ScholarWorks@GSU

Dietary Reconstruction in Medieval Holbæk, Denmark using Dental Microwear and Macrowear, Isotopic Analyses, and Dental Caries

Authors	Turner, Sara A
Citation	Turner, Sara A. 2013. "Dietary Reconstruction in Medieval Holb#k, Denmark using Dental Microwear and Macrowear, Isotopic Analyses, and Dental Caries." Georgia State University. https://doi.org/10.57709/4077338
DOI	https://doi.org/10.57709/4077338
Download date	2025-12-13 12:49:17
Link to Item	https://hdl.handle.net/20.500.14694/679

DIETARY RECONSTRUCTION IN MEDIEVAL HOLBÆK, DENMARK USING DENTAL MICROWEAR AND MACROWEAR, ISOTOPIC ANALYSES, AND DENTAL CARIES

by

SARA A. TURNER

Under the Direction of Dr. Bethany L. Turner

ABSTRACT

The medieval period in Denmark (11^{th}-16^{th} century) was a time of great social and economic change. The current study seeks to analyze dietary patterns of individuals from a medieval site in Holbæk, Denmark who lived during this historically dynamic and tumultuous period. A previous isotopic analysis indicated a mixed terrestrial C_3 based diet with varying amounts of marine foods (Jørkov 2007). This study compares the existing isotopic data with collected data from dental microwear, macrowear, and caries in order to provide a more complete picture of diet and subsistence patterns of these individuals during their latter years. Results suggest that there were some dietary and behavioral differences between males and females with a lack of change in diet over time that run counter to expectations given the historical record. A subset of males were also discovered with entirely different dietary patterns. This study contributes a better understanding of variation in medieval European populations.

INDEX WORDS: Holbæk, Dental microwear, Medieval Europe, Dental macrowear, Isotopic analysis, Denmark, Dental caries

DIETARY RECONSTRUCTION IN MEDIEVAL HOLBÆK, DENMARK USING DENTAL MICROWEAR AND MACROWEAR, ISOTOPIC ANALYSES, AND DENTAL CARIES

by

SARA A. TURNER

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Arts

in the College of Arts and Sciences

Georgia State University

2013

Copyright by
Sara A. Turner
2013

DIETARY RECONSTRUCTION IN MEDIEVAL HOLBÆK, DENMARK USING DENTAL MICROWEAR AND MACROWEAR, ISOTOPIC ANALYSES, AND DENTAL CARIES

by

SARA A. TURNER

Committee Chair: Bethany L. Turner

Committee: Frank L. Williams

Jeffrey B. Glover

Electronic Version Approved:

Office of Graduate Studies

College of Arts and Sciences

Georgia State University

May 2013

DEDICATION

I dedicate this thesis to the love of my life, my husband Michael; to my mother Sonja who has never failed me; to Gordon Rakita who started, supported, and inspired my academic career; and to Bethany Turner who advised me to the best of her abilities.

ACKNOWLEDGEMENTS

So many people have helped me through my two years at Georgia State. First and foremost, I want to thank my husband who has loved and supported me in and out of this program. You cooked and cleaned for me while I was going insane writing papers and grading. My favorite was your omelets that always brightened my day. Thank you for making my life creative and imaginative. I also want to thank my mom who funded my trip to Denmark and translated many pages for me in order to complete my thesis. Mom, you have always been the guiding light through my life, and I will be eternally thankful.

I would never have gotten through this program without the many friends I made in the past two years. Elise, you have been my greatest friend. You helped me to finish classes, been a shoulder to cry on, and was always there for me when I needed a friend. I will never forget all the hours we spent pouring over schoolwork, the dinner where we ate bone marrow, and going shopping for dresses. I also want to thank Sarah Livengood who made me feel right at home when I started in the program. Thank you for all of your advice in how to be a great teaching assistant and helping me to become a better writer. Our nights of boxed wine at your house, with Emily Vanderpool, are some of the most memorable moments I have of laughing and playing games! Heather Kerr, I honestly don’t know what I would have done without you these past two years. When times got tough, you were there for me to carry me through and I will be forever thankful for your friendship. Engrained in my memory will be our pedicure visits, the massages we got on my birthday, and the surprise birthday at your house! Thank you Lain Graham, who has become a dear friend. You have been so supportive at school, out in the field, and on sushi nights. You all have been my rock, for without, I would not have been able to stand.

I would also like to thank my committee, Bethany Turner, Jeffrey Glover, and Frank Williams for all of their advice and support through this program. I never would have finished my thesis without our endless hours discussing, writing, and rewriting! A special thank you to Bethany Turner, who supported me not only in academics, but also in my personal life. You were there for me when I needed a friend or when classes were tough, and even those times when I simply just broke down. My success in finishing my masters could not have been achieved without your help. Additionally, I would like to thank Niels Lynnerup and Marie Jørkov for opening up their department at the University of Copenhagen, allowing me to conduct my analyses on the fascinating Holbæk skeletal collection, giving me access to the isotopic data, and sharing in wonderful lunches with me.

An extremely special thank you to Gordon Rakita, who was the first professor to take notice of me as a young and aspiring anthropologist during my undergraduate years at the University of North Florida. You gave me experience as a teaching assistant, helped me create my All About Archaeology kits, taught me conference etiquette, and most of all became my friend. I will always be grateful for the start you gave me in my academic career.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Study Objectives

Dietary reconstruction is one of the most important aspects in understanding past human life histories, subsistence strategies, status and sex distinctions, health, and stress (Hogue and Melsheimer 2008, Larsen 2002). Discovering what people ate can provide insight into how daily life is structured and the relationship between subsistence and larger social processes. Examination and analysis of an individual's skeleton can present a wealth of information on their health, diet, and the intersections of subsistence, health, and lifeways (Larsen 2002). Specifically, examination of skeletal material from medieval Europe (11^{th} – 16^{th} centuries) provides more direct insight into the relationship between dietary patterns and lifeways of individuals who lived in the medieval period. Historical records and archaeological evidence from medieval Europe offer helpful interpretations of lifestyles, migration patterns, trade, and customs. Together, bioarchaeological analyses can illuminate meaningful clues about the broader social and economic processes of the medieval period.

This study analyzes bones and teeth excavated from a medieval cemetery Ahlgade 15-17, in Holbæk, Denmark in order to reconstruct individual diets. The large skeletal collection and associated burials contexts were excellently preserved and provided an opportunity to study dental wear, sex differences, and diet in the medieval period (AD 1200-1573). Jørkov (2007), in a previous study, sampled 74 individuals for stable isotope analysis in order to compare medieval and earlier Roman Iron Age diet composition in Denmark. Jørkov (2007) found isotopic diversity among individuals in medieval Holbæk suggesting a combined marine and terrestrial diet C_3 diet with no class distinctions that remained uniform through life. This study is a complimentary analysis and employs dental microwear, dental macrowear, and oral pathologies to determine more subtle variations in diet, such as diets with contrasting amounts of similar food resources beyond the resolution of stable isotope analysis (Hogue and Melsheimer 2008, Schmidt 2001). Employing multiple dental analyses and interpreting these results along with archaeological and historical records provides a more comprehensive and accurate picture of life in medieval Holbæk. Several studies have examined dental wear patterns and oral pathologies in medieval European populations, providing valuable comparative information about medieval life (Boldsen 1991, Esclassan *et al.* 2008, Ganss *et al.* 2002, Lunt 1978). However, none of these studies have used dental microwear to examine medieval Scandinavian populations. The dental microwear analysis utilized in this study contributes to the understanding of diet not only of those individuals from medieval Holbæk, but also represents an early step in understanding the variation of consumption and subsistence patterns in medieval Denmark. In addition to shedding light on consumption patterns of individuals in Holbæk, this study conducts a methodological analysis to assess microwear patterns on both enamel and dentin surfaces.

1.2 Research Questions and Expectations

This study aims to analyze Jørkov's (2007) stable isotope data in conjunction with collected data from dental microwear, macrowear, and caries. In addition to bioarchaeological analyses, inferences will be drawn from historical records and archaeological evidence.

- I expect all teeth will have high average macrowear scores that will not be correlated with isotopic indicators of diet.

It has been suggested in other studies that medieval grain processing techniques (i.e. using millstones) introduced harsh abrasives into food and likely contributed to high degrees of tooth wear in an individual's lifetime (Boldsen 1991, Esclassan *et al.* 2008, Ganss *et al.* 2002, Helm and Prydsø 1979). Boldsen (1991) analyzed wear patterns of individuals from medieval Tirup, Denmark AD 1100-1200 and found high rates of wear that were possibly caused by increased consumption of grains contaminated with abrasives. Thus, I suggest that tooth wear in individuals from Holbæk will follow a similar pattern. Botanical remains in Holbæk also show high amounts of grains cultivated in the surrounding farms of Ahlgade 15-17 (Asmussen 1997). Subsequently, should exogenous abrasives be the probable causes of tooth wear, macrowear patterns should also not be correlated with isotopic measures of diet.

- I hypothesize that dental microwear patterns will produce deeper types of microwear and will not be correlated with isotopic indicators of diet.

Following macrowear expectations, microwear patterns on the occlusal surface of enamel will be due to mastication of grit from millstones. Microwear patterns will therefore exhibit more evidence for food preparation techniques like grinding millstones rather than consumption. Consumption of large amounts of cereal grains, as a primary dietary source, should then also result in deeper types of microwear (i.e. hypercoarse scratches, large pits, puncture pits) since harder foods require more force to masticate (Schmidt 1998, Teaford and Lytle 1996). Thus, if my hypothesis is supported then the deeper microwear patterns will be interpreted as due to grit from millstones rather than indicative of a cereal grain-based diet. If my hypothesis is falsified, than the deeper microwear patterns will be indicative of a cereal grain-based diet rather than grit.

- In assessing any dietary and/or behavioral differences between males, females, and non-adults, I hypothesize that no significant differences will exist in isotopic indicators of diet. However, I hypothesize that there may be some use-wear differences between males and females.

Holbæk was a small countryside town where no evidence of trade was found (Asmussen 1997). Individuals more likely consumed similar diets with no discrimination between males, females, and non-adults due to access and availability of food resources. Jørkov's (2007) isotopic study also suggests uniformity of diet among the Holbæk population. Conversely, medieval historical records and osteological studies indicate that males and females likely had different daily activities and occupations (Mays 1999, Pearson 1997, Turner and Anderson 2003). Women would prepare foods and cook while men farmed, fished, and crafted. For example, marked dental abrasion patterns were discovered in medieval Kent due to a carpenter holding nails in his teeth (Turner and Anderson 2003). Due to occupational differences and the likelihood that teeth may have been used as tools, males and females in medieval Holbæk may show different use-wear patterns in their teeth.

- I expect to find comparably low caries frequencies at Holbæk that will be correlated with isotopic indicators of diet.

Other studies have linked lower prevalence of dental caries in medieval populations to lower sugar diets prior to the introduction of cane sugar (Esclassan *et al.* 2008). High rates of tooth wear, discussed above, also have been suggested to slow down the process of tooth decay (Schmidt 1998). Individuals from Holbæk likely followed similar patterns as other medieval populations and their teeth will present lower frequencies of caries. The caries that are present in the teeth were probably due to cariogenic foods like grain, fruit, and dairy.

- I hypothesize that isotopic indicators of diet from individuals in Holbæk will not show any change over time (13^{th} – 16^{th} centuries), though I expect some changes in prevalence of caries.

Yoder (2010) conducted stable isotope analyses from three different medieval sites in Denmark to detect changes in diet over time from the 12th century to the 16th century. Results indicated a lack of significant differences in diet through time, which is a surprising contrast to historical evidence of changing food and agricultural systems in medieval Denmark. I expect isotopic signatures from Holbæk to follow a similar pattern to Yoder's (2010) isotopic results and find no change over time. However, an increase or decrease in the prevalence of caries could indicate a shift in diet if more or different cariogenic foods were being consumed. Microwear and macrowear scores would be excellent indicators of subtle variations in change in diet over time, though I expect they are not correlated with diet,

As a result of all the research questions and expectations, dental microwear and macrowear analysis and frequencies of caries combined with Jørkov's (2007) stable isotope analyses will provide comparable insight into diet, health, and subsistence practices from a sample population in Holbæk with historical records and archaeological evidence and larger dietary and subsistence patterns in medieval Denmark.

2 CULTURAL CONTEXT OF MEDIEVAL DENMARK

The king rules over the castle tower,
And lords it over land,
And many a gallant champion leads
All armed and sword in hand.
While the king rules over the castle tower

Then let the peasant till his farm,
His horse the trooper guide,
The king of Denmark, he alone,
O'er fort and tower preside.
While the king rules over the castle tower
(Steenstrup 1914: 29)

This study investigates diet and food practices among populations from Holbæk, Denmark dated to AD 1200-1573. In order to better understand diet in this small city, it is necessary to discuss the broader historical, ecological, and cultural contexts of medieval Denmark. This chapter will provide an overview of this historical period in Denmark, the ecology and agricultural technology of the medieval period, disease epidemics, and how all of these compounding factors impacted diet in medieval Denmark.

Denmark was an agrarian society in Scandinavia (Fig. 1) made up of kings, lords, craftsmen, fishermen, peasants, and serfs. During the medieval period (11^{th}—16^{th} centuries), the country became more connected with the rest of Europe, primarily due to the spread of Christianity. New trade networks were formed with other neighboring countries, novel agricultural technologies were developed, and towns and markets became more urbanized. A major turning point between the early and late medieval period can be conceived as a series of socially relevant events: a demographic crisis, an agricultural reorganization, and a re-orientation of Danish foreign trade (Hoffman 1981). Contact with the rest of Europe also brought war, disease, and famine. All of these factors, in turn, greatly impacted diet and subsistence patterns.

Moreover, the establishment of the Church defined new regulations of consumption, new trade routes and markets brought in an assortment of foodstuffs, and innovative farming technology transformed cultivation practices.

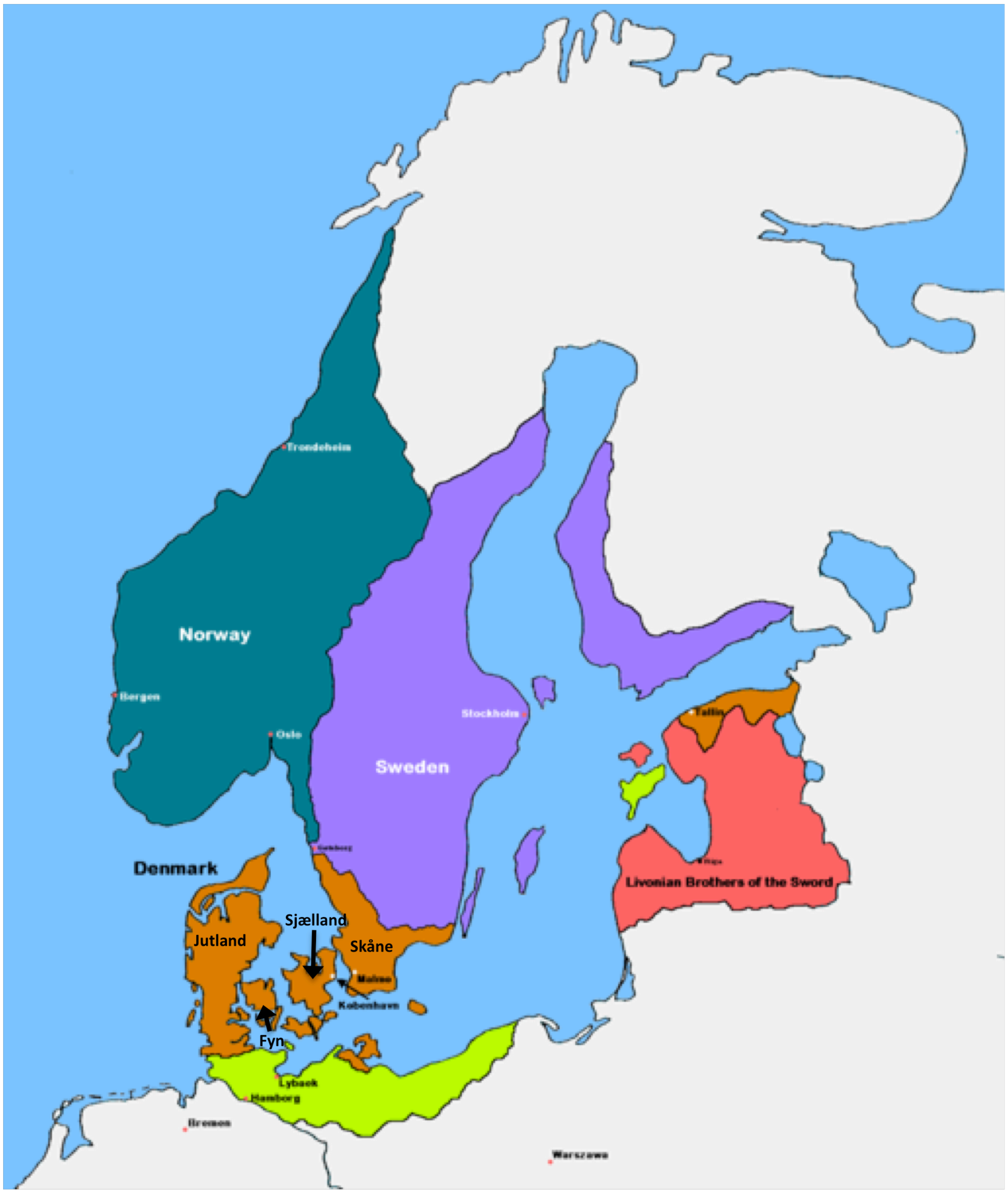

Figure 1. Scandinavia in AD 1219. Photo from wikipedia.org

2.1 A Brief History of Denmark

Scandinavia is a large region in northern Europe (Fig. 1). The term Scandinavia generally refers to the southern region in Sweden where the city of Skåne lies (Sawyer and Sawyer 1993). This region has included different kingdoms over the medieval period when Scandinavian kingdoms conquered other lands. Scandinavia has also been described as the great peninsula shared between Norway and Sweden (Sawyer and Sawyer 1993). However, the geography and history of Scandinavia do not always correspond. For instance, Skåne was actually part of Denmark for most of the medieval period while Finland was part of the Swedish kingdom from the thirteenth to the nineteenth century (Sawyer and Sawyer 1993). For the purposes of this study, the term Scandinavia will encompass the modern identification of Scandinavian countries: Sweden, Norway, Denmark and associated islands, Finland, and Iceland. Modern country names will be used to describe and locate places or regions since the boundaries of past kingdoms change over the centuries. The kingdom of Denmark consists of a large peninsula, Jutland, as well as several notable islands: Sjælland (or Zealand), Fyn (or Funen), Lolland, Falster, and Bornholm (Fig. 1). Denmark also possesses many minor islands termed the Danish Archipelago.

During the 9^{th} and 10^{th} centuries, Scandinavia was made up of chieftains and rulers, many of whom recognized Danish kings to be their overlords (Sawyer and Sawyer 1993). The authority of Danish kings depended on naval power as well as an army during this Viking (which means ‘raiding’) era. The kings could then control and profit from trade between the Baltics and Western Europe. Over the next two centuries, Danish armies would conquer and lose control of several surrounding countries like Norway and England. The medieval period in Denmark (AD 1050 - 1550) began as a shift away from the Viking economy based on raids and tributes to a feudal society made up of lords and peasants (Poulsen 1997, Yoder 2012). Social stratification was prominent throughout medieval Europe with merchant, noble, and royal classes at the top and craftsmen and apprentices in the middle class (Yoder 2006). Servants, beggars, serfs, and the extremely poor made up the bottom of the class system.

Conversion to Christianity and the establishment of the Church played an important role in shaping medieval kingdoms during the 11th century. The monarchies and kingdoms were supported by the bishops, who in turn gained a means of exercising power (Hoffman 1981). Christianity spread into Denmark and churches were built out of granite, limestone, or sandstone brought from quarries in Norway and Sweden (Lauring 1976). Danish Christianity resembled that of European countries to its south. For instance, students of theology would study in Paris and travel back to Denmark to further spread Christian ideals during the fourteenth century when the Papacy was in Avignon, France (Lauring 1976). By the 12th century, Cistercians were the main monastic order in Denmark. The Rule of St. Benedict and the Cistercian constitution, which structured monastic daily meals and activities, were the guiding forces of Cistercian life (Yoder 2010).

The Danish kingdom was comprised of modern Denmark (Jutland peninsula and associated islands), parts of southern Sweden, which included Skåne, and at various times the western Baltic region. Skåne market became one of the major fairs in medieval Europe, which made it all the more attractive for Norway, Sweden, and Denmark to gain control (Sawyer and Sawyer 1993). Denmark was in much disarray during the early 12th century due to many internal difficulties of Danish kings and their heirs, trade and agriculture somehow continued to survive despite frequent feeble attacks from Norway. In the latter 12th century, Denmark made considerable progress and experienced a peaceable time due to the extraordinary leadership of King Valdemar I who expanded Danish territory to the east (Lauring 1976, Hoffman 1981, Sawyer and Sawyer 1993). Under King Valdemar I, the Danes declared war on the Wends (West Slavs), inhabited Pomerania, and controlled the island of Rügen (a Pomeranian island in the Baltic). Continuing into the 13th century with King Valdemar's heirs at the throne of Denmark, trade flourished and capital continued to increase through the construction of churches that were decorated with colorful paintings and copper altars (copper was a specialty worked in Jutland) (Lauring 1976). However, this amiable period in Denmark did not last; at the turn of the 14th century, the period of prosperity came to an abrupt halt with worsening weather conditions (see below), severe famines, the Hundred Years War, and the bubonic plague or Black Death. The economy was on the verge of collapse, citizens were rebelling and the sons of King Valdemar II were fighting over the throne, which resulted in an eight-year stretch where the Danish kingdom was without a king (Lauring 1976, Sawyer and Sawyer 1993). Danes had also fortified their towns with walls for protection against foreign invaders. This meant that living quarters were close together with tight living conditions, which led to sewage problems and unhygienic practices (Hanawalt 1993). Unsanitary conditions only encouraged epidemic diseases to thrive. Not until the late 1300s was Denmark once more free, united, and re-established. For a time between the late 14th century and the early 16th century, the Scandinavian Union (or Kalmar Union) was enacted between three kingdoms—Sweden, Denmark, and Norway—with the Danish crown at the head (Lauring 1976, Hoffman 1981). Foreign and domestic policies were being directed under one monarch. However, only in the 16th century did Denmark really begin to recuperate from the effects of the bubonic plague and all of the political confusion from the preceding four centuries. The Protestant Reformation in the 16th century marks the end of the medieval period in Denmark.

2.2 Ecology and Agricultural Technology

Medieval Denmark was an agrarian society that relied primarily on agriculture for support and sustenance. Most small villages throughout Denmark consisted of about ten to thirty farms. They typically grew their own food from personal garden plots or larger fields surrounding the town (Yoder 2010). Denmark was a part of the feudal system with lords and peasants. Noble houses and religious institutions owned large manor estates that were leased to tenant farmers. Many of these tenants comprised the Danish *landboer* class and became a large portion of rural society (Poulsen 1997).

From the 8th to the 13th centuries, Europe was experiencing the "Medieval Warm period" or "Little Optimum" (Anderson et al. 2007: 179). The weather was stable with pleasant, dry summers and mild winters. Without May frosts and frigid winters, more and more land was opened up for cultivation. Pollen data suggest renewed deforestation in Europe that was followed by greatly intensified arable farming (Rasmussen and Olsen 2009: 39). As a result of more available land, crop cultivation intensified. The intensification of agriculture facilitated the introduction of new farming technologies around AD 1000, such as the mouldboard plough and its emphasis on ridge-and-furrow cultivation (Poulsen 1997, Rasmussen and Olsen 2009). The mouldboard plough allowed for more effective ploughing of manure into the soil to fertilize crops, and many farms also practiced animal husbandry with cattle to supply manure. The ridge-and-furrow system helped ensure proper drainage and was a necessity for winter crops such as rye, a cereal crop that became widespread in Denmark between AD 900 and 1100 (Poulsen 1997). The harrow was also introduced in the early medieval period as a compliment to the mouldboard plough to break up lumps of soil, remove weeds, and spread manure. During harvesting season, cereal grains were ground in mills, which were built by lords attempting to increase their share of the surplus (Poulsen 1997). Water mills, widespread in the 12th century, were replaced in the 13th century by horse mills and windmills. Barley and rye served as staple grains for the new technological complex that developed from the 11th century onwards (Poulsen 1997, Yoder 2010). New technologies and larger arable land increased agricultural production and strengthened rural communities.

The increase in arable land and the food supply led to a rise in population size, and in fact, doubled from 750,000 in AD 900 to over one and a half million by AD 1300 (Yoder 2010: 2224). Towns and cities started to become more urbanized, and Denmark became the most urbanized kingdom in Scandinavia, where 10% of the population lived in urban centers (Yoder 2010). These urban environments, including cities such as Ribe, Viborg, and Odense, functioned as important centers for markets, trade, and craft (Kristensen 1988). Odense connected the western and southern trade routes of Denmark (Nielsen 2011), while Ribe controlled the connection to the European market. Many of the inhabitants of Odense and Ribe were craftsmen, dignitaries, merchants, and clergymen (Nielsen 2011).

This time period of excellent weather and surplus food did not last. In the 14th century, the onset of the "Little Ice Age" brought unstable and cold weather (Anderson et al. 2007: 181) that would last for the next five centuries. This time period is also called the Late Medieval Agrarian Crisis because Denmark experienced poor crop yields and regular famines (Yoder 2010). The upper class, mainly the church and nobility, were not as affected as the rural population during the events of the 14th century, particularly since the latter was dependent upon their own land for crops while the upper class could afford imported food in markets and through trade. However, land and produce values also began to decline (Yoder 2010). The aristocrats were not pleased with this because they were receiving less income. In response, they raised rents and taxes in order to maintain their luxurious lifestyles. The agrarian way of life in turn increased the burden on peasant farmers and made their life all the more difficult (Yoder 2010). To add to the hardship of crop failure and dwindling food supplies, the 14th century was also the time of the Black Death. This epidemic of bubonic plague was one of several that greatly impacted demography and diet.

2.3 Disease Epidemics

The Black Death during the medieval period (AD 1347-1351) was an epidemic of highly virulent *Yersinia pestis* bacteria that rapidly spread from Asia to Europe. It is estimated that between one-third and one-half of Europe's population died due to the plague and secondary causes such as starvation, dehydration, and opportunistic infection between 1346 and 1350 (DeWitte 2009, Gowland and Chamberlain 2005). The plague initiated large social, economic, and demographic changes throughout Europe. Chroniclers during this medieval period documented how the plague swept through their cities by estimating how many people died, describing their symptoms, and noting historical events that surrounded this devastating time (Kelly 2005). The plague reached Denmark in 1348 along the coast from Norway and lasted until 1350 and approximately 50% of the population of Scandinavia fell victim to the Black Death (DeWitte 2009).

Populations in northern Europe were unlikely to have ever come into contact with *Y. pestis* before the Black Death. This would have made human exposure to this bacterium all the more virulent, thus creating such high mortality rates (Antoine 2008: 104). Warfare, environmental disasters, poor hygiene, and unsanitary living conditions can exacerbate the spread of plague. For example, social conditions played a critical role in the outbreak of pestilence, particularly in London (Kelly 2005). Extremely poor hygienic practices in urban centers encouraged fungus and infected fleas to spread from person to person and thus contributed to the spread of disease. During this time, leprosy was also prevalent in Scandinavia (Bennike *et al.* 2005, Boldsen 2005b). Leprosy is an infectious disease caused by the infectious bacterium *Mycobacterium leprae*, which affects the peripheral nervous system and results in the atrophy of the midfacial region, fingers, and toes (Larsen 2002). Particularly in Scandinavia, almshouses offered shelter, food, and services for the sick and poor (Møller-Christensen *et al.* 1952). Historical records state that individuals suffering from leprosy were primarily dependent upon parishes for food and shelter (Yoder 2010). When parishes experienced hardships, certain responsibilities may have been neglected, which could have led to poor sanitation and dietary conditions for all those people dependent upon parishes (Bennike *et al.* 2005). Additionally, monasteries in Sjælland (Zealand) provided shelter for the poor and lodging for the upper class. These monasteries offered free food for all the guests. Those individuals who fell victim to the plague or leprosy were buried in the adjacent cemetery unless they could pay a high price to be buried inside the walls of the monastery (Bennike *et al.* 2005, Yoder 2010). Consequently, burials in cemeteries near parishes or monasteries are most likely farmers and their families. Europe did not officially recover from the affects of plague until about AD 1450 and recovery continued into the 16th century.

2.4 Diet in Medieval Europe

Most of the historical sources that discuss medieval diet come from cookbooks and ledgers written in England. Scandinavian and English cuisines, however, were quite similar throughout the medieval ages (DeWitte 2009). Though Danish recipes will exhibit some differences in quantity and/or variety, the "overall character of the medieval diet can be reasonably generalized from these sources" (Yoder 2012: 1184). Furthermore, it is important to note the interaction between food and religion in the medieval ages, as the latter stipulated strict rules about consumption. Denmark followed the Catholic Church and thus adhered to fasting rules. On Fridays, Saturdays, certain Wednesdays, and during Lent, the Danes were prohibited from consuming animal meat, dairy products, and eggs (Adamson 2004, Yoder 2012). Therefore, the Danes substituted fish for meat during fasting. Only children, the elderly, pregnant women, and women breastfeeding were exempt from fasting (Yoder 2012). In most of Scandinavia, women were allowed to breastfeed no longer than 22-34 months (Yoder 2012). However, it is not apparent how closely the fasting rules were followed and thus how much they really impacted diet.

Diet in medieval Europe experienced a shift in the mid 14th century. Disease, famine, and a change in climate severely impacted not only the demography of Denmark but diet as well. In order to effectively discuss the wealth of information about these changes, the medieval period has been broken up into two sections, before AD 1350 and after AD 1350, with a particular focus on dietary shifts.

2.4.1 Before AD 1350

The primary food resource in all of Europe during the medieval period was cereal grains, which made up approximately half of the foods consumed (Yoder 2010). The most common cereals grown were barley and winter rye, whereas wheat was a luxury crop (Yoder 2010). Barley was particularly used to make malt and both winter rye and barley were used to make bread. Historical documents and stable isotopic analyses of medieval skeletal remains suggest that social class had a great influence on diet (Yoder 2010, Müldner and Richards 2005). The lower class (or peasant) diet was mainly comprised of cereals and fish, which corresponds to historical records indicating that peasants ate dark bread and porridge made from barley and oats (Adamson 2004). Fish was considerably cheaper at markets than animal meat. Cattle, sheep, and pigs constituted the main sources of protein in the peasant diet when they were able to afford animal meat (Adamson 2004, Yoder 2012). Many peasant families grew their own garden plots with various fruits and vegetables. A common vegetable consumed was kale, which was an important source of vitamin C. Turnips, onions, mustards, cabbage, beets, legumes, hops, and other root crops were also grown in household gardens (Yoder 2010: 2225). Dairy products, eggs, and meat were available in limited supplies, and milk was only available seasonally. Wheat was an important cereal grain in the upper class diet, whereas vegetables were not considered to be an upper class food so aristocrats did not frequently consume fresh garden produce (Yoder 2012). Fish was also an important part of upper class diet because of religious restrictions on animal meat.

Fish was readily available to Danish populations because of their proximity to the ocean and would be dried and/or salted and sold at markets (Adamson 2004). Salt-water fish were cheaper and more available than fresh-water fish. The key types of fish consumed were herring, cod, eel, and haddock. Herring comprised one of the largest fish industries due to its great availability in the North Atlantic Ocean (Enghoff 1996). Other types of fish available included pike, cod, ling, salmon, perch, dab, and sturgeon (Adamson 2004). Fish meat was not included in the religious dietary restrictions, so marine foods were staples for both upper and lower classes. The upper class consumed more fish when adhering to the fasting rules. The lower class peasants could not afford much animal meat, so whether adhering to fasting or not, their diet was mainly composed of marine food. Cistercians (or monastery monks) were completely prohibited from eating animal meat, dairy products, or eggs before the 14th century (Yoder 2012). Between the 14th and 16th centuries, many of the Benedictine Rules became relaxed, allowing monks bigger portions of food as well as a limited amount of animal meat (Yoder 2012).

2.4.2 After AD 1350

The demographic decline due to the Black Death and agrarian crises of the Little Ice Age greatly reduced the production of grain in Denmark. During this time, Denmark imported cereals from the peripheral regions and islands of Denmark and from Germany (Sawyer 1986, Yoder 2010). Many regions in Denmark began exporting butter, dried and salted meat, hides, and live cattle while importing spices, salt, cloth, wine, and beer (Dahlback, 2003, Yoder 2010). Part of the change in production was due to the fact that it was now easier and more economical to raise and to transport livestock and animal products than cereal grains. Additionally, there was a greater demand for cattle in many European markets (Sawyer 1986, Poulsen 1997), and peasants exported cattle and grain to Germany and the Low Countries, i.e. Belgium, France, and the Netherlands (Poulsen 1997). Second to cattle for both local and foreign trade were horses and pigs. Animal meat, now available in greater amounts, changed Danish diets from marine-based to more terrestrially-based. Peasants began to produce and consume more wheat, drink more ale, and eat more animal meat (Poulsen 1997). Animal meat was more affordable to peasants due to its greater availability. After the Black Death, there were fewer food shortages, so wealthier peasant groups could occasionally afford more luxury food items, such as spices (Yoder 2010: 2225).

Yoder (2012) conducted stable isotope analyses (carbon and nitrogen) of medieval Danish skeletons at Øm Kloster, Denmark in order to compare peasant, elite, and monastic diets. Yoder (2012) concludes that there were some socially based differences in Danish medieval diets. The monks showed a slight shift in diet, which corresponds to the change from consuming a more peasant type diet (fish) to and more upper class diet (adding animal meat). Interestingly, neither the elite nor the peasant diets significantly changed through time. Elite diet was characterized by access to high quality protein and peasants had a diet that was primarily C_3 plants, but Yoder (2012) found no difference in isotopic values between the two groups that would indicate variation in diet. Yoder (2010) conducted another stable isotope study of three medieval Danish sites in Jutland: Øm Kloster, St. Mikkel, and Ribe, and concluded that diet was primarily composed of C_3 plants, meat, and dairy products from terrestrial animals with varying amounts of freshwater and marine fish. The results also suggest that urban sites had a diet richer in marine and terrestrial animal resources, but residents of the rural sites had greater variability in their diets (Yoder 2010). Even given the historical evidence of a change in the agricultural and food system during this period, Yoder (2010) found no significant changes in isotopic indicators of diet through time. Perhaps a shift in agriculture does not correlate to a change in diet in medieval Denmark; another explanation could be that a change in diet may not be detected through isotope analyses.

2.5 Summary

Events of the medieval age in Denmark had both positive and negative effects on Danish populations. While expansion into other parts of Europe brought trade, new religious institutions, and power, it also brought large-scale war and disease. The stable and warm weather of the

Medieval Warm Period provided more arable land to farm, providing more food, and thus population size began to increase. However, Denmark's luck began to turn when the Little Ice Age arrived in the 14th century, creating widespread famine. The Black Death also entered Denmark in the mid-14th century, claiming almost half of the Danish population. Trade, religion, war, class, climate, disease, and famine all had an impact on Danish medieval diets, but the exact nature of these impacts is unclear. Diet and subsistence practices may or may not have shifted in some way when the prosperous period ended in the 14th century and the Danish people began to venture into new production and agricultural systems.

3 THEORETICAL AND METHODOLOGICAL ORIENTATION

Human teeth can provide many clues about age, diet, disease, and behavior. Enamel is a complex structure made up of hydroxyapatite crystals spun together to form prisms (Hillson 1998, Teaford 2007b). Since teeth are primarily made up of inorganic material they are resilient against diagenetic change and most taphonomic processes (Teaford 2007b). Because teeth are often preserved in context where bones may not be, they offer valuable information useful in reconstructing human behavior. Enamel is typically studied in relation to diet since it is the component of teeth that usually comes into contact with food and other objects (Teaford 2007b). Stable isotope, dental microwear, and oral pathology analyses are the most common methods used in reconstructing dietary patterns and subsistence practices (Barrett *et al.* 2011, Jørkov *et al.* 2010, Müldner and Richards 2005, Price *et al.* 2012, Yoder 2012).

This chapter will first discuss stable nitrogen and carbon isotope analyses and their uses and limitations in reconstruction diet. I will then describe the three most frequent methods of dental microwear: scanning electron microscopy, low-magnification stereomicroscopy, and microwear texture analysis. The limitations in to each method are also laid out as well as to dental microwear as a whole. Third, dental macrowear is detailed. Fourth, various oral pathologies are discussed and how they relate to diet. The combination of stable isotope, dental microwear, and oral pathology analyses provide a more cohesive and accurate reconstruction of diet and subsistence practices.

3.1 Stable Isotope Analysis

Stable isotope analyses from bones and teeth can be used to reconstruct animal and human diets. Both carbon and nitrogen isotope ratios offer a direct measure of diet because they do not decay over time and are the same as they were at the time of death. Stable isotope analyses can distinguish between plant and animal proteins from varying ecosystems, like terrestrial and marine ones (Katzenberg 2011). However, a limitation of stable isotopes is that they do not differentiate between the many species of fish or type of meats that were consumed. Humans' and animals' body tissues, including enamel and bone, incorporate the isotopic composition of ingested food (Hillson 1996). The carbon in consumed foods is incorporated into bones and teeth where fractionation of the isotopes occurs. Fractionation is the process of "discrimination against the heavier isotope in favor of the lighter one" (Yoder 2010: 2226), whereby lighter isotopes are typically excreted and heavier isotopes are more likely to be used to synthesize body tissues (Hillson 1996, Yoder 2010). It is the fractionation process that allows for the reconstruction of past diet because the changes in isotope ratios are measurable and fairly predictable as these elements cycle through foodwebs (Ambrose *et al.* 2003). These signatures allow researchers to determine a population's relative dependence on certain dietary resources (Ambrose *et al.* 2003, Barrett *et al.* 2011, Jørkov *et al.* 2010, Müldner and Richards 2005, Price *et al.* 2012, Yoder 2012).

The most common tissue used for stable isotopic analysis is bone collagen, which disproportionately incorporates the isotopic signatures of the primary protein source consumed (Ambrose *et a.* 2003, Yoder 2010). Additionally, stable isotope analyses of collagen provide information of diet over a long period of time because bone turnover rates are very slow. Thus, collagen stable isotope data reflects diet of at least the last decade of life (Yoder 2010). Conversely, tooth enamel does not remodel over an individual's life, thus stable isotopes examined from enamel hydroxyapatite provide information on and individual's diet consumed during childhood (Hillson 1996). Carbon and nitrogen stable isotopes from both bone and teeth facilitate the reconstruction of diet at different points in an individual's life by following the "flow of nutrients from the base of the food web up through the trophic levels" (Katzenberg 2011: 97).

3.1.1 Carbon

The relative abundance of different stable carbon isotopes varies between different ecosystems and various groups of plants and animals (Hillson 1996, Katzenberg 2011). The ratio of stable isotopes of carbon (^{13}C and ^{12}C, expressed as $\delta^{13}C$) distinguishes between plants that use different pathways for photosynthesis, referred to as C_3, and C_4 (Katzenberg 2011). C_3 plants include peanuts, most trees and their fruits, potatoes, and some cereal grains like wheat, oats, and barley. C_4 plants include millet, sugar cane, sorghum, maize, and amaranth (Yoder 2010). Three macronutrients, carbohydrates, fats, and protein, make up the bulk of one's diet. Each of these macronutrients are utilized differently in the body and thus influence the isotopic signatures of carbon. The most common tissue for isotopic analysis is collagen, which contains about 45% carbon and reflects the protein component of diet (Krueger and Sullivan 1984, Larson 2002).

Stable carbon isotopes are useful in several ways. Firstly, stable carbon isotope ratio analysis is able to determine the relative importance of various C_3, and C_4 plants in individual human diets and use these data to infer larger socioeconomic processes. For example, in a study by Ambrose *et al.* (2003), stable carbon isotopes were able to distinguish sex- or status-based differences in consumption of maize in North American diet. Secondly, carbon isotopes can confirm the relative importance of marine foods in a diet when terrestrial foods are also being consumed, though not as clearly as nitrogen isotope values (see next section) (Larsen 2002, Katzenberg 2011). The distinction between marine and terrestrial diets exists in the difference between dissolved inorganic carbon in the ocean versus the carbon in atmospheric carbon dioxide (Katzenberg 2011: 100). Interestingly, freshwater fish may exhibit a range of $\delta^{13}C$ values among and/or between species due to varying habitats in large lakes (Yoder 2010). Thus, human consumers of freshwater fish would also incorporate the range of $\delta^{13}C$ values into their bones and teeth (Larsen 2002, Katzenberg 2011). However, the reason carbon is not as beneficial in the distinction between aquatic/marine and terrestrial diets is because marine isotope values often overlap with C_4 terrestrial isotope values and freshwater aquatic foods often overlap with C_3 terrestrial isotope values.

3.1.2 Nitrogen

Stable nitrogen isotopes (^{15}N and ^{14}N, expressed as $\delta^{15}N$) can also facilitate diet reconstruction (Katzenberg 2011). Nitrogen comes from dietary protein in both plants and animals. Nitrogen can be particularly helpful when a population may have consumed "more than one source of food that is enriched in the heavier isotope of carbon (C_4 plants and marine foods, for example)" (Katzenberg 2011: 101). The $\delta^{15}N$ values of marine animals are often higher than the $\delta^{15}N$ values of terrestrial animals, and these values are measured relative to atmospheric nitrogen isotope ratios (Katzenberg 2011: 101). Therefore, $\delta^{15}N$ values provide information on the source or relative proportion of different types of proteins, not the quantity of protein (Larsen 2002). Additionally, rainfall, ocean water, and disturbed soils can all influence nitrogen content and thus produce a variation in the $\delta^{15}N$ values in plants. Therefore, the values for $\delta^{15}N$ may be higher than expected due to the isotope ecology of a region (Katzenberg 2011). Once these variations are taken into account, stable isotope analyses of nitrogen can therefore determine the relative contribution of marine and/or terrestrial food sources to ancient diet.

3.2 Dental Microwear

Teeth are composed of an enamel surface that sits on a core of dentin, and unlike bone, enamel does not remodel. Primary crowns start to form in utero while permanent crowns form around the time of birth. Even over time as enamel wears away due to mastication of food or other abrasives, new enamel will not form. Enamel begins to wear as soon as it reaches occlusion (Hillson 1996). Consumption over an individual's lifetime creates microscopic scratches and pits on the enamel surface, which can eventually expose the dentin underneath. Tooth wear therefore offers direct insights into how teeth were used (e.g. for chewing food or as a tool). However, not all foods are hard enough to damage the occlusal surface of the tooth. Sometimes it is not food that affects the enamel surface but abrasives associated with food, which is considered an indirect (abrasives) cause of microscopic wear patterns (Hillson 1996).

Dental microwear features are "microscopic wear patterns on the chewing surfaces of teeth" (Teaford 2007a: 107). Types of microscopic wear patterns include various sizes and shapes of pits and scratches on the occlusal enamel surface. Pits can be defined as circular features that have similar lengths and widths (Semprebon *et al.* 2004). Scratches are longer than they are wide with parallel sides (Semprebon *et al.* 2004). Analyses of microwear patterns of pits and scratches offer insight into past behaviors. The properties of food and other substances introduced by various types of processing (e.g. abrasives from grain ground on millstones) cause these microscopic wear patterns over an individual's lifetime (Larsen 2002). Many studies have utilized this method to effectively demonstrate the connection between diet and foods' abrasiveness in both humans and non-human primates (Covert and Kay 1981, Grine 1977, Pérez-Pérez *et al.* 2003, Peters 1982, Puech 1979, Puech and Prone 1979, Rensberger 1978, Rose and

Ungar 1998, Semprebon *et al.* 2004, Teaford 2007a, Ungar *et al.* 2008, Walker *et al* 1978, Williams and Patterson 2010) However, dental microwear analyses do not provide information about diet over long periods of time; rather, it indicates "subtle, short-term variations in diet that potentially fossilize information pertaining only to the last meals consumed before an individual's death" (Grine 2007: 295). The idea that dental microwear indicates the last meal has been termed the Last Supper Effect (Grine 2007), since microwear feature turnover rates can occur even within one or two days (Rose and Ungar 1998). Nonetheless, dental microwear techniques (described in detail below) are useful tools in learning more about types of foods consumed.

The cause of microwear in humans varies between populations due to different dietary habits and food processing techniques. Archaeological and ecological evidence can provide suggestions for various microwear patterns, though the actual food or abrasive that scratched the tooth may not be known (Schmidt 1998). Tougher foods (e.g. nuts) require more force during mastication and can lead to more pitting in the enamel (Teaford 1991). Softer foods (e.g. fruit) leave fewer pits and smaller scratches on the occlusal surface (Schmidt 1998). Foods that are contaminated with abrasives or grit will lead to a higher percentage of pits and scratches. Human cooking techniques (e.g. boiling) soften meat and plant material, which likely leaves less microwear on teeth (Pérez-Pérez *et al.* 2003). Thus, a diet primarily consisting of fish, animal meat, and/or vegetables would exhibit more shallow microwear patterns with relatively low frequencies. However, such softer foods may contain exogenous abrasives. Abrasives in food generally point to "presence of ambient sand and grit, the presence of phytoliths, and the manner in which food is processed" (Schmidt 1998: 108). Dental microwear analysis can be a very effective method in detecting human dietary transitions from 'harder' foods to 'softer' foods.

Scholars have known about the relationship between tooth wear and diet for over 50 years (Baker *et al*. 1959, Dahlberg and Kinzey 1962, Walker 1976). One of the earliest publications associated with the use of this method was Baker *et al*. (1959) who suggested that opal-phytoliths in pasture plants were the main cause of wear (pits and scratches) in sheep teeth. Dahlberg and Kinzey (1962) were the first to publish on dental microwear analysis by using light microscopy to reconstruct human diet. A decade later, Walker (1976) published on dental microwear also using light microscopy but used the method to reconstruct primate diet. Walker (1976) noted diet-based differences between terrestrial and arboreal cercopithecoids. In addition, tooth wear differences were also observed between foliovores and frugivores. These types of studies employ several different methods of dental microwear analysis, which include scanning electron microscopy (SEM), low-magnification stereomicroscopy, and microwear texture analysis.

3.2.1 Scanning Electron Microscope (SEM)

In the 1970s, the scanning electron microscope (SEM) became popular among researchers conducting dental microwear analyses (Grine 1977, Rensberger 1978, Walker *et al.* 1978). The SEM provides more depth and magnification than light microscopy (500X), which allows for more accurate recordings of microscopic feature patterns. The SEM was particularly used to analyze dietary differences in early hominins (Grine 1977, Puech 1979, Puech and Prone 1979). In the 1980s, researchers began to question whether dental microwear reflects diet and past behaviors (Covert and Kay 1981, Peters 1982). Experimental studies by Covert and Kay (1981) and Peters (1982) suggested that different diets did not produce different microwear patterns, and that grit was the culprit that created similar patterns to food on the enamel surface.

Gordon and Walker (1983) suggested that these issues with dental microwear could have been due to SEM settings, tooth position, and magnification.

The SEM allowed for the analysis of discrete feature types that would describe the enamel surface. However, SEM analyses also produce measurement errors that can lead to high inter-observer error rates (Ungar *et al.* 2008). Measurement errors are "data loss inherent in characterizing 3D surfaces in two dimensions" (Ungar *et al*. 2008: 397). Additionally, SEMs are extremely time-consuming in imaging the occlusal surface of the tooth and identifying specific features. The cost and use of the SEM is also expensive (Ungar *et al.* 2008).

3.2.2 Low-Magnification Stereomicroscopy

The measurement errors attributed to SEM have been refined in the novel method of low-magnification stereomicroscopy. Low-magnification refers to the enamel surface amplified 35X as opposed to the 500X magnification in SEM (Semprebon *et al.* 2004). With a reduced magnification a larger portion of the enamel surface can be observed and more features (like pits and scratches) can be quantified, which allows for a better representation of the entire enamel surface. Low-magnification stereomicroscopy identifies pits and scratches by their light refractive properties (Semprebon *et al.* 2004). This method does not measure scratches or pits; features are simply