collagen, enamel and bone apatite values, cautioning against uncritical acceptance of $\delta^{13}C_{\text{ap}}$ values in paleodietary studies (Koch et al. 1997; Nielsen-Marsh and Hedges 2000a). Apatite is more susceptible to diagenetic processes than collagen, including contamination by sedimentary carbonates, post-mortem recrystallization of apatite, and recrystallization or isotope exchange during sample preparation (Koch et al. 1997). Strategies for alleviating these problems do exist, such as consistent pre-treatment with 0.1 M acetic acid and restricting analyses to well-
preserved bone (Koch et al. 1997; Nielsen-Marsh and Hedges 2000a). When interpreted cautiously, data from bone apatite can serve as a useful compliment to data from collagen.

3.8 Answering Archaeological Questions: $\delta^{13}\text{C}_{\text{coll}}$ or $\delta^{13}\text{C}_{\text{ap}}$?

Often, the appropriateness of the sample medium for dietary reconstruction depends on the archaeologist’s research question. In some cases, information from $\delta^{13}\text{C}_{\text{ap}}$ is critical. An important issue that has been addressed with stable isotope analyses is the spread of maize agriculture throughout the Americas (Schoeninger 2009). Harrison and Katzenberg (2003) demonstrated that dates for maize adoption in Southern Ontario (approximately AD 1000) previously obtained by Schwarcz et al. (1985) and Katzenberg et al. (1995) via $\delta^{13}\text{C}_{\text{coll}}$ may have been inaccurate. Assays of bone apatite from the previously studied populations yielded maize-based $\delta^{13}\text{C}_{\text{ap}}$ enrichment at earlier dates than those obtained with $\delta^{13}\text{C}_{\text{coll}}$. Furthermore, the transition appeared to be more gradual than indicated by $\delta^{13}\text{C}_{\text{coll}}$ data (Katzenberg et al. 1995; Schwarcz et al. 1985). In the earlier studies, $\delta^{13}\text{C}_{\text{coll}}$ had under-represented the C$_4$ signal of maize in samples prior to AD 1000 because it was not a principle source of protein. In this case, the authors were interested in when maize was introduced to Southern Ontario, not whether maize composed a significant portion of the diet, and concluded that $\delta^{13}\text{C}_{\text{coll}}$ alone was not sensitive enough to detect this.

In other cases, the use of $\delta^{13}\text{C}_{\text{coll}}$ by itself is suitable for answering research questions. For example, Larsen et al. (1992) investigated the shifting importance of maize in the diets of people from six populations dating between 1100 BC and AD 1702.
By associating stable carbon isotope data with $\delta^{15}$N ratios, information on dental caries, historical records, environmental and other archaeological data, the authors were able to track alterations in subsistence economy related to maize agriculture and marine resource exploitation. In this case, stable isotope ratios in collagen provided compelling answers to the research questions regarding fluctuating importance of maize after its adoption.

Collagen-apatite spacing values ($\Delta^{13}$C$_{ap-coll}$) can provide useful information on trophic position of an organism when the $\delta^{13}$C values of macronutrients do not differ substantially. Herbivores obtain energy from carbohydrates (with a $\delta^{13}$C of approximately 3‰) whereas carnivores obtain dietary energy primarily from lipids in their prey, which are isotopically depleted compared to the collagen of their prey (approximately 4‰). After accounting for a 7‰ diet-tissue space resulting from the expulsion of $^{12}$C as CO$_2$, the apatite values of herbivores and carnivores are +12‰ and +11‰, respectively, compared to energy diets of +3‰ and +4‰, respectively. The difference between the $\delta^{13}$C$_{coll}$ and $\delta^{13}$C$_{ap}$ values of carnivores is thus smaller than that of herbivores. Omnivores are highly variable in terms of $\Delta^{13}$C$_{ap-coll}$. For example, 72 Bronze Age and Neolithic individuals from the Lake Baikal region in Siberia believed to have consumed broad-spectrum diets exhibit a mean $\Delta^{13}$C$_{ap-coll}$ value of 5.0±1.4‰ (Katzenberg et al. 2009). Somewhat systematic differences in $\Delta^{13}$C$_{ap-coll}$ values of herbivores, omnivores and carnivores have led many researchers to use the spacing as an estimate of trophic position. This is not tenable when stable isotope ratios of macronutrients in the diet vary widely. For example, animals fed monoisotopic diets in controlled feeding experiments exhibit mean $\Delta^{13}$C$_{ap-coll}$ values of between 4‰ and 5‰.
whereas animals fed diets with isotopically different macronutrient components exhibit values ranging from -0.7‰ to 11.3‰ (reviewed by Kellner and Schoeninger 2007).

Predicted $\Delta^{13}C_{ap-coll}$ for a vegetarian population consuming the C$_4$ plant millet will be affected by the fact that $\delta^{13}C_{ap}$ is more sensitive than $\delta^{13}C_{coll}$ to the high $\delta^{13}C$ signal of millet. Millet will increase $\Delta^{13}C_{ap-coll}$ independent of trophic position.

Kellner and Schoeninger (2007) proposed an innovative method of combining collagen and apatite isotope data that is more informative than either $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap}$ used in isolation or $\Delta^{13}C_{ap-coll}$ values. In their model, they demonstrate the clarity with which a regression of $\delta^{13}C_{coll}$ against $\delta^{13}C_{ap}$ from experimental studies can sort stable isotope ratios of consumers into particular spectra of diets. The authors used previously published data from controlled feeding experiments to calculate regression lines of a C$_3$ protein diet, a marine protein diet, and a C$_4$ protein diet with 100% C$_3$ and 100% C$_4$ energy end-points. Because the experimental animals in this study are modern, a correction of 1.5‰ is subtracted from archaeological values for comparison (Marino and McElroy 1991). The experimental data produced regression lines with $R^2$ values of 0.95, 0.90 and 0.85, respectively. When archaeological data are plotted these linear relationships are not as strong, due in part to the confounding digestive physiology of large ruminant animals present in human diet. The model is nevertheless argued to be more accurate than using collagen, apatite, or collagen-apatite spacing relationships alone in reconstructing past diet (Kellner and Schoeninger 2007).

Figure 3.1 shows data from diet research at Giecz, Poland ($11^{th}$-$12^{th}$ c.) superimposed on these regression lines (Reitsema et al. 2010). The location of Giecz data
points indicates a diet of C₃ protein (fish consumption would plot on/near the marine protein line). The location toward the middle of the line indicates a mixture of C₃ and C₄ energy sources (C₃-only energy would plot at the base of the line). The method revealed that $^{13}$C$_{coll}$ enrichment observed among the sample was primarily due to millet consumption, not marine fish consumption. In this context, where multiple sources of $^{13}$C$_{coll}$ enrichment were possible, using δ$^{13}$C$_{coll}$ and δ$^{13}$C$_{ap}$ in conjunction with the regression line model gave the most comprehensive picture of diet.

### 3.9 Studying Bone Diagenesis with Fourier Transform Infrared Spectroscopy

Biological hydroxyapatite is a carbon-bearing mineral in bone. Apatite crystals are small, and consequently have a high surface area to volume ratio. “This gives bone mineral a massive surface area upon which physiological processes can occur” (Pollard et al. 2007: 88), such as adsorption of contaminating carbonates from soil and groundwater.
Another diagenetic process that may alter bone mineral in archaeological samples is the dissolution of the small, thermodynamically unstable apatites and subsequent re-crystallization into larger, more thermodynamically stable crystals (Ostwald ripening). This second diagenetic process is referred to as an increase in crystallinity. During this process, original biogenic $\delta^{13}\text{C}_{\text{ap}}$ signals may be lost. The detection of crystallinity changes can help identify altered stable isotope signatures (Pollard et al. 2007).

As previously reviewed, for many years following the discovery that stable carbon isotope signatures in bone mineral may be used in paleodiet reconstructions, researchers distrusted the technique because of the unknown but presumed high risk of diagenetic alteration of apatite (Schoeninger and DeNiro 1982). Later, sample preparation techniques were developed to minimize the effects of diagenesis (Lee-Thorp et al. 1989), and use of bone mineral in paleodiet and paleoclimate studies became increasingly common. It is still recognized that bone apatite is more susceptible to diagenesis than are enamel or collagen (Koch et al. 1997; Lee-Thorp and van der Merwe 1987; Wright and Schwarcz 1996). Rigorous screening of samples for paleodiet analyses are advocated (Garvie-Lok 2001; Wright and Schwarcz 1996; Yoder and Bartelink 2010).

In the 1990s, anthropologists began to use Fourier transform infrared (FTIR) spectroscopy to identify bone diagenesis based on earlier work by Termine and Posner (1966) and LeGeros et al. (1970) (e.g.: Lee-Thorp and van der Merwe 1991; Shemesh 1990; Weiner and Bar-Yosef 1990). FTIR analysis is based on the principle that the pattern of absorbance of infrared radiation by a sample depends on the bonds of its
molecular constituents. These different bonds absorb infrared radiation at different wavenumbers on the infrared spectrum. Absorbance peaks are smaller or larger depending on the amount of a molecule present. A schematic example of human bone apatite is pictured in Figure 3.2. FTIR peaks that indicate carbonate substitutions in the apatite matrix of bone include 1545, 1450 and 890 cm$^{-1}$ (Type A substitutions of carbonate in the OH$^{-}$ position) and 1465, 1415 and 870 cm$^{-1}$ (Type B substitutions of carbonate in the phosphate position) (Garvie-Lok 2001). Other carbonate peaks represent labile carbonates (Shemesh 1990a). Calcite presents peaks at 713 cm$^{-1}$, 875 cm$^{-1}$ and 1435 cm$^{-1}$ (Nielsen-Marsh and Hedges 2000a). Because peaks will be larger when more powder is analyzed, samples must either be weighed very precisely, or peak heights must be measured as ratios to other peaks in the same sample.

FTIR has been applied to monitor diagenesis of apatites in a limited number of contexts, including fossil hominin bioapatites (Lee-Thorp and van der Merwe 1991),
prehistoric skeletal remains (Katzenberg et al. 2009; Weiner and Bar-Yosef 1990; Wright and Schwarcz 1996) and historic skeletal remains (Garvie-Lok 2001).

As previously mentioned, increased crystallinity in bone is an indicator of diagenetic changes. Crystallinity can be measured in bone with FTIR by measuring peak splitting in the wavenumber region of bioapatites. For the purpose of identifying recrystallization, a “crystallinity index” (CI) is obtained by measuring absorbance peaks at 605 and 565 cm\(^{-1}\) and the lowest point between them, near 590 cm\(^{-1}\) (Termine and Posner 1996). Peak splitting reflects a “combination of the relative sizes of the crystals as well as the extent to which the atoms in the lattice are ordered” (Weiner and Bar-Yosef 1990: 190). Less peak splitting is characteristic of modern bone mineral, indicating small biogenic apatite crystals and less overlap between the peaks. Greater peak splitting reflects a diagenetic increase in crystal size or select dissolution of more soluble, less-ordered crystals (Shemesh 1990) and most likely, a subsequent shift in isotope values.

Modern bone treated with acetic acid to mimic archaeological sample preparation exhibits CI values of between 2.7 and 3.6 (Nielsen-Marsh and Hedges 2000b; Wright and Schwarcz 1996). In archaeological samples, CI is typically higher. Shemesh (1990) advocates for a “cut-off” point of 3.8, above which samples should no longer be considered “pristine”. This is relatively conservative, as de la Cruz Baltazar (2001) reports a range of 2.8 – 4.0 in a well-preserved archaeological sample, and Wright and Schwarcz (1996) report well-preserved values above 4.0. Values above 7.0 have been reported from archaeological bones although these are certainly diagenetically altered (Shemesh 1990b; Weiner and Bar-Yosef 1990).
The overall carbonate content in bone may also be used to identify whether significant diagenetic alteration has occurred. Carbonate content can be measured using FTIR as the ratio of a carbonate and a phosphate peak in the spectrum (C/P ratio). Wright and Schwarcz (1996) advocate using the carbonate peak at 1415 cm\(^{-1}\) in relation to the neighboring phosphate peak at 1035 cm\(^{-1}\) to estimate carbonate content with FTIR because this ratio is strongly correlated with CO\(_3^2\) measured manometrically as gas evolved from bone (Wright and Schwarcz 1996). High carbonate content in a sample can indicate diagenetic inclusion of calcite or high-carbonate recrystallized apatite (Lee-Thorp et al. 1989). Low C/P ratios can indicate recrystallization of biogenic apatite into new, low-carbonate containing apatites.

Acid washing archaeological samples reduces the scatter of C/P ratios within a sample, suggesting successful removal of diagenetic carbonates (Nielsen-Marsh and Hedges 2000b). Modern bones treated experimentally with acetic acid to mimic archaeological bone preparation exhibit C/P values of between 0.10 to 0.24, and well-preserved archaeological materials range between 0.12 and 0.20 (Wright and Schwarcz 1996). Somewhat higher acceptable C/P values of 0.3 to 0.4 are reported by Nielsen-Marsh and Hedges (2000a; 2000b). An acceptable range of C/P values should probably be determined alongside close consideration of other diagenetic indicators within particular sites, and the same is likely true for CI (Garvie-Lok 2001).

A final indicator of diagenesis is presence of a distinct peak at 1096 cm\(^{-1}\). In well-preserved bone, the largest IR peak at 1035 cm\(^{-1}\) forms as a smooth line. A separate peak on the left shoulder forms when fluorine substitutes into the biogenic apatites.
forming francolite (F-apatite) (Wright and Schwarcz 1996). Samples exhibiting this peak often – though not always – exhibit high CI and anomalous δ18O values. Well-preserved and modern bones exhibit only a slight shoulder at 1096 cm\(^{-1}\).

Wright and Schwarcz (1996) consider δ\(^{13}\)C\(_{ap}\) signals to be relatively unaffected by diagenesis when CI is no greater than 4.4 and C/P is between 0.125 and 0.200, and when a separate peak at 1096 cm\(^{-1}\) is absent. These criteria are used to screen samples in the present study, although an effort will be made to establish site-specific “acceptable” ranges by considering CI and C/P values alongside other indicators of diagenesis according to the recommendation of Garvie-Lok (2001).
Chapter 4: Materials and Methods

In this chapter, I describe methods used for collagen and carbonate preparation and analysis (section 4.1) and outline sample preparation protocol (sections 4.2 and 4.3). In section 4.4 I describe analyses of apatite and KBr “pellets” for Fourier transform infrared (FTIR) spectroscopy. FTIR results are presented in Chapter 5, along with results of duplicate analyses.

4.1 Materials

Five skeletal samples from 3 sites in North-Central Poland’s Vistula River valley were selected for this analysis (Fig. 4.1). The rationale for choosing this sample was based on four factors. First, the sites are located in close proximity to one another, meaning that regional variations in diet are controlled. Second, together they represent a broad chronological time period that can nevertheless be sub-divided into distinct phases of shorter duration. Third, the sites are located within the original borders of Poland, yet in a “conflict zone” where tensions with neighboring pagans and Germanic influences were felt. It is important to note that between the 13th and 15th c., this part of North-Central Poland (and Prussia and Pomerania) were under the control of the Teutonic Order, and experienced strong Germanic influences. Finally, these collections have been
fully excavated and are well-studied, such that biological profiles and details on burial contexts are available for all individuals.

In addition to the main sample of five sites, four individual skeletons were sampled from the Neolithic and Iron Ages. The first Neolithic skeleton (Neo-1) dates to the Globular Amphora culture (approximately 4,100 years ago) and is from Kowal in the Kujawia region of Central Poland. The other Neolithic skeleton (Neo-2) is of unknown age but likely represents the Corded Ware Pottery culture which occupied much of Northern Europe between approximately 5200 and 4300 years ago (Mallory 1997). It comes from Niedrzwica in Northeast Poland and is thought to represent a more pastoral
Table 4.1: Number of Individuals Investigated From Each Site

<table>
<thead>
<tr>
<th>Site</th>
<th>Time</th>
<th># Male</th>
<th># Male</th>
<th># Female</th>
<th># Female</th>
<th>Total # individuals investigated per site:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>coll.</td>
<td>ap.</td>
<td>coll.</td>
<td>ap.</td>
<td></td>
</tr>
<tr>
<td>(Neolithic)</td>
<td>3,500 BC</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2 / 2</td>
</tr>
<tr>
<td>(Iron Age)</td>
<td>700 BC</td>
<td>2¹</td>
<td>2*</td>
<td>0*</td>
<td>0*</td>
<td>2 / 2</td>
</tr>
<tr>
<td>Rogowo</td>
<td>2nd c. AD</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>14</td>
<td>30 / 29</td>
</tr>
<tr>
<td>Kaldis 4</td>
<td>11th c. AD</td>
<td>19²</td>
<td>15</td>
<td>15</td>
<td>14</td>
<td>37 / 29</td>
</tr>
<tr>
<td>Gruzno 1</td>
<td>12th c. AD</td>
<td>17³</td>
<td>15</td>
<td>17</td>
<td>14</td>
<td>34 / 29</td>
</tr>
<tr>
<td>Kaldus 1</td>
<td>12th-13th c. AD</td>
<td>15</td>
<td>15</td>
<td>15⁴</td>
<td>15</td>
<td>30 / 30</td>
</tr>
<tr>
<td>Gruzno 2</td>
<td>13th-14th c. AD</td>
<td>17</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>32 / 30</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td>86</td>
<td>78</td>
<td>78</td>
<td>73</td>
<td>coll=167; ap=151</td>
</tr>
</tbody>
</table>

¹ Of two Iron Age individuals, one was male and one of undetermined sex.
² Two individuals from Kaldus site 4 were of undetermined sex but were probably male and have been grouped with males for analysis.
³ Three individuals from Gruzno site 1 were of undetermined sex, most likely male, and have been grouped with males for analysis.
⁴ One individual from Kaldus site 1 was of undetermined sex, most likely female, and has been grouped with females for analysis.

Details of the sample are presented in Table 4.1. Individuals sampled for collagen are in bold; from these, individuals from whom carbonate was also sampled are in italics. The cemetery sites follow each other in a chronological sequence that spans the period between AD 100 and 1400. An effort was made to collect at least 15 males and 15 females from each site. Age was controlled for as much as possible by only selecting population, as was typical in Northeast Poland. One of the Iron Age samples is from Gziń, Central Poland. It is from the Lusatian culture, found in Poland during the Hallstatt D period and dating to approximately the 8th-6th c. BC. The other Iron Age sample is from Bożejewice, also in Central Poland, and of unknown antiquity.
adult individuals for analysis, and maximizing the number of individuals who died between the ages of 25 and 55 in particular. Individuals representing all burial styles were intentionally included in the sample. In total, collagen of 164 humans were chemically treated and analyzed for this study. Of these, carbonate was assayed from 151 individuals. Bone collagen of 16 fish and 16 animals were also analyzed. Of the animals, carbonate of 13 samples was also assayed.

An outlier sample which predates socioeconomic and religious changes associated with the medieval period is from Rogowo, and dates to the Roman period (2nd c. AD). Rogowo is located approximately 10 km North-East of Toruń. An early medieval population is from Kalduś (site 4) which dates to the 11th c. Another early medieval population is from Gruczno (site 1) and dates to the 12th century. Gruczno and Kalduś are located approximately 15 km apart from each other on opposite sides of the Vistula River, and approximately 45 km North-West of Rogowo. Two later medieval populations are from Kalduś (site 1) which dates to the 12th through 13th c., and Gruczno (site 2) which dates to the 13th through 14th c.

4.1.1 Rogowo

The Roman-era cemetery at Rogowo was excavated in 1999 and 2000. The cemetery includes 137 inhumation and 151 cremation burials (Fig. 4.2). Birritual cemeteries such as this are characteristic of the Wielbark culture, which occupied Poland during the 2nd and 3rd centuries AD. It is possible that Wielbark populations were one of several referred to by the Romans as “Goths” (Heather 1996). It is also possible that the
Figure 4.2: Map of Rogowo Cemetery

[Image courtesy of Dr. Tomasz Kozłowski, Nicolaus Copernicus University]
Figure 4.3: Burial from Rogowo

Wielbark are early Slavs from which modern Slavs are descended (for discussion, see Piontek 2006).

Rogowo dates to the 2nd c. AD, and is associated with a nearby settlement that covers approximately 6 ha (Krenz-Niedbała and Kozłowski nd). Skeletons were interred in a flexed position, many with copper-alloy jewelry that has left green stains on skeletal elements (Figure 4.3). One of Eastern Europe’s most important trade routes, the Amber Road, connected Rogowo with the Baltic Sea to the North, and the Roman Empire to the south (Buko 2008). Interregional trade and iron smelting, in addition to animal husbandry and agriculture, shaped the economy of this Wielbark population (Piontek et al. 2006). Rogowo was chosen to be an outlier sample predating socioeconomic and religious changes associated with the medieval period.
4.1.2 *Kaldus*

Two samples are from Kałdus, a medieval settlement located near modern-day Chełmno on the East bank of the Vistula River (Fig 4.4). Kałdus has been under systematic excavation since 1997 although previous excavations earlier in the century unearthed approximately 500 skeletons. Population estimates for Kałdus range from 100 to 500 inhabitants, and archaeologists believe that during its earlier phase, Kałdus was an economic hub rather than a primarily agricultural center (Chudziak 1997).

Kałdus comprises four sites: a stronghold (site 3), a settlement (site 2), and two cemeteries dating to different time periods (sites 1 and 4) (Fig. 4.5) (Chudziak 1997; Chudziak 2010). The stronghold is located atop Mount St. Lawrence, an artificially
augmented natural mound. Near the turn of the 11th c. construction of a Romanesque basilica began, but was interrupted by the pagan revolts of the 1030s. Skeletal materials have been excavated from the medieval sites 1, 2 and 4 located near the foot of the hill.
(Chudziak 1997; Chudziak 2010). Sites 1 and 4 are the focus of this study. The Kałdus site complex is located just east of Lake Starogrodzkie, an oxbow lake east of the Vistula River. Lake Starogrodzkie is shallow with a maximum depth today of 5.2 meters that may have been warmer in the past (Krzymińska 2004). Lake Starogrodzkie existed at the time of medieval occupation (cf. Makowiecki 2010 p. 29), and the entire region is characterized by shallow oxbow lakes and inlets associated with the Vistula River. The Kałdus complex is across the valley of the Vistula River from Gruczno, the other medieval settlement area examined in this study.

Kałdus site 4 is a cemetery that was in use primarily during the 11th c., a period immediately post-dating state formation and Christianization in Poland. Since 1997, approximately 130 inhumation graves were excavated from Kałdus site 4. The majority of burials were oriented East-West, a defining characteristic of Christian mortuary customs. Ten of the graves exhibit pagan or “vampire” elements, including unusual body positioning (Fig. 4.6), dismemberment, and/or large stones atop the skeleton, presumably intended to pin down the corpse. Also at Kałdus 4, four graves exhibit Scandinavian-style burial elements. For example, skeletons 13A (male) and 13B (female) were buried in a double grave in a wooden chamber, and with bowls of bronze and wood (respectively) placed at their feet (Figure 4.7). Skeleton 60 (male) was also buried with a bronze bowl. Non-local origins of these individuals is suspected on the basis of these Scandinavian elements (Janowski and Kurasiński 2003; Linderholm et al. 2008). Approximately half the burials at site 4 contained grave goods.
Figure 4.6: Example of a Flexed Burial, Kalduś

[Image courtesy of Dr. Tomasz Kozłowski, Nicolaus Copernicus University]

Figure 4.7: Kalduś site 4, Schematic of Double Burials 13A and 13B

[Image courtesy of Dr. Tomasz Kozłowski, Nicolaus Copernicus University]
Kaldu site 1 is a cemetery used by the Kaldu settlement in the 12th-13th centuries. Skeletons sampled from Kaldu site 1 are indicated in Figure 4.8. During the 12th-13th c., the economic importance of Kaldu declined. Paleopathological analyses conducted by Tomasz Kozlowski with the Nicolaus Copernicus University in Toruń, Poland reveal that during this second phase, degenerative changes of the knee and hip are most common, attesting to a more strenuous, probably subsistence-based lifestyle. Frequency of dental caries is also higher in the later phase which further suggests heavier reliance on the carbohydrate-rich produce of an agriculture-based economy. Porotic hyperostosis resulting from infection or nutritional deficiencies are also higher during the second phase at Kaldu among individuals who died before the age of 20. However, prevalence of linear enamel hypoplasias (LEH) is greater during the earlier phase (T. Kozłowski, pers. comm.). LEH are bands on the apical portion of teeth that result from temporary interruption of tooth formation due to severe malnutrition during childhood (Larsen 1997).

The Teutonic Order was invited to Poland in the early 13th c. and established their center in the “Chelmno Lands,” which includes both Kaldu and Gruczno (Knoll 2008; Piskorski 2008). Remains of a Teutonic castle are located near the Kaldu settlement complex; it was constructed from stones used for the (never completed) basilica on Mount St. Lawrence (T. Kozłowski, pers. comm.). Individuals buried in the Kaldu site 1 cemetery would have experienced the Christianizing, Germanic influence of the Teutonic Order.
Figure 4.8: Map of Graves From Kaldus Site 1

[Modified from Mons Sancti Laurenti vol. 3]

*Not highlighted: Graves 57, 39, 45, 93-M and 13-F (represented as lines and not shapes).

Recently, coins, radiocarbon dates and other grave goods were used to assign more precise, albeit relative, chronological phases within the 11th c. to the comingled burials at Kaldus sites 4 and 1 (T. Kozlowski, pers. comm.). Phase 1a represents the earliest time period, and phase 3 represents the latest. In several cases, phases from Kaldus site 4 overlap those of Kaldus site 1. All burials from Kaldus site 1 date to phase 2b-3, and approximately 25% of the burials from Kaldus site 4 do as well.

Over 400 skeletons were excavated from Kaldus site 1 since 1997. Unlike at Kaldus site 4, all of the skeletal remains at Kaldus site 1 are located on an East-West axis, suggesting a more widespread adherence to Christian burial customs in this later period. However, like the earlier cemetery, approximately half of the burials at Kaldus site 1
contained grave goods. Kalduś sites 1 and 4 were dated using pottery, coins, and radiocarbon techniques.

4.1.3 Gruczno

Two samples are from Gruczno, a rural medieval village located opposite Kalduś on the West bank of the Vistula River (today, the Vistula is patchier) (Fig. 4.4). The village is located near a settlement complex comprising a stronghold, a surrounding non-fortified settlement, and two cemeteries (Fig. 4.9). Gruczno was first excavated between 1869 and 1899, and again between 1964 and 1973 by the Archaeology Museum in Grudziądz and the Department of Anthropology at Nicolaus Copernicus University in Toruń. Gruczno sites 1 and 2 were dated with pottery and coins found in the cemetery.

The earliest settlement at Gruczno dates to the 7th-8th c., and in the 9th-10th c. a stronghold was constructed at the site (Bojarski 1995). During the 12th c. Gruczno was an agricultural village, but by the 13th-14th c. the settlement had grown in economic importance. This shift is probably linked to a concomitant decline at Kalduś. Health at Gruczno may have been worse than at other contemporary medieval Polish sites, as assessed with by measuring prevalence of cribra orbitalia in subadults (Piontek and Kozłowski 2002).

Gruczno site 1 is a 12th c. cemetery located within the stronghold from which 489 skeletons were recovered (Fig. 4.10) (Piontek and Kozłowski 2002). Gruczno site 2 is a 13th-14th c. cemetery located outside the stronghold, in the non-fortified settlement.
Figure 4.9: Gruczno Settlement Complex

Figure 4.10: Gruczno site 1 Cemetery, Sampled Skeletons Highlighted


[Image courtesy of T. Kozłowski, Nicolaus Copernicus University, Poland]
Figure 4.11: Gruczno Site 2 Cemetery: Plan 1, Sampled Skeletons Highlighted

[Image courtesy of T. Kozłowski, Nicolaus Copernicus University, Poland]
Figure 4.12: Gruczno Site 2 Cemetery: Plan 2, Sampled Skeletons Highlighted

[Image courtesy of T. Kozłowski, Nicolaus Copernicus University, Poland]
Figure 4.13: Gruczno Site 2 Cemetery: Plan 3, Sampled Skeletons Highlighted

[Image courtesy of T. Kozłowski, Nicolaus Copernicus University, Poland]
(Piontek and Kozłowski 2002). Of the four medieval sites studied here, Gruczno site 2 most closely resembles a true medieval village in terms of size and socioeconomic function (T. Kozłowski, pers. comm.). From Gruczno site 2 1297 skeletons were recovered. In both cemeteries at Gruczno, bodies are oriented on an East-West axis (Figs. 4.11, 4.12 and 4.13). Whereas the earlier cemetery at Gruczno site 1 contains a small number of grave goods, Gruczno site 2 contains none, possibly a reflection of Christianity’s impact on burial customs through time.

4.2 Collagen Preparation

A modified Longin method was used to prepare collagen samples. This method has been shown to reduce or eliminate contaminants, safeguard against sample degradation and loss, and allows comparison between many different isotope studies because it is widely used (Ambrose 1990).

4.2.1 Pre-processing

Loose dirt was scraped from samples using a probe. Initially, no further attempt was made to clean bone (e.g.: ultrasonically or by mechanical filing). Once it was decided to prepare carbonate samples in addition to collagen samples, a new pre-processing system was employed in which bone was first ultrasonically cleaned, dried, and then mechanically filed to remove bone surfaces and any adhering cancellous bone. Thus, approximately half the samples were prepared without cleaning and contain varying amounts of cancellous bone.
Small pieces of bone were ground by hand in a mortar and pestle. A marble mortar was used. After several months of use, small chips in the mortar and pestle were noted in the sample. After this a steel mortar and pestle were used in order to avoid contamination of the sample with fragments of marble. FTIR analysis was used to investigate whether marble may contaminate apatite samples.

Ground bone was passed through a 1 mm sieve (tea strainer), and then again through a 0.5 mm sieve. The fraction trapped between the sieves was used for collagen preparation, and an attempt was made to maximize the 0.75 mm fraction. The bone powder that passed through both sieves was reserved in 2 dram glass vials for carbonate preparation. For approximately half of the samples, the carbonate fraction was ground using a marble mortar and pestle. The remaining samples were ground with a steel mortar and pestle.

4.2.2 Chemical treatment

The collagen (~0.75 mm) fraction of bone was prepared according to Ambrose (1990) and Ambrose et al. (1997). Two slightly different sample preparation methods were employed. Of the total 199 samples prepared (including duplicates), 116 were prepared using Method 1 and 83 were prepared using Method 2.

There were three primary differences between Methods 1 and 2: type of glassware used during preparation, the number of times samples were manually transferred between glassware, and demineralization time. Both methods are based on Ambrose (1990) and Ambrose et al. (1997) and involve grinding bone to a coarse powder, demineralizing over
several days in a hydrochloric acid solution, removing organic contaminants using sodium hydroxide, and dissolving collagen in hot, weakly acidic solutions. Differences between methods are discussed in greater detail in each section below. Duplicates of five samples (K4-60-M, K4-75-F, K1-21-F, K4-243-F and K4-364-M) were prepared and analyzed in order to assess error introduced by using different methods and are discussed in Chapter 5.

4.2.3  *Collagen Preparation Method 1*

Preparation of collagen samples using Method 1 commenced in Spring 2009 using materials from the Human Biology Laboratory with The Ohio State University’s Department of Anthropology.

4.2.3.i  *Demineralization*

Approximately 0.20 – 0.70 g of ground bone was placed in 100 mL beakers. Fifty mL of 0.2 M HCl was introduced to the beakers and a loose wad of glass wool placed onto the surface of the solution. Beakers were covered with tin foil. Beginning 24 hours after initial addition of acid, HCl solutions were replaced twice daily by pipetting acid waste out using the glass wool in each beaker as a sieve, and pouring another 50 mL of acid into the beakers. This continued for 5 – 10 days, until bone particles became translucent. This process dissolves and removes the mineral component of bone. Collagen is not unsusceptible to attack by the acid solution, however. For this reason, a
0.2 M solution was preferred over a more concentrated 1.0 M solution which is sometimes used in stable isotope research (e.g.: Ambrose 1990).

At this point in demineralization when bone particles were mostly translucent, samples and glass wool were transferred to glass frit filter funnels (without stopcocks) and flushed to neutrality with at least 250 mL of distilled, demineralized water. After rinsing and washing the original 100 mL beakers, samples and glass wool were returned to the beakers.

4.2.3.ii Removal of organic contaminants

50 mL of 0.125 M NaOH were added to beakers, covered with tin foil and left overnight at room temperature. This step removes secondarily deposited organic contaminants (such as fungii and bacteria) and some lipids (Ambrose 1990). After 20 hours, samples were again transferred to the filter funnels and rinsed with at least 250 mL of distilled demineralized water.

4.2.3.iii Solubilization of collagen particles

Once rinsed, samples and glass wool were transferred into pre-labeled 50 mL centrifuge tubes to which 50 mL of $10^{-3}$ M HCl were added. Centrifuge tubes were placed in a floating rack inside a water bath preheated to 90°C in order to solubilize (dissolve) the remaining collagen particles. Samples were left in the bath for at least 10 hours and were occasionally shaken vigorously to help break up the collagen particles. This breaking down of tightly wound collagen tendrils separates any remaining
contaminants from the sample. After the first 4-6 hours, 1 µL of 1 M HCl were added to maintain a pH of 3, which helps prevent any remaining organic contaminants from dissolving into and contaminating the collagen “broth” (Chisholm 1989). During the 10-hour period of solubilization, centrifuge tubes were uncovered for at least 4 hours to allow sample to condense via evaporation.

If bone particles were mostly dissolved after 10 hours, the tubes were removed from the water bath. If many visible particles remained after 10 hours, an additional 1 µL of 1 M HCl was added to tubes to maintain a pH of ~3, and heating was allowed to continue for up to 5 more hours. This usually increased the amount of sample that dissolved. In some cases samples dissolved entirely; in others, varying amounts of particles remained intact.

After solubilization, samples were transferred to and drawn through the glass frit filter funnels into clean 250 mL Erlenmeyer sidearm flasks. The filtrate was retained, and the glass wool and any remaining residues were discarded. Centrifuge tubes were cleaned, and the sample returned to them to condense further in the 90°C water bath (usually an additional 5 – 10 hours).

Once samples were condensed to approximately 3 mL, they were transferred through plastic funnels into labeled 2-dram glass vials with screw caps, and frozen. To permit a later comparison of weight-percent lost during sample preparation (i.e., the amount of bone that was mineral vs. the amount that was collagen prior to chemical treatment), most of the empty vials were pre-weighed. Not all vials were pre-weighed due to problems with the electronic scale at several points in the data collection period.
Frozen samples were taken to be lyophilized at the Department of Food Sciences at The Ohio State University. If samples thawed during transit, they were re-frozen on arrival using liquid nitrogen. After 24 hours of lyophilization samples were usually dry and were brought back to the Department of Anthropology to be weighed. The collagen content (\( \% \text{coll} \)) of the initial bone powder was calculated according to the following equation:

\[
\% \text{coll} = \frac{W_{t \text{sample}} - W_{t \text{vial}}}{W_{t \text{powder}}}
\]

Equation 4.1

where \( W_{t \text{sample}} \) is the weight of the freeze dried collagen inside the glass vial, \( W_{t \text{vial}} \) is the pre-recorded weight of the labeled vial before introducing the collagen broth, and \( W_{t \text{powder}} \) is the initial weight of the ground bone sample. Collagen content in bone is one of several accepted indicators of bone preservation and collagen quality in stable isotope studies, discussed in Chapter 5.

The final preparation of collagen samples involved powdering the dried, weighed collagen by hand in an agate mortar and pestle. This process homogenizes the sample, ensuring little or no sampling bias when a very small fraction of the overall sample is ultimately weighed out for mass spectrometry. Usually, the purified collagen remaining after preparation weighed approximately 20 to 80 milligrams. Only 0.6 to 0.7 milligrams (or roughly one one-hundredth of the powder) are actually needed for analysis.
4.2.4 Collagen Preparation Method 2

In March 2010 glass frit filter funnels fitted with stopcocks were obtained and replaced the other glassware and containers used in Method 1. Stopcocks in the filter funnels were an important addition that allowed the samples and various liquid chemical solutions to be suspended in a single piece of glassware – the filter funnel – throughout the entire preparation process. This obviated the needs to (1) replace acids by pipetting during acid replacements as part of demineralization, (2) transfer the samples between the beakers and the filter funnels for rinsing between processing steps, and (3) transfer the sample to the 50 mL centrifuge tubes for heating; solubilization could now be accomplished by placing the entire funnel apparatus into the oven overnight. A significant benefit of using Method 2 was a reduction in sample loss throughout preparation. The sample never had to be transferred except into 2 dram glass vials at the end. Because no fundamental change was occurring in the sample prep (chemicals and their concentrations remained the same), the benefits of using Method 2 were determined to outweigh the costs of switching methods two-thirds of the way into the study. Method 2 is summarized below.

4.2.4.i Demineralization

Ten 60 mL filter funnels fitted with coarse glass frits and bearing stopcocks on their stems were coupled to 250 mL sidearm flasks by way of a rubber stopper with a hole bored in it (Fig. 4.14; adapted from Ambrose 1990). Bone powders and a loose wad of glass wool were placed into 60 mL glass frit filter funnels (coarse porosity). With
stopcocks closed, 50 mL of 0.2 M HCl were added, and the funnels covered with foil. Samples were thus suspended in the acid solutions until the stopcocks were turned. Beginning the following day, acid was drained and replaced twice daily by turning the stopcock to drain. This continued for approximately 4 days (~7 replacements) or until bone particles were mostly translucent. Samples were flushed in the funnels with 250 mL of distilled, demineralized water.

4.2.4.ii Removal of organic contaminants

50 mL of 0.125 NaOH were added to funnels and samples were allowed to soak for 20 hours. After soaking, samples were again rinsed with 250 mL distilled, demineralized water. Care was taken to rinse the rim of the filter funnels as well.
4.2.4.iii Solubilization

Filter funnels were removed from the sidearm flasks and coupled to new, clean flasks. 50 mL of $10^{-3}$ M HCl were added to the funnels, and the apparatuses were placed into a 90°C oven overnight. After approximately 5 hours of heating, solutions were stirred and 1 μL of 1.0 M HCl was added to maintain a pH of 3. The next day, samples were drawn through the frit by opening the stopcocks and carefully applying a vacuum to the sidearm. A few squirts of $10^{-3}$ M HCl were used to purge the glass wool and rinse the sides of the funnel of any adhering collagen “broth”. Flasks were returned to the oven to condense to approximately 3 mL, a process that typically took 4 – 6 hours, and were then transferred to 2 dram glass vials and frozen. Lyophilization, homogenization and analysis of samples were identical in Methods 1 and 2.

4.2.5 Collagen Analysis

Approximately 600 – 700 μg of purified collagen powder were weighed into tin capsules in the Stable Isotope Biogeochemistry Laboratory at the Department of Earth Sciences at The Ohio State University. Approximately 10% of samples were weighed and analyzed in duplicate in order to assess intra-sample variability and mechanical precision of the elemental analyzer and mass spectrometer. Collagen samples were analyzed on a Costech Elemental Analyzer coupled to a Finnigan Delta IV Plus stable isotope ratio mass spectrometer under continuous flow using a CONFLO III interface in the Stable Isotope Biogeochemistry Laboratory at The Ohio State University. Stable carbon ($\delta^{13}$C = permil deviation of the ratio of $^{13}$C:$^{12}$C relative to the Vienna Peedee
Belemnite Limestone standard) and stable nitrogen ($\delta^{15}N = \text{permil deviation of} ^{15}N: ^{14}N \text{ relative to AIR}$) measurements were made where repeated measurements of the USGS24 and IAEAN1 standards were $\pm 0.06\%$ for $\delta^{13}C$ and $\pm 0.17\%$ for $\delta^{15}N$.

### 4.3 Carbonate Preparation and Analysis

Apatite was extracted according to Garvie-Lok et al. (2004). A fraction of bone weighing $\sim 0.25 \text{ g}$ was reserved from the original bone for carbonate preparation. In approximately half the cases, pre-processing steps included washing and filing the outer surface of bone chunks. Bone remaining after collagen analysis was ground in a mortar to a fine powder ($<0.25 \text{ mm}$) and weighed. Initially, a marble mortar and pestle were used. After particles of marble were observed in the mortar, a steel mortar and pestle were used to eliminate any inorganic contaminants. FTIR analysis of the marble and the samples they may have contaminated demonstrates that carbonate purification steps sufficiently removed any contaminating particles from the final carbonate sample.

To remove the organic fraction of bone (i.e., bone collagen) for this component of the analysis, bone powder was soaked for 48 hours in 10 mL 2% NaOCl solution, replacing solutions every 12 hours with centrifugation. Deproteinated powders were centrifuged and rinsed two times using distilled, deionized water. After rinsing, samples were dried in a 70-90°C oven for at least 12 hours. Dried samples were tapped onto weigh papers and weighed to the nearest 0.01 g. This weight was compared to initial bone powder weight in order to quantify the percent of bone that was lost during deproteinization; i.e., the percent of bone that was collagen. This measurement was
compared to the collagen content of modern bone, and to ancient bone from other studies in order to characterize bone preservation. Following demineralization of bone, a portion of approximately 30% of the samples was reserved in glass vials for FTIR analysis to compare acetic-treated and non-acetic-treated samples.

As discussed in Chapter 3, biogenic apatite crystals are small and have large surface area to mass ratio that encourages adsorption of diagenetic carbonates in the burial environment. The small crystals are unstable and tend to recrystallize to larger, more carbonated crystals during deposition. Acetic acid can be used to remove diagenetic apatites which are more highly carbonated and thus more soluble in acid than biogenic apatites, which contain relatively little carbonate. Although some of the biogenic carbonate may be lost through acetic acid leaching, it withstands the attack whereas the diagenetic carbonates are flushed away. Acetic acid has, however, been shown to encourage crystallization on apatite crystal surfaces during acetic acid treatment when the acid solution used is more concentrated (1.0 M) or when soak-times are prolonged (Garvie-Lok et al. 2004). In this study, diagenetic carbonates were removed by soaking deproteinated powders in 50 mL 0.1 M acetic acid for four hours. This concentration has been shown to minimize sample loss and recrystallization during sample preparation (Garvie-Lok et al. 2004; Koch et al. 1997; Nielsen-Marsh and Hedges 2000b). Halfway through acid treatment, bone powder in solution was exposed to vacuum to ensure thorough interaction between sample and acid. A FTIR comparison of acetic-treated and non-acetic-treated samples is discussed in Chapter 5.
Following treatment with acetic acid, samples were rinsed three times by centrifugation and dried in a 70-90 degree oven for at least 12 hours. Approximately 10% of these samples were weighed a second time in order to quantify the amount of bone lost during acid leaching. Dried, purified carbonate samples were homogenized with an agate mortar and pestle and stored in 2 dram glass vials in a dry box.

A 1.0 – 1.2 mg subsample was analyzed for $\delta^{18}O$ ($\delta^{18}O = \text{permil deviation of } ^{18}O: ^{16}O \text{ relative to Vienna Peedee Belemnite Limestone standard (VPDB)}$) and $\delta^{13}C$ ($\delta^{13}C = \text{permil deviation of } ^{13}C: ^{12}C \text{ relative to VPDB}$) using an automated Carbonate Kiel device coupled to a Finnigan Delta IV Plus stable isotope ratio mass spectrometer in Andréea Grottoli’s Stable Isotope Biogeochemistry Laboratory at The Ohio State University. Samples were acidified under vacuum with 100% ortho-phosphoric acid, the resulting CO$_2$ cryogenically purified, and delivered to the mass spectrometer. Approximately 5% of all samples were run in duplicate. The mean standard deviation of all analytical duplicates was 0.05‰ for $\delta^{13}C$ and 0.17‰ for $\delta^{18}O$. The standard deviation of repeated measurements of limestone internal standard (NBS-19) for $\delta^{13}C$ was ± 0.03‰ (values will be reported to the nearest 0.01‰ accordingly), and of a biogenic calcite standard (sclerosponge skeleton) for $\delta^{18}O$ was ± 0.06‰.

4.4 Preparation of KBr Pellets for FTIR Analysis

Subsamples of bone apatite treated for analysis of carbonate were analyzed using Fourier transform infrared spectroscopy to characterize the carbonate composition of apatite. FTIR-grade potassium bromide (KBr) crystals weighing 0.3 ±0.05 g were
weighed into plastic vials. Approximately 1.5 – 2.0 mg of purified, homogenized apatite was added to the vials and mixed in a shaker mill for 30 seconds. A pure sample of 0.3g KBr was also weighed to serve as a background baseline for analyses.

Sample and KBr mixtures were compressed into thin transparent discs using a die and a Carver lab press under 20,000 lb of pressure for two minutes. KBr “pellets” were scanned 16 times between 4000 and 400 cm\(^{-1}\) at a resolution of 4 cm\(^{-1}\) using a Perkin Elmer IR 16PC FTIR spectrometer housed at The Ohio State University’s Department of Chemistry (Fig. 4.15). Each day, a separate KBr baseline pellet was prepared and scanned initially to provide a baseline which was subtracted automatically from each sample scan by the computer using Spectra® software. Spectrum heights were measured at 565, 590, 605, 1035 and 1415 cm\(^{-1}\) (see Figure 3.2).

Crystallinity indices (FTIR CI) were calculated using the following equation:

\[
FTIR CI = \frac{565_{ht} + 605_{ht}}{590_{ht}}
\]

Equation 4.2

Carbonate-phosphate ratios (FTIR C/P), a measurement of overall carbonate content in bone, were calculated for each sample using the following equation:

\[
FTIR C/P = \frac{1415_{ht}}{1035_{ht}}
\]

Equation 4.3
For 9 samples, both an acetic-treated and a non-acetic-treated subsample were analyzed to compare the effects of acid leaching during sample preparation.
Chapter 5: Diagenesis of Collagen and Carbonate

5.1 Collagen Quality

In this section I summarize results of collagen quality analyses. Complete data sets are presented in Appendix I. Criteria for good preservation are presented in Table 3.1. Collagen preservation is reviewed for each time period and, where applicable, the rationale for discarding samples on the basis of poor preservation is given. Isotope data are presented for diet reconstruction in Chapter 6, but are used here in comparison with collagen quality indicators to identify isotopically altered samples. Correlations between $\delta^{13}$C and $\delta^{15}$N and any of these indicators suggest poor collagen quality is affecting isotope values and signatures may be of non-biogenic origins. In Figures 5.1 through 5.4 collagen quality indicators from all analyzed samples are displayed with $R^2$ values. These early figures may be compared to Figures 5.37 through 5.40, which show the reduced sample after removing several bones due to suspected diagenetic alteration along with new $R^2$ values.

Criteria used in this study include atomic C:N ratios (C:N), percent carbon (%C) and percent nitrogen (%N) from the purified collagen sample, and collagen yields (%coll) from the overall bone sample. These criteria are based on previously reported studies of archaeological and modern bones (Ambrose 1990; DeNiro 1985; Garvie-Lok 2001; van Klinken 1999). To summarize these criteria, samples with a C:N ratio outside the 2.9-3.6
range, a %N value of below 5% or a %C value of below 13% are scrutinized for
diagenetic alteration. In general, collagen yield (%coll) was not a reliable indicator of
collagen quality. %coll was measured by weighing a freeze-dried collagen sample and
comparing it to the initial total bone weight. In some cases, the post-freeze-dried weight
of a sample was less than the tare of the scale. There are also opportunities for small
sample losses during chemical preparation and freeze drying that may appear
disproportionately large when starting with small amounts of powder (Dufour et al.
1999): loss of a fraction of bone with an initial weight of 0.15 g will affect %coll more
than loss of sample with an initial weight of 0.50 g. Although the %coll data are
mentioned here and reported in Appendix I, no samples were ruled out based on %coll.

There was little agreement amongst collagen quality indicators: for example,
bones with unacceptable C:N ratios generally produced acceptable collagen yields.
Samples which fall outside acceptable ranges for a collagen quality indicator are not
clearly associated with anomalous isotope values, or with other evidence of poor collagen
preservation. Samples with low %C and %N values, but acceptable C:N values, may
contain lingering hydroxyapatite, or salts, which are produced during sample preparation,
especially when rinsing between HCl and NaOH was incomplete (Ambrose 1990). When
samples fall outside acceptable ranges for %C, %N and C:N, it suggests: (1) selective
dissolution of particular amino acids within the overall collagen of bone, different amino
acids having different isotope signatures (Hare and Estep 1982) and C and N content
(Ambrose 1993), (2) presence of other contaminating substances containing C or N, such
as carbon-rich decaying plant material (Katzenberg 1989) or lipids (Vogel 1978), or (3)
significant amounts of non-collagenous proteins, which exist to varying degrees in the final product of collagen extraction. Previous research shows that samples within the %C, %N and C:N ranges exhibit stable isotope ratios expected for their archaeological and ecological contexts (e.g.: Ambrose 1990; DeNiro 1985). Within the C:N range, a sample with a C:N of 3.6 differs from a sample with a C:N of 2.9 in that it contains more or less of a particular amino acid by chance or has been affected by a difference in sample preparation (i.e.: humic substances were more or less completely removed).

In general, collagen was well-preserved. Among all human samples %N ranged from 3.5% to 15.5% (mean, 11.5±2.5%) and %C ranged from 9.9% to 43.1% (mean, 32.4±6.7%). For comparison, modern bones exhibit mean %N values of 5.5-17.3% and mean %C values of 15.3-47.0% (Ambrose 1990). C:N ratios among all human samples ranged from 3.2 to 4.0 with a mean value of 3.3. Modern bones exhibit C:N ratios of between 2.9 and 3.5 (Ambrose 1990). There is a weak inverse relationship between C:N ratios and both %N and %C in the sample (Figs. 5.1 and 5.2). All samples with C:N ratios of 3.6 or higher are associated with relatively low %C and %N values. This trend is expected, because as collagen degrades into non-collagenous proteins, small changes in carbon and nitrogen produce disproportionally large shifts in C:N ratios. In the following subsections these high-C:N samples are examined closely. Ultimately, ten samples were excluded from the study on the basis of diagenetically altered collagen. The reduced sample is displayed at the end of this subsection in Figures 5.37-5.40. Individual skeletons are referred to by their site, ID number and sex. For example, G1-347-M refers to the male buried in grave 347 from Gruczno site 1.
Figure 5.1: %C vs. C:N, All Human Samples

Figure 5.2: %N vs. C:N, All Human Samples
Figure 5.3: C:N vs. $\delta^{13}$C All Samples

Figure 5.4: C:N vs. $\delta^{15}$N, All Samples
5.1.1 Ancient samples

Collagen from these four samples is well-preserved, despite great antiquity. C:N ratios and %N and %C values from the Neolithic and Iron Age samples were all within acceptable ranges, displayed as horizontal lines in Figures 5.5 and 5.6. Iron B exhibited somewhat low %N and %C values (5.4% and 15.2%, respectively) and Iron A exhibited a
relatively high C:N ratio of 3.5. With only four samples it is not possible to discern any relationships between collagen quality indicators and isotope ratios (Figs. 5.7 and 5.8).

5.1.2 Rogowo

Macroscopically, most bones from Rogowo are dense and appear to have high organic content. C:N ratios showed the least variation at Rogowo (Figs. 5.9 and 5.10).
Values ranged between 3.2 and 3.4 but only one sample exhibited a C:N ratio of 3.4. At Rogowo %N and %C values were all greater than 4.8% and 13.0% respectively, cut-points advocated by Ambrose (1990). Only 1 sample exhibited low %N and %C values (less than 7% and 20%, respectively). There are no relationships between %C, %N and
Figure 5.11: $\delta^{13}$C vs. %C, Rogowo

Figure 5.12: $\delta^{15}$N vs. %N, Rogowo

isotope ratios (Figs. 5.11 and 5.12). The average collagen yield from Rogowo samples was 6.3%, the lowest among the five study sites. Ten Rogowo samples yielded less than 0.1% collagen, the most of any of the study sites. There is no relationship between collagen yield and $\delta^{13}$C$_{coll}$ values.
5.1.3 Kaldus Site 4

Macroscopically, bones from Kaldus site 4 appear to be less well-preserved. Many are chalky, dry and/or flaky. Unlike at Rogowo, C:N ratios were variable at Kaldus site 4 (Figs. 5.13 and 5.14). The majority of C:N values fell between 3.2 and 3.4;
four were 3.5 and one was 3.6. The only sample in the entire study that fell below the desireable %N and %C values of 4.8% and 13.0% is from Kaldus site 4 (sample K4-186-F) with a %N value of 3.5% and a %C value of 9.9% (C:N=3.4). Including this sample,
six of the Kaldus site 4 collagen samples contained below 7% nitrogen and 20% carbon, more than at any other site. Low nitrogen or carbon content is not associated with isotopic anomalies, however (Figs. 5.15 and 5.16). Despite a wide range of variation in collagen quality indicators at Kaldus site 4, no samples are discarded.

5.1.4 Kaldus Site 1

Kaldus Site 1 data are presented in Figures 5.17-5.20. Preservation at site 1 was macroscopically better than at Kaldus site 4; most bones were dense and difficult to cut during sampling. At Kaldus site 1 all C:N ratios were between 3.2 and 3.4. No samples fell below 7% nitrogen or 20% carbon. There is a weak relationship between $\delta^{13}C_{coll}$ and %C at Kaldus site 1 ($R^2 = 0.2175$). This may indicate diagenesis or contamination, but none of the stable isotope or %C values are outside the common range and there are no outliers. The average %coll was 10.3%. Only 1 sample yielded less than 1% collagen.
Figure 5.18: $\delta^{15}$N vs. C:N, Kaldus Site 1

R² = 0.0002

Figure 5.19: $\delta^{13}$C vs. %C, Kaldus Site 1

R² = 0.2175
5.1.5 Gruczno Site 1

Collagen quality indicators are presented graphically in Figures 5.21-5.30. Overall, skeletons from Gruczno (both sites) are remarkably complete. However, at Gruczno site 1 many bones were dry and friable. At Gruczno site 1 all C:N ratios were between 3.2 and 3.3, with two outliers at 3.9 (Table 5.1; Figs. 5.21 and 5.22). These outliers also exhibit the lowest %N and %C values and are the only two below 6% nitrogen and 20% carbon (Table 5.1; Figs. 5.25 and 5.26). Gruczno site 1 %N values ranged from 5.4% to 14.0% and %C values ranged from 18.0% to 39.1%. All %N and %C measurements fall within the acceptable range, aside from the aforementioned two samples (G1-271-M and G1-54-F). When these two outliers were removed, the slight correlations observed between %N and %C and C:N disappear, suggesting these samples had been diagenetically altered (compare Figures 5.21 and 5.22 with Figures 5.30 and
Table 5.1: Samples to be Excluded from Gruczno Site 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>%C (by weight)</th>
<th>%N (by weight)</th>
<th>C:N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1-271-M</td>
<td>17.9%</td>
<td>5.4%</td>
<td>3.9</td>
</tr>
<tr>
<td>G1-54-F</td>
<td>18.4%</td>
<td>5.5%</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Figure 5.21: %C vs. C:N Ratios, Gruczno Site 1

5.31). Removing these samples has little effect on the correlations between collagen quality and isotope ratios, however (compare Figures 5.25 and 5.26 with Figures 5.27 and 5.28). The average collagen yield at Gruczno site 1 is 11.7%. Two samples (not G1-271-M and G1-54-F) yielded less than 0.1% collagen.
Figure 5.22: %N vs. C:N Ratios, Gruczno Site 1

Figure 5.23: $\delta^{13}C$ vs. C:N, Gruczno Site 1
Figure 5.24: $\delta^{15}N$ vs. C:N, Gruczno Site 1

![Graph showing C:N ratio vs. $\delta^{15}N_{\text{AIR}}$ with a linear trend line and R² = 0.0814.]

Figure 5.25: $\delta^{13}C$ vs. %C, Gruczno Site 1

![Graph showing %C vs. $\delta^{13}C_{\text{coll (VPDB)}}$ with a linear trend line and R² = 0.0016.]

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Figure 5.26: $\delta^{15}$N vs. %N, Gruczno Site 1

$R^2 = 0.1367$

Figure 5.27: $\delta^{13}$C vs. C:N, Gruczno Site 1 (Reduced Sample)

$R^2 = 0.0817$
Figure 5.28: $\delta^{15}$N vs. C:N, Gruczno Site 1 (Reduced Sample)

Figure 5.29: $\delta^{13}$C vs. %C, Gruczno Site 1 (Reduced Sample)
5.1.6 Gruczno Site 2

Skeletons from Gruczno site 2 are more well-preserved than those from Gruczno site 1. While skeletons from both sites are quite intact, bones from Gruczno site 2 more closely resembled modern bone in their macroscopic density and apparent collagen content. The %N values from Gruczno site 2 ranged from 5.3 to 13.8% and %C values ranged from 14.6 to 38.6%. All were above 7% nitrogen and 20% carbon except one. At Gruczno site 2 most C:N ratios were between 3.2 and 3.3, but eight outliers had C:N ratios of 3.5 – 4.0. The average collagen yield at Gruczno site 2 is 13.6%, the highest among the five study sites. Three samples yielded less than 0.1% collagen.
High C:N ratios are linked to lower $\delta^{13}\text{C}_{\text{coll}}$ values only at Gruczno site 2: in nearly every case, the highest C:N ratios are associated with the lowest $\delta^{13}\text{C}_{\text{coll}}$ values (Fig. 5.31). At all other sites, there is no relationship between C:N and $\delta^{13}\text{C}_{\text{coll}}$ ratios. High C:N ratios can be caused by incomplete removal of humic contaminants and/or lipids during collagen sample preparation (specifically, during the NaOH soak). Humic substances, including humic acid, fulvic acid and humin, are relatively carbon-rich, comprising between 40 and 60% carbon in comparison to between <1 and 6% nitrogen (Katzenberg 1989). When humic contaminants are present they will increase the C:N ratio and affect isotope signatures variably depending on the $\delta^{13}\text{C}$ ratios of source residues. In Northern Europe, source residues should reflect the low $\delta^{13}\text{C}$ ratios of decomposing C$_3$ organic matter. Humic contaminants, with low nitrogen content, will have little effect on $\delta^{15}\text{N}$ ratios of buried skeletons. Incomplete removal of humic contaminants as well as $^{13}\text{C}$-depleted lipids during collagen sample preparation most likely explain the correlation between $\delta^{13}\text{C}$ and C:N ratios at Gruczno site 2. Either base-soluble humic contaminants were not completely removed during NaOH soak, or they dissolved into the broth solution. Dissolution during solubilization could be due to inadequately high pH during solubilization. Although the two samples with the highest C:N ratios are not those with the lowest $\delta^{13}\text{C}$, the presence of a relationship between C:N and $\delta^{13}\text{C}$ is troubling, and suggests these samples may have high C:N because they have been altered.
Figure 5.31: $\delta^{13}$C vs. C:N, Gruczno Site 2, All Samples

![Graph showing $\delta^{13}$C vs. C:N with R² = 0.4727](image)

Figure 5.32: $\delta^{15}$N vs. C:N, Gruczno Site 2, All Samples

![Graph showing $\delta^{15}$N vs. C:N with R² = 0.0219](image)
Figure 5.33: $\delta^{13}\text{C}$ vs. $\%C$, Gruczno Site 2, All Samples

Figure 5.34: $\delta^{15}\text{N}$ vs. $\%N$, Gruczno Site 2, All Samples
The collagen yields from Gruczno site 2 were the highest of any site, on average. Considering there may be a diagenetic problem at Gruczno site 2, the high yields should be scrutinized, as they may represent salts or contaminants in the sample. In Figure 3.35, collagen yields from the Gruczno site 2 sample are plotted against C:N ratios. There is an inverse relationship between the two collagen quality criteria. That high C:N samples have relatively low collagen yields suggest (1) these samples have degraded and noncollagenous proteins are present (Ambrose 1990), or (2) lipids (high C, low N content). δ13C and C:N ratios correlate, which further suggests lipids may be the contaminating substance, as they have lower δ13C than overall collagen, or noncollagenous proteins contaminating the sample have low δ13C ratios. The primary amino acids in bone collagen are glycine, proline and hydroxyproline. Other amino acids in collagen are glutamate, aspartate, serine, serine, alanine, threonine and valine (Hare et al. 1991). Hydroxyproline is the most depleted in 13C followed by glutamate, aspartate, and alanine (Hare et al. 1991; Tuross et al. 1988). Glycine, the major constituent of bone collagen, is 13C-enriched. Disproportionate dissolution of different amino acids (in this case, glycine) during diagenesis or sample preparation could explain the δ13C and C:N inverse relationship. As noted by Tuross et al. (1988: 934), “The loss of glycine relative to aspartic acid would occur if a gelatinization procedure of glycine-rich, collagen-derived peptides were solubilized in HCl and lost through the coarse filters generally used”. Low-13C contaminants (lipids, microorganisms or humic acids) in the final collagen sample could also produce an inverse correlation between δ13C and C:N.
One possible explanation for why this may be a problem at Gruczno site 2 but not at the other sites involves the excellent preservation of Gruczno site 2 materials. Because skeletal materials from Gruczno site 2 were the least friable, initial grinding of the bones may not have produced particles as small as at the other sites. Larger particles of bone have relatively less surface area exposed to the chemical treatments, meaning that HCl and/or NaOH may not have completely interacted with the samples from Gruczno site 2. This could contribute to the incomplete separation and removal of lipids, or the selective dissolution of high-$^{13}$C and retention of low-$^{13}$C amino acids (cf. Bell et al. 2001). Indeed, many of the samples from Gruczno site 2 with high C:N ratios did not completely dissolve during the final step of collagen extraction, but rather left particles on top of the
Table 5.2: Samples to be Excluded from Gruczno Site 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>% C (by weight)</th>
<th>% N (by weight)</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>G2-1604-M</td>
<td>25.0</td>
<td>8.0</td>
<td>3.6</td>
</tr>
<tr>
<td>G2-1606-M</td>
<td>26.4</td>
<td>8.7</td>
<td>3.6</td>
</tr>
<tr>
<td>G2-1607-F</td>
<td>27.5</td>
<td>9.0</td>
<td>3.5</td>
</tr>
<tr>
<td>G2-1643-M</td>
<td>28.7</td>
<td>9.7</td>
<td>3.5</td>
</tr>
<tr>
<td>G2-1549-M</td>
<td>31.8</td>
<td>10.0</td>
<td>3.7</td>
</tr>
<tr>
<td>G2-1563-M</td>
<td>30.3</td>
<td>8.8</td>
<td>4.0</td>
</tr>
<tr>
<td>G2-1576-F</td>
<td>27.6</td>
<td>9.1</td>
<td>3.5</td>
</tr>
<tr>
<td>G2-1703-M</td>
<td>28.5</td>
<td>9.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

glass frit after filtration. On the other hand, the good preservation and high density of bone may have resulted in over-processing when grinding the bone powder, which could have begun to destroy some of the peptide bonds of collagen, facilitating selective dissolution of certain amino acids.

Garvie-Lok (2001) also reported an inverse correlation between C:N ratios and $\delta^{13}C_{coll}$ values within her sample. To address the problem she removed all the high C:N samples from the data set until a significant correlation disappeared. In general she removed samples with C:N above 3.4. This requires flexible exclusion criteria: rather than C:N of 3.4 being a cut-point throughout the sample, it was only the basis for exclusion if linked to some other indicator of diagenetic alteration. At Gruczno site 2 a relationship “disappears” when eight outliers are removed (Figs. 5.36-5.39). At this site, the C:N cut-point ratio appears to be 3.5.
Figure 5.36: $\delta^{13}$C vs. C:N, Gruczno Site 2 (Reduced Sample)

Figure 5.37: $\delta^{15}$N vs. C:N, Gruczno Site 2 (Reduced Sample)

Figure 5.38: $\delta^{13}$C vs. %C, Gruczno Site 2 (Reduced Sample)
5.1.7 Animal bone collagen

Animal bones are well-preserved. Percent N values range from 11.0% to 16.1% with a mean of 13.9±1.6%. Percent C values range from 31.6% to 44.5% with a mean of 37.7±0.4%. All C:N ratios were either 3.2 or 3.3 with the exception of the sheep sample with a C:N ratio of 3.4. These restricted ranges demonstrate excellent collagen quality among animal bones. Percent collagen was measured from ten of the 17 bones and ranged from 5% to 22%. Fish bones also are well-preserved. Percent N values range from 4.1% to 12.9% and %C values range from 11.7% to 34.9%. These ranges are slightly lower and more variable than reported in other studies (Reitsema et al. 2010). All fish bones exhibit C:N ratios of 3.2 or 3.3 which are comparable to previously published data for well-preserved fish bone (Dufour et al. 1999; Müldner and Richards 2005; Redfern et al. 2010).
Table 5.3: Summary of Collagen Quality

<table>
<thead>
<tr>
<th></th>
<th>Rogowo 2\textsuperscript{nd} c.</th>
<th>Kaldus 4 11\textsuperscript{th} c.</th>
<th>Gruczno 1 12\textsuperscript{th} c.</th>
<th>Kaldus 1 12\textsuperscript{th}-13\textsuperscript{th} c.</th>
<th>Gruczno 2 13\textsuperscript{th}-14\textsuperscript{th} c.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>%collagen</td>
<td>Low</td>
<td>Average</td>
<td>Average</td>
<td>Good</td>
<td>Best</td>
</tr>
<tr>
<td>C:N ratio</td>
<td>Best</td>
<td>Poor</td>
<td>Average</td>
<td>Best</td>
<td>Poor</td>
</tr>
<tr>
<td>%N and %C</td>
<td>Average</td>
<td>Poor</td>
<td>Average</td>
<td>Best</td>
<td>Average</td>
</tr>
</tbody>
</table>

5.1.8 **Final sample**

A summary of collagen quality at each of the five main sites is presented in Table 5.3. Although this table presents a patchwork of good and bad preservation, in general Kaldus 1 exhibits the best preservation of all five sites. Kaldus site 4 exhibits the poorest. Aside from these, there is little agreement between the quality indicators within a particular site. Very few samples (n=10) were actually outside acceptable ranges for any quality indicator.

The final data set is presented in Figures 5.40-5.43. Initially, there were slight relationships between some of the collagen quality indicators (%C, %N and C:N ratios) and isotope ratios (Figs. 5.1-5.4). Removing 10 collagen samples from Gruczno sites 1 and 2 caused a *decrease* in all four of these relationships between collagen quality indicators and stable isotope ratios (Figs. 5.40-5.43). Because biogenic stable isotope values should always be unrelated to collagen quality, these reductions suggest that diagenetically altered samples were successfully identified and removed from the sample. The final data set comprises 157 individuals. It is interesting that collagen diagenesis was greatest at Gruczno, as skeletons from this site are generally much more complete than skeletons from Kaldus and Rogowo.

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Figure 5.40: $\delta^{13}C_{coll}$ vs. C:N, Final Data Set

Figure 5.41: $\delta^{15}N$ vs. C:N, Final Data Set

R² = 0.033

R² = 0.0633
Figure 5.42: $\delta^{13}C_{\text{coll}}$ vs. %C, Final Data Set

Figure 5.43: $\delta^{15}N$ vs. %N, Final Data Set
5.2 Collagen Duplicates

Differences in stable isotope signatures between individuals are not necessarily dietary. They may be the unwanted product of variations in sample preparation or analysis. To assess this type of variability, a number of duplicates were prepared and analyzed. Two types of collagen duplicates include procedural duplicates, where a single prepared sample is divided and analyzed twice, and preparation duplicates, where fractions of a single bone are prepared separately and analyzed separately. Because two slightly different methods were used to extract collagen from bone in this study, some of these preparation duplicates compare methods. In the following three sections, each of the three types of duplicate are discussed. In section 5.2.6, overall comparisons of collagen data are made between Methods 1 and 2.

5.2.1 Procedural collagen duplicates (n=14)

Following preparation as a single sample, fourteen samples of purified bone collagen were divided into subsamples immediately before mass spectrometry. These subsamples were thus treated as a single sample throughout sample preparation, and were prepared at the same time using the same method. The purpose of these duplicates is twofold: to assess reproducability of the mass spectrometer in the same manner as the acetanilide, IAEA-N1 and USGS24 laboratory standards, and also to assess how well the sample was homogenized (ground in the agate mortar/pestle) immediately prior to analysis.
These procedural duplicates demonstrated a high level of reproducability of within 0.3‰ for each stable isotope. Many measurements of %N, %C, $\delta^{13}$C and $\delta^{15}$N were identical. Differences between subsamples are presented in Table 5.4. For comparison, isotope reproducability reported by Iacumin et al. (1997) was generally within 1‰.

5.2.2 Duplicates prepared separately using the same method (n=6)

Six samples of bone were prepared separately in order to assess the reliability of sample preparation Method 1. These were samples K1-100 (a probable female), K1-80-M, G1-300-M, G2-1703-M, R-39-M and Iron-A (male). These samples were taken from the same bone, but subjected to all phases of collagen purification in separate batches, during different weeks. These duplicates were less similar than the procedural duplicates, although many measurements were identical. Differences between these duplicates are presented in Table 5.5.

5.2.3 Duplicates prepared separately using different methods (n=6)

Six bones were prepared using the two different preparation methods in order to ensure their comparability (Type 3 duplicates). As detailed in Chapter 4, the primary difference between these methods was the type of glassware used. In the first method, demineralization and removal of organic contaminants took place in 100 mL glass beakers, and solubilization of collagen into a broth took place in centrifuge tubes using a hot water bath. Using the second method, all phases of preparation took place in glass frit
Table 5.4: Bone Collagen Procedural Duplicates (Divided Powder)

<table>
<thead>
<tr>
<th>Type 1 (Procedural) Duplicates (n=14)</th>
<th>N by weight (%)</th>
<th>C by weight (%)</th>
<th>δ¹⁵N (‰)</th>
<th>δ¹³C (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong> difference between duplicates of the same sample</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Maximum</strong> difference between duplicates of the same sample</td>
<td>0.3</td>
<td>0.9</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 5.5: Bone Collagen Same Method, Separate Preparation Duplicates

<table>
<thead>
<tr>
<th>Type 2 Duplicates: same method (n=6)</th>
<th>N by weight (%)</th>
<th>C by weight (%)</th>
<th>δ¹⁵N (‰)</th>
<th>δ¹³C (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong> difference between duplicates of the same sample</td>
<td>1.8</td>
<td>5.0</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Maximum</strong> difference between duplicates of the same sample</td>
<td>2.4</td>
<td>5.8</td>
<td>0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 5.6: Bone Collagen Different Method Duplicates

<table>
<thead>
<tr>
<th>Type 3 Duplicates: different methods (n=6)</th>
<th>N by weight (%)</th>
<th>C by weight (%)</th>
<th>δ¹⁵N (‰)</th>
<th>δ¹³C (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong> difference between duplicates of the same sample</td>
<td>2.8</td>
<td>7.0</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Maximum</strong> difference between duplicates of the same sample</td>
<td>5.4</td>
<td>13.4</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Filter funnels with stopcocks coupled to 250 mL Ehrlenmeyer flasks, and solubilization took place in an oven. There was a slightly greater risk of collagen loss in the first method due to rinsing and replacing solutions using a pipette, rather than simply flushing the sample in a filter funnel. Additionally, samples had to be transferred from beakers into centrifuge tubes in the first method, which may have allowed more sample loss in Method 1.
Another difference between the methods was length of demineralization. In the first method, samples soaked in a 0.2 M HCl solution of acid for approximately 7 days. Using the second method, bone was soaked for just 4 days. Of the three types of duplicate, those prepared using different methods showed the highest variation, summarized in Table 5.6.

Differences between duplicates prepared with two different techniques were greater than those of duplicates prepared with the same method but in no case are the isotopic differences greater than 1‰. When the sample with the greatest intra-sample variability is excluded (K4-364-M), the %N, %C and $\delta^{15}$N values of type 2 and type 3 duplicates are actually comparable in reproducability. However, the $\delta^{13}$C$_{coll}$ of all type 3 duplicates were slightly higher using sample preparation Method 2 than using Method 1 with the exception of K1-31-F, which was lower. This may have something to do with the selective dissolution of high-$^{13}$C amino acids in Method 1, or selective dissolution of low-$^{13}$C amino acids in Method 2.

### 5.2.4 Summary and implications of collagen duplicates

The implication of all three types of duplicate is that the average margin of error for stable isotope values is less than ~0.5‰ (Tables 5.4-5.6). Thus, a difference in values of less than 0.5‰ between individuals does not necessarily imply a difference in diet, but may instead be due to differences in sample preparation or to analytical error.

For the 116 samples prepared using Method 1, stable isotope differences of more than 0.3‰ are within the range of experimental error (Table 5.5). In comparison to these,
the remaining 83 samples may differ by as much as 0.9‰ for $\delta^{15}$N and 0.8‰ for $\delta^{13}$C$_{coll}$ from the samples prepared using Method 1 (Table 5.6). Details on which method was used for which particular samples are provided in Appendix I.

5.2.5 *Differences between sample preparation methods*

Of the total samples analyzed here, 116 were prepared using Method 1 and 83 were prepared using Method 2. The primary difference between the methods is that in Method 2, chemical treatments were completed using glass frit filter funnels instead of beakers (see Chapter 4 for more details).

Collagen quality indicators and stable isotope ratios of samples prepared with each method are presented in Figures 5.44-5.49. There are some differences in collagen quality indicators (especially C:N ratios), but not in the stable isotope ratios overall. As discussed earlier, most of the higher C:N samples came from Gruczno site 2; whether anomalously high C:N ratios of these samples are due to site-specific diagenesis or the fact that they happened to be prepared using Method 1 is unclear. Slightly higher collagen yields are associated with Method 2. However, as previously discussed, collagen yields were considered less reliable indicators of diagenesis. Several collagen yields exceeded 22%, the upper limit for modern bone (Ambrose 1990), which may reflect this measurement problem but could also indicate higher production of inorganic salts during Method 2. Salts likely form during interactions between residual amounts of NaOH and HCl in the sample and glassware and are produced even in blank samples (Ambrose 1990), one of which was run during this research.
Figure 5.44: Comparing Methods 1 and 2, C:N Ratios of All Samples

Figure 5.45: Comparing Methods 1 and 2, % coll Ratios of All Samples
Figure 5.46: Comparing Methods 1 and 2, Percent Carbon Ratios of All Samples

Figure 5.47: Comparing Methods 1 and 2, Percent Nitrogen Ratios of All Samples
Figure 5.48: Comparing Methods 1 and 2, $\delta^{13}C_{\text{coll}}$ Ratios of All Samples

Figure 5.49: Comparing Methods 1 and 2, $\delta^{15}N$ Ratios of All Samples
5.3  Diagenesis in Bone Mineral

All bone apatite samples analyzed for $\delta^{13}C_{ap}$ (n=151) were also analyzed using Fourier transform infrared (FTIR) spectroscopy to assess diagenetic alteration. This technique is described in detail in Chapter 3. To summarize, FTIR compares archaeological bone mineral to modern bone mineral and provides some information on the nature of any differences. As previously described, two measurements were recorded using FTIR spectra: crystallinity index (CI) which measures the size and organization of carbonate crystals, and carbonate content (C/P). Both measurements are compared to modern and well-preserved archaeological bones, and considered in relation to $\delta^{13}C_{ap}$ and $\delta^{18}O$ values to detect and explain diagenesis. The goal of this investigation was to identify apatite samples that have been diagenetically altered so that they may be excluded from isotope analysis.

In this section, FTIR results from the entire sample are discussed first. Each site is then examined separately, and the rationale for discarding some samples is given. Finally, results of duplicate stable isotope and FTIR analyses comparing the effects of acetic acid treatment and mechanical cleaning of bones are discussed.

5.3.1  FTIR results from the entire sample

Summary data for all samples are presented in Table 5.7. Some examples of FTIR spectra are presented in Figure 5.50. These include (a) a well-preserved sample with a smooth line at 1091 cm$^{-1}$, (b) a sample with a shoulder and (c) a sample with a peak at 1091 cm$^{-1}$, suggesting recrystallization into francolite. Many samples may still
Figure 5.50: Sample FTIR spectra

a. Neo 1a

b. K4-13B-F

c. R-705-F

have acceptable CI and C/P values, despite a peak at this wavenumber (Garvie-Lok 2001; Wright and Schwarcz 1996).
The overall range of C/P values was 0.09 to 0.41 and the range of CI values was 2.1 to 4.4. The sample G1-347-M is a low-CI outlier and when excluded, the remaining CI values fall between the more restricted range of 2.7 and 4.4. Sample G1-347-M had an unusual texture, like fine-grained salt, that was notably unlike the other, flour-like powders. Its spectrum differed considerably from the rest of the sample and from other archaeological samples. Its stable isotope values are likely diagenetically altered.

The mean CI value was 3.4±0.4 and the mean C/P value was 0.19±0.05. For comparison, modern bones that have been treated with chemicals to mimic archaeological sample preparation exhibit average CI value of approximately 3.0-3.3 and C/P values of approximately 0.22-0.24 (Garvie-Lok 2001; Wright and Schwarcz 1996).

FTIR CI and C/P values are inversely correlated in the sample (Fig. 5.51). This is to be expected, for as recrystallization occurs (increasing CI), it usually produces low-carbonate apatites with larger crystal sizes and more fluorine (Garvie-Lok 2001; Shemesh 1990a). Compared to modern bone, also pictured in Figure 5.51 (data from Garvie-Lok [2001] and Wright and Schwarcz [1997]), the Polish archaeological samples tend to exhibit lower C/P and higher CI. There is only one outlier (G1-347-M) and the rest of the samples are similar to those reported from other archaeological contexts (de la Cruz Baltazar 2001; Wright and Schwarcz 1996).

Samples with a peak, shoulder and smooth profile at 1091 cm\(^{-1}\) are separated and displayed in Figure 5.52. As discussed in Chapter 3, this peak indicates diagenetic recrystallization of the carbonate sample to francolite. Wright and Schwarcz (1997) report a tendency for samples with high CI and low C/P to exhibit these peaks more often
Figure 5.51: FTIR Results from All Sites and 3 Modern Bones

*Data for modern bones from Garvie-Lok (2001) and Wright and Schwarcz (1996).
Figure 5.52: FTIR Results Sorted by Presence/Absence of 1091 cm$^{-1}$ Peak
than other samples, although this was not always the case. In this study, there is a slight tendency for samples with a peak at 1091 cm\(^{-1}\) to exhibit higher CI and lower C/P, but this is not as consistent as that reported by Wright and Schwarcz (1997).

Figures 5.53 and 5.54 display FTIR data in relation to stable isotope data. Ideally, these should be de-coupled: stable isotope data should not correlate with FTIR indices. If they do, it suggests that alteration of the bone mineral in the burial environment or during sample preparation has affected isotope ratios in a systematic way. Figures 5.53 and 5.54 show no relationship between FTIR indices and \(\delta^{13}C\) ratios in the samples, meaning diagenesis has not likely altered stable isotope signals in a significant way. The relationship between FTIR indices and stable isotope ratios is examined site-by-site in later subsections of this chapter in order to ensure that poor preservation at a site is not masked by the overall sample.

Samples with poorly preserved collagen may be more susceptible to carbonate diagenesis because collagen in bone pores protects the mineral from contact with surrounding groundwater and sediments. In light of this possibility, the relationships between FTIR indices and collagen quality indicators were examined. There are no significant relationships between FTIR indices and collagen quality indicators, as presented in Figure 5.55. Overall the sample appears relatively unaffected by collagen and carbonate diagenesis.
Figure 5.53: No Relationship Between $\delta^{13}\text{C}_{\text{ap}}$ and FTIR CI, All Samples

$R^2 = 0.023$
Figure 5.54: No Relationship Between $\delta^{13}\text{C}_{\text{ap}}$ and FTIR C/P, All Samples

R² = 0.0072
Stable oxygen isotope ratios in bone carbonate are more highly susceptible to diagenesis than are carbon isotope ratios, causing some researchers to use $\delta^{18}O$ values as a proxy indicator for diagenesis (Garvie-Lok 2001). There is no relationship between
\( \delta^{18} \text{O} \) ratios and either FTIR CI or C/P (Figs. 5.54 and 5.55). Because \( \delta^{18} \text{O} \) ratios in human bone reflect drinking water sources, they should be de-coupled from \( \delta^{13} \text{C}_{\text{ap}} \) values, which reflect foods. If a relationship between the two is detected, it is likely diagenetic. Garvie-Lok (2001) explored this by dividing her sample into two groups: one with FTIR CI values of more than 3.5 (a “High Crystallinity” group) and one with values equal or less than 3.5 (a “Low Crystallinity” group) and plotting their \( \delta^{18} \text{O} \) and \( \delta^{13} \text{C}_{\text{ap}} \) values. Garvie-Lok (2001) found that high crystallinity was not associated with a broader scatter of either \( \delta^{18} \text{O} \) or \( \delta^{13} \text{C}_{\text{ap}} \) values, which could be expected if recrystallization caused \( \delta^{13} \text{C}_{\text{ap}} \) variations. In this study too the relationship is weak suggesting that isotope differences are not attributable to recrystallization (Fig. 5.58). Because some of the samples reported by Garvie-Lok (2001) nevertheless had anomalous \( \delta^{18} \text{O} \) ratios that were certainly diagenetic, she concluded that diagenesis may have proceeded by difference mechanisms that differentially affected \( \delta^{18} \text{O} \) and \( \delta^{13} \text{C}_{\text{ap}} \) values. \( \delta^{18} \text{O} \) data in this study suggest little diagenetic alteration of the sample, but their usefulness as diagenetic indicators is limited.

5.3.2 FTIR results from the individual sites

FTIR results were similar at all sites despite widely varying antiquity (Table 5.7). Gruczno site 2, the youngest site, exhibits the best preservation in terms of FTIR. Older samples exhibit a higher incidence of peaks at 1091 cm\(^{-1} \) than younger samples. Peaks at this wavenumber indicate recrystallization of apatite into F-apatite (francolite), a feature correlating with poorer preservation (Wright and Schwarcz 1996).

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Figure 5.56: No Relationship Between $\delta^{18}$O and FTIR CI

$R^2 = 0.0075$
Figure 5.57: No Relationship Between $\delta^{18}$O and FTIR C/P

$R^2 = 0.0029$
Figure 5.58: “High” and “Low” Crystallinity Samples Have Similar Isotopic Ranges

![Graph showing δ18O vs δ13C for High and Low Crystallinity samples.]

Table 5.7: Summary of FTIR Data for All Samples

<table>
<thead>
<tr>
<th>Site</th>
<th>c. AD</th>
<th>FTIR CI</th>
<th>FTIR C/P</th>
<th>Percent with FTIR Peak at 1091 cm-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neo/Iron Age</td>
<td>3.5 ± 0.4</td>
<td>0.21 ± 0.07</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>Rogowo 2nd</td>
<td>3.6 ± 0.4</td>
<td>0.18 ± 0.07</td>
<td>34%</td>
<td></td>
</tr>
<tr>
<td>Kaldus 4</td>
<td>3.6 ± 0.4</td>
<td>0.16 ± 0.04</td>
<td>38%</td>
<td></td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>3.4 ± 0.3</td>
<td>0.18 ± 0.03</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Kaldus 1</td>
<td>3.4 ± 0.2</td>
<td>0.19 ± 0.03</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Gruczno 2</td>
<td>3.2 ± 0.2</td>
<td>0.22 ± 0.05</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>

At each site, possible relationships between isotope values and FTIR indices are investigated. Ideally, no relationship exists, but if recrystallization and/or adsorption of carbonates as measured by FTIR indices are associated with isotopic shifts, isotope differences are less likely to be biogenic and more likely to be diagenetic.
At Rogowo, Gruczno site 1 and Gruczno site 2, there is no relationship between FTIR indices and $\delta^{13}C_{ap}$ (Figs. 5.59 to 5.68). At Kaldus site 4, there is a slight negative correlation between CI and $\delta^{13}C_{ap}$ and a slight positive correlation between C/P and $\delta^{13}C_{ap}$ (Figs. 5.61 and 5.62). At Kałdus site 1, there is no significant relationship between FTIR indices and stable isotope ratios (Figs. 5.65 and 5.66). There are several outliers that should be investigated more closely. Two samples with the highest $\delta^{13}C_{ap}$ ratios, K1-93-M and K1-58-F, also exhibit the highest CI values (3.7 and 3.8, respectively). However, their C/P values are not unusual. When considered in the context of the entire sample (Fig. 5.51) these samples no longer seem unusual. Another sample with a high $\delta^{13}C_{ap}$ ratio, K1-101-F, exhibits a relatively high C/P value, but its CI is within the normal range.

Only at Kałdus site 4 are suspicious correlations between FTIR and stable isotope values observed. Weaker correlations are observed at Kałdus site 1, although these are probably negligible. Removing outliers will not eliminate the correlations in Figures 5.61-5.66 as Garvie-Lok (2001) accomplished in her historic Greek sample. To further investigate possible diagenesis at Kałdus, $\delta^{18}O$ ratios were also considered alongside FTIR indices (Figs. 5.69 to 5.72). There were no relationships between $\delta^{18}O$ ratios and CI, or between $\delta^{18}O$ and C/P. There were no outliers at Kaldus site 4, but at Kaldus site 1, the sample with the highest $\delta^{18}O$ ratio, K1-109-F, exhibits the lowest CI and the highest C/P value (Figs. 5.71 and 5.72). There is nothing else unusual about sample K1-109-F, however.
Figure 5.59: Rogowo: Crystallinity Index (FTIR CI) vs. $\delta^{13}C_{ap}$

Figure 5.60: Rogowo: Carbonate Content (FTIR C/P) vs. $\delta^{13}C_{ap}$
Figure 5.61: Kaldus Site 4: Crystallinity Index (FTIR CI) vs. $\delta^{13}\text{C}_{\text{ap}}$

\[ R^2 = 0.2021 \]

Figure 5.62: Kaldus Site 4: Carbonate Content (FTIR C/P) vs. $\delta^{13}\text{C}_{\text{ap}}$

\[ R^2 = 0.3204 \]
Figure 5.63: Gruczno Site 1: Crystallinity Index (FTIR CI) vs. $\delta^{13}\text{C}_\text{ap}$

Figure 5.64: Gruczno Site 1: Carbonate Content (FTIR C/P) vs. $\delta^{13}\text{C}_\text{ap}$
Figure 5.65: Kaldus Site 1: Crystallinity Index (FTIR CI) vs. $\delta^{13}C_{\text{cap}}$

![Crystallinity Index vs $\delta^{13}C_{\text{cap}}$](image)

$R^2 = 0.0556$

Figure 5.66: Kaldus Site 1: Carbonate Content (FTIR C/P) vs. $\delta^{13}C_{\text{cap}}$

![Carbonate Content vs $\delta^{13}C_{\text{cap}}$](image)

$R^2 = 0.1118$
Figure 5.67: Gruczno Site 2: Crystallinity Index (FTIR CI) vs. $\delta^{13}$C<sub>ap</sub>

Figure 5.68: Gruczno Site 2: Carbonate Content (FTIR C/P) vs. $\delta^{13}$C<sub>ap</sub>
Figure 5.69: Kaldus Site 4: Crystallinity Index (FTIR CI) vs. δ\(^{18}\)O

![Graph showing the relationship between FTIR (CI) and δ\(^{18}\)O with a regression line R\(^2\) = 0.0393.]

Figure 5.70: Kaldus Site 4: Carbonate Content (FTIR C/P) vs. δ\(^{18}\)O

![Graph showing the relationship between FTIR (C/P) and δ\(^{18}\)O with a regression line R\(^2\) = 0.016.]

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Figure 5.71: Kaldus Site 1: Crystallinity Index (FTIR CI) vs. $\delta^{18}$O

There is only one clear outlier in the sample, judging from Figures 5.59 to 5.68.

This is G1-347-M from Gruczno site 1. This sample exhibits the lowest CI of the entire
sample, 2.1. More importantly perhaps is its unusual spectrum which was completely unlike the rest of the samples.

5.3.3 Final Data Set

Carbonate is generally well-preserved at all study sites. In her historic Greek sample, Garvie-Lok (2001) ultimately excluded approximately one-third of her total samples from analysis on the basis of suspected diagenesis. In this study, the only sample clearly identified as altered is from Gruczno site 1. Sample G1-347-M, with a “normal” C/P ratio of 0.22 and a low CI of 2.1, exhibits a very different spectrum than the remaining samples and will be excluded from subsequent analyses. Although this sample shows signs of mineral alteration and will be excluded, it is notable that its stable carbon and stable oxygen isotope data are within 1 standard deviation of the mean for Gruczno site 1, and there is nothing anomalous about its collagen quality indicators.

5.4 Discussion of Carbonate Duplicates

For apatite samples, three types of duplicates were analyzed. As with collagen, procedural duplicates were used to assess intra-sample variability (Type 1). Other duplicates were analyzed both before and after acetic acid treatment to compare its effects (Type 2; acetic-treated samples notated with the letter ‘a’ at the end of the sample ID and non-acetic-treated samples notated with the letter ‘b’). A third type of duplicate involved analyzing bone that had been mechanically cleaned with a Dremel® tool prior to chemical preparation, and bone that had not been mechanically cleaned (Type 3;
cleaned bone indicated with the number ‘1’ at the end of the sample ID and non-cleaned samples indicated with the number ‘2’). All three types of carbonate duplicate are discussed here. In addition to isotope ratios, duplicate FTIR analyses are also discussed. Stable oxygen isotope data, which are produced in the course of stable carbon isotope analysis of carbonate samples, are considered here because they are more sensitive to diagenetic alteration. δ¹⁸O ratios have been considered in prior studies for another perspective on diagenesis (Garvie-Lok 2001; Wright and Schwarcz 1996).

5.4.1 Procedural duplicates of carbonate samples

To establish a range of intra-sample variability and analytical error, 9 duplicate samples of bone mineral were analyzed for stable carbon and oxygen isotope ratios, reported in Table 5.8 and Figure 5.73. These include K4-364-M, K1-58-F, K1-7-F, G1-760-F, G2-1302-F, G2-1411-M, R-29-F, R-688N-F and R-680-M. They are subsamples from a single vial of prepared sample powder. Procedural duplicates exhibit a mean δ¹³C ap difference of 0.08‰ and a mean δ¹⁸O difference of 0.27‰. Maximum differences are also presented in Table 5.8. Larger shifts were observed in δ¹⁸O ratios than in δ¹³C ap, which was expected based on other studies that found stable oxygen isotopes to be most susceptible to diagenetic alteration from surrounding groundwater (Wright and Schwarcz 1996).
Table 5.8: Results of Duplicate Stable Isotope Analyses – Bone Mineral

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$\delta^{13}\text{C}_{\text{VPDB}}$ (‰) bone apatite</th>
<th>$\delta^{18}\text{O}_{\text{VPDB}}$ (‰) bone apatite</th>
</tr>
</thead>
<tbody>
<tr>
<td>K4-364-Ma</td>
<td>-10.67</td>
<td>-7.02</td>
</tr>
<tr>
<td></td>
<td>-10.49</td>
<td>-6.45</td>
</tr>
<tr>
<td></td>
<td>-10.59</td>
<td>-6.76</td>
</tr>
<tr>
<td>G2-1411-M</td>
<td>-12.85</td>
<td>-5.11</td>
</tr>
<tr>
<td></td>
<td>-12.84</td>
<td>-5.17</td>
</tr>
<tr>
<td>K1-58-F</td>
<td>-7.89</td>
<td>-6.97</td>
</tr>
<tr>
<td></td>
<td>-7.94</td>
<td>-6.87</td>
</tr>
<tr>
<td>R-688N-F</td>
<td>-10.45</td>
<td>-5.76</td>
</tr>
<tr>
<td></td>
<td>-10.47</td>
<td>-5.81</td>
</tr>
<tr>
<td>R-680-M</td>
<td>-12.14</td>
<td>-6.46</td>
</tr>
<tr>
<td></td>
<td>-12.19</td>
<td>-6.40</td>
</tr>
<tr>
<td>K1-7-F</td>
<td>-13.18</td>
<td>-6.10</td>
</tr>
<tr>
<td></td>
<td>-13.31</td>
<td>-6.53</td>
</tr>
<tr>
<td>G1-760-F</td>
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<td>-5.98</td>
</tr>
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<td></td>
<td>-11.10</td>
<td>-6.02</td>
</tr>
<tr>
<td>G2-1302-F</td>
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<td>-5.92</td>
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<td></td>
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<td>-6.19</td>
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<td>R-29-F</td>
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</tr>
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<td></td>
<td>-11.46</td>
<td>-6.87</td>
</tr>
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<td>G1-357-M</td>
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<tr>
<td></td>
<td>-12.08</td>
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<tr>
<td>Max difference</td>
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<td>0.85</td>
</tr>
<tr>
<td>Mean difference</td>
<td>0.08</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Duplicates to compare the effects of acetic acid treatment

Duplicates that were analyzed to compare the effects of acetic acid treatment include G1-357-M, Neo-2, G1-766-F, and K4-13B-F (Table 5.9). One sample of “raw” bone powder that received no treatment except powdering was also analyzed to compare it to the analyzed fraction (K1-225-F). These are pictured in Figure 5.74 and summarized in Table 5.9.

In all cases, acetic acid treatment lowers the $\delta^{13}C$ ratio of bone. This suggests removal of labile carbonates from the depositional soil matrix, soil carbonates being relatively high in $^{13}C$ (much like the VPDB standard against which sample carbon isotope ratios are reported. Labile carbonates, adsorbed onto crystal surfaces or incorporated into immature crystals, are more easily removed by acid leaching than are structural
carbonates (including Type A carbonates substituting in the OH position of the apatite crystal, and Type B carbonates substituting in the phosphate position of apatite) (Betts et al. 1981).

The effect of acetic acid treatment on δ¹⁸O ratios not consistent. δ¹⁸O ratios in soils do vary between sites, which can explain inconsistencies in pre- and post-acetic treatment values. However, in this study even two samples from the same site do not show the same post-acetic treatment effect: sample K4-225-F becomes ¹⁸O enriched and sample K4-13B-F becomes ¹⁸O depleted with acetic leaching. In all cases, acetic acid treatment reduces scatter in isotope signatures (Fig. 5.74). It may be the case that during acetic leaching, samples recrystallized and their δ¹⁸O ratios equilibrated with oxygen in the acetic acid solution, which has a chemical formula of CH₃COOH. Although more duplicate analyses would help clarify the issue, it appears that stable oxygen isotope ratios in samples are not entirely biogenic, and also that diagenesis and sample preparation have affected stable oxygen and carbon isotope ratios differently.

Also shown in Figure 5.74 are a pair of duplicates comparing effects of mechanical cleaning on stable isotope ratios (K4-13B-F1 [clean] and K4-13B-F2 [not cleaned]). Cleaning involved filing away the outer surfaces of bone pieces with a Dremel® tool prior to grinding bones into powders to remove the most likely contaminated or altered components. From this duplicate it appears that mechanical cleaning has no detectable effect on the isotope ratios of bones. Another subsample from K4-13B-F was measured
Figure 5.74: Effects of Acetic Acid Treatment on Carbonate Isotope Ratios

![Graph showing effects of acetic acid treatment on carbonate isotope ratios.](image)

- **Mechanically Cleaned**
- **Not Cleaned**

Figure 5.75: No Isotope Differences with Mechanical Cleaning, All Samples

![Graph showing no isotope differences with mechanical cleaning.](image)

- **Mechanically Cleaned**
- **Not Cleaned**
Table 5.9: Effects of Acetic Acid Treatment on Stable Isotope Ratios of Duplicates

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Treatment</th>
<th>$^{13}$C&lt;sub&gt;VPDB&lt;/sub&gt; (%)</th>
<th>$^{18}$O&lt;sub&gt;VPDB&lt;/sub&gt; (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>bone apatite</td>
<td>bone apatite</td>
</tr>
<tr>
<td>G1-357-M</td>
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<td>-5.89</td>
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<td></td>
<td>no acetic</td>
<td>-11.95</td>
<td>-6.09</td>
</tr>
<tr>
<td>G1-766-F</td>
<td>acetic</td>
<td>-13.62</td>
<td>-6.40</td>
</tr>
<tr>
<td></td>
<td>no acetic</td>
<td>-11.49</td>
<td>-5.38</td>
</tr>
<tr>
<td>K4-13B-F</td>
<td>acetic</td>
<td>-10.02</td>
<td>-5.88</td>
</tr>
<tr>
<td></td>
<td>no acetic</td>
<td>-8.98</td>
<td>-5.36</td>
</tr>
<tr>
<td>Neo-2</td>
<td>acetic</td>
<td>-13.88</td>
<td>-6.87</td>
</tr>
<tr>
<td></td>
<td>no acetic</td>
<td>-12.38</td>
<td>-8.27</td>
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<tr>
<td>Maximum difference:</td>
<td>2.13</td>
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</tr>
<tr>
<td>Mean difference:</td>
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<td>0.79</td>
<td></td>
</tr>
</tbody>
</table>

without acetic acid treatment. The differences with acetic acid are obviously much greater than the differences with mechanical cleaning. Of the entire sample, 123 bones were mechanically cleaned and 66 were not. When the entire sample is compared, there are no consistent differences between samples that were and were not mechanically filed (Fig. 5.75).
5.4.3 *Fourier Transform Infrared Spectroscopy of Duplicates*

The effects of acetic acid treatment and mechanical cleaning were also examined using FTIR spectroscopy. FTIR spectra of nine samples with and without acetic acid treatment were compared (G1-766-F, R-688N-F, K4-122-F, K1-85-F, Neo-1, G1-760-F, G2-1576-F, Iron B, K4-13B-F) (Fig. 5.76). Results were variable: in approximately half the samples, acetic acid treatment decreased CI and increased CP. The difference in CI between two such subsamples ranged from 0.1 to 0.9, and the difference in C/P between two subsamples ranged from 0.01 to 0.11. Intra-sample variation which is indicated by the + symbol in Figure 5.76. Despite the fact that acetic acid treatment did not produce the same type of effect in all the samples (e.g.: uniformly increasing or decreasing CI), Figure 5.76 illustrates that acid treatment reduces scatter in both CI and C/P values, drawing them toward a more clustered middle range of values. Acetic acid treatment has likely effectively removed diagenetic contaminants from the samples.

It may also be concluded that there are multiple pathways to diagenetic alteration in the sample. For example, in those samples whose C/P decreased after acetic acid treatment, it may be surmised that carbonates had been (1) adsorbed onto crystals or (2) substituted in crystal lattices. Acetic acid treatment produces a significant drop in C/P when bone is poorly preserved, because recrystallization of poorly-organized, high-carbonate, acid-soluble mineral (such as calcite) has occurred, which can be removed with acid leaching (Nielsen-Marsh and Hedges 2000b). Indeed, many samples with high C/P exhibit slightly larger calcite peaks at 713 cm\(^{-1}\), 875 cm\(^{-1}\) and 1435 cm\(^{-1}\) (Nielsen-Marsh and Hedges 2000a). In samples whose C/P values increased after acetic acid...
Figure 5.76: Effect of Acetic Acid Treatment on FTIR Indices
treatment, the diagenetic process affecting them is likely recrystallization of low-carbonate (Lee-Thorp et al. 1989).

The effects of mechanically cleaning bones on FTIR duplicates are displayed in Figure 5.77. In all cases but one, removing the outer surface of bone and cancellous bone increases CI by approximately 0.4 – 0.6, and decreases C/P by approximately 0.03 – 0.06. This is close to, but larger than the variation observed by analyzing exact duplicate subsamples of the same sample: the variation between two exact duplicates was 0.2 for CI and 0.03 for C/P (Garvie-Lok [2003] found CI values to vary by 0.1 and C/P values by 0.03 in duplicates). The reason for FTIR shifts with mechanical cleaning is unclear. It may be the case that contaminants adhering to the outside of bone have low CI and high C/P. It may also be the case that pre-treating bone in this manner leaves it more susceptible to alteration during chemical treatment. In a comparison to the entire sample, mechanically cleaned bone was not significantly differences than non-mechanically-cleaned bone in terms of either CI (p=0.957; Mann-Whitney U) or C/P (p=0.313; Mann-Whitney U) (Fig. 5.78). The FTIR shifts observed by analyzing cleaned and non-cleaned duplicate subsamples may therefore be unimportant.

### 5.5 Summary of Sample Quality

Collagen quality indicators (%C, %N, C:N ratios) were studied to identify well- and poorly-preserved bone collagen. Most collagen is of excellently quality. Ten samples from Gruczno are suspected of being poorly preserved because they show relationships between isotope values and quality indicators; specifically, C:N ratios
Figure 5.77: Effects of Mechanical Cleaning on FTIR Indices
Figure 5.78: No FTIR Differences with Mechanical Cleaning

(Table 5.1 and 5.2). These samples are excluded from analyses in Chapter 6. Site-by-site examination of collagen diagenesis has underscored the importance of using flexible criteria for assessing collagen quality. For example, throughout the sample there are 15 samples with C:N ratios higher than 3.5, yet only 10 of these were deemed diagenetically altered based on other indicators. DeNiro (1985) reports that C:N ratios higher than 3.6 are likely diagenetically altered, whereas Ambrose (1990) advocates a cut-off of 3.5. At Gruczno, Ambrose’s (1990) criterion is more applicable, whereas for the rest of the sample, DeNiro’s (1985) criterion is. The reduced sample contains well-preserved collagen of 157 individuals that will yield reliable stable isotope data. Effectiveness and reproducability of collagen extraction techniques were assessed through duplicate analysis. For duplicate samples, reproducability was within 0.03‰ for both stable carbon and stable nitrogen isotopes. Duplicates were also used to compare collagen extraction
Method 1 and Method 2. Reproducibility was reduced between methods but still within the ranges of other stable isotope studies (e.g. Iacumin et al. 1997).

Carbonate diagenesis was assessed with Fourier transform infrared spectroscopy. Crystallinity and carbonate content of bone apatite were compared to previously published modern and archaeological samples to evaluate carbonate diagenesis and any unwanted effects of chemical treatments. These guidelines were not particularly useful in this study because no consistent relationships were identified between high and low CI and C/P, isotope ratios and presence/absence of a fluoride peak at 1091 cm\(^{-1}\). Samples with apparently high CI of around 4.0 showed no other signs of being diagenetically altered. Only sample G1-347-M will be excluded from analyses on the basis of its unusual FTIR spectrum and macroscopic consistency and its anomalously low CI of 2.1 (the lowest in the entire sample). This reflects very good carbonate sample integrity: for comparison, Garvie-Lok (2001) ultimately excluded approximately one-third of her carbonate sample from Greece based on analyses of diagenesis. The final carbonate data set comprises 150 individuals.

Finally, the effectiveness of acetic acid in removing diagenetic contaminants was assessed with duplicate stable isotope and FTIR analyses. Acetic acid affected these measurements in different ways, depending on the sample, but in general decreased variability in the sample. While this pattern in FTIR indices reflects removal of contaminants, the reduced heterogeneity in isotope ratios after acetic acid treatment is troubling. Removal of contaminants should theoretically increase the scatter of stable isotope values, because diagenesis causes samples to incline toward a “middle ground” reflective of the depositional environment. There is no other indication that sample
treatment has negatively altered stable isotope ratios, however. It is possible that the depositional environments were highly varied between sites and cemetery areas to begin with, and the increased homogeneity in isotope values with acetic treatment actually reflects removal of isotopically varied contaminants. Unfortunately, no soil samples were collected during the fieldwork portion of this study to test this hypothesis. The effects of mechanical cleaning on stable isotope and FTIR values were also examined. No significant effects were identified and data from cleaned and uncleaned samples should be considered comparable.
Chapter 6: Results

Results of stable isotopic assays are presented in this section. I provide limited interpretations here, with the complete discussion in Chapter 7. First, I present a general overview of trends, followed by detailed information for each site highlighting intrapopulation variation in stable isotope signatures. Last, I compare sites, highlighting differences in stable isotope value means and dispersion, with summaries of changes in over time and among regions. In all the following figures that compare carbonate and collagen $\delta^{13}C$ values with regression lines of Kellner and Schoeninger (2007), a 1.5‰ $\delta^{13}C$ correction has been added to the regression lines (both $\delta^{13}C_{ap}$ and $\delta^{13}C_{coll}$) to account for the Suess effect (Marino and McElroy 1991).

6.1 General Overview

Faunal remains sampled here include freshwater fish (carp, catfish, tench, pike, perch and asp), anadromous fish (sturgeon), and domestic and wild terrestrial animals. Collagen data from these samples are displayed in Figure 6.1 and carbonate data from some of the domestic and wild terrestrial animals are shown in Figures 6.2 and 6.3. Animal data are discussed in greater detail in section 6.4. Unless otherwise noted, Neolithic and Iron Age skeletons are excluded from mean values in this sub-section. Neolithic and Iron Age samples are discussed in section 6.2.1. Summary data for all samples are presented in Table 6.1. Complete data tables are presented in Appendix I.
The five main study sites exhibit a mean δ¹⁵N value of 9.8±0.8‰, and a mean δ¹³C_coll value of -19.1±1.0‰. Overall, δ¹⁵N values range from 7.6‰ to 11.9‰ and δ¹³C_coll values range from -20.6‰ to -16.3‰ (Fig. 6.1). These data are consistent with a diet based primarily on C₃ terrestrial resources and including substantial amounts of animal protein, with variable inputs from either marine or C₄ plant resources.

In general, earlier sites are characterized by higher variability than later sites. There is a general decrease in δ¹³C values through time, whereas δ¹⁵N values remain relatively constant. Two samples, those from Gruczno sites 1 and 2, cluster near a δ¹³C_coll value of -20.0‰ and a δ¹⁵N value of 9.0‰. Stable isotope data from Kalduś (sites 1 and 4) and Rogowo are more scattered. There is no clear relationship between δ¹⁵N and δ¹³C_coll values when data from all five sites are considered together. The average δ¹³C_ap value among all five samples is -12.53±1.29‰. Values range from -15.40 to -7.89‰ (Figs. 6.2). δ¹³C_ap and δ¹³C_coll values are modestly related (R² = 0.4022) (Fig. 6.2). This is comparable to other medieval populations consuming primarily C₃ terrestrial resources with C₄ inputs from plants (Garvie-Lok 2001). The slope of the δ¹³C_ap vs. δ¹³C_coll line (0.75) and distribution of each stable isotope’s values

<table>
<thead>
<tr>
<th>Site</th>
<th>C. AD</th>
<th>δ¹³C_coll (VPDB) (‰)</th>
<th>δ¹⁵N (‰)</th>
<th>δ¹³C_ap (VPDB) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rogowo 2nd c.</td>
<td>-17.9 ± 0.7</td>
<td>9.7 ± 0.5</td>
<td>-11.60 ± 0.76</td>
<td></td>
</tr>
<tr>
<td>Kalduś 4</td>
<td>-18.5 ± 1.0</td>
<td>10.2 ± 0.8</td>
<td>-11.87 ± 1.32</td>
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</tr>
<tr>
<td>Gruczno 1</td>
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<td>9.3 ± 0.6</td>
<td>-12.98 ± 0.70</td>
<td></td>
</tr>
<tr>
<td>Kalduś 12th-13th c.</td>
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<td>10.2 ± 0.7</td>
<td>-12.97 ± 0.69</td>
<td></td>
</tr>
<tr>
<td>Gruczno 2</td>
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<td>9.2 ± 0.8</td>
<td>-13.40 ± 0.70</td>
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</tr>
<tr>
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<td>-19.1 ± 1.0</td>
<td>9.8 ± 0.8</td>
<td>-12.53 ± 1.30</td>
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</tr>
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</table>
Figure 6.1: Collagen $\delta^{13}$C vs. $\delta^{15}$N, All Samples

- **203**
- **Rogowo (2nd c.)**
- **Kaldus site 4 (11th c.)**
- **Gruczno site 1 (12th c.)**
- **Kaldus site 1 (12th-13th c.)**
- **Gruczno site 2 (13th-14th c.)**
- **Neolithic**
- **Iron Age**
- **Animal (domestic)**
- **Animal (wild)**
- **Fish**
Figure 6.2: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$, All Samples

$y = 0.7559x + 1.9755$

$R^2 = 0.4022$
Figure 6.3: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$: All Samples Displayed on C$_3$, C$_4$ and Marine Protein Lines$^1$

Regression lines from Kellner and Schoeninger (2007). 1.5‰ added to regression $\delta^{13}C$ values to correct for the Suess effect (Marino and McElroy 1991).

---

1 Regression lines from Kellner and Schoeninger (2007). 1.5‰ added to regression $\delta^{13}C$ values to correct for the Suess effect (Marino and McElroy 1991).
demonstrate greater variations in collagen values than in carbonate values (Fig. 6.3). This suggests protein sources are more variable than are energy sources, while protein and energy sources differ in their δ\(^{13}\)C signatures. The majority of plants in medieval Northern Europe were C\(_3\) plants, although at least one C\(_4\) plant (millet) was consumed by Slavic populations. Millet is the likely source of this C\(_4\) stable isotope signature in human bone.

There are stable isotope differences between sites. Through time, δ\(^{15}\)N ratios remain relatively uniform. However, when each site is considered separately, δ\(^{13}\)C\(_{\text{coll}}\) values become more negative over time (e.g: δ\(^{13}\)C\(_{\text{coll}}\) values at Kaldu site 1 are lower than at Kaldu site 4, and those at Gruczno site 2 are lower than at Gruczno site 1). At Kaldu (sites 4 and 1), both δ\(^{15}\)N and δ\(^{13}\)C\(_{\text{coll}}\) values are generally 1‰ higher than at Gruczno (sites 1 and 2).

The four Neolithic and Iron Age samples are widely scattered, but three of them, including both Neolithic samples, are relatively depleted in \(^{13}\)C\(_{\text{coll}}\) compared to the rest of the sample. All are within the δ\(^{15}\)N range of the rest of the sample. In general, human δ\(^{15}\)N values here are approximately 3.0‰ higher than those of domesticated animals, which is consistent with one trophic level. Domesticated animals exhibit consistently higher δ\(^{15}\)N values than do wild animals. Some domesticated animals (chickens and dog) exhibit δ\(^{15}\)N values within the range of human values. Human δ\(^{13}\)C\(_{\text{coll}}\) values are all higher than animal δ\(^{13}\)C\(_{\text{coll}}\) values with a few exceptions: the chickens, dog, and some cows exhibit high δ\(^{13}\)C\(_{\text{coll}}\) values. Animal data are discussed in more detail in section 6.4.
As discussed in Chapter 3, $\Delta^{13}\text{C}_{\text{(ap-coll)}}$ has been used to represent trophic position because the $\Delta^{13}\text{C}_{\text{(ap-coll)}}$ ratios of carnivores are smaller, due to the fact that carnivores obtain more of their dietary energy from isotopically depleted lipids. This is only true when dietary macronutrients do not differ isotopically (i.e., the ecosystem must be purely C$_3$ or purely C$_4$). The two measures of trophic level, $\delta^{15}\text{N}$ values and $\Delta^{13}\text{C}_{\text{(ap-coll)}}$, are unrelated to each other in this study (Fig. 6.4). This suggests that the $\delta^{13}\text{C}$ values of protein and energy sources differ in these samples. Manuring is another possible explanation for disjunction between $\delta^{15}\text{N}$ and $\Delta^{13}\text{C}_{\text{(ap-coll)}}$ values. Manuring does not alter $\Delta^{13}\text{C}_{\text{(ap-coll)}}$ values in consumers, but does change the $\delta^{15}\text{N}$ values of plants at the base of the human food chain by increasing the $^{15}\text{N}$ values of available nitrogen sources in soils. Omnivorous chickens and a dog plot within the cluster of human values (Figs. 6.1)
The other 10 animals for which both collagen and carbonate were assayed are wild fauna, pigs and a cow, and are clearly separated from human values.

6.2 Stable Isotope Values at Each Site

In this section, data from each site are presented individually in tabular and graphic form. Only collagen and carbonate data deemed to be well-preserved in Chapter 5 are reported here. Individuals are referred to by their ID names which include the abbreviated site number, the individual number and the sex (e.g: K4-186-F is the female skeleton #186 from Kaldus site 4). Tables with all data (including samples rejected based on quality indicators) are listed in Appendix I. Sex-based differences in stable isotope signatures are discussed site-by-site in this subsection, along with stable isotope differences between different burial styles. The p-values reported in tables throughout these sections are from Dwass-Steel-Critchlow-Fligner pairwise comparisons following Kruskal-Wallis ANOVA tests.

6.2.1 Neolithic and Iron Age

Data from 2 Neolithic and 2 Iron Age skeletons are reported. No faunal remains from these burial contexts are available; therefore medieval animal remains must be used for comparisons. It is possible that food production strategies (foddering animals, fertilizing crops) differ between ancient and medieval periods. Medieval domesticated
fauna are therefore excluded from the Neolithic and Iron Age baseline, which only includes medieval wild animals.

Neolithic individuals exhibit relatively low $\delta^{13}C_{\text{coll}}$ values of $-21.3\%$ (Niedzwica, or Neo-2) and $-20.6\%$ (Kowal, or Neo-1). The $\delta^{13}C_{\text{ap}}$ values are $-11.22\%$ (Kowal) and $-13.88\%$ (Niedzwica). The $\delta^{15}N$ values are $9.9\%$ (Kowal) and $10.2\%$ (Niedzwica), which are near the average for all samples in this study. These values are 4-5\% higher than wild animal $\delta^{15}N$ values, which are at the upper end of enrichment expected from one trophic level (Hedges and Reynard 2007) (Fig. 6.5). Both Neolithic samples plot far to the left of the $C_3$ protein line, indicating a diet entirely based on $C_3$ protein sources (Fig. 6.6). $\Delta^{13}C_{(\text{ap-coll})}$ values of the Neolithic samples are high (9.0\% and 7.7\%), which along with $\delta^{15}N$ values suggests either a diet low in meat or fish and high in plant materials, or including millet as an energy source (Fig. 6.7). A high $\delta^{13}C_{\text{ap}}$ value from the Kowal individual reinforces the possibility of millet consumption (Fig. 6.6).
Figure 6.6: $\delta^{13}$C_{coll} vs. $\delta^{13}$C_{ap}, Neolithic and Iron Age Samples

- C3 Protein Line
- Kowal
- Bożejewice
- Nierdrzwica
- Gziń

Figure 6.7: $\Delta^{13}$C_{ap-coll} vs. $\delta^{15}$N, Neolithic and Iron Age Samples

- Gziń
- Nierdrzwica
- Kowal
- Bożejewice

- Neolithic
- Iron Age
- Animal (wild)
The two Iron Age samples are dissimilar in both their $\delta^{13}C_{\text{coll}}$ and their $\delta^{15}N$ values. The Iron Age sample from Bożejewice exhibits a $\delta^{15}N$ value of 9.5‰ and a $\delta^{13}C_{\text{coll}}$ value of -20.7‰ and plots near the Neolithic samples in Figure 6.5. Its $\Delta^{13}C_{(\text{ap-coll})}$ value is high, like the Neolithic samples, at 8.3‰. The Bożejewice sample exhibits a $\delta^{13}C_{\text{ap}}$ value of -12.40‰ and when $\delta^{13}C$ from collagen and apatite are considered in tandem, plots far to the left of the C$_3$ protein line, with the Neolithic samples (Fig. 6.6).

The Iron Age sample from Gziń exhibits a higher $\delta^{15}N$ value of 10.5‰ and higher $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ values of -18.5‰ and -12.86‰, respectively. It plots to the right of the C$_3$ protein line. Of the four ancient samples, Gziń exhibits the lowest $\Delta^{13}C_{(\text{ap-coll})}$ value of 5.6‰. When this value is plotted against $\delta^{15}N$, the Gziń sample again is an outlier (Fig. 6.7). Together these data suggest a diet based on plants with a C$_3$ signature and including a mixture of C$_3$ and C$_4$ protein. Marine fish may contribute to this C$_4$ signature in the Gziń sample.

### 6.2.2 Rogowo, 2$^{nd}$ c. AD

The Roman Era bone collagen sample consists of 30 individuals; 29 of these were assayed for carbonate data. All samples exhibited acceptable collagen and carbonate quality indicators and none were excluded from these analyses. Summary data are presented in Table 6.2 and Figures 6.8-6.10.

Rogowo $\delta^{13}C_{\text{coll}}$ values range from -19.5 to -16.4‰ and $\delta^{15}N$ values range from 8.6 to 10.9‰. No correlation was observed between $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N$ values ($R^2 = 0.1463$) (Fig. 6.8). $\delta^{13}C_{\text{ap}}$ values range from -13.09 to -9.69‰. $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ values
are modestly correlated at Rogowo ($R^2=0.3439$) (Fig. 6.9). When plotted on Kellner and Schoeninger’s (2007) regression lines, Rogowo plots considerably to the right of the $C_3$ protein line, approximately at its mid-point (Fig. 6.9), suggesting dietary energy came from both $C_3$ and $C_4$ plants, with supplemental $C_4$ or marine protein. $\Delta^{13}C_{(ap-coll)}$ and $\delta^{15}N$ values are not correlated (Fig. 6.10).

Men and women exhibit significantly different $\delta^{13}C$ values (Table 6.2). The $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap}$ values of females are significantly higher (Kruskal-Wallis Test, $p=0.014$ and $0.015$, respectively). Women exhibit lower mean $\delta^{15}N$ than men ($p=0.078$). Some women were buried with copper-alloy jewelry and exhibit green staining on their bones, especially at the clavicles, first ribs and distal radii and humeri. Five female skeletons with jewelry were sampled in this study. The $\delta^{13}C_{coll}$, $\delta^{13}C_{ap}$ and $\delta^{15}N$ values of women with and without jewelry are similar, although $\delta^{13}C_{ap}$ of women without jewelry is lower ($p=0.157$). The “richest” grave at Rogowo is skeleton R-59-F, a woman buried with substantial quantities of jewelry. This individual exhibits relatively high $\delta^{13}C_{coll}$ value (-16.8‰) compared to mean values, but $\delta^{13}C_{ap}$ (-10.95‰), $\Delta^{13}C_{(ap-coll)}$ (5.9‰), and

<table>
<thead>
<tr>
<th></th>
<th>$\delta^{13}C_{coll}$ (VPDB) (‰)</th>
<th>$\delta^{15}N_{AIR}$ (‰)</th>
<th>$\delta^{13}C_{ap}$ (VPDB) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-17.9 ± 0.8</td>
<td>9.7 ± 0.5</td>
<td>-11.60 ± 0.76</td>
</tr>
<tr>
<td>Male (n=15)</td>
<td>-18.3 ± 0.7</td>
<td>9.8 ± 0.5</td>
<td>-11.92 ± 0.69</td>
</tr>
<tr>
<td>Female (n=15)</td>
<td>-17.5 ± 0.6</td>
<td>9.5 ± 0.5</td>
<td>-11.26 ± 0.69</td>
</tr>
<tr>
<td>Females; jewelry (n=5)</td>
<td>-17.6 ± 0.6</td>
<td>9.7 ± 0.6</td>
<td>-10.84 ± 0.80</td>
</tr>
<tr>
<td>Females; no jewelry (n=10)</td>
<td>-17.5 ± 0.7</td>
<td>9.5 ± 0.4</td>
<td>-11.42 ± 0.60</td>
</tr>
</tbody>
</table>

Table 6.2: Summary Data from Rogowo
Figure 6.8: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, All Rogowo Samples

$y = -0.2644x + 4.9482$
$R^2 = 0.1463$

Figure 6.9: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$, All Rogowo Samples

C3 protein line
δ\(^{15}\)N values (9.3‰) are not unusual. The fact that a low Δ\(^{13}\)C\(_{(ap-coll)}\) value is associated with a low δ\(^{15}\)N value in R-59-F is an example of how this overall sample contradicts the expectation that these measurements both record trophic level. This expectation is only tenable if diets are purely C\(_3\) or C\(_4\) (Garvie-Lok 2001; Tieszen and Fagre 1993).

6.2.3 **Kaldus Site 4, 11\(^{th}\) c. AD**

From Kaldus site 4, 37 skeletons were examined including 18 women, 17 men and two probable male skeletons that have been grouped with men for analysis. Of these, bone carbonate from 15 men and 14 women were also analyzed. Collagen preservation was acceptable from Kaldus site 4 samples with the possible exception of one individual,
Table 6.3: Kaldus 4 Summary Data

<table>
<thead>
<tr>
<th></th>
<th>( \delta^{13}C_{\text{coll}} , (\text{VPDB}) , (%) )</th>
<th>( \delta^{15}N , (\text{AIR}) , (%) )</th>
<th>( \delta^{13}C_{\text{ap}} , (\text{VPDB}) , (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-18.5 ± 1.0</td>
<td>10.2 ± 0.8</td>
<td>-11.87 ± 1.32</td>
</tr>
<tr>
<td>Male</td>
<td>-18.3 ± 1.0</td>
<td>10.2 ± 0.8</td>
<td>-11.64 ± 1.28</td>
</tr>
<tr>
<td>Female</td>
<td>-18.7 ± 1.1</td>
<td>10.1 ± 0.8</td>
<td>-12.11 ± 1.36</td>
</tr>
<tr>
<td>&quot;Christian&quot;-style</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>burial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scandinavian-style</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>burial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;Pagan&quot;-style</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>burial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p=0.111 )</td>
<td>( p=0.584 )</td>
<td>( p=0.275 )</td>
<td></td>
</tr>
</tbody>
</table>

K4-186-F. K4-186-F had low %N and %C values (3.5% and 9.9%, respectively). For comparison, the lowest values for modern bones observed by Ambrose (1990) were 5.5% and 15.3%, respectively. K4-186-F was not excluded from the following analyses because its C:N ratio was acceptable and no anomalies were observed in stable isotope signatures. No apatite samples were excluded from Kaldus site 4 on the basis of FTIR results (Chapter 5).

At Kaldus site 4 \( \delta^{15}N \) values range from 8.7 to 11.9‰ and \( \delta^{13}C_{\text{coll}} \) range from -20.3 to -16.3‰ (Table 6.3). There is no strong correlation between \( \delta^{15}N \) and \( \delta^{13}C_{\text{coll}} \) values (\( R^2 = 0.0115 \)) (Fig. 6.11). \( \delta^{13}C_{\text{ap}} \) values ranged from -14.20 to -9.23‰. There is a relationship between \( \delta^{13}C_{\text{ap}} \) and \( \delta^{13}C_{\text{coll}} \) values (\( R^2 = 0.5211 \)) (Fig. 6.11), which is stronger than at any other site. There is no relationship between \( \delta^{15}N \) and \( \Delta^{13}C_{\text{(ap-coll)}} \) values (\( R^2 = 0.0098 \)). Kaldus site 4 data plot to the right of the C3 protein line (Fig. 6.12), and
Figure 6.11: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Kaldus Site 4

Figure 6.12: $\delta^{13}C_{coll}$ vs. $\delta^{13}C_{ap}$, Kaldus Site 4 Divided Into $\delta^{15}N$ Groups
approximately at its midpoint. Data points that plot to the right of the C₃ protein line do
not exhibit consistently higher δ¹⁵N values, as would be expected if marine fish were
being consumed.

6.2.3.i Phases at Kaldus Site 4 (11th c.)

At Kaldus site 4 it is possible to identify five relative chronological phases within
the 11th c. cemetery. These are grouped into two broader phases, Phase 1 and Phase 2
(Table 6.4). This was accomplished using radiocarbon data along with coins and other
grave goods found in the cemetery. Phase 1 comprises expanded phases 1a, 1b and 2a.
Phase 2 comprises expanded Phases 2b and 3. All five expanded phases are represented
at Kaldus site 4, meaning that although the average date of site 4 (11th c.) is older than
that of site 1 (12th-13th c.), some skeletons from Kaldus site 4 represent Phases 2b and 3
and were contemporary with those from Kaldus site 1. All skeletons from Kaldus site 1
are from Phase 2 but cannot be dated more precisely than this. Here they are considered
to be from expanded Phase 2b/3. Small-scale changes between phases at Kaldus site 4
are plotted in Figure 6.13 a, b and c. The first five expanded phases represent data from
Kaldus site 4. Data from Kaldus site 1 represent the last expanded phase, although
Kaldus site 1 overlaps completely with Phases 2b and 3 skeletons from Kaldus site 4.

There are no statistically significant differences in stable isotope ratios between
Kaldus site 4 Phases 2b and 3 and Kaldus site 1 (Phases 2b/3). Over time, δ¹³C_coll values
gradually decrease and become more homogeneous. δ¹³C_ap values also decrease, but not
gradually: all Phase 1 samples are higher than all phase 2 samples (including Kaldus site
Table 6.4: Kaldus Stable Isotope Data in Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Expanded phase</th>
<th>Collagen; (n=)</th>
<th>(\delta^{13}\text{C}_{\text{coll}}) (VPDB) (‰)</th>
<th>(\delta^{15}\text{N}_{\text{AIR}}) (‰)</th>
<th>Apatite; (n=)</th>
<th>(\delta^{13}\text{C}_{\text{ap}}) (VPDB) (‰)</th>
<th>(\delta^{18}\text{O}_{\text{VPDB}}) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>7</td>
<td>-17.9 ± 1.4</td>
<td>10.6 ± 0.6</td>
<td>7</td>
<td>-11.63 ± 1.3</td>
<td>-6.33 ± 0.28</td>
</tr>
<tr>
<td>1</td>
<td>1b</td>
<td>9</td>
<td>-18.4 ± 0.9</td>
<td>10.3 ± 0.9</td>
<td>6</td>
<td>-11.75 ± 1.2</td>
<td>-6.76 ± 0.47</td>
</tr>
<tr>
<td>1</td>
<td>2a</td>
<td>11</td>
<td>-18.5 ± 0.9</td>
<td>10.2 ± 0.6</td>
<td>8</td>
<td>-11.15 ± 1.35</td>
<td>-6.98 ± 0.40</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td>1</td>
<td>-19.4</td>
<td>9.2</td>
<td>1</td>
<td>-13.02</td>
<td>-6.84</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>7</td>
<td>-19.3 ± 0.6</td>
<td>9.8 ± 0.6</td>
<td>5</td>
<td>-13.18 ± 0.62</td>
<td>-7.20 ± 0.35</td>
</tr>
<tr>
<td>2</td>
<td>2b-3 (Kaldus 1)</td>
<td>30</td>
<td>-19.5 ± 0.4</td>
<td>10.2 ± 0.7</td>
<td>30</td>
<td>-12.78 ± 1.69</td>
<td>-6.75 ± 0.49</td>
</tr>
</tbody>
</table>

1). There is no consistent temporal change in \(\delta^{15}\text{N}\) values. The apparent drop in \(\delta^{15}\text{N}\) ratios at Phase 2b is misleading as Phase 2b was represented by a single individual. Additionally, an unknown number of skeletons from Kaldus site 1 (Phase 2b/3) would also fall into this phase were they as precisely dated.

Pairwise comparisons of stable isotope values between expanded phases were calculated using a Dwass-Steel-Critchlow-Fligner test. Significance of differences in each stable isotope ratio between expanded phases are overlaid in Figure 6.13 and indicated by the unequal symbol (≠). Statistical comparisons demonstrate no statistically significant stable isotope differences between \(\delta^{13}\text{C}_{\text{coll}}\) and \(\delta^{13}\text{C}_{\text{ap}}\) values of the earliest three expanded phases (which together equate to Phase 1). However \(\delta^{13}\text{C}_{\text{coll}}\) and \(\delta^{13}\text{C}_{\text{ap}}\) values of skeletons from the second two expanded phases (they along with all of Kaldus site 1 equate to Phase 2) differ significantly from earlier phase 1 skeletons. This appears to be a general trend caused by absence of high \(\delta^{13}\text{C}\) values in the later phases (Fig. 6.13). \(\delta^{15}\text{N}\) values were significantly different between all phases except 1b and 2a which both represent Phase 1.
Figure 6.13: Kaldus Site 4 Phases and Isotope Values

1a = 1b = 2a ≠ 2b ≠ 3 ≠ 2b/3

1a ≠ 1b = 2a ≠ 2b ≠ 3 ≠ 2b/3

1a = 1b = 2a ≠ 2b ≠ 3 ≠ 2b/3
6.2.3ii Sex differences

In general, females at Kałdus site 4 exhibit $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ values approximately 0.5‰ lower than those of males (p=0.111 and 0.275, respectively) (Table 6.3; Figs. 6.14-6.15). $\delta^{15}N$ values are similar for men (10.2‰) and women (10.1‰) (p=0.584). Average $\Delta^{13}C_{\text{(ap-coll)}}$ values also are similar; men 6.6‰, women 6.5‰.

Sex-based differences in isotope signatures were examined within each Kałdus site 4 phase using the Kolomogorov-Smirnov Test. Significant difference between men and women only are present in phase 2a: $\delta^{13}C_{\text{coll}}$ values were significantly lower among women than among men (p=0.023). $\delta^{13}C_{\text{ap}}$ values also were lower (p=0.053).

6.2.3iii Burial style differences

Kałdus site 4 shows considerable variation in burial styles. Data were sorted into three groups for the purposes of statistical comparisons: “Christian”-style graves (supine, East-West axis), “Scandinavian”-style graves (wood chambers, double graves) and “pagan”-style graves (flexed position, stone on chest). Among these groupings, stable isotope values are similar between “Christian” and “pagan” skeletons, but Scandinavian-style burials are associated with slightly higher $\delta^{15}N$, $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ values (Table 6.3; Figs. 6.16-6.18). The highest $\delta^{15}N$ value at Kałdus site 4 is from an individual buried with a large stone on her chest, an anti-vampire mortuary practice (T. Kozlowski, pers. comm.).
Figure 6.14: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Kaldus Site 4 Males and Females

$y = 0.0782x + 11.624$
$R^2 = 0.0115$ (All Samples)

Figure 6.15: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$, Kaldus Site 4 Males and Females

$R^2 = 0.5211$ (All Samples)
6.2.3.iv Grave Goods

At Kaldus site 4, 13 of the 37 individuals sampled were interred with grave goods. There are no large δ¹⁵N and δ¹³C_coll differences between skeletons buried with and without grave goods (δ¹⁵N p=0.949; δ¹³C_coll p=0.546) (Fig. 6.19). δ¹³C_ap differences also are small (Kolomogorov-Smirnov, p=0.251). When δ¹³C_coll and δ¹³C_ap are plotted together, several individuals without grave goods plot above the rest; that is, they exhibit relatively high δ¹³C_ap values for their corresponding δ¹³C_coll values (Fig. 6.20). δ¹³C_ap values being more sensitive to dietary energy (carbohydrate) sources, this relationship could indicate greater millet consumption among individuals interred without grave goods, which might suggest millet was a “low-status” food. This difference also is reflected in Figure 6.21 where δ¹⁵N values are plotted against Δ¹³C_(ap-coll) values. In Figure 6.21, the lack of a relationship between δ¹⁵N and Δ¹³C_(ap-coll) values for individuals without grave goods indicates that their protein and energy sources differ in their δ¹³C signatures: energy sources are more enriched in ¹³C than are protein sources. Millet is the only possible high ¹³C energy source in medieval Poland. Apparently individuals buried with grave goods were less likely to consume millet than those buried without.

6.2.3.v Double Graves

At Kaldus site 4, three pairs of individuals were buried in double graves. These are K4-13A-M and K4-13B-F, K4-256A-F and K4-256B-M, and K4-261A-M and K4-261B-M (Figs. 6.22-6.23).
Figure 6.16: Collagen $\delta^{13}\text{C}$ vs. $\delta^{15}\text{N}$, Kaldus Site 4 Burial Styles

Figure 6.17: $\delta^{13}\text{C}_{\text{coll}}$ vs. $\delta^{13}\text{C}_{\text{cap}}$, Kaldus Site 4 Burial Styles

C$_3$ protein line
Figure 6.18: $\Delta^{13}C_{\text{ap-coll}}$ vs. $\delta^{15}N$, Kałdus Site 4 Burial Styles

Figure 6.19: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Kałdus Site 4 Grave Goods
Figure 6.20: $\delta^{13}$C$_{\text{coll}}$ vs. $\delta^{13}$C$_{\text{ap}}$, Kałdus Site 4, Grave Goods

Figure 6.21: $\delta^{15}$N vs. $\Delta^{13}$C$_{\text{(ap-coll)}}$, Kałdus Site 4 Grave Goods
Figure 6.22: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{15}N$ at Kaldus site 4 showing Double Burial Pairs

Figure 6.22: Single burials from Kaldus site 4 are represented by gray circles. Most are supine and oriented E-W. Eight flexed burials are demarcated by an “X” over the circle. Other data points represent double burials. Pairs are represented by data points of the same color (dark vs. light) and shape and are connected by lines. Stable isotope signatures of individuals in double graves are not similar.
Figure 6.23: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$, Kaldus Site 4 Showing Double Burial Pairs
6.2.4 Kaldus Site 1, 12th-13th c. AD

At Kaldus site 1, collagen and apatite were extracted from bones of 30 individuals, including 15 men and 15 women. Collagen preservation was very good. All C/N ratios were acceptable, ranging from 3.2 to 3.4. Percent C and N were also acceptable. One sample yielded low values of 7% nitrogen and 19% carbon, but these are still acceptable. Bone mineral was also well preserved as measured using FTIR. No samples were excluded from analyses due to preservation quality.

δ¹⁵N values ranged from 8.7 to 11.6‰, a range nearly identical to that at Kaldus site 4. δ¹³Ccoll values ranged from -18.7 to -20.5‰, somewhat lower than at Kaldus site 4. δ¹⁵N values and δ¹³Ccoll values show little relationship (R² = 0.0482) (Table 6.5; Fig. 6.24). δ¹³Cap values exhibit a wide range of -7.89 to -15.40‰. The possibility that relatively higher values may be due to diagenetic alteration of bone mineral was discussed earlier and is considered unlikely. Unlike Kaldus site 4, δ¹³Ccoll values and δ¹³Cap values are not closely related (R² = 0.1805) (Fig. 6.25).

Table 6.5: Kaldus Site 1 Summary

<table>
<thead>
<tr>
<th></th>
<th>δ¹³Ccoll (VPDB) (‰)</th>
<th>δ¹⁵NAIR (‰)</th>
<th>δ¹³Cap (VPDB) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-19.5 ± 0.4</td>
<td>10.2 ± 0.7</td>
<td>-12.78 ± 1.69</td>
</tr>
<tr>
<td>Male</td>
<td>-19.4 ± 0.5</td>
<td>10.4 ± 0.7</td>
<td>-12.84 ± 1.60</td>
</tr>
<tr>
<td>Female</td>
<td>-19.6 ± 0.3</td>
<td>10.1 ± 0.8</td>
<td>-12.72 ± 1.83</td>
</tr>
<tr>
<td>Grave goods (n=24)</td>
<td>10.1 ± 0.7</td>
<td>-19.7 ± 0.5</td>
<td>-12.96 ± 0.82</td>
</tr>
<tr>
<td>No grave goods (n=6)</td>
<td>10.3 ± 0.7</td>
<td>-19.4 ± 0.4</td>
<td>-12.73 ± 1.82</td>
</tr>
<tr>
<td></td>
<td>p=0.110</td>
<td>p=0.395</td>
<td>p=0.395</td>
</tr>
</tbody>
</table>

No grave goods (n=6)

No grave goods (n=6)
6.2.4.i Sex Differences

At Kaldu site 1 men show slightly higher $\delta^{15}N$ ($p=0.110$) and $\delta^{13}C_{\text{coll}}$ values (0.395) compared to women, but $\delta^{13}C_{\text{ap}}$ values are indistinguishable ($p=0.934$) (Table 6.5; Figs. 6.24 and 6.25).
6.2.4.ii Grave Goods

There are fewer grave goods at Kaldus site 1 than at site 4. They are limited to knives, temporal rings (worn as women’s headdresses), rings and flint. Of the 30 individuals sampled, 24 were buried with grave goods. There are no clear differences in stable isotope values of skeletons buried with or without grave goods (Figs. 6.26-6.28).
6.2.5 *Gruczno Site 1, 12th c. AD*

Collagen from 34 individuals was sampled from Gruczno site 1, including 17 men and 17 women. Of these, 32 samples yielded well-preserved collagen with nitrogen yields of between 7.5 and 14%, carbon yields of between 25 and 40%, and C:N ratios of between 3.2 and 3.4. Collagen from two samples (G1-271-M and G1-54-F) yielded low nitrogen and carbon concentrations (approximately 5% and 18%, respectively). Although still within an acceptable range (Ambrose 1990), the C/N ratios of these samples were 3.9, which is quite different than the rest of the sample. These two samples were excluded from analyses as discussed in Chapter 5. Thus, the final collagen sample from Gruczno site 1 comprises 32 individuals.

From 34 samples, 29 individuals were also sampled for apatite, including 15 males and 14 females. One sample (G1-347-M) yielded apatite with unacceptable FTIR
indices and is excluded from analyses, as discussed in Chapter 5. The final apatite sample includes 14 men and 14 women.

At Gruczno site 1, $\delta^{15}$N ranges from 8.1 to 11.2‰ with a mean of 9.3±0.6‰. $\delta^{13}$C$_{coll}$ ranges from -20.6 to -19.0‰ with a mean value of -19.8‰. The relationship between $\delta^{15}$N and $\delta^{13}$C$_{coll}$ is weak ($R^2$=0.1567) (Fig. 6.29). Gruczno site 1 $\delta^{13}$C$_{ap}$ values range from -14.22‰ to -11.12‰ with a mean value of -12.98‰. There is little correlation between $\delta^{13}$C$_{coll}$ and $\delta^{13}$C$_{ap}$ values (Fig. 6.30). Together these results may indicate a more terrestrial diet.

### 6.2.5.i Sex Differences

At Gruczno site 1 males have a higher mean $\delta^{13}$C$_{coll}$ value than do females (-19.7‰ vs. -19.9‰; $p$=0.07) (Table 6.6; Figs. 6.28, 6.29). The $\delta^{13}$C$_{ap}$ mean of men is slightly higher than that of women as well ($p$=0.646). $\delta^{15}$N values of men and women are indistinguishable.

<table>
<thead>
<tr>
<th></th>
<th>$\delta^{13}$C$_{coll}$ (VPDB) (‰)</th>
<th>$\delta^{15}$N$_{AIR}$ (‰)</th>
<th>$\delta^{13}$C$_{ap}$ (VPDB) (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-19.8 ± 0.4</td>
<td>9.3 ± 0.6</td>
<td>-12.98 ± 0.70</td>
</tr>
<tr>
<td>Male</td>
<td>-19.7 ± 0.2</td>
<td>9.3 ± 0.5</td>
<td>-12.95 ± 0.69</td>
</tr>
<tr>
<td>Female</td>
<td>-19.9 ± 0.5</td>
<td>9.4 ± 0.8</td>
<td>-13.00 ± 0.72</td>
</tr>
<tr>
<td>Grave goods</td>
<td>-19.8 ± 0.4</td>
<td>9.2 ± 0.6</td>
<td>-12.95 ± 0.55</td>
</tr>
<tr>
<td>No grave goods</td>
<td>-19.1 ± 0.3</td>
<td>9.4 ± 0.7</td>
<td>-13.00 ± 0.82</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$p$=0.070</th>
<th>$p$=0.910</th>
<th>$p$=0.646</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grave goods</td>
<td>$p$=0.613</td>
<td>$p$=0.243</td>
<td>$p$=0.516</td>
</tr>
<tr>
<td>No grave goods</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.29: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Gruczno Site 1 Males and Females

$$R^2 = 0.1567$$
(All Samples)

Figure 6.30: $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$, Gruczno Site 1, Males and Females

$$R^2 = 0.0001$$
(All Samples)
6.2.5.ii Grave Goods

Stable isotope ratios of skeletons buried with and without grave goods are similar (Table 6.6; Figs. 6.31-6.32). $\delta^{15}$N of skeletons without grave goods is slightly higher (p=0.243).
6.2.6  *Gruczno Site 2, 13th-14th c. AD*

From Gruczno site 2, 32 individuals were sampled including 17 males and 15 females. Of these, 30 individuals were sampled for apatite (including 15 men and 15 women). Collagen quality was more variable at Gruczno site 2 than at any other site. The %N values ranged from 5.3 to 13.8%, and %C values ranged from 14.6 to 38.6%. One sample fell below the minimum acceptable values of 5.5% nitrogen and 15.3% carbon. Eight samples exhibited C:N ratios of 3.5 or higher, several outside the acceptable range of 2.8 to 3.6, with a maximum value of 4.0 (SD = 0.2). High C:N ratios are associated with lower $\delta^{13}C_{\text{coll}}$ values at Gruczno site 1 ($R^2=0.4727$). This suggests contamination of collagen by low-$^{13}$C microorganisms or incomplete removal of low-$^{13}$C lipids from these samples. When samples with C:N ratios of 3.5 or higher are removed, the association between C:N and $\delta^{13}C_{\text{coll}}$ values declined from $R^2=0.4727$ to 0.0509 (Figs. 5.31, 5.36). Because these eight collagen samples likely are contaminated, they are excluded from analyses unless otherwise noted.

At Gruczno site 2, $\delta^{13}C_{\text{coll}}$ values exhibit a relatively narrow range, from -20.5‰ to -19.5‰. The mean $\delta^{13}C_{\text{coll}}$ value is -19.9±0.3‰. $\delta^{15}N$ values range from 7.5‰ to 10.7‰ with a mean value of 9.2±0.8‰ (Table 6.7). There is little association between $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N$ values ($R^2=0.012$) (Fig. 6.33). $\delta^{13}C_{\text{ap}}$ values ranged from -14.9 to -11.69‰ with a mean value of -13.41±0.70. This is the lowest among all the sites, suggesting a diet of predominantly C$_3$ resources with the smallest contribution of millet to dietary energy of all sites. Gruczno site 2 data points plot on the C$_3$ protein line (Fig. 6.34). The relationship between $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ values is low ($R^2=0.1143$) (Fig. 6.34).
### Table 6.7: Gruczno Site 2 Summary

<table>
<thead>
<tr>
<th></th>
<th>$\delta^{13}\text{C}_{\text{coll}}$ (VPDB) (%)</th>
<th>$\delta^{15}\text{N}_{\text{AIR}}$ (%)</th>
<th>$\delta^{13}\text{C}_{\text{ap}}$ (VPDB) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-19.9 ± 0.3</td>
<td>9.2 ± 0.8</td>
<td>-13.40 ± 0.70</td>
</tr>
<tr>
<td>Male</td>
<td>-19.8 ± 0.2</td>
<td>9.2 ± 0.9</td>
<td>-13.12 ± 0.70</td>
</tr>
<tr>
<td>Female</td>
<td>-20.1 ± 0.3</td>
<td>9.1 ± 0.6</td>
<td>-13.69 ± 0.59</td>
</tr>
</tbody>
</table>

|        | $p=0.040$                                     | $p=0.839$                              | $p=0.026$                                     |

#### 6.2.6.i Sex differences

At Gruczno site 2, men exhibit significantly higher $\delta^{13}\text{C}_{\text{coll}}$ and $\delta^{13}\text{C}_{\text{ap}}$ values than women ($\delta^{13}\text{C}_{\text{coll}}$: -19.8±0.2‰ vs. -20.1±0.3‰, $p=0.04$; $\delta^{13}\text{C}_{\text{ap}}$: -13.12 vs. -13.69, $p=0.026$) (Table 6.7; Figs. 6.33-6.34). This is the sole medieval site under study where sex-based differences in diet are obvious. When plotted on the regression lines of Kellner and Schoeninger (2007) at Gruczno site 2 women plot lower than men on the $\text{C}_3$ protein line (Fig. 6.34). There is no sex difference in locations of data points to the left or right of the $\text{C}_3$ protein line. This suggests that different stable isotope values of men and women are due to different amounts of $\text{C}_4$ energy in diet – that is, differences in millet consumption, not differences in protein sources (such as fish). $\delta^{15}\text{N}$ values of men and women are not as different ($p=0.839$).
Figure 6.33: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, Gruczno Site 2 Males and Females

Figure 6.34: $\delta^{13}C_{coll}$ vs. $\delta^{13}C_{ap}$, Gruczno Site 2, Males and Females
6.3 Site Comparisons

I use this section to compare temporal trends in stable isotopes at each site. Trends for each stable isotope are presented tabularly along with Tukey tests from ANOVA, and p-values for inter-site comparisons. Figures 6.35 and 6.36 display collagen and carbonate data from all sites side-by-side. Most discussion in this section is on the Roman Era and medieval samples. Neolithic and Iron Age samples already were discussed in section 6.2. To summarize, with the exception of the Iron Age individual from Gziń, these individuals differ from the rest of the sample by exhibiting lower $\delta^{13}C$ values. $\delta^{15}N$ values from the Neolithic and Iron Age skeletons are not different from the rest of the sample (Fig. 6.35).

6.3.1 Comparison of $\delta^{15}N$ values among sites

Over time there is little change in $\delta^{15}N$ values (Figs. 6.35; 6.37). For example, at Kaldus sites 4 and 1, mean $\delta^{15}N$ values are both 10.2‰. Despite a lack of temporal change in the medieval sample, $\delta^{15}N$ values from Kaldus sites are about 1‰ higher than those from Gruczno (ANOVA, p<0.001).

The mean $\delta^{15}N$ value at Rogowo is 9.7±0.5‰. Rogowo is not statistically different from either Gruczno site 1 or 2, but is significantly different from Kaldus sites 4 and 1 (Table 6.8). The four medieval sites exhibit similar $\delta^{15}N$ ranges with standard deviations of 0.6‰ and 0.7‰. Rogowo exhibits a slightly more restricted range and a standard deviation of 0.5‰.
Figure 6.35: Collagen $\delta^{13}C$ vs. $\delta^{15}N$, All Sites (Mean±1σ) and Animals
Figure 6.36: $\delta^{13}$C$_{\text{coll}}$ vs. $\delta^{13}$C$_{\text{ap}}$, All Sites (Mean±1σ) and Animals

- 100% C4 energy
- C3 protein line
- Marine protein line
- C4 protein line

- Rogowo (2nd c.)
- Kaldus 4 (11th c.)
- Gruczno 1 (12th c.)
- Kaldus 1 (12th-13th c.)
- Gruczno 2 (12th-13th c.)
- Neolithic
- Iron Age
- Wild Fauna
- Domestic Fauna

<table>
<thead>
<tr>
<th>δ$<em>{13}$C$</em>{\text{ap (VPDB)}}$ (‰)</th>
<th>δ$<em>{13}$C$</em>{\text{coll (VPDB)}}$ (‰)</th>
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</thead>
<tbody>
<tr>
<td>24.0</td>
<td>100% C4 energy</td>
</tr>
<tr>
<td>22.0</td>
<td>C3 protein line</td>
</tr>
<tr>
<td>20.0</td>
<td>Marine protein line</td>
</tr>
<tr>
<td>18.0</td>
<td>C4 protein line</td>
</tr>
<tr>
<td>16.0</td>
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<td>-23.50</td>
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<td>-24.0</td>
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240
Figure 6.37: $\delta^{15}$N and Time Period, All Sites

Table 6.8 $\delta^{15}$N: Results of Tukey’s Honestly-Significant-Difference Test

<table>
<thead>
<tr>
<th>Site</th>
<th>Site</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gruczno 1</td>
<td>Gruczno 2</td>
<td>0.914</td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>Kalduś 1</td>
<td>0.000</td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>Kalduś 4</td>
<td>0.000</td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>Rogowo</td>
<td>0.257</td>
</tr>
<tr>
<td>Gruczno 2</td>
<td>Kalduś 1</td>
<td>0.000</td>
</tr>
<tr>
<td>Gruczno 2</td>
<td>Kalduś 4</td>
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<td>Rogowo</td>
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<tr>
<td>Kalduś 1</td>
<td>Kalduś 4</td>
<td>0.996</td>
</tr>
<tr>
<td>Kalduś 1</td>
<td>Rogowo</td>
<td>0.014</td>
</tr>
<tr>
<td>Kalduś 4</td>
<td>Rogowo</td>
<td>0.026</td>
</tr>
</tbody>
</table>
There are no significant sex-based differences in δ^{15}N ratios at any of the sites. However, at all sites except Gruczno site 1, the average δ^{15}N values of men are slightly higher than those of women. At Gruczno site 1 men exhibit a mean δ^{15}N value of 9.3±0.5‰, whereas women are slightly higher 9.4±0.8‰.

6.3.2 Comparison of δ^{13}C_{coll} values among sites

In general, mean δ^{13}C_{coll} values decrease over time (Fig. 6.38). There is one interruption to the trend of decreasing δ^{13}C_{coll} through time. The mean δ^{13}C_{coll} value at the 12th-13th c. Kaldus site 1 is slightly, though significantly, higher than that at the 12th c. Gruczno site 1. However, within each study area (Kaldus site 4 vs. 1, and Gruczno site 1 vs. 2) δ^{13}C_{coll} values decrease through time. δ^{13}C_{coll} differences are significant Rogowo, Kaldus site 4 and Kaldus site 1 (δ^{13}C_{coll} decreases at each site). They are not as large between Kaldus site 1, Gruczno site 1 and Gruczno site 2 (Table 6.9).

The difference between δ^{13}C_{coll} values at Kaldus and Gruczno is not due to an overall shift in the distribution of values. Rather, it is due to a loss of individuals with 13C enrichment above -19.0‰ at Gruczno (see Fig. 6.1). Whereas at Kaldus sites 4, 60% (n=22) of the δ^{13}C_{coll} values are higher than -19.0‰ and at Kaldus site 1, 13% are (n=4), no samples at Gruczno site 1 or 2 exhibit values higher than -19.0‰. Despite this difference in maximum values, all four sites share a similar minimum δ^{13}C_{coll} value of -20.5±0.2‰.
Figure 6.38: $\delta^{13}C_{coll}$ and Time Period, All Sites

![Graph showing $\delta^{13}C_{coll}$ values for different sites over time.]

Table 6.9: $\delta^{13}C_{coll}$: Results of Tukey’s Honestly-Significant-Difference Test

<table>
<thead>
<tr>
<th>Site</th>
<th>Site</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gruczno 1</td>
<td>Gruczno 2</td>
<td>0.909</td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>Kałdus 1</td>
<td>0.405</td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>Kałdus 4</td>
<td>0.000</td>
</tr>
<tr>
<td>Gruczno 1</td>
<td>Rogowo</td>
<td>0.000</td>
</tr>
<tr>
<td>Gruczno 2</td>
<td>Kałdus 1</td>
<td>0.096</td>
</tr>
<tr>
<td>Gruczno 2</td>
<td>Kałdus 4</td>
<td>0.000</td>
</tr>
<tr>
<td>Gruczno 2</td>
<td>Rogowo</td>
<td>0.000</td>
</tr>
<tr>
<td>Kałdus 1</td>
<td>Kałdus 4</td>
<td>0.000</td>
</tr>
<tr>
<td>Kałdus 1</td>
<td>Rogowo</td>
<td>0.000</td>
</tr>
<tr>
<td>Kałdus 4</td>
<td>Rogowo</td>
<td>0.002</td>
</tr>
</tbody>
</table>
At Rogowo and Kaldus site 4, $\delta^{13}$C$_{coll}$ ratios exhibit a relatively wide range with standard deviations of 0.7% and 1.0‰, respectively. Standard deviations at Kaldus site 1 and Gruczno site 1 and 2 were lower at just 0.4‰, suggesting less variability in diet.

At Rogowo and Gruczno site 2, there are significant sex differences in $\delta^{13}$C$_{coll}$ values. At Rogowo, the mean $\delta^{13}$C$_{coll}$ value of men is -18.2±0.7‰ and of women is -17.5±0.6‰ (p=0.014). At Gruczno site 2, the opposite is observed: females exhibit lower $\delta^{13}$C$_{coll}$ values than do men (-20.1±0.3‰ vs. -19.8 ±0.2‰) (p=0.04). Interestingly, this $\delta^{13}$C$_{coll}$ difference only emerges at Gruczno site 2 after eight individuals with comparatively low $\delta^{13}$C$_{coll}$ values are excluded from the collagen analysis due to their high C:N ratios.

### 6.3.3 Comparison of $\delta^{13}$C$_{ap}$ values among sites

Trends in $\delta^{13}$C$_{ap}$ ratios mimic trends in $\delta^{13}$C$_{coll}$. In general, $\delta^{13}$C$_{ap}$ values decrease through time with the exception of the 12$^{th}$-13$^{th}$ c. (Fig. 6.39). Kaldus site 1 which exhibits a higher average value than the 12$^{th}$ c. Gruczno site 1 is observed. Table 6.10 shows that $\delta^{13}$C$_{ap}$ values are significantly higher at Rogowo than at all other sites except the earliest medieval sample, 11$^{th}$ c. Kaldus site 4, where $\delta^{13}$C$_{ap}$ values did not differ statistically (p=0.896).

Within Kaldus and within Gruczno, $\delta^{13}$C$_{ap}$ ratios decrease significantly over time (Table 6.10). As with $\delta^{13}$C$_{coll}$ ratios (Table 6.9), the $\delta^{13}$C$_{ap}$ ratios from the later phase of Kaldus (site 1) are indistinguishable from both Gruczno sites (Table 6.10). In terms of $\delta^{13}$C, Gruczno site 1 (12$^{th}$ c.), Kaldus site 1 (12$^{th}$-13$^{th}$ c.) and Gruczno site 2 (13$^{th}$-14$^{th}$ c.) form a group (Figs. 6.32; 6.33).
Figure 6.39: $\delta^{13}C_{ap}$ and Time Period, All Sites

Table 6.10: $\delta^{13}C_{ap}$: Results of Tukey’s Honestly-Significant Difference Test

<table>
<thead>
<tr>
<th>Site</th>
<th>Site</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
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<td>Gruczno 1</td>
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<tr>
<td>Gruczno 1</td>
<td>Kałdus 1</td>
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</tr>
<tr>
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<td>Kałdus 4</td>
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</tr>
<tr>
<td>Gruczno 1</td>
<td>Rogowo</td>
<td>0.000</td>
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<tr>
<td>Gruczno 2</td>
<td>Kałdus 1</td>
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</tr>
<tr>
<td>Gruczno 2</td>
<td>Kałdus 4</td>
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<td>Rogowo</td>
<td>0.000</td>
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<tr>
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<td>Kałdus 1</td>
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</tr>
<tr>
<td>Kałdus 4</td>
<td>Rogowo</td>
<td>0.896</td>
</tr>
</tbody>
</table>
Kałdus sites 4 and 1 exhibit a broad range of δ\(^{13}\)C\(_{ap}\) values with standard deviations of 1.32‰ and 1.69‰, respectively. It is interesting that the widest range is at Kałdus site 1, because the range of δ\(^{13}\)C\(_{coll}\) ratios at Kałdus site 1 is smaller than it is at Kałdus site 4 (SD=0.4 at Kałdus site 1 vs. 1.0 at Kałdus site 4). Removing three outlying enriched-\(^{13}\)C\(_{ap}\) values at Kałdus 1 reduces but does not eliminate this effect (the standard deviation at Kałdus site 1 becomes 0.96‰). This discrepancy between δ\(^{13}\)C\(_{ap}\) and δ\(^{13}\)C\(_{coll}\) variation suggests that while dietary protein sources became more homogeneous through time at Kałdus (i.e., a decrease in fish consumption or fewer varieties consumed), dietary energy sources remained equally variable. It will be recalled from section 2.6.3 that fewer varieties of fish were consumed through time, according to archaeoichthyology. Rogowo and Gruczno sites 1 and 2 exhibit lower standard deviations of approximately 0.7‰. At Rogowo, the range of δ\(^{13}\)C\(_{ap}\) values is greater than the range of δ\(^{13}\)C\(_{coll}\) values. At Gruczno sites 1 and 2, both δ\(^{13}\)C\(_{ap}\) and δ\(^{13}\)C\(_{coll}\) values are relatively homogeneous.

As with their δ\(^{13}\)C\(_{coll}\) values, Rogowo and Gruczno site 2 are the only two sites to exhibit sex differences in δ\(^{13}\)C\(_{ap}\) values. At Rogowo men exhibit a mean δ\(^{13}\)C\(_{ap}\) ratio of -11.92±0.69‰ and women a higher mean of -11.32±0.67‰ (p = 0.015). At Gruczno site 2 of the male mean is -13.12±0.70‰ and the female mean is -13.29±0.69‰ (p=0.026).

6.3.4 Comparison of Δ\(^{13}\)C\(_{coll-ap}\) values among sites

No large differences in Δ\(^{13}\)C\(_{coll-ap}\) values between sites are observed (Table 6.11; Fig. 6.40). As previously discussed, Δ\(^{13}\)C\(_{coll-ap}\) is a useful indicator of trophic position in cases where macronutrients in the diet do not differ isotopically (i.e., energy sources and
protein sources have similar stable isotope signatures). This is not the case in the study area, where millet is an energy source in the diet enriched in $^{13}$C by nearly 15‰ over the other local energy and protein sources. I compare $\Delta^{13}$C$_{\text{coll-ap}}$ values between sites to better examine the differences in dietary macronutrients (i.e., to gauge millet consumption), not to tease apart differences in trophic position.

Across the four medieval sites, $\Delta^{13}$C$_{\text{coll-ap}}$ ranges between 3.6‰ and 11.4‰. If three high-$^{13}$C$_{\text{ap}}$ outlier samples from Kałdus site 1 are removed, the range becomes 3.6‰ to 9.5‰. As indicated in Figure 6.34, the average $\Delta^{13}$C$_{\text{coll-ap}}$ value at Rogowo is somewhat lower than at the medieval sites (6.3‰).

At Kałdus site 4, $\delta^{13}$C$_{\text{coll}}$ and $\delta^{13}$C$_{\text{ap}}$ values are more strongly correlated than at any other site ($R^2 = 0.5211$). As reported in Table 6.1, Kałdus site 4 also exhibits the highest $\delta^{13}$C and $\delta^{15}$N values. Together these results suggest marine fish were consumed by the Kałdus site 4 population (this will be discussed in Chapter 7). More modest $\delta^{13}$C$_{\text{coll}}$ and $\delta^{13}$C$_{\text{ap}}$ correlations are observed at Rogowo and Gruczno site 2 ($R^2 = 0.3439$ and 0.3553, respectively). At Kałdus site 1 and Gruczno site 1, this correlation was negligible ($R^2 = 0.1795$ and 0.0048 respectively). When four outliers were removed from Kałdus site 1 (samples 93, 18, 58, and 101) the association was closer ($R^2 = 0.6121$). These outliers could not distinguished clearly as diagenetically altered by their CI, C/P or C:N values and were not excluded from analysis. Individuals K1-93-M and K1-16-M were among several Kałdus site 1 samples that had CI and C/P values outside the range typical for well-preserved archaeological samples (CI above 3.5), but so did a handful of other non-outliers.
Figure 6.40: $\delta^{15}$N vs. $\Delta^{13}$C$_{(ap-coll)}$, All Sites

Table 6.11: $\Delta^{13}$C$_{(ap-coll)}$: Results of Tukey’s Honestly-Significant-Difference Test

<table>
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<tr>
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</table>
6.4 Animals

6.4.1 Domestic animals

Complete animal data sets are presented in Appendix II. The $\delta^{15}$N values of domestic animals range from 5.9‰ (pig) to 9.6‰ (dog). The pigs in general exhibit lower $\delta^{15}$N values than was expected, ranging from 5.9‰ to 7.9‰. Pigs reported in other studies exhibit values of up to 10‰ or higher in the medieval period (Linderholm et al. 2008; Müldner and Richards 2005), but are highly variable due to their omnivorous, opportunistic diets. Chickens in this study exhibit high $\delta^{15}$N values of 9.1‰. Together with the dog, the chickens are widely separated isotopically from the other animals sampled and plot amidst human values instead (Figs. 6.1; 6.41). Cattle exhibit $\delta^{15}$N values between 6.4‰ and 7.9‰ which is somewhat higher than expected based on previously reported data for cattle in Europe (e.g. Herrscher et al. 2001; Linderholm et al. 2008; Lynch et al. 2008; Müldner and Richards 2005; Noe-Nygaard et al. 2005). Aside from the chickens and pigs which plot with human data points, domesticated animals are 1-6‰ lower than the human $\delta^{15}$N values (Figs. 6.1; 6.41) and are, on average, 2.4‰ lower than the human $\delta^{15}$N mean.

The $\delta^{13}$C$_{col}$ values of domestic animals except the chickens and dog range from -21.5‰ to -19.5‰. As with their $\delta^{15}$N values, chicken and dog $\delta^{13}$C$_{col}$ values are higher than the other domestic animals and fall at the center of the range of human values. Eight of the 12 domestic animals were also sampled for $\delta^{13}$C$_{ap}$ data. The mean $\delta^{13}$C$_{ap}$ value was -13.52±1.22‰. One cow and one chicken show a C$_4$ signal in their $\delta^{13}$C$_{ap}$
Figure 6.41: Collagen Stable Isotope Data from Animals

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<th>Species</th>
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<th>δ¹³C_{coll (VPDB)} (‰)</th>
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<tr>
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<tr>
<td>Aspe</td>
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</table>
values at -11.41‰ and -11.67‰, respectively. Other than these animals, there is no
evidence that animals were foddered on C\textsubscript{4} crops such as millet. The mean $\Delta^{13}$C\textsubscript{(ap-coll)}
value was 7.4±0.93‰, and chickens exhibit the lowest $\Delta^{13}$C\textsubscript{(ap-coll)} values.

6.4.2 Wild Animals

The stable isotope values of wild animals are lower than those of domestic
animals. They are comparable to values reported elsewhere in Europe (e.g.: Drucker et
al. 2003; Lynch et al. 2008; Rodiere et al. 1996). Low $\delta^{13}$C ratios in forests are due
primarily to the recycling of low-$^{13}$CO\textsubscript{2} under the canopy. Forest biomes also exhibit
lower $\delta^{15}$N values. $\delta^{15}$N values are higher in agricultural fields that have been ploughed,
burned or manured (Bogaard et al. 2007; Grogan et al. 2000; Hobson 1999).

Among the wild animals, the most isotopically depleted are the aurochs and elk.
This reflects their dense-forest habitats. The deer and hare are less isotopically depleted,
reflecting their exploitation of forests as well as more open areas.

6.4.3 Fish

None of the 16 fish sampled in this study were marine species. All were
freshwater varieties except for sturgeon, which are anadromous and migrate along the
Vistula River. Excluding one anomalous fish that will be discussed next, the remaining
freshwater fish in this study exhibit a $\delta^{15}$N range of 6.6‰ to 12.1‰ and a $\delta^{13}$C -21.6‰ to
-28.2‰. Such ranges indicate how easily freshwater fish may be confused with domestic
animals when interpreting human diet isotopically. The anadromous fish, sturgeon,
exhibit a $\delta^{15}\text{N}$ range of 9.9‰ to 11.3‰ and a $\delta^{13}\text{C}$ -15.6‰ to -17.1‰. These values are similar to the chickens sampled in this study, albeit slightly more enriched in $^{13}\text{C}$.

One of the *Tinca tinca* samples (tench) exhibited anomalously low $\delta^{15}\text{N}$ and high $\delta^{13}\text{C}$ values of 3.1‰ and -5.6‰, respectively. It is possible that these values are biogenic, and not the product of diagenesis or contamination: tench occupy among the lowest aquatic trophic positions, feeding on algae and macrophytes in the benthic zone of freshwater bodies (Alas et al. 2010). If so, this value is perhaps the lowest $\delta^{15}\text{N}$ value reported for freshwater Eurasian fish (for more values, see Dufour et al. 1999; Redfern et al. 2010; Katzenberg and Weber 1999). $\delta^{15}\text{N}$ values around 2-3‰ are characteristic of some of freshwater zooplankton and zoobenthos (France 1994).

### 6.5 Summary of Results

In general, $\delta^{13}\text{C}$ values decrease through time, and become less variable. Sex differences in $\delta^{13}\text{C}$ are observed at Rogowo, the earliest site, and Gruczno site 2, the latest site. $\delta^{15}\text{N}$ values do not show temporal changes; rather, they differ by site location. $\delta^{15}\text{N}$ values are highest at the two Kaldus sites and lowest at the two Gruczno sites. $\delta^{15}\text{N}$ values at Rogowo, the earliest site, are intermediate. Stable isotope values are more variable at the earlier sites, Rogowo and Kaldus site 4, than at Kaldus site 1 and Gruczno. In general, $\Delta^{13}\text{C}_{\text{coll-ap}}$ values are not very useful for determining trophic position at these sites because millet, an energy source, differs isotopically from all other available foods. Nevertheless, $\Delta^{13}\text{C}_{\text{coll-ap}}$ is modestly related to $\delta^{15}\text{N}$ at Kaldus site 4 which is the most convincing evidence for fish consumption at any of the sites.
Chapter 7: Discussion and Conclusions

In this chapter I discuss the data reported in Chapter 6 within the context of medieval Polish diet, described in Chapter 2. In section 7.1, I discuss the ecological niches of animals in human diet. The dietary baseline provided by animal stable isotope data will be used to evaluating human diet. In section 7.2 I outline the types of stable isotope values expected for certain diets, basing expectations on the original hypotheses (Chapter 1). After reviewing expected values, I reconstruct diets of human populations at each time period and/or site starting with the pre-medieval samples (section 7.3) followed by the medieval samples (section 7.4). Individuals are referred to in these sections by their site initial, grave number and sex (for example, K4-13A-M is a male from grave 13A at Kaldu site 4). In addition to diet reconstructions specific to this study, in section 7.5 I discuss broader trends in the stable isotope data and their implications for diet reconstruction in Europe. These trends are 1) relatively high $\delta^{15}$N values among most humans and some animals, and 2) millet consumption. Finally, in section 7.6 I revisit the original hypotheses guiding this study and discuss whether stable isotope data presented here support or refute them. In all the following figures that compare carbonate and collagen $\delta^{13}$C values with regression lines of Kellner and Schoeninger (2007), a 1.5‰ $\delta^{13}$C correction has been added to the regression lines (both $\delta^{13}$C$_{ap}$ and $\delta^{13}$C$_{coll}$) to account for the Suess effect (Marino and McElroy 1991).
7.1 Animals

A comprehensive reconstruction of diet using stable isotope ratios begins with an understanding of plants and animals at the base of the human food chain. First, I discuss stable isotope values from animals emphasizing their environmental and economic contexts. I compare them to animal stable isotope data from elsewhere in Europe. Next, I discuss implications of the observed animal data for interpreting human stable isotope values.

7.1.1 Domestic Animals

The bones from five cattle show a mean δ¹⁵N value (7.2‰) that is higher than typically reported for cattle. Across other studies, values for cattle range from 4‰ to 6‰ (Herrscher et al. 2001; Linderholm et al. 2008; Lynch et al. 2008; Müldner and Richards 2005). At Giecz, a medieval site in Greater Poland, a single cow exhibited a δ¹⁵N value of 6.8‰ (Reitsema et al. 2010). Higher δ¹⁵N values in the present study are not likely due to differences in cattle physiology in this region of North-Central Poland. Rather, they likely reflect high δ¹⁵N values in local plants. Indeed, sheep also exhibit a relatively high δ¹⁵N value (7.1‰). For comparison, one sheep at Giecz exhibited a value of just 6.5‰ (Reitsema et al. 2010).

High animal δ¹⁵N is an important isotopic difference that affects how human values are interpreted. If cattle and sheep were a significant food resource for Polish populations (meat and/or dairy) they would enrich human values by approximately 1-3‰ in relation to other European samples. High δ¹⁵N values among animals likely reflect
high plant values at the base of the food chain. Humans consuming them also may be expected to exhibit high δ^{15}N values. High plant δ^{15}N values most likely result from land management strategies such as manuring crops or burning fields (Bogaard et al. 2007; Grogan et al. 2000). Unfortunately, no archaeobotanical remains were available for analysis. The possibility of high-^{15}N plants being consumed by local animals is discussed further in section 7.4. In terms δ^{13}C values, cattle and sheep exhibit values within the range of C_3 feeders indicating they were not foddered on millet.

Bones of three pigs were assayed. Pigs generally are isotopically similar to other domesticated animals (sheep/goat and cattle) but exhibit a broader range of values. The δ^{15}N values of three pigs included in this study range from 5.9‰ to 7.9‰ while δ^{13}C values range from -19.8‰ to -21.6‰. Variability across pigs is not surprising as these animals are free-ranging omnivores. In the medieval period pigs may have lived in close quarters with humans and consumed human foods and wastes. In urban settings higher δ^{15}N values are expected for pigs. In rural Poland pigs likely were shoed into forests to feed on acorns and other vegetation (Van Vuure 2005). Because pigs in this study exhibit relatively low δ^{15}N ratios that are comparable to the other domestic animals, they likely were raised in this manner, independently of humans. In terms δ^{13}C values, one pig (816-02) is an outlier with a value of -19.8‰. In Britain where millet was absent at this time, a larger sample of pig δ^{13}C ratios clustered around -21.5‰. Enrichment in ^{13}C above this value therefore may indicate inclusion of a C_4 plant, perhaps by millet-foddering or scavenging millet or fish from human refuse. Tafuri et al. (2009) report values for
medieval terrestrial animals that ranged from -15.4‰ to -17.8‰, clearly indicative of millet-foddering.

$\delta^{15}$N and $\delta^{13}$C values of one dog examined are higher than those of other domestic animals and indistinguishable from humans, suggesting dogs lived in close proximity to humans and had access to humans’ foods. Domestic chickens in this sample exhibit a high mean $\delta^{15}$N ratio of 9.1‰. Like pigs, in the medieval period domestic fowl were a solution to food production in urban settings, because many chickens could be raised and tended in a household. In such contexts, chickens fed opportunistically on scraps of human food (including meat and fish) as well as human and animal waste. High $\delta^{15}$N values of chickens attest to this type of relationship. When compared to values reported for domestic fowl in Roman and medieval Europe, $\delta^{15}$N values are comparable, but $\delta^{13}$C values are slightly higher in Poland. For example, Chenery et al. (2010) report a $\delta^{13}$C value of -20.7 for a domestic fowl in England. The bones sampled here exhibit values of -19.0‰ and -18.2‰, which may indicate consumption of either millet or marine fish. Because poultry was an important protein source in medieval Poland (Dembińska 1999), they may be a source of both $^{13}$C- and $^{15}$N-enrichment in humans. As a result, it will be difficult to determine whether $^{15}$N enrichment among humans is due to consumption of fish or of poultry, a problem I return to later in this chapter.

7.1.2 Wild Animals

As expected considering their closed-forest ecosystems, wild animals are depleted compared to domestic animals in both $^{15}$N and $^{13}$C. This is significant, as it reveals an
isotopically depleted biome in the study area. In contrast, high $\delta^{15}$N and $\delta^{13}$C values of domestic animals reveal a stable isotope environment been modified by human activity. Differences in stable isotope signatures between modified, open environments and forests in Europe have been demonstrated by comparing stable isotope ratios of physically similar animals dwelling in each: aurochs (isotopically lighter) and cattle (isotopically heavier) (Lynch et al. 2008; Noe-Nygaard et al. 2005). The impact of human activity on stable isotope ratios is discussed in more detail in section 7.4.

7.1.3 Fish

13 of the 16 fish are freshwater species with $\delta^{13}$C values below -21.0‰. Three are anadromous sturgeon with $\delta^{13}$C values of -15.6‰ to -17.1‰. One Tincus tincus (tench) sample exhibits anomalous values unlike all the other fish, including the other tench, of $\delta^{15}$N 3.1‰ and $\delta^{13}$C -5.6‰. Although unusual in this study, similar values have been reported for fish occupying littoral zones of freshwater lakes (Hecky and Hesslein 1995). Freshwater fish with below-average $\delta^{13}$C values (< -23.1‰) include one tench, two catfish, all three pike, one pike-perch, one carp-bream and the asp. Above-average $\delta^{13}$C values (> -23.1‰) include other members of these same species: the other tench, one of three catfish, one pike-perch and one carp-bream. Clearly, these fish cannot be distinguished based on species, but rather must be considered in terms of their aquatic niches. “Bottom-feeder” freshwater fish exhibiting below-average $\delta^{15}$N values (<9.5‰) include both carp-bream, one catfish, both tench, the asp, and surprisingly considering their typically high trophic position, two of the three pike. Above-average $\delta^{15}$N values
(>9.5‰) are found in all pike-perch, one of the three pike and two of the three catfish examined. All three anadromous sturgeon exhibit high δ\(^{13}\)C and high δ\(^{15}\)N values.

Importantly, most stable isotope values of fish assayed in this study, including freshwater and anadromous varieties, are close to values from terrestrial animals and may confound interpretations of human stable isotope ratios. Carp are the most common freshwater fish species found at Polish sites, including Kałdus site 4 (Makowiecki 2001). Although one of the two carp studied here exhibits an anomalously low δ\(^{13}\)C ratio that would stand out in human diet, the other exhibits a δ\(^{13}\)C ratio (-23.0‰) similar to that of a wild animal. Both carp samples exhibit δ\(^{15}\)N signatures similar to chickens (8.7‰ and 9.4‰). The problem of fish masquerading as terrestrial animals in human diet is discussed in further in section 7.4.

7.2 Predicted Variation in Stable Isotope Ratios

Before discussing the data, it is helpful to revisit the biocultural context and expectations of this study to see if the expectations are met. Samples from the Neolithic and Iron Age are exploratory, therefore no predicted values are given for these. The biocultural context in Poland (Chapter 2) indicates that populations in both Roman Era and medieval Poland were consuming a mixture of C\(_3\) and C\(_4\) plants, terrestrial animal protein and some fish (more freshwater varieties than marine). In the Roman Era, cows were more common in diet unlike in the medieval period where pigs made more significant contributions. My hypotheses predict an increase in fish consumption and increased variability within populations through time.
These expectations for diet translate into expectations for stable isotope signatures. A predicted isotopic space for Rogowo ranges from 9‰ to 10‰ for δ¹⁵N and -19‰ to -21‰ for δ¹³C_coll, reflecting a protein diet based on cattle and given the faunal baseline values presented here. Status-based differences in diet were not expected at Rogowo in reflection of the relatively egalitarian nature of Wielbark society.

Chronologically between Rogowo, Kaldus site 4, Gruczno site 1, Kaldus site 1 and Gruczno site 2, a steady increase in both δ¹⁵N and δ¹³C was expected, with a high endpoint of approximately 11‰ to 12‰ for δ¹⁵N and -17‰ to -16‰ for δ¹³C_coll, reflecting a diet with considerable amounts of marine fish (especially herring). Isotopic scatter was expected to increase between these populations as well.

Given the fact that botanical remains of millet are found at all five of the investigated sites, a C₄ signal was expected to be visible in the δ¹³C_ap values. Millet in human diet is of general interest for several related reasons. First, millet is argued to be a characteristically Slavic food and has the potential to track not just diet, but cultural affiliations of past European groups during the medieval period when Europe was increasingly mobile and interlinked. Second, because of its association with Slavs, millet may be useful in tracking Slavic migrations during the Roman Era and Migration Period. Finally, millet is isotopically distinct from wheat, rye and barley, and the diversification or specialization of agricultural techniques can be studied by examining millet in crop-growing regimes.

There is very little carbonate evidence for diet and especially, millet consumption in Europe to help built a predictive model for values, but evidence for maize consumption
in the New World is abundant. Based on the work of Harrison and Katzenberg (2003), δ\(^{13}\)C\(_{ap}\) values of C\(_4\) plant consuming humans are expected to range from -4‰ (very high-maize diet) to approximately -12‰ (representing a broad spectrum diet including maize). From this range, δ\(^{13}\)C\(_{ap}\) values of approximately 9‰ to 12‰ are expected from the Polish samples, because millet was one of several common cultigens, most of which were C\(_3\) plants. The data of Harrison and Katzenberg (2003) suggest that C\(_4\) plants only begin to contribute to higher δ\(^{13}\)C\(_{coll}\) signatures among humans when δ\(^{13}\)C\(_{ap}\) values reach approximately -9‰; therefore, very little enrichment of \(^{13}\)C\(_{coll}\) is expected from millet-eating Polish populations, on the order of -17‰ to -19‰. Importantly, values such as these will not necessarily implicate consumption of \(^{13}\)C-enriched fish.

7.3 Human Diet before Medieval Sociopolitical Changes

I examine Neolithic, Iron Age and Roman Era samples as outliers representing diet in Poland before medieval state formation. Four ancient skeletons were studied, rendering these interpretations preliminary. A larger sample from the Roman Era was examined. I reconstruct diet from these early samples to assess the dietary background before the medieval period.

7.3.1 Neolithic and Iron Age

Two Neolithic and two Iron Age individuals were studied. The stable isotope differences between three of these (Kowal and Niedrzwica from the Neolithic and Bożewice from the Iron Age) are within the “within group” differences for sites with
larger samples. In spite of this, preliminary analyses of the data can be proposed drawing from the archaeological context of these time periods.

Sample Neo-1 from Kowal in Central Poland belongs to the Globular Amphorae culture. This skeleton is radiocarbon dated to approximately 2,100 BC. At this time, Neolithic populations in Poland practiced a mixed subsistence strategy of agriculture and animal husbandry. Sample Neo-2 is from Niedrzwica in Northern Poland, where Neolithic populations are thought to have been more reliant on animal husbandry (T. Kozlowski, pers. comm.).

Isotope data support these interpretations. The individual from Kowal (Neo-1) exhibits a δ¹³C value of -20.3‰ and a δ¹⁵N value of 9.9‰, suggesting terrestrial animals were the primary protein source. Assuming a δ¹³C fractionation of +1‰ and a δ¹⁵N fractionation of +3-5‰ (Drucker and Bocherens 2004; Schoeninger 1989), animals consumed by this individual had δ¹³C values of approximately -21‰ to 22‰ and δ¹⁵N values of approximately 5‰ to 7‰. Such values are reported for pigs, cows, and deer in Neolithic Germany (Dürrwächter et al. 2006), and bones from all these animals are found at Neolithic sites in Central Poland (Grygiel and Bogucki 1993).

Compared to Kowal, the individual from Niedrzwica exhibits a lower δ¹³C value (-21.6‰) and a higher δ¹⁵N value (10.2‰). These differences may reflect more freshwater fish in the diet. Pike and cyprinids are the most common fish from Neolithic sites in Central Poland (Grygiel and Bogucki 1993). In Neolithic Germany, these species are shown to exhibit δ¹³C values of -22.5‰ to -20.4‰ and δ¹⁵N values of 7.5‰ to 10.2‰ (Dürrwächter et al. 2006). δ¹³C values of these fish fall within the expected range for
protein diets of both the Kowal and Niedrzwica individuals. The depletion in $^{13}$C also may reflect the “canopy effect” and/or latitude-dependent variations in $\delta^{13}$C values of atmospheric CO$_2$ (van Klinken et al. 2000). Niedrzwica is located further Northeast in Poland and was more densely forested compared to the woodland/lakeland of Central Poland. It also should be borne in mind that the Niedrzwica individual may have come from a less-fully agricultural population than the Kowal individual, and thus may have obtained more resources from forested environments with lower $\delta^{13}$C values than open fields (van Klinken et al. 2000).

The individual from Kowal exhibits a $\delta^{13}$C$_{ap}$ value of -11.22‰, whereas the individual from Niedrzwica exhibits a lower value of -13.88‰. Because $\delta^{13}$C$_{ap}$ values are more sensitive to dietary energy sources than are $\delta^{13}$C$_{coll}$, this difference may reflect millet agriculture at Kowal. Assuming respective C$_3$ and C$_4$ endpoints of -26‰ and -14‰ and a +12‰ diet-apatite fractionation factor, the $\delta^{13}$C$_{ap}$ value for the Kowal skeleton indicates the diet may have contained as much as 25% millet. The $\delta^{13}$C$_{ap}$ value from the Niedrzwica individual indicates no millet in the diet.

The Iron Age individual from Bożejewice (Iron B) is similar to the two Neolithic samples. All three of Bożejewice’s isotope values are intermediate between Kowal and Niedrzwica. Bożejewice’s diet also was based on C$_3$ foods with input from $^{13}$C-depleted protein from animals and/or freshwater fish. The Iron Age sample from Gziń (Iron A) is dissimilar from the other three ancient samples. Compared to Bożejewice, $\delta^{13}$C$_{ap}$ from Gziń is lower (-12.86‰ vs. -12.40‰) but its $\delta^{13}$C$_{coll}$ signatures is more than 2‰ higher,
Figure 7.1: Comparison of Ancient Collagen $\delta^{13}C$ vs. $\delta^{15}N$

![Graph showing comparison of ancient collagen δ13C vs. δ15N](image)

Giving Gziń the lowest $\Delta^{13}C_{(ap-coll)}$ value of all ancient samples, only 5.5‰. Both Iron Age samples exhibit $\delta^{13}C_{ap}$ values indicating a bulk diet with little or no millet.

Stable isotope ratios from collagen of these four ancient samples are compared to other ancient samples in Figure 7.1. The Niedrzwica individual (Neolithic) plots near a freshwater fish-consuming Ukrainian population dating to the Mesolithic-Neolithic transition. The Kowal individual (Neolithic) and the Bożejewice individual (Iron Age) plot near a Neolithic sample from Germany which consumed terrestrial, C₃-based protein diets (Dürrwächter et al. 2006). Gziń (Iron Age) is more similar to a Mesolithic fishing group from Portugal that consumed marine fish (Lubell et al. 1994). Compared to a Neolithic Anatolian population that also had a terrestrial diet (Lösch et al. 2006), the Polish and German Neolithic samples exhibit higher $\delta^{15}N$ values. This may be due
greater consumption of animals in Northern Europe, especially omnivore protein (such as pigs), supplemental amounts of or low-$^{15}$N fish, or consumption of plants grown on manured fields in Northern Europe.

Kellner and Schoeninger’s (2007) regression lines are used to further sort stable carbon isotope data from apatite and collagen into C$_3$, C$_4$ and marine protein lines with 0-100% C$_3$ and C$_4$ energy, and compare the data to other European samples (Fig. 7.2). This approach temporarily ignores $^{15}$N data and focuses instead on the two major sources of stable carbon isotopes in human tissues: dietary protein and dietary energy. With the exception of data points from the present study, in Figure 7.2 data points represent populations, not individuals. The two Neolithic samples and the Iron Age sample from
Bożejewice plot near other examples of terrestrial-based diets: Neolithic Greece (the two inland sites reported) (Papathanasiou 2003), Neolithic and Bronze Age Siberia (also inland sites) (Katzenberg and Weber 1999) and Neolithic Anatolia (Lösch et al. 2006). The fact that Kowal plots slightly higher than those samples reflects its relative enrichment in $\delta^{13}C_{ap}$, likely due to millet consumption. Stable isotope signatures of the Neolithic and Iron Age Bożejewice individuals are dissimilar from populations where marine and anadromous fish contributed to diet (Papathanasiou 2003).

Looking at Figure 7.2, the role of freshwater fish in diets of these three individuals is unclear. A freshwater seal from Lake Baikal is pictured here to represent a diet based on low-$^{13}C$ freshwater fish for comparison (Katzenberg and Weber 1999). The location of Bożejewice and Kowal data points far to the left of the C$_3$ protein line (like the Lake Baikal seal) indicates that dietary protein was relatively $^{13}C$-depleted compared to (1) energy sources from the same population, and (2) the dietary protein of the animals whose values were used to develop the regression lines. This supports the idea that the Polish Neolithic individuals (and one of the Iron Age individuals) obtained a significant amount of their dietary protein from eating $^{13}C$-depleted fish or forest-dwelling animals.

To illustrate the possible reliance on forest resources, Polish data are plotted alongside wild animals from Neolithic Anatolia (hare, aurochs, deer and wild ass; Fig. 7.3) and humans (Figs. 7.2; 7.3) (Lösch et al. 2006). Data points of the comparative sample represent groups, not individuals. Trophic position aside, Neolithic humans in Poland appear to have shared a habitat similar to these wild animals. That wild animals also plot to the left of the C$_3$ protein line indicates freshwater fish consumption is not the
only reason for humans’ location left of the C3 line in the figure. Kellner and Schoeninger’s (2007) regression lines were not developed using animals fed freshwater fish; there may be a fourth protein line yet to be identified.

7.3.2 Rogowo

Stable isotope evidence from Rogowo supports a diet including millet. Evidence for fish consumption is equivocal, partly because δ15N values are not as high as would be expected if fish were an important protein source in diet. Samples from Rogowo exhibit the highest δ13Ccoll and δ13Can values of all five study sites. Either millet, marine fish, or animals foddered on millet are responsible for Rogowo’s high δ13C values. Anadromous fish (sturgeon) sampled here also exhibit values enriched in 13C that range from -15.6‰ to -17.1‰. Although none of the animals sampled here (from the medieval period)
exhibit $^{13}$C-enrichment, animals foddered on C$_4$ grain from Bronze Age Italy exhibit values -15.4‰ to -17.8‰, similar to those of anadromous fish. Consumption of anadromous fish or C$_4$-foddered animals could therefore explain some of the $^{13}$C enrichment in humans, although individuals such as R-688N-F, with a $\delta^{13}$C$_{coll}$ value of -16.4‰, would have consumed a great deal of these resources were they the only source of $^{13}$C enrichment.

Unlike $\delta^{13}$C values, $\delta^{15}$N values at Rogowo are not the highest among the sites, suggesting $^{13}$C enrichment is not primarily due to consumption of different protein sources, but rather is due to differential consumption of millet. If a 12‰ diet-carbonate fractionation factor is applied (as advised by Garvie-Lok 2001), the $\delta^{13}$C ratios of bulk diets at Rogowo ranged between 21.7‰ and 25‰. The isotopic “space” of a C$_3$ diet is 23‰ to 25‰ (Garvie-Lok 2001). The $\delta^{13}$C values from Rogowo indicate millet contributed between 0% and 35% to overall diet, depending on the individual. The fact that $\delta^{13}$C and $\delta^{15}$N values are not positively correlated also supports an interpretation of direct millet consumption, rather than marine fish, anadromous fish or C$_4$-foddered animal consumption.

For comparison, collagen data from Rogowo are plotted alongside other European populations (Fig. 7.4). Three of these populations ate fish: medieval England with a mix of freshwater and marine fish (Müldner and Richards 2005), Viking and medieval Sweden with marine fish (Kosiba et al. 2007), and Byzantine Crete where a few individuals supplemented their diets with marine fish (Bourbou and Richards 2007). In comparison, individuals from Rogowo do not show a strong marine or freshwater signal.
There is overlap between Rogowo and the Byzantine individuals who consumed marine fish. I return to this in the following paragraph. Other comparative populations pictured in Figure 7.4 represent terrestrial diets with a mix of C₃ and C₄ resources. Data from Murray and Schoening (1988) represent an Iron Age population from Slovenia that consumed terrestrial plant and animal resources with a C₄ signal. This C₄ signal is either via direct consumption of millet, or via consumption of animals foddered on millet. Data from LeHuray and Schutkowski (2005) represent two La Tène populations from the modern day Czech Republic, and individuals from Hallstatt sites in Austria. Data from Tafuri et al. (2009) represent another diet with a C₄ signal from Bronze Age Italy.

Comparing European samples, δ¹⁵N values among the Slovenian, Czech and Polish samples are very similar, ranging from approximately 8.5‰ to 11.0‰. The δ¹³C_coll values at Rogowo are intermediate, but more closely resemble values from La Tène Czech individuals with low millet consumption than values from Iron Age Slovenia with high millet consumption. This suggests a terrestrial-based diet including millet at Rogowo.

Interestingly, the Iron Age sample from Gziń is within the range of collagen values from Rogowo. Yet, because of the low δ¹³C_ap from Gziń, millet can probably be ruled out from this individual’s diet. This illustrates that there is more than one way to way to interpret the same isotope values depending on context. Unfortunately, the context of a larger sample is unavailable for the Iron Age individual.
Figure 7.4: Comparing Rogowo $\delta^{15}N$ and $\delta^{13}C_{coll}$ Values to Other European Populations

- Rogowo (this study)
- Iron Age Poland, this study
- Byzantine Crete - C3/marine
- Viking & Medieval Sweden - C3/marine
- Medieval England - C3/marine/freshwater
- Iron Age Slovenia - C4/C3 terrestrial
- La Tène Czech Republic - C3/C4 terrestrial
- Bronze Age Italy - C3/C4 terrestrial
As mentioned before, there is overlap between Rogowo and a population from Byzantine Crete that consumed marine fish. In light of this, marine or high-$^{13}$C anadromous fish could be potential food sources at Rogowo. However, the overall scatter of both populations suggests different stable isotope baselines for each environment. The “high-$^{13}$C”, marine fish eating individuals at Crete overlap with the “low-$^{13}$C” individuals from Rogowo and in general, $^{15}$N values at Rogowo are consistently higher. The Byzantine population apparently had access to animals with low $^{15}$N signatures, hence human data points with values of only 7.8‰ and 8.2‰. No individuals from Rogowo have values this low, suggesting they had access to animals with higher $^{15}$N signatures, consistent with animal values reported here. The individuals from Byzantine Crete that break away from the main low-$^{15}$N, low-$^{13}$C cluster to overlap with Rogowo probably consumed marine fish. However, fish consumption at Rogowo is not the most likely explanation for the overlap.

Garvie-Lok (2001) found that in another Byzantine sample from Greece, the $^{13}$C$_{coll}$ values of some individuals “changed more rapidly” than the associated $^{13}$C$_{ap}$ values, suggesting that increased fish consumption (and not millet consumption) was responsible for $^{13}$C enrichment. At Rogowo, the variance of both $^{13}$C$_{coll}$ and $^{13}$C$_{ap}$ is similar ($\sigma = 0.75\%$ and 0.76‰, respectively): $^{13}$C$_{coll}$ values are not more variable, nor change more rapidly than $^{13}$C$_{ap}$. Rather than high-protein fish “pulling” $^{13}$C values up, it appears that millet consumption in a terrestrial-based and possibly even plant-based diet is doing so. Finally, in the Byzantine sample, $^{13}$C and $^{15}$N values correlate positively. A closer examination shows that at Rogowo, high $^{15}$N values are not clearly
associated with high $\delta^{13}C_{\text{coll}}$ or $\delta^{13}C_{\text{ap}}$ values (Fig 7.5). In fact, the minor relationship that does exist between $\delta^{13}C_{\text{coll}}$ and $\delta^{15}N$ ($R^2=0.1463$) is an inverse one: the highest $\delta^{13}C$ values at Rogowo are associated with the lowest $\delta^{15}N$ values. Collagen data indicate that fish may have been consumed by these people, explaining intermediate $\delta^{15}N$ values, but they are not the source of $^{13}C$ enrichment: thus, the fish in question are not marine or anadromous. We are left with millet to explain $\delta^{13}C$ enrichment, and the question of whether or not there is evidence of freshwater fish consumption to explain the intermediate $\delta^{15}N$ values.

So far, collagen data support a diet at Rogowo of primarily terrestrial foods based on C$_3$ resources with input from a C$_4$ plant. Carbonate data, which better represent plants in diet, may or may not corroborate this interpretation. Rogowo exhibits the highest mean $\delta^{13}C_{\text{ap}}$ value of this entire study and a relatively low standard deviation (-11.60‰±0.76), supporting the interpretation of a plant diet with a C$_4$ signal. The model of Kellner and Schoeninger (2007) which combines collagen and carbonate $\delta^{13}C$ data predicts that individuals consuming $^{13}C$ fish will plot to the right of the C$_3$ protein line, and more high-$^{13}C$ fish in diet should imply greater distance from the C$_3$ protein line. Rogowo data plot to the right of the C$_3$ protein line, suggesting fish consumption – likely anadromous fish. Carbonate data have thus complicated the picture of diet that emerged using collagen data alone.
Figure 7.5: $\delta^{13}\text{C}_{\text{coll}}$ vs. $\delta^{13}\text{C}_{\text{ap}}$ Values at Rogowo, Sorted into $\delta^{15}\text{N}$ Groups

More fish in the diet should also affect $\delta^{15}\text{N}$ values, and a relationship could be expected between proximity to the C$_3$ protein line and $\delta^{15}\text{N}$ values. Figure 7.5 shows the Rogowo sample divided into three $\delta^{15}\text{N}$ groups: low ($<9.5\%$), intermediate (9.5-9.9$\%$) and high (>10.0$\%$). The two highest $\delta^{15}\text{N}$ values (above 10.5$\%$) also are demarcated. As Figure 7.5 shows, higher $\delta^{15}\text{N}$ values are not associated with greater distance from the C$_3$ protein line as would be expected if marine or anadromous fish were being consumed. Rather, high $\delta^{15}\text{N}$ values are randomly scattered throughout the overall distribution. The anadromous sturgeon in this study all exhibit relatively high $\delta^{15}\text{N}$ values (9.9$\%$ to 11.3$\%$) which would cause a relationship between $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values, were they consumed in large amounts by humans. It is most likely that the source of $^{13}\text{C}$ enrichment among humans is not due to either anadromous fish or millet consumption, but rather that both these resources were consumed in differing amounts. Though
complicated to decipher with these stable isotope data, diet at Rogowo was likely terrestrial based, with substantial input from terrestrial protein (milk, meat or cheese) and millet, and supplemental input from anadromous fish (sturgeon).

7.4 The Medieval Sample: Kaldus and Gruczno

7.4.1 Kaldus Site 4, 11th c. AD

Expectations for Kaldus site 4 presented in section 7.2 are partially met. Diet at this site included slightly more fish than at Rogowo. However, low variability was expected from stable isotope values at Kaldus site 4, yet it is actually distinct from the other sites in that is is the most isotopically varied sample.

Average $\delta^{15}$N is similar to but slightly higher than at Rogowo ($10.2\pm0.8\%$ vs. $9.7\pm0.5\%$). $\delta^{13}$C$_{coll}$ values are slightly lower than at Rogowo ($-18.5\pm1.0\%$ vs. $-17.9\pm0.7\%$) and they exhibit a broader range (Fig. 7.6). Like $\delta^{13}$C$_{coll}$, $\delta^{13}$C$_{ap}$ values at Kaldus site 4 are lower and more variable than at Rogowo ($11.87\pm1.32\%$ vs. $11.60\pm0.76\%$) but the difference in $\delta^{13}$C$_{ap}$ is smaller than the difference in $\delta^{13}$C$_{coll}$.

Together these observations suggest diet change between the Roman and medieval periods involved protein sources, not energy sources. In other words, millet consumption may not have changed much, but fish consumption apparently increased at Kaldus site 4.

A wide range of stable isotope values at Kaldus site 4 renders diet reconstruction here more complex. Freshwater fish, marine fish, C$_4$ and C$_3$ plants (which may have been manured, as will be discussed in section 7.6), and omnivore protein were likely all
on the menu. This is why it is possible to have, in the same population, individuals like K4-60-M whose $\delta^{15}$N is high (11.1‰) and whose $\delta^{13}$C$_{coll}$ is low (-20.1‰), K4-13B-F, whose $\delta^{15}$N is low (9.5‰) and whose $\delta^{13}$C$_{coll}$ is high (-16.4‰), K4-48-F whose $\delta^{15}$N is low (9.4‰) and whose $\delta^{13}$C$_{coll}$ is also low (-19.6‰) and K4-14-M whose $\delta^{15}$N is high (11.0‰) and whose $\delta^{13}$C$_{coll}$ is also high (-17.3‰). They are all eating different local diets.

Kaldu site 4 overlaps with several other European populations (Fig. 7.6). At the left of the scatterplot area, three individuals are within the scatter of a medieval English population that consumed a mix of $C_3$, marine and freshwater protein (Müldner and Richards 2005). In the middle of the plot area, many Kaldu site 4 data points plot near values from the Czech Republic reported to have consumed a mix of $C_3$ and $C_4$ terrestrial foods (Le Huray and Schutkowski 2005). Also in this space, there is overlap with multiple Rogowo data points. At the bottom of the figure, two data points plot near individuals from Byzantine Crete who reportedly consumed $C_3$ terrestrial foods (Bourbou and Richards 2007). At the right of the figure, several data points plot near a Bronze Age Italian sample reported to have consumed millet (Tafuri et al. 2009), but do not fall within this same range, indicating less reliance on millet at Kaldu site 4. Clearly, there was a wide variety of diets at Kaldu site 4.

Because of high individual variability, few sweeping statements can be made about diet at Kaldu site 4 other than individuals may have had opportunities to choose what foods they consumed. Individuals with lower $\delta^{15}$N probably consumed more terrestrial resources. Individuals with high $\delta^{13}$C probably consumed more millet,
Figure 7.6: Collagen Data from Kaldus Site 4

<table>
<thead>
<tr>
<th>Site</th>
<th>Diet Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaldus site 4 (this study)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rogowo (this study)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Byzantine Crete - C3/marine</td>
<td>(Bourbou and Richards 2007)</td>
<td></td>
</tr>
<tr>
<td>Viking &amp; Medieval Sweden - C3/marine</td>
<td>(Kosiba et al. 2007)</td>
<td></td>
</tr>
<tr>
<td>La Tène Czech Republic - C3/C4 terrestrial</td>
<td>(LeHuray and Schutkowski 2005)</td>
<td></td>
</tr>
<tr>
<td>Bronze Age Italy - C3/C4 terrestrial</td>
<td>(Tafuri et al. 2009)</td>
<td></td>
</tr>
</tbody>
</table>
anadromous fish (e.g.: sturgeon) and/or marine fish (e.g.: herring). The wide range of \( \delta^{13}C_{ap} \) values indicates that some individuals consumed diets consisting of up to 40\% millet, or no millet at all. The mean \( \delta^{13}C_{ap} \) value of -11.87±1.32‰ suggests millet contributed an average of 18\% to the diet (either directly or via foddered animals). This corresponds well with the archaeobotanical record: 17\% of the cereals recovered from Kalduś site 4 were millet. Herein lies an excellent example of how bulk archaeobotanical data can be corroborated by stable isotope data (estimates for millet consumption from both values are very similar), and also supplemented by stable isotope data (individual differences in millet consumption can be studied). Individuals with low \( \delta^{13}C \) probably consumed more freshwater fish and/or C\(_3\) plants.

Stable isotope diversity at Kalduś site 4 can be sorted out to a limited extent using the regression model of Kellner and Schoeninger (2007). Looking at Figure 7.7, there appear to be two groups of data points that can be divided on the basis of high or low \( \delta^{13}C \) values. These groups were created arbitrarily by separating relatively low- and relatively high- \( \delta^{13}C \) individuals. The group with \( \delta^{13}C \) values of below 18.0\% plots near the C\(_3\) protein line but with considerable scatter (\( R^2 = 0.3736 \)). This suggests that the \( \delta^{13}C \) signatures of protein and carbohydrates differed considerably. In this sub-group, freshwater fish, C\(_3\) plants, C\(_4\) plants and terrestrial animal protein were likely all part of diet. The second, arbitrarily created group has \( \delta^{13}C \) values of above 18.0\%. This group forms a finger away from the C\(_3\) protein line to the right, and its \( \delta^{13}C_{coll} \) values and \( \delta^{13}C_{ap} \) values exhibit a strong positive relationship (\( R^2 = 0.8945 \)). For these
individuals, δ¹³C signatures of major macronutrients in the diet were very similar. One such possible diet is protein enriched in ¹³C from fish or millet-foddered animals, and C₄ energy from millet. Another possibility is that individuals could choose to eat a diet with more or less of a single C₄ food source, such as millet. Within the “high-¹³C” group, there is no relationship between δ¹⁵N and δ¹³C (Fig. 7.7 and also Fig. 7.8), suggesting this finger-like formation is due to differential millet consumption and not to fish consumption. Differential consumption of omnivore protein also complicates the relationship between δ¹⁵N and δ¹³C.

On closer examination of the collagen data from Kaldus site 4, there seem to be two groups of data points that I emphasize by separating them with an otherwise arbitrary line in Figure 7.9. One of these arbitrary clusters plots near data from Viking and
medieval Sweden representing populations that reportedly consumed C₃ and marine foods, but no millet (Kosiba et al. 2007). The Swedish population is also pictured in Figure 7.9 where it is clearly distinct from the millet-consuming Kaldus population.

Interestingly, this first cluster is composed exclusively of individuals from Kaldus phases 1a, 1b and 2a (although it does not include all these individuals). The second cluster plots further to the left nearer to other European populations with a terrestrial, mixed C₃/C₄ diet (Le Huray and Schutkowski 2005). This cluster represents individuals from all Kaldus phases, but importantly, it includes all the individuals from Kaldus phases 2b and 3 and all Kaldus site 1 data points (assigned less precisely to phase 2b/3). Although these groups were created subjectively and somewhat arbitrarily, they seem to reflect two different diets at two different times. This is another perspective on the reduction of fish
in diet at Kałdus through time. Dividing Kałdus site 4 into phases enables a more refined snapshot of this transition than would otherwise be available, despite the fact that phases within each site cannot be assigned absolute dates.

During the 11th c., Kałdus was an important regional economic center. It was located at the crossroads of two major trade routes linking the Baltic Sea to Southern Europe, and modern-day Russia to Western Europe. The population was likely multi-ethnic, and comprised people of different socioeconomic classes. Both non-local origins and different diets likely contribute to diverse diets at Kałdus site 4. Ethnic heterogeneity is indicated by diverse burial customs at the site, including simple Christian-style East-West burials without grave goods, double graves, chamber graves, and burials including bronze bowls and hazelnuts (Scandinavian rituals).

7.4.1.i Flexed burials, Christian burials and grave goods

It was expected that diets of individuals in Christian-style graves would differ from diets of individuals buried in a flexed position or on a North-South axis in terms of fish consumption. This is not the case. All isotope values of flexed and supine individuals are intermingled (Figs. 6.16-6.18). Stable isotope values are also similar for individuals buried with and without grave goods (Figs. 6.19-6.21).

The two individuals with the richest graves were a female buried with a coin purse in her underarm (K4-210-F) and a male buried with a sword (K4-364-M). Although their $\delta^{15}N$, $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ values are unremarkable, these two individuals exhibit relatively low $\Delta^{13}C_{\text{(ap-coll)}}$ values (5.6‰ and 5.9‰, respectively).
A closer examination reveals that this results from two different diets. Individual K4-364-M exhibits a relatively high δ\(^{13}\)C\(_{\text{coll}}\) signature, perhaps indicating marine fish consumption, whereas individual K4-210-F exhibits a relatively low δ\(^{13}\)C\(_{\text{ap}}\) value, perhaps indicating a diet of less millet. It is not possible to identify any high- or low-status foods at Kaldus site 4.

7.4.1.ii Double-graves – Shared diets?

It is possible that pairs of individuals buried in double graves (data in Figures 6.22 and 6.23) had similar cultural or geographic backgrounds. An interesting question is
whether their diets reveal any such similarity. Individuals K4-256A-F and K4-256B-M were interred in a double grave, and both had been decapitated. Although their $\delta^{15}$N values are similar (10.7‰ and 10.5‰), suggesting a similar source of protein in diet, their $\delta^{13}$C_coll values are dissimilar (-19.3‰ and -17.7‰). A parsimonious explanation for why these two individuals share similar $\delta^{15}$N values but differ in their $\delta^{13}$C values is that the female ate more animal protein with low $\delta^{13}$C values (e.g.: pork, beef) and the male ate animal protein with high $\delta^{13}$C values (e.g.: chicken).

Individuals K4-261A-M and K4-261B-M (both probable males) were interred together in a wooden chamber, a burial style influenced by Scandinavian customs. These two individuals exhibit similar $\delta^{13}$C_coll values (-18.7‰ and -18.1‰) and have in common their relatively high $\delta^{13}$C_ap signatures of -9.23‰ and -10.47‰. Their $\delta^{15}$N values differ by 1.2‰. The $\delta^{15}$N value of 261B is 11.1‰, making it one of the highest in the Kałdus site 4 sample. They both exhibit relatively high $\Delta^{13}$C_coll values (9.5‰ and 7.6‰) due to their high $\delta^{13}$C_ap signatures, suggesting a diet high in millet (approximately 40% and 25%).

The double grave containing individuals K4-13A-M and K4-13B-F also was “Viking-style.” The male was buried with a bronze bowl at his feet, and the female with a bucket at her feet. These individuals’ diets differed significantly. The male’s diet may have included marine fish, as the indicators of protein sources, $\delta^{15}$N and $\delta^{13}$C_coll values, are high but his indicators of energy sources, $\delta^{13}$C_ap and thus $\Delta^{13}$C_coll values, are low. The female’s diet does not suggest marine fish consumption, but rather a diet based on terrestrial resources with approximately 30% of the dietary energy coming from millet.
7.4.1.iii Other notable individuals

Like individual K4-13A-M, individual K4-60-M was buried with a bronze bowl at his feet, an element of Scandinavian style burials (Biermann 2008; Chudziak 2003). Interestingly, his $\delta^{13}C_{ap}$ signature was next to the lowest at Kaldu site 4 (-14.05‰) and one of only two to indicate a diet devoid of millet. This suggests he had migrated from Scandinavia, where millet is not documented in diet during the medieval period (Eriksson et al. 2008; Kjellström et al. 2009; Kosiba et al. 2007; Liden and Nelson 1994; Linderholm et al. 2008; Wasylikowa et al. 1991). The other individual with very low $\delta^{13}C$ isotope signatures at Kaldu site 4 is K4-192-F. This female may also have migrated from a region where millet was not consumed. Another single burial exhibiting Scandinavian elements is individual K4-101-F, who was interred in a wooden chamber. Like K4-60-M, her isotope values also suggest no or very little millet. A total of 4 individuals at Kaldu site 4 had $\delta^{13}C_{ap}$ values below -13.2‰, including the three discussed here. This $\delta^{13}C_{ap}$ number corresponds with approximately 5% millet in diet.

A final observation that may be significant is that the highest $\delta^{15}N$ value (11.9‰) is from a female buried with a large stone on her chest, the only such burial at Kaldu. Placing a stone on a deceased individual’s chest was believed to deter the individual from sitting upright in the grave after death and wandering into the nearby settlement (vampirism). It would not be inconsistent with the evidence to interpret the high $\delta^{15}N$ value as reflecting this alleged vampire’s tendencies toward blood-drinking. She also exhibits a relatively high $\delta^{13}C_{ap}$ value of -10.90‰ and a relatively high $\Delta^{13}C_{(ap-coll)}$ value.
of 7.4‰, which both suggest unusually high millet consumption for the population. Her relatively low δ\(^{13}\)C\(_{\text{coll}}\) value of -18.3 suggests that despite her high δ\(^{15}\)N value, her diet was not high in marine fish.

7.4.1.iv Change through time: Kaldus site 4 in phases

When Kaldus site 4 is divided into five chronological phases changes in diet are detected at a fine resolution. As shown earlier (Table 6.4 and Fig. 6.13), δ\(^{15}\)N, δ\(^{13}\)C\(_{\text{coll}}\) decreases steadily through time. δ\(^{13}\)C\(_{\text{ap}}\) values also decline but sharply, between Phase 1 and Phase 2. Ignoring the Kaldus site 1 data, δ\(^{15}\)N values also decline steadily within Kaldus site 4 (but increase at Kaldus site 1). Both fish and millet consumption appears to have decreased gradually through time. This is corroborated by the archaeozoological record. This dietary change probably reflects socioeconomic decline at Kaldus site 4 over time. During the earlier phases when Kaldus was a socioeconomic hub, the population likely was more diverse, attracting people from many social strata and geographic origins. Not everyone was engaged in food production, and one solution to the problem of feeding an urban population was importing salted, smoked or pickled fish, most often from the Baltic Sea port Gdańsk (Makowiecki 2001). This accounts for high fish consumption at Kaldus site 4. The expected impact of religious change on diet was an increase in fish consumption. Fish consumption is believed to have increased during the medieval period (Barrett et al. 2008; Müldner and Richards 2005; Woolgar 2000). The Church was partly responsible for catalyzing trade in fish. Religious orders imported large quantities of fish, and sold the excess for profit (Makowiecki 2001). Herring trade
reached its zenith in the 12th-13th centuries with the influence of the Cistercian Order (Makowiecki 2001: 238). In addition to the religious elite, the general populace in Poland was increasingly exposed to Christianity and was expected to have begun observing fasts in the decades and/or centuries following Christianization of Poland. Fish consumption should theoretically increase in the medieval period. However, the reverse appears to be true: supplemental dietary input from marine fish at Kałdus site 4 decreases through time. Fish at Kałdus, which according to the wide range of stable isotope variation and the archaeoichthyological record included a mix of freshwater and anadromous varieties, were replaced gradually by a terrestrial diet.

Kałdus site 4 inhabitants were likely more affluent than Kałdus site 1 or Gruczno inhabitants and had more access to fish, a relatively expensive commodity. The socioeconomic climate apparently trumped religious fasting restrictions in structuring human diet. Another interpretation of a decrease in fish consumption involves the rejection of Christianity by Kałdus site 4 inhabitants. This cemetery was in use during the time of the pagan revolt in the mid-11th c. Contrary to this hypothesis, mortuary analysis suggests an increased adherence to Christian burial customs through time. Through phases, burials become more “Christian” at Kałdus site 4. Within Kałdus site 4, all but 2 of the 16 unusual burials come from the earlier phases (including expanded phases 1a, 1b and 2a, all subsumed by broader Phase 1) including 6 of the 8 graves exhibiting pagan or anti-vampire elements (flexed position or stone atop chest). Kałdus site 4 burials exhibit the most diversity in burial styles within the medieval sample. Thus,
the most logical explanation for the reduction in fish consumption through time at Kaldu is the change in socioeconomic functions of the site.

Sturgeon played an important role in diet of many Kaldu site 4 inhabitants. Sturgeon are large anadromous fish inhabiting the Baltic Sea and its major tributaries, including the Vistula River (Makowiecki 2001). Sturgeon are common in archaeological assemblages from the 10th c. (54% of finds). Beginning in the 11th c. they are increasingly rare and by the 12th c. only 12% of fish bones in archaeological assemblages are sturgeon (Makowiecki 2001: 240). Over-fishing and pollution caused sturgeon populations to decline in the medieval period. The response to this was tighter restrictions on their capture and trade and a subsequent increase in value. Sturgeon in this study exhibit stable carbon isotope ratios of approximately -15 to -17, making them candidates for isotope enrichment at early Kaldu site 4. This agrees with stable isotope data, as many individuals at Kaldu site 4 show a marine or (more likely) anadromous fish signal which tapers off in later periods. At Kaldu during the 12th c. (site 2, a settlement) sturgeon is the third most common fish, comprising 6% of the total fish remains (Makowiecki 2010b). This number seems low, but it should be borne in mind that sturgeon are quite large, at least several feet long, and relative to the meat they provide, have proportionally fewer bones than does a single carp or pike (which are the two most common fish finds at Kaldu site 4 comprising 63% and 15% of the total remains, respectively) (Makowiecki 2010b).
7.4.2 Kaldus site 1, 12th-13th c. AD

Diet changed significantly at Kaldus between the 11th and the 12th-13th c. but not in the ways expected, as reviewed in section 7.2. Both δ\textsubscript{13}C\textsubscript{coll} and δ\textsubscript{13}C\textsubscript{ap} values are not higher in site 1 compared to site 4; they are in fact lower in this later period (12th-13th c.) (t-test; p<0.001 and p=0.023). There is no apparent shift in δ\textsubscript{15}N values (t-test; p=0.737).

Furthermore, although there is no change in the range of δ\textsubscript{13}C\textsubscript{ap} values between the two phases, the δ\textsubscript{13}C\textsubscript{coll} range is more restricted at Kaldus site 1. Apparently, dietary protein sources were less varied at Kaldus site 1, or dietary protein sources had less varied isotope ratios. At Kaldus site 4 protein included animals and marine and freshwater fish. At Kaldus site 1, the small range of δ\textsubscript{13}C\textsubscript{coll} values indicates a protein base of C\textsubscript{3} terrestrial animals with less fish consumption. This agrees with the archaeozoological record: as reviewed in Chapter 2, Makowiecki (2010) documents a drop in fish from 28.6% of total faunal assemblages in the 11th c. site 4 to just 2.9% in the 12th-13th c. site 1.

Comparing Kaldus site 1 data points to Kaldus site 4 and other European populations, collagen stable isotope data from Kaldus site 1 diet most closely resembles Neolithic populations from Southern Germany that consumed C\textsubscript{3}, terrestrial foods (Dürrwächter et al. 2006) (Fig. 7.10). However, Kaldus site 1 data points are shifted to the right of the German sample, reflecting millet consumption, and are at the upper range of δ\textsubscript{15}N values, discussed further in section 7.4. Several samples overlap with individuals from a medieval English sample that consumed freshwater fish.
Figure 7.10: Collagen Data from Kaldus Site 1 Compared to Other European Populations

- Kaldus Site 1 (this study)
- Kaldus site 4 (this study)
- Neolithic Germany - C3/terrestrial (Durrwachter et al. 2006)
- Medieval Poland - C3/C4 (Reitsema et al. 2010)
- Byzantine Crete - C3/marine (Bourbou and Richards 2007)
- Viking & Medieval Sweden - C3/marine (Kosiba et al. 2007)
- La Tène Czech Republic - C3/C4 terrestrial (LeHuray and Schutkowski 2005)
Apatite and collagen $\delta^{13}$C from Kaldus site 1 are compared to data from other
European samples and to Kaldus site 4 in Figure 7.11. Whereas Kaldus site 4 overlaps
with fish-consuming populations from Siberia (data points represent population averages,
not individuals) (Katzenberg and Weber 1999) and Sweden (Kosiba et al. 2007), Kaldus
site 1 does not. Two individuals at the bottom of the Figure 7.11 plot area may be exceptions.

One of the comparison populations in Figure 7.10 is from ancient Greek Bulgaria
(Keenleyside et al. 2006). Although $\delta^{15}$N values from this population are relatively low
and only slightly higher than Kaldus values, Keenleyside et al. (2006) report a diet of
purely-$C_3$ plant diet with marine protein for this sample. However, Bulgaria data plot on
the $C_3$ protein line and higher than all other comparative samples. They are clearly
separated from the high-$^{13}$C fish consuming samples which plot to the right of the $C_3$
protein line, as expected. This suggests millet was an important source of dietary energy
for the Bulgarian population, contrary to the authors’ interpretation. Several of the
Bulgaria datapoints overlap with the anomalously high-$^{13}$C$_{ap}$ Kaldus site 1 datapoints
observed here, corroborating the interpretation from Chapter 5 that the values are
biogenic and not diagenetic. Keenleyside et al. (2006) propose that in their sample,
macronutrient scrambling (rather than routing), as discussed in Chapter 3 (section 3.7) is
occurring. This may also explain the unusual scatter of Kaldus site 1 data points,
although low-protein diets are inconsistent with $\delta^{15}$N data from both this and the
Bulgarian study. Variable millet consumption seems a more likely explanation in both
samples. Using regression lines of Kellner and Schoeninger (2007) considerably revises
diet reconstruction from Keenleyside et al. (2006) and clarifies the negligible role of marine fish in Kałdus site 1 diet.

Millet was consumed less in the 12th-13th c. at Kałdus. Three individuals are exceptions to this: K1-101-F ($\delta^{13}C_{ap} = -9.79‰$), K1-58-F ($\delta^{13}C_{ap} = -7.89‰$), and K1-93-M ($\delta^{13}C_{ap} = -8.24‰$). Assuming a 12‰ diet-carbonate space and $C_3$ and $C_4$ endpoints of -26‰ and -14‰, respectively, the diets of these three individuals comprised between 35% and 50% millet. Other than this, the Kałdus site 1 sample’s $\delta^{13}C_{ap}$ values are low, most of them (63%) below -13.0‰. At Kałdus site 4, only 24% fell below a $\delta^{13}C_{ap}$ value of -13.0‰. Again, this difference in $\delta^{13}C_{ap}$ values occurs in spite of no corresponding change in $\delta^{15}N$ values. There is much overlap between Kałdus sites 1 and 4; many site 4 samples were likely contemporary with the Kałdus site 1 population (clarified in Figure 7.9).

As discussed in section 7.4.1, skeletons from Kałdus sites 4 and 1 represent two phases. Most of the skeletons from Kaldu site 4 are from Phase 1. All skeletons from site 1 and some from site 4 are from Phase 2. Kaldu site 1 data points overlap with Kaldu site 4 data points from the later phases (2b, 3) but are distinct from the earlier phases (1a, 1b and 2a) (Fig. 7.9). In the earlier Phase 1, Kałdus was an economic center that housed a socioeconomically diverse population. By the later phase, Kałdus had declined in importance and was a farming settlement. Incidence of periostitis and degenerative joint disease are considerably more frequent in skeletons from the later phase, attesting to a physically demanding agricultural lifestyle. The shift to a more
Figure 7.11: Kaldus $\delta^{13}C_{\text{coll}}$ vs. $\delta^{13}C_{\text{ap}}$ Data Compared to Other European Populations

- **C3 Protein Line**

- **Kaldus site 1**
- **Kaldus site 4**
- **Giecz**
- **Siberia - Freshwater Fish (Katzenberg and Weber 1999)**
- **Siberia - High 13C FW Fish (Katzenberg and Weber 1999)**
- **Neolithic Anatolia (Losch et al. 2006)**
homogeneous diet without fish reflects this shift in occupation at Kalduś. Despite the fact that burial styles at Kalduś site 1 are more “Christian”, diet does not reflect Christianization through time in the form of more fish consumption to adhere to Church-imposed fasts. Diets of men and women did not differ at either Kalduś site.

7.4.3 Gruczno

Diets at Gruczno were predominantly terrestrial and included smaller amounts of millet than at Kalduś. This is completely contrary to the expectations proposed in section 7.2. The $\delta^{15}N$ values at Gruczno are relatively low although they still indicate contributions of animal protein to diet. $\delta^{15}N$ values of more than 11‰ are generally indicative of a diet including fish, as are $\delta^{13}C$ values outside a terrestrial C$_3$ range of approximately -21 and -19‰. Fish consumption is not indicated as $\delta^{15}N$ values are within a single trophic level from terrestrial animals, and $\delta^{13}C$ values are within a “terrestrial” range.

Collagen data from Gruczno are shown in Figure 7.12 in comparison to other European samples. A comparative sample from medieval England shows a diet including C$_3$ foods and marine and freshwater fish (Müldner and Richards 2005). Also from medieval England is a population consuming a C$_3$ terrestrial diet from Wharram Percy (Fuller et al. 2003). Gruczno data are most similar to this sample. Another comparative sample is from Byzantine Crete and shows a C$_3$ diet with only a few cases of marine fish input (Bourbou and Richards 2007). Finally, the sample from ancient Greek Bulgaria reportedly reflects a diet of marine fish, but as discussed in section 7.3.2, may reflect
Figure 7.12: Collagen Data from Gruczno in Comparison to Other European Populations

- Gruczno site 1, 12th c. AD (n=32)
- Gruczno site 2, 13th-14th c. AD (n=24)
- Byzantine Crete (Bourbou and Richards 2007)
- Ancient Greek Bulgaria (Keenleyside et al. 2006)
- Medieval England (Muldner and Richards 2005)
- Medieval England (Fuller et al. 2003)
a diet of millet. In comparison, Gruczno shows no evidence of millet consumption.

At Gruczno (both sites), $\delta^{13}$C$_{ap}$ values range from -14.90‰ (G2-1607-F) to -11.12‰ (G1-760-F). Assuming a diet-to-apatite space of +12‰ (Garvie-Lok 2001; Prowse et al. 2005), the diet at Gruczno (both sites) comprised between approximately 25% and 0% millet, which is less than at Kałdus and Rogowo. At Gruczno site 1, the mean $\delta^{13}$C$_{ap}$ value is slightly higher than at Gruczno site 2. Also, sixteen individuals from Gruczno site 1 have $\delta^{13}$C$_{ap}$ values lower than -13.00‰, whereas at Gruczno site 2, 21 individuals do. These observations suggest millet consumption decreased through time at the site. The same trend was observed at Kałdus, described in the previous section. Reduced millet consumption at Gruczno is supported by the comparison with other European samples shown in Figure 7.13, where Gruczno is clearly distinct from two populations where millet was likely consumed, one from ancient Greek Bulgaria as discussed in section 7.3.2 and one from elsewhere in medieval Poland (Keenleyside et al. 2006; Reitsema et al. 2010).

A difference between Kałdus and Gruczno is the range of $\delta^{13}$C$_{ap}$ values: at Kałdus the range is much wider than it is at Gruczno, suggesting the latter consumed a more homogenous diet. More homogeneous stable isotope composition appears to be caused by the decrease in millet consumption and a shift to a purely C$_3$ diet. Consumption of animal products and fish was less at Gruczno than at Kałdus (especially Kałdus site 4). Only four individuals at Gruczno site 1 and four at Gruczno site 2 exhibit $\delta^{15}$N values higher than 10‰. At Kałdus site 4, 23 individuals had $\delta^{15}$N values above 10‰ and at Kałdus site 1, 20 individuals had $\delta^{15}$N values of 10‰ or above. Considering apatite and
collagen $\delta^{13}C$ in tandem in Figure 7.13, Gruczno is dissimilar from populations consuming high-$^{13}C$ fish (Katzenberg and Weber 1999; Kosiba et al. 2007). Within Gruczno, there was temporal change (between sites 1 and 2) in animal consumption.

Gruczno was a rural settlement more based on agricultural than Kaldus. Cribra orbitalia is relatively high at Gruczno, especially among subadults, which is due either to poor nutrition or infection. Periostitis is also common at Gruczno. Compared to Kaldus, Gruczno has a higher incidence of Schmorl’s nodes and osteochondrosis. At the time of this writing, it is believed that degenerative changes of joints are more common at Gruczno (almost 50% of the skeletons are affected) than at Kaldus, though Kaldus has not been completely studied yet (T. Kozlowski, pers. comm.).

Unlike at Kaldus, at Gruczno, sex-based differences in isotope signatures exist. At Gruczno site 2, both $\delta^{13}C_{\text{coll}}$ and $\delta^{13}C_{\text{ap}}$ are significantly lower among females (p=0.040 and 0.026, respectively). At Gruczno site 1, only $\delta^{13}C_{\text{coll}}$ differs between the sexes. Female values are lower than male values (p=0.070). Interestingly, $\delta^{13}C_{\text{ap}}$ of males and females at Gruczno site 1 are not different (p=0.646). Thus, the sex-based difference in diet is protein sources. Excluding fish, which were not consumed in large quantities at Gruczno, other possible high-protein sources are wild animals, cattle, sheep and pigs (low-$^{13}C$ in this study), and chicken (high-$^{13}C$). There may have been differential access to these animals and/or their products at Gruczno. At least at Gruczno site 2 where sex-based differences in $\delta^{13}C_{\text{ap}}$ also exist, millet was apparently consumed more by men than by women. The $\delta^{15}N$ values of men and women are similar (at Gruczno site 1, p=0.910; at Gruczno site 2, p=0.839).
Figure 7.13: Collagen and Apatite $\delta^{13}$C Data from Gruczno in Comparison to Other European Populations

- $\delta^{13}$C$_{\text{ap}}$ (VPDB) (‰)
- $\delta^{13}$C$_{\text{coll}}$ (VPDB) (‰)

- Gruczno site 1
- Gruczno site 2
- Ancient Siberia - Freshwater Fish (Katzenberg and Weber 1999)
- Ancient Siberia - High-13C fw Fish (Katzenberg and Weber 1999)
- Neolithic Anatolia - C3 Terrestrial (Losch et al. 2006)
- Viking/Medieval Sweden - Marine Fish (Kosiba et al. 2007)
- Ancient Greek Bulgaria (Keenleyside et al. 2006)
- Medieval Poland - C3/C4, Some Marine (Reitsema et al. 2010)
7.4.4  Summary of Diet Reconstructions

Diets of the Neolithic and Iron Age individuals were more exclusively based on $C_3$ plants. Because of the canopy effect whereby flora in closed forests are $^{13}$C-depleted due to the recycling of CO$_2$, the very low $\delta^{13}$C signatures of three of these individuals suggest foods may have come from forests, rather than open fields. Recent archaeological research suggests that the adoption of agriculture in Poland during the Neolithic was patchy and gradual, with agriculture supplemented by hunting and gathering and animal husbandry (Grygiel and Bogucki 1993). It is also possible that the primarily terrestrial diets of Neolithic and Iron Age populations were supplemented by low-$\delta^{13}$C freshwater fish, much like the Early Neolithic individuals reported by Bonsall et al. (2004) from the Iron Gates in Southeast Europe. Stable isotope evidence from elsewhere in Europe demonstrates that subsistence strategies did not transition sharply between the Mesolithic and the Neolithic from hunting-gathering to agriculture. These stable isotope data support the interpretation of a mixed economy, rather than a purely-agricultural economy, for Neolithic Polish populations. The Iron Age sample from Bożejewice is very similar to these Neolithic individuals. The Iron Age individual from Gziń has relatively higher $\delta^{13}$C values which may indicate marine fish consumption or millet consumption. All four ancient samples came from inland sites, excepting the individual from Gziń. The absence of marine fish in their diets suggests limited trade connection with the Baltic Sea in these earlier periods.

The low level of millet consumption in these early periods is interesting. As will be discussed in greater detail later, millet is associated with Slavic populations in Europe.
The origins of modern-day Slavs is hotly debated, with some researchers supporting an early (e.g. Neolithic) in situ ethnogenesis and other supporting a more recent migration of Slavs into the area (reviewed by Dąbrowski 2006). That the Neolithic samples investigated here did not cultivate and consume this characteristically Slavic crop suggests Slavic origins in Poland may be more recent than the Neolithic. It is noted that millet is found in Neolithic archaeobotanical assemblages (Grygiel and Bogucki 1993). More samples from these periods will clarify these issues.

In general, diets of Roman Era and medieval Polish populations are based on C₃ plants (wheat, barley, vegetables) and terrestrial animals. Supplemental input from fish is likely, particularly from freshwater fish with low δ¹⁵N and (relatively) high δ¹³C values such as those inhabiting in oxbow lakes. At Rogowo and Kalduś there were significant contributions to diet from a C₄ plant (millet). A significant difference between diets at Kalduś and at Gruczno, the two medieval settlement areas, is greater fish consumption at Kalduś, although this was still low. Kalduś was more of an economic hub than Gruczno and this dietary difference likely reflects the degree to which each site was connected to Baltic Sea trade routes.

Only small amounts of fish were consumed at Rogowo and Kalduś, and fish were not consumed in detectable amounts at Gruczno. This is contrary to the expectation that through time, fish consumption would consistently increase throughout the medieval period in response to transitions to market economies and Christianization, as has been reported elsewhere in Europe (Barrett and Richards 2004; Müldner and Richards 2007b; Salamon et al. 2008). There are several explanations for why fish consumption does not
increase through time in this sample. First, fish may not be a useful proxy indicator for Christianization. Many varieties of fish were more expensive than other protein sources, and some (e.g: sturgeon) became increasingly expensive through time (Makowiecki 2001). Populations studied here may simply not have been able to afford fish. Second, Christianization may not have progressed in a linear fashion in this region of Poland. During the 11th c. AD Northern Poland underwent a pagan revolt and many territories of the state (including the region in which Kalduś and Gruczno were located) rejected the Polish monarchy and Church. The Teutonic Order restored Christianity to the area in the 13th c, the time when the Kalduś site 1 cemetery was in use. Thus, the populations at Kalduś site 4 and Gruczno site 1 experienced relatively feeble efforts towards Christianization. Christianity clearly influenced burial style through time – by the 12th c. cremation had been replaced by inhumation in Poland, for example (Kloczowski 2000). However, Christianity’s influence may have been tenuous, explaining why it could affect more public activities such as funerals but not private, domestic affairs such as diet.

An expectation at the beginning of this study was that dietary differences would increase within the populations through time, reflecting social differentiation in the medieval period. However, there is little evidence for differences in diet based on mortuary style (a proxy for status) or sex in the sample with the exceptions of sex-based differences in δ¹³C at Rogowo and Gruczno site 2. Sex-based differences in stable isotope ratios at Rogowo indicate that females consumed more millet than did males, with no significant difference in the amounts or types of animal protein between the sexes. Sex-based differences at Gruczno site 2 are the opposite of those at Rogowo.
Women exhibit lower $\delta^{13}$C ratios than do men without a corresponding difference in $\delta^{15}$C values, suggesting women consumed less millet. Why this should be the case at Gruczno site 2 and not any of the other medieval sites is unclear. Because Gruczno site 2 is the latest site in time, it could indicate that sex-based differences in status were greater towards the end of the medieval period than at the beginning, which agrees with the initial expectations of this research. However, there are other variables that should be considered before concluding the medieval period was an increasingly negative time for women. Differences in economies between Kałdus and Gruczno and within the same settlement area through time, and the influence of the Teutonic Order could also influence sex-based differences in diet.

General stable isotope variability is greatest in the Roman Era sample (Rogowo) and the two medieval samples from Kałdus (Kałdus site 4, 11\textsuperscript{th} c. and Kałdus site 2, 12\textsuperscript{th}-13\textsuperscript{th} c.). The samples from Gruczno are less isotopically variable. This suggests that populations at Rogowo and Kałdus were more socially stratified than those at Gruczno. Interpretations of the lifestyles of these populations based on archaeology and paleopathology reveal that Kałdus was more of an economic center while Gruczno was more of an agricultural village, which supports the idea that Gruczno was less socially stratified. It is also possible that heterogeneity at Rogowo and Kałdus is merely the result of variable amounts of millet consumption, independent of social status. Millet appears not to have been cultivated at Gruczno, which alone could explain dietary homogeneity at this site without evoking social differentiation.
Another explanation for differences in millet consumption between Kalduś and Gruczno is the relative influences of Germanic and Slavic culture. The Teutonic Order was formed and run by Germans, and encouraged German immigrants to many areas of its monastic state in Northern Europe. The Germanic cultural input to Poland during the medieval period is particularly well-evidenced by Poland’s adoption of German town laws known as Madgeburg and Lübeck Laws granting economic independence to urban areas. The general decline in millet consumption through time in the study samples may reflect a Germanization of diet, as millet cultivation was rare or absent to the West of Poland during the medieval period.

7.5 General Trends and Implications for Isotope Paleodiet Studies in Europe

Underlying these interpretations are assumptions about the nature of stable isotope variation in Northern European foodwebs. There are two trends in the stable isotope ratios of the samples in this study that merit further attention. These are (1) enrichment of $^{13}$C in human bones relative to other European populations and (2) intermediate $\delta^{15}$N values relative to what might be expected from purely-terrestrial diets and diets including fish. The causes of these trends have serious implications for diet reconstructions based on stable isotope signatures in the study samples.

7.5.1 Explaining High $\delta^{13}$C Values

One of the most notable differences between the Polish samples investigated here and other samples from elsewhere in Europe are the relatively high $\delta^{13}$C values,
which appear to be associated with relatively low (i.e., terrestrial) \( \delta^{15}N \) values. Possible sources of \( ^{13}C \)-enrichment in past European diets include millet consumption, consumption of animals foddered on millet, and consumption of marine fish. To illustrate the degree of \( ^{13}C \)-enrichment observed in the present study, Rogowo, Kałdus and Gruczno are shown plotted along with the mean±1sd of previously published reference populations elsewhere in Europe (Fig. 7.14). Three diets are estimated in Figure 7.14; lines are drawn around them only to include the representative comparison samples in hypothetical diet groups, and are not precise estimates. Low \( \delta^{13}C \) values of most comparative populations (and Gruczno) reveal no millet consumption. High \( \delta^{13}C \) values at Rogowo are similar to at Bronze Age Italy where millet was consumed. Kałdus site 4 includes individuals that plot in all three hypothetical dietary spaces.

The source of \( \delta^{13}C \) in the study areas can be further clarified by considering more lines of evidence that would support either millet consumption or alternative explanations. In Table 7.1, three possible sources of higher \( \delta^{13}C \) ratios are listed along with some other predictions that correspond to each. The possible sources are marine fish, animals foddered on C\(_4\) grain, and direct millet consumption by humans. Each hypothesis is shown with its expected isotope outcomes. In the final column it is noted whether or not each expectation is met. By showing only limited support for other provisional \( ^{13}C \)-enrichment explanations, Table 7.1 shows the strongest support for direct millet consumption by humans.
Figure 7.14: Millet Consumption at Kaldus, Rogowo and Gruczno Compared to Other European Samples

- Rogowo (millet)
- Kaldus (millet)
- Gruczno (no millet)
- Early Medieval Sweden (n=6)
- Medieval Belgium (n=19)
- Early Medieval Germany (n=37)
- Medieval UK (n=8)
- Iron Age UK (n=62)
- Medieval France (n=34)
- Bronze Age Italy - No Millet (n=14)
- Bronze Age Italy - Millet (n=25)

Legend:
- Cross: Rogowo (millet)
- Square: Kaldus (millet)
- Circle: Gruczno (no millet)
- Triangle: Early Medieval Sweden (n=6)
- Circle with a cross: Medieval Belgium (n=19)
- Triangle with a cross: Early Medieval Germany (n=37)
- Circle with a dot: Medieval UK (n=8)
- Circle with a line: Iron Age UK (n=62)
- Triangle with a line: Medieval France (n=34)
- Diamond with a dot: Bronze Age Italy - No Millet (n=14)
- Diamond with a line: Bronze Age Italy - Millet (n=25)
Table 7.1: Hypotheses and predictions for $^{13}$C enrichment

<table>
<thead>
<tr>
<th>Sources of $^{13}$C Enrichment:</th>
<th>Associated predictions:</th>
<th>Support?</th>
</tr>
</thead>
</table>
| Marine fish                     | 1. Fish bones excavated from the sites will be $^{13}$C-enriched  
  2. Human bones will exhibit high $\delta^{15}$N ratios  
  3. Humans’ $\delta^{13}$C and $\delta^{15}$N values will positively correlate  
  4. Human isotope data will be comparable to those from other European populations known to have consumed marine fish  
  5. Humans’ $\delta^{13}$C data points will plot near Kellner and Schoeninger’s (2007) marine protein line | 1. Partial  
  2. No  
  3. No  
  4. No  
  5. No |
| Animals foddered with C$_4$ grain | 1. Animal bones excavated from the area will be $^{13}$C-enriched  
  2. Humans’ $\delta^{13}$C and $\delta^{15}$N values will positively correlate  
  3. Humans’ $\delta^{13}$C data points will plot to the right of Kellner and Schoeninger’s (2007) C$_3$ protein line or near the C$_4$ protein line | 1. No  
  2. No  
  3. Yes |
| Millet                          | 1. Millet will be found in local archaeobotanical assemblages  
  2. Humans’ $\delta^{13}$C and $\delta^{15}$N values will not positively correlate  
  3. $\Delta^{13}$C$_{coll-ap}$ values will be high and unrelated to $\delta^{15}$N values | 1. Yes  
  2. Yes  
  3. Yes |

$^1$Sturgeon exhibit intermediate $\delta^{13}$C values of -15.6‰ to -17.1‰

Millet was first cultivated in Asia in as early as 12,000 years ago (Pechenkina et al. 2005) and introduced to Northern Europe during the Neolithic (Grygiel and Bogucki 1993). Historic records from as early as Pliny in the 1st c. AD indicate that millet was commonly consumed as a mush or gruel by Central European populations (Dembińska 1999; Renfrew 1973). Isotopic evidence of millet consumption in Europe prior to the medieval period comes from Slovenia and Austria ca. 800 and 400 BC (Le Huray and Schutkowski 2005; Murray and Schoeninger 1988), and Serbia ca. AD 250 and AD 400 (Bonsall et al. 2004). Isotope evidence for medieval millet consumption in Poland comes from 11th-12th c. Giecz, Poland (Reitsema et al. 2010). At Giecz, a sample of 24
individuals exhibited a somewhat high mean $\delta^{13}C_{\text{coll}}$ ratio of -18.9‰ and a relatively low $\delta^{15}N$ ratio of 9.2‰. The $\delta^{13}C_{\text{ap}}$ ratios of five individuals at Giecz ranged from -11.52 to -12.67‰. Together these data indicate a relatively homogeneous diet including millet with perhaps supplemental inputs from marine fish. The study at Giecz and the present research corroborate extensive archaeobotanical evidence of millet consumption since the Neolithic throughout Central Europe (Le Huray and Schutkowski 2005; Polcyn 2002; Randsborg 1985; Rösch et al. 1992; Schutkowski et al. 1999; Wasylikowa et al. 1991). It is not clear whether millet may have been used as animal fodder.

According to the archaeobotanical record, millet cultivation was especially prevalent in the Polish Roman Era (Wasylikowa et al. 1991). Although commonly consumed as a gruel, millet was also used to brew ale and beer during the medieval period in Poland, although barley, oats, rye, and wheat were also typical ingredients (Dembińska 1999). Sausages were stuffed with millet, and it was also fried in butter to make kasha, a dish still ubiquitous in Poland. Millet may have also had non-dietary importance as part of burial rituals to deter vampires (Barber 1988), a concern that escalated among Slavic peoples as Christian customs demanded corpses be buried rather than cremated (Barford 2001).

Further West in Northern Europe, neither archaeobotany nor stable isotope research have yielded evidence for millet consumption during or before the medieval period (Grygiel and Bogucki 1993). Because climates are not dissimilar, this suggests Slavic populations had a cultural preference for millet. As discussed earlier, not all
samples in the present study exhibit evidence for millet consumption, including several of the ancient skeletons and many of those from Gruczno.

Millet was a daily staple, which would seem to suggest it was a low-status food in the medieval period. In a large scale study of botanical remains in Central Europe from the Roman to the Post-medieval periods, millet was more commonly found in towns than in castles (Rösch et al. 1992). Nevertheless, Dembińska (2000) reviews recipes from elite households in medieval Poland and concludes that millet was also consumed regularly by high-status individuals.

7.5.2 Explaining intermediate $\delta^{15}N$ values

Fairly often in stable isotope diet reconstructions in Europe, $\delta^{15}N$ values of humans fall into an intermediate range of 9.0‰ to 11.0‰. This range borders the expected ranges for purely-terrestrial diets and diets including fish. However, in many cases the corresponding $\delta^{13}C$ values do not indicate fish consumption, making these values difficult to explain (Bonsall et al. 2004; Garvie-Lok 2001; Linderholm et al. 2008; van Klinken et al. 2000). As discussed in Chapter 3, plants generally exhibit low $\delta^{15}N$ values of approximately 3‰ whereas most terrestrial animals exhibit $\delta^{15}N$ values in excess of 5‰. Fish often exhibit $\delta^{15}N$ values in excess of 7.0‰ or 8.0‰ (e.g: Bonsall et al. 2004, Garvie-Lok 2001). After metabolic fractionation, humans exhibit $\delta^{15}N$ values approximately 2-5‰ higher than diet $\delta^{15}N$ (Drucker and Bocherens 2004). Theoretically, a value of 9‰ in a human indicates a purely carnivorous diet. Values of more than 11.5‰ are characteristic of populations consuming fish (Rutgers et al. 2009).
A δ\textsuperscript{15}N value of 10‰ is high enough to question the validity of an explanation based purely on terrestrial foods, but low enough to preclude fish consumption. This is the case in the present study, where 76% of the δ\textsuperscript{15}N values are between 9.0‰ and 11.0‰, including both Neolithic samples. Only 16% of the samples fall below 9.0‰ and only 8% are higher than 11.0‰. In many cases, enrichment in \textsuperscript{15}N is accompanied by enrichment in \textsuperscript{13}C and clearly reveals marine fish consumption. When δ\textsuperscript{13}C values are not as enriched as they “should” be considering the associated δ\textsuperscript{15}N values (as in the present study), other factors contributing to intermediate δ\textsuperscript{15}N values should be considered. Several explanations for intermediate δ\textsuperscript{15}N have been advanced, and next I evaluate these in light of Poland’s geographic, historic and archaeological contexts.

7.5.2.i Biogenic fractionation effects

An unusually high degree of δ\textsuperscript{15}N fractionation could be biogenic. High protein diets may cause large stable nitrogen isotope fractionation outside the normally encountered range of +2-5‰. In controlled experiments with animals, alpacas fed a high protein diet (20%) exhibited a diet-hair trophic level enrichment of 6‰ (Sponheimer et al. 2003). This is due to the fact that on low-protein diets, relatively more nitrogen is excreted in feces than in urine, and on high-protein diets more nitrogen is excreted in urine. Urine is more isotopically depleted than feces, so when it is the primary source of nitrogen loss, the remaining tissue will be heavier than it would have been had feces been the primary source of nitrogen loss (Sponheimer et al. 2003). However, a very high protein diet is as unlikely as a very low protein diet in medieval North-Central Poland.
Arid environments also increase fractionation of nitrogen isotopes in the body due to increased urea concentration and recycling of amino acids (Ambrose 1991; Schoeninger and DeNiro 1984; Schwarcz et al. 1999), but arid conditions were not present in Northern Europe during this time period.

7.5.2.ii Salt marsh grazing

Britton et al. (2008) review how plants exposed to sea spray can become enriched in δ\(^{15}\)N. This is due in part to the isotopic composition of soils exposed to sea spray and salinity’s effect on nitrification/denitrification reactions at plant roots (Britton et al. 2008). Salt-marsh grazing was a deliberate strategy in Bronze Age animal husbandry in England, and indeed, animal bones from ancient animals suspected of this behavior exhibited δ\(^{15}\)N that were significantly higher than an inland control sample. The \(^{15}\)N-enrichment of salt-marsh-grazing animals is transferred to humans consuming these animals. There are no salt marshes in any of the study areas in Poland which obviates this as a possible explanation for intermediate δ\(^{15}\)N values.

7.5.2.iii Consumption of low- δ\(^{15}\)N fish

It is now well-known that freshwater fish may exhibit highly variable δ\(^{13}\)C and δ\(^{15}\)N values (Dufour et al. 1999; Hecky and Hesslein 1995; Müldner and Richards 2005; Müldner and Richards 2007b; Rutgers et al. 2009; van Klinken et al. 2000)(Katzenberg 1989; Katzenberg and Weber 1999). For example, the δ\(^{15}\)N values of freshwater fish from Lake Baikal in Siberia range from 7.3‰ to 13.7‰, although the majority fall
between 10.0‰ and 12.5‰ (Katzenberg and Weber 1999). Freshwater fish sampled from a medieval Polish site at Giecz exhibit δ\textsubscript{15}N values ranging from 6.4‰ to 12.3‰ (Reitsema et al. 2010). This wide variation is largely due to the fact that in aquatic foodwebs, the number of possible trophic positions is greater than in terrestrial foodwebs due to presence of zooplankton, zoobenthos and insect prey at the base of the food chain (France 1994). It is also due to the fact that the top predator species differs across freshwater sites. In terms of carbon, variables such as water turbulence, depth and clarity all influence δ\textsubscript{13}C ratios of dissolved inorganic carbon within the same lake or river (France 1995). Also, phytoplankton and benthic algae can have dramatically different δ\textsubscript{13}C ratios which strongly influences the δ\textsubscript{13}C ratios of primary consumers (Hecky and Hesslein 1995). Consequently, even fish of the same species in the same environment may have isotopically heterogeneous diets and exhibit a wide range of stable isotope ratios. For example, perch from Lake Baikal exhibit a range from -23.6‰ to approximately -10.5‰ for δ\textsubscript{13}C and 10.4‰ to 12.7‰ for δ\textsubscript{15}N (Katzenberg et al. 2010). With such a broad range, fish can either mimic terrestrial animals in human diet, or be quite isotopically distinct.

It is possible that consumption of low-\textsuperscript{13}C, high-\textsuperscript{15}N freshwater fish are responsible for intermediate (and not low) δ\textsuperscript{15}N values in human samples that do not show δ\textsuperscript{13}C evidence for marine fish consumption. Some marine fish occupying shallow waters, such as herring, also exhibit relatively low δ\textsuperscript{15}N and δ\textsuperscript{13}C values of approximately -10‰ and -15‰, respectively (Müldner and Richards 2005). Some lakes contain fish
with very high $\delta^{13}$C ratios: values as high as -6.3‰ are reported for freshwater, benthic algae-consuming fish from Lake Malawi (Hecky and Hesslein 1995).

In the present study and in one other stable isotope study of medieval Polish fauna, freshwater fish bones are shown to exhibit $\delta^{15}$N values ranging from 6.4‰ to 12.3‰ with corresponding $\delta^{13}$C values of between -21.6‰ and -26.5‰ with one outlier (tench) exhibiting a $\delta^{15}$N value of 3.8‰ and a $\delta^{13}$C value of -5.6‰ (Reitsema et al. 2010). Depending on which species were consumed and temporarily excepting the anomalous tench specimen, humans who ate freshwater fish could exhibit $\delta^{15}$N values ranging from approximately 9.0‰ to 15.0‰ – a very broad range that encompasses nearly all the isotopic diversity seen among the current samples (a few samples are slightly below a $\delta^{15}$N value of 9.0‰). Freshwater fish were available to the populations investigated in this study, either from the nearby Vistula River or its many oxbow lakes. Oxbow lakes, which tend to be shallow and non-turbulent, can contain freshwater fish with quite high $\delta^{13}$C ratios. This may explain the anomalous tench sample reported here.

High isotopic variability in fish values should translate to high variability in the stable isotope values of humans consuming fish. Table 7.2 presents previously published data from a number of comparative European samples to investigate whether or not fish consumption translates into higher stable isotope variation among humans. The table displays means and standard deviations for both stable carbon and nitrogen isotopes from 14 groups reported to have consumed either marine fish, freshwater fish, a mixture of both, or no fish. Standard deviations are used as a proxy for variability. In general, populations consuming fish exhibit higher standard deviations for both stable carbon and
nitrogen isotopes (0.6‰ to 2.5‰ for δ¹³C; 0.9‰ to 1.8‰ for δ¹⁵N) than do populations with reported terrestrial diets (0.6‰ to 1.7‰ for δ¹³C; 0.6‰ to 1.1‰ for δ¹⁵N), but this is not always the case. In the context provided by Table 2, standard deviations from Rogowo and Gruczno appear relatively low, whereas Kaldus values are consistent with a population consuming fish.

7.5.2.iv Omnivore protein

When animals that are part of the human food chain eat (1) other animal protein including fish or animal waste, (2) milk as with suckling animals or (3) fertilized plants, their δ¹⁵N values are relatively high. Several animals sampled for this research exhibit δ¹⁵N values of approximately 8-10‰. These include domestic fowl and some of the pigs and cattle. As reviewed in Chapter 2, domestic fowl, including meat and eggs, are recorded historically as the most common source of animal protein for medieval Poles (Dembińska 1999; Dzieduszycka 1985). Pork products also were relatively common in medieval Polish diet. Less common in the diet are herbivores with lower δ¹⁵N values including cattle and wild animals such as deer, elk and aurochs. Human consumption of omnivorous animals is a likely source of the relatively high δ¹⁵N values, and one that would not have significantly raised or lowered the associated δ¹³C values as would fish.

7.5.2.v Crop manuring

In Europe, populations have been manuring their agricultural fields to increase productivity for thousands of years (Barker 1985). Muck hauled from wetlands, domestic
debris and animal dung are all methods used since the Neolithic in Europe to increase field productivity. Both cattle and sheep/goat provided dung for prehistoric farmers. Cattle require penning at night, thus their manure must be hauled to fields from stables. Sheep and goat can be left in fields overnight and provide a simpler form of fertilization (Barker 1985). As reviewed by Bakels (1997), the earliest known evidence of using animal dung to fertilize a field comes from Switzerland ca. 3880-3480 BC. The ancient field was identified because of its plough furrows. Fly larvae were identified after sediment analysis, suggesting manure was hauled from stables onto the field. Bakels (1997) points out that ancient fields predating the introduction of the ard will be very difficult to detect, making the earliest date of crop manuring difficult to discern. Despite early evidence of manuring, some authors maintain that swidden agriculture was the primary means of fertilization throughout the Roman Era in Poland (Gieysztor et al. 1979). Barker (1985) points out that in order to sustain the animals producing manure a great deal of fodder was required. Because fodder also (ideally) required manuring, there was a cyclical constraint on the amount of manure available and subsequently the upper limit of agricultural productivity throughout even the medieval period in Europe.

Manuring agricultural fields can cause plants to be significantly enriched in $\delta^{15}N$. Bogaard et al. (2007) studied the isotopic effects of manuring in plant tissues, discovering that grain from manured plants exhibited $\delta^{15}N$ values of over 7‰, compared to non-manured plants from the same field that exhibited grain $\delta^{15}N$ values of less than 1‰. Although no archaeological plant samples were assayed for this study, one modern sample of wheat (kernel) taken in 2008 from the field of the Kałdus excavations
Table 7.2  Influences of Fish in Diet on Isotope Variability of Human Consumer Populations

<table>
<thead>
<tr>
<th>Protein Diet</th>
<th>(\delta^{13}C_{coll} (%))</th>
<th>s.d.</th>
<th>(\delta^{15}N (%))</th>
<th>s.d.</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater Fish</td>
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<td>9.7</td>
<td>0.5</td>
<td>Rogowo</td>
</tr>
<tr>
<td></td>
<td>-18.9</td>
<td>1.0</td>
<td>10.2</td>
<td>0.7</td>
<td>Kaldus</td>
</tr>
<tr>
<td></td>
<td>-19.9</td>
<td>0.3</td>
<td>9.3</td>
<td>0.7</td>
<td>Gruczno</td>
</tr>
<tr>
<td></td>
<td>-15.8</td>
<td>1.1</td>
<td>14.4</td>
<td>1.0</td>
<td>Katzenberg and Weber (1999)</td>
</tr>
<tr>
<td></td>
<td>-18.7</td>
<td>0.9</td>
<td>13.6</td>
<td>1.6</td>
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</tr>
<tr>
<td></td>
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<td>Neolithic</td>
</tr>
<tr>
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<td>1.0</td>
<td>14.4</td>
<td>1.7</td>
<td>Bronze Age</td>
</tr>
<tr>
<td></td>
<td>-21.5</td>
<td>2.5</td>
<td>10.8</td>
<td>1.8</td>
<td>Lillie and Richards (2000)</td>
</tr>
<tr>
<td>Terrestrial Fish</td>
<td>-20.6</td>
<td>0.6</td>
<td>6.5</td>
<td>0.9</td>
<td>Lösch et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>-19.8</td>
<td>0.7</td>
<td>8.7</td>
<td>0.6</td>
<td>Schutkowski et al. (1999)</td>
</tr>
<tr>
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<td>0.6</td>
<td>12.0</td>
<td>0.8</td>
<td>Jorkov et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>-14.7</td>
<td>1.7</td>
<td>9.4</td>
<td>1.1</td>
<td>Murray and Schoeninger (1988)</td>
</tr>
<tr>
<td>Marine Fish</td>
<td>-18.5</td>
<td>1.2</td>
<td>12.3</td>
<td>1.8</td>
<td>Richards et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>-17.3</td>
<td>1.3</td>
<td>11.1</td>
<td>1.0</td>
<td>Kosiba et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>-17.8</td>
<td>0.6</td>
<td>12.8</td>
<td>1.3</td>
<td>Keenleyside et al. (2009)</td>
</tr>
<tr>
<td></td>
<td>-18.5</td>
<td>1.2</td>
<td>12.3</td>
<td>1.8</td>
<td>Richards et al. (2006)</td>
</tr>
<tr>
<td>Mixed Fish</td>
<td>-19.5</td>
<td>0.6</td>
<td>12.3</td>
<td>0.9</td>
<td>Müldner and Richards (2005)</td>
</tr>
</tbody>
</table>
yielded a $\delta^{15}N$ value of 7.2‰ (and a $\delta^{13}C$ value of -23.6‰). The $^{15}N$ enrichment of this plant could be due to current, historic or prehistoric agricultural practices carried out on that land. With plant values as high as 7‰, even a vegetarian diet could cause human tissues to exhibit $\delta^{15}N$ values of over 10‰. Manuring is very likely a contributing factor to the intermediate $\delta^{15}N$ values here.

7.5.2. ViLegumes

It may be the case that diets in the study did consist of marine protein, but that high human $\delta^{15}N$ values expected for such a diet are masked by consumption of low-$^{15}N$ legumes. Legumes typically exhibit low $\delta^{15}N$ ratios because they can obtain nitrogen through symbiotic relationships with myccorhizal bacteria at their root nodules. Fractionation of nitrogen by these symbiont bacteria is low, such that the nitrogen passed to the plant is isotopically similar to that of the atmosphere (Kohl and Shearer 1980). Legumes can also fix nitrogen from the soil when it is abundant (Amarger et al. 1979) and therefore typically, though not necessarily, exhibit relatively low $\delta^{15}N$ values (Schoeninger 1989). Legumes include beans and peas, both of which were consumed in Poland (Dembińska 1999). Legumes were likely an important part of Polish diet, but it is not known to what extent legumes are capable of drawing human $\delta^{15}N$ values down. High $\delta^{15}N$ variability among humans might be expected if legumes were affecting $\delta^{15}N$ values. Additionally, legumes drawing human $\delta^{15}N$ down does not explain intermediate $\delta^{15}N$ values among animals.
From the possible explanations for intermediate $\delta^{15}\text{N}$ values discussed above, the most likely in the present study are crop manuring, omnivore protein and low-$^{15}\text{N}$ fish consumption. Crop manuring accounts for intermediate $\delta^{15}\text{N}$ values among both humans and animals. Omnivore protein was, according to historical records, the most common protein source for humans in medieval Poland (Dembińska 1999; Dzieduszycka 1985). Many fish bones in this study exhibit low $\delta^{15}\text{N}$ ratios. They are freshwater varieties, however, and thus do not explain high $\delta^{13}\text{C}$ values, as was discussed in section 7.4.1.

7.6 Conclusions: Addressing the Original Hypotheses

Hypothesis 1 predicted that over time, stable isotope ratios would increase due to consumption of marine fish, particularly herring. Underlying Hypothesis 1 were Christian fasting regulations, urbanization and the transition to a market economy, all of which were expected to have stimulated trade in marine fish. Hypothesis 1 is not supported by data reported here. In fact, rather than stable isotope ratios increasing through time and reflecting marine fish consumption, stable isotope values decreased through time. This cannot be attributed to increased freshwater fish in diet. The only compelling evidence for fish consumption is at the beginning of the medieval period from Kaldus site 4. There, a mix of freshwater, anadromous and marine species was eaten. Within the Kaldus site 4 sample, when it is divided into five phases, $\delta^{13}\text{C}_{\text{coll}}$ ratios track a gradual decline in fish consumption (Fig. 6.10). Rather than assuming Christianity, urbanization and long-distance trade were inconsequential for diet in medieval Poland, local variables must be considered. First, in 1039 AD a pagan revolt occurred.
Populations on the fringes of the Polish state overthrew the Church and monarchy. All inroads the Church had made in this region since Poland’s conversion to Catholicism in AD 996 were lost. The basilica at Kalduś well illustrates this process. Its construction began immediately following state Christianization. After the pagan revolt, construction was halted and was never resumed (Chudziak 2010). It may be that at the 11th c. Kalduś site 4, Christian fasting peaked early but declined after the pagan revolt. Declining fish consumption over time at Kalduś actually agrees with the known religious events in the region: fish consumption might be tracking the rejection of Christian beliefs.

Another factor to consider is that by the 12th-13th c. Kaldus had declined from an economic hub to an agricultural village. Trade items – possibly including fish – formerly imported to the site when it was a market center became less available in an agricultural setting. Without fish available, no relationship between fish and fasting is expected and no isotopic reflection of people’s religious beliefs is possible. Even if Christian beliefs held sway, fasts could have been satisfied by vegetarianism or ignored out of necessity, not denunciation. Indeed, fish consumption is lowest at Gruczno, where neither marine nor freshwater resources have contributed greatly to diet. Gruczno was always a more rural and agricultural settlement throughout its occupation and it may never have been well-connected with the Baltic trade in fish.

One of the goals of this study was to identify a rate of diet change through time. It is difficult to determine the rate of change in fish consumption because (1) different varieties of fish exhibit widely differing isotope ratios, some of which overlap with terrestrial fauna, and (2) social conditions influencing diet at Kaldus and Gruczno are not
directly comparable. However, it can be determined that at Kałdus over a period of approximately 150 years (between the 11\textsuperscript{th} and 12\textsuperscript{th}/13\textsuperscript{th} c.), fish consumption fell from a significant source of dietary protein at site 4 to contributing negligible amounts at site 1.

Hypothesis 2 predicted that stable isotope signatures of medieval samples are more heterogeneous than those of Roman period samples, reflecting increased social differentiation. This is not the case. The greatest heterogeneity is from the 11\textsuperscript{th} c. Kałdus site 4, followed by the Roman Era site, Rogowo, followed by 12\textsuperscript{th}/13\textsuperscript{th} c. Kałdus site 1. Gruczno (12\textsuperscript{th} c. and 13\textsuperscript{th}/14\textsuperscript{th} c.) exhibits the least variability. The expectation that diet would become more variable through the medieval period was based on the assumption that occupational differentiation also increased (T. Kozlowski; pers. comm.). At Kałdus occupational differentiation decreased over time, and Gruczno was a more rural settlement from its start.

It must be borne in mind that diet variation does not necessarily translate to isotopic variation in Europe, because the majority of food sources are isotopically similar. Sources of stable isotope heterogeneity across samples include millet and fish: these are the foodstuffs to which this discussion primarily pertains. The reason millet consumption declined through time is uncertain, but it may be related to influences from the Teutonic Order and German immigrants. Millet is a characteristically Slavic food in contrast to the typical Germanic diet that the Order likely introduced. At Kałdus it was possible to estimate a rate of change in millet consumption through time. Kałdus site 4 could be divided into five sub-phases, and over the course of 200 years the contribution of millet to diet decreased from 20\% to 7\%, an average of 2.6\% per year.
Hypothesis 3 predicted that sex differences in diet increased through time. Stable isotope data partially support this hypothesis. Only two sites exhibit sex differences in δ¹³C ratios: the earliest site (Rogowo, 2nd c. AD) and the latest site (Gruczno site 2, 13th/14th c.). Biodistance analysis of a Wielbark cemetery at Gdańsk, Poland suggest sex-based differences in post residential mobility (Gładykowska-Rzeczycka et al. 1997). It may be the case that at Rogowo, females immigrated from a different region where diet included millet, which would account for their significantly different δ¹³C ratios. Southern regions are a likely place of origin for Rogowo women. A stable isotope study of a cemetery in Britain identified a probable immigrant from continental Europe based on his slightly elevated δ¹³C ratios (Richards et al. 1998). Therefore, sex differences in stable isotope ratios at Rogowo may reflect different geographic origins rather than differences in diet. There is potential for the study of dental caries in the population (not studied here) to illuminate whether δ¹³C differences at Rogowo are dietary or due to migration.

Sex-based inequalities or a sexual division of labor that affected diet may explain sex differences in δ¹³C ratios at Gruczno site 2, as there is historical evidence that both were pervasive in the medieval period (Arnold and Faulkner 1985; Bennett 1992). The greatest sex-based difference is in δ¹³Cap ratios. Females consumed plants that were relatively depleted in ¹³C compared to males. This is similar to what was reported for an 11th-12th c. cemetery at Giecz, Poland, although the stable carbon isotope differences in that study were for collagen, and were not statistically significant (Reitsema et al. 2010). Men may have consumed more millet than did women, or women consumed relatively
more plants from forested regions with low $\delta^{13}$C ratios. Because Gruczno site 2 is considered the only “true medieval village” in this sample by archaeologists (T. Kozlowski, pers. comm.), it could imply that sex differences in diet characterized the medieval period compared to earlier periods.

Sex differences in diet do not necessarily imply inequality, but may rather reflect a sexual division of labor. Women’s activities may have led them to consume more C$_3$ plants than men in the course of their daily activities. For example, by being in contact with and consuming C$_3$ plants while selling and buying at markets or tending household gardens. Men may have accessed more millet by purchasing it from “hucksters” in towns or when dining in taverns. This model links dietary differences to complementary activities and tasks performed by men and women, but does not imply social inequalities. Also, during the medieval period men and women were believed to be of different physical constitutions. Medieval culinary records (cookbooks, diaries, and memoirs) suggest that “‘heavy food,’ especially meat, was seen as more appropriate for men and lighter food for women, in part because meat had, for a thousand years, been seen as an aggravator of lust” (Bynum 1987: 191). This may explain why sex differences in diet exist in the later medieval period (Gruczno site 1).

Hypothesis 4 predicted that at Rogowo, differences in status as assessed through mortuary analysis are not related to differences in stable isotope ratios. The assumption behind this hypothesis was that the people at Rogowo lived a relatively egalitarian life, where any differences in prestige that may have existed were not matched by differential access to food. This hypothesis is supported. Sex, a biological variable, appears to have
been more important in structuring Roman Era diet than was status, a cultural variable.

Hypothesis 5 predicted that in medieval samples, differences in status as assessed through mortuary analysis are related to differences in stable isotope ratios. Contrary to this prediction, no consistent status differences in isotope ratios were identified in the medieval sample. There are at least two explanations for this. First, all skeletons from each site were excavated from the same cemetery. This alone may preclude variation in status of the interred individuals. Burial location is related to status in medieval Europe, with individuals buried nearer the church typically of high status. It would be interesting to study two subpopulations from a single site buried inside and outside the churchyard to confirm this. Second, status in life may not be reflected straightforwardly in mortuary style. Grave goods were not part of Christian burial rites, which alone masks social differentiation in cemeteries. Thus, using mortuary style as a proxy indicator of status may be inaccurate. Third, differences in status may not have translated into different diets during life, with individuals of all social statuses consuming similar foods. This would certainly be true if the total number of foodstuffs available in medieval settlements was small, as appears to have been true at Gruczno and in the later phase at Kalduś. In general, social variables such as status and religion did not strongly influence diet in Roman and medieval Poland. Rather, biological variables—in this study sex because age was controlled—were more important in structuring diet, albeit to a limited extent.

Diets at Kalduś and Gruczno differed markedly in spite of similar time periods and shared geographic region. Diet at Kalduś was isotopically varied and included more fish and the $C_4$ plant millet. Diet at Gruczno was more restricted to $C_3$ terrestrial
resources. Diet change through time included a reduction in fish and millet. Stable isotope ratios of men and women did not differ except during the latest time period, and burial style (e.g.: Christian vs. “pagan”/“antivampire”) did not predict stable isotope signatures. Although some changes in diet concomitant with religious and political upheavals were detected, the most significant influence on diet appears to have been a site’s economic function. The influences of state-wide sociopolitical and religious transformations are often assumed to structure diet and health in direct ways, but these results demonstrate the relative insulation of rural settlements from many of these national and international changes.
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Appendix A: Data from Human Bone Samples

This appendix contains a full list of human samples collected for analysis. All raw data are presented, including stable isotope data, collagen quality indicators and FTIR results. All known demographic data (sex, age, and grave goods) are also shown. In some cases, demographic information was unknown or approximated, indicated by a missing value or a “?” to express uncertainty. These data are discussed in detail in Chapters 6 and 7.

Data presented here include samples that were rejected from analyses, as described in Chapter 5. These discarded samples are shaded and italicized within the complete data sets. Only Grucznio sites 1 and 2 contained samples that were rejected from analyses.

The right-most columns include information about sample preparation. The method used for collagen extraction is indicated for each sample (1= Method 1 and 2= Method 2). Also, whether or not bone pieces were mechanically cleaned by grinding away the outer surface prior to carbonate preparation is indicated (0= clean and 1= uncleaned or “dirty”).
### Table A.1: Human Data from Ancient Sites (Neolithic and Iron Age)

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sex</th>
<th>Age</th>
<th>Grave Goods</th>
<th>Nitrogen [%]</th>
<th>Carbon [%]</th>
<th>$\delta^{15}$N_Air [%o]</th>
<th>$\delta^{13}$C_VPDB [%o]</th>
<th>$\delta^{13}$C_VPDB (‰)</th>
<th>$\Delta^{13}$C (ap-coll) (‰)</th>
<th>$\delta^{18}$O_VPDB (‰)</th>
<th>Coll (%)</th>
<th>C/N Ratio</th>
<th>C/P Ratio</th>
<th>Coll: Prep Method</th>
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</tr>
</thead>
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<td></td>
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Table A.2: Human Data from Rogowo (Roman Era, 2\textsuperscript{nd} c. AD)

<table>
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<tr>
<th>Sample ID</th>
<th>Sex</th>
<th>Age</th>
<th>Grave Goods</th>
<th>Nitrogen [%]</th>
<th>Carbon [%]</th>
<th>$\delta^{15}$N\textsubscript{Air} [‰]</th>
<th>$\delta^{13}$C\textsubscript{VPDB} [‰]</th>
<th>$\delta^{13}$C\textsubscript{VPDB} (‰)</th>
<th>$\Delta^{13}$C (ap-coll) (‰)</th>
<th>$\delta^{18}$O\textsubscript{VPDB} (‰)</th>
<th>Coll (%)</th>
<th>C/N Ratio</th>
<th>C/I</th>
<th>C/P Ratio</th>
<th>Coll: Prep Method</th>
<th>Carb: Clean=0 Dirty=1</th>
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<tr>
<td>R-100</td>
<td>F</td>
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<td>26.4</td>
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<p>| K4-231 | M  | 25-30 | No  | 5.9 | 18.5 | 8.7 | -17.84 |  | 0.0 | 3.6 | 1 | 0 |
| K4-243 | F  | 25-35 | Knife | 9.0 | -19.59 | -13.25 | 6.3 | -7.08 | 0.0 | 3.5 | 3.7 | 0.14 | 1 | 1 |
| K4-254 | M  | 30-35 | No  | 11.7 | 33.5 | 11.1 | -19.68 | 7.7 | 3.3 |  | 1 | 0 |
| K4-256A | F | 35-45 | Dbl grave Decap | 13.2 | 36.9 | 10.7 | -19.34 | -11.98 | 7.4 | -6.44 | 14.0 | 3.3 | 3.5 | 0.17 | 1 | 1 |
| K4-256B | M  | 35-40 | Dbl grave Decap | 10.8 | 30.9 | 10.5 | -17.75 | -11.40 | 6.3 | -6.45 | 15.0 | 3.3 | 3.0 | 0.24 | 1 | 1 |
| K4-261A | M  | 25-55 | Dbl grave, wooden | 12.5 | 35.4 | 10.0 | -18.69 | -9.23 | 9.5 | -6.88 | 15.0 | 3.3 | 3.3 | 0.25 | 1 | 1 |
| K4-261B | M  | 25-35 | Dbl grave, wooden | 7.8 | 23.5 | 11.2 | -18.12 | -10.47 | 7.6 | -7.16 | 6.7 | 3.5 | 3.7 | 0.17 | 1 | 1 |
| K4-263 | F  | 25-30 | Temp ring | 12.7 | 35.6 | 10.5 | -19.12 | -12.35 | 6.8 | -6.24 | 12.0 | 3.3 | 3.0 | 0.22 | 1 | 1 |
| K4-264 | M  | 30-50 | Finger ring, belt | 12.3 | 34.7 | 9.9 | -17.59 |  | 6.7 | 3.3 | 1 | 0 |
| K4-267 | F  | 25-30 | No  | 12.9 | 36.3 | 10.0 | -19.31 | 10.0 | 3.3 |  | 1 | 0 |
| K4-31 | M  | 50-60 | Silver coin ribs, On L side | 10.6 | 30.3 | 9.9 | -18.70 | -12.39 | 6.3 | -7.54 | 20.8 | 3.3 | 2.7 | 0.27 | 1 | 1 |
| K4-32 | F  | 13.1 | 36.6 | 9.7 | -19.02 | 14.3 | 3.3 | 1 | 0 |
| K4-364 | M  | ? | Sword | 9.7 | 28.7 | 10.4 | -16.49 | -10.58 | 5.9 | -6.73 | 4.5 | 3.4 | 4.0 | 0.17 | 1 | 0 |
| K4-41 | M  | 35-55 | On R side | 7.4 | 22.3 | 10.3 | -16.73 | -10.23 | 6.5 | -7.55 | 0.0 | 3.5 | 3.1 | 0.21 | 1 | 1 |
| K4-48 | F  | 50-60 | Stone on chest | 9.0 | 26.1 | 11.9 | -18.28 | -10.90 | 7.4 | -6.77 | 8.2 | 3.4 | 3.4 | 0.18 | 1 | 1 |
| K4-60 | M  | 30-40 | Bronze bowl, hazelnuts, rich grave | 14.4 | 40.0 | 11.1 | -20.08 | -14.05 | 6.0 | -6.27 | 11.5 | 3.2 | 3.6 | 0.14 | 1 | 0 |
| K4-64 | M  | 25-35 | On R side | 10.6 | 30.4 | 10.1 | -19.15 | -10.24 | 8.9 | -6.70 | 8.8 | 3.4 | 3.4 | 0.18 | 1 | 1 |
| K4-75 | F  | 35-45 | No  | 10.7 | 30.2 | 9.6 | -19.50 | 14.3 | 3.3 | 1 | 0 |
| K4-86 | F  | 25-30 | No  | 5.2 | 15.2 | 10.0 | -19.08 | -13.07 | 6.0 | -6.85 | 20.0 | 3.4 | 4.1 | 0.11 | 2 | 0 |</p>
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Appendix B: Data from Animal Bone Samples

This appendix contains the carbon and nitrogen isotope data from all animals analyzed. Many animals were also analyzed for carbonate data. For fish bones, only collagen was extracted. Therefore, $\delta^{13}\text{C}_{\text{ap}}$, $\delta^{18}\text{O}$ and FTIR data are not reported for fish (Table A2.2). These data are discussed in detail in Chapters 6 and 7.
Table B.1: Animal Data

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<th>%Coll</th>
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<th>δ¹³C_{VPDB} (‰) bone collagen</th>
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Table B.2: Fish Data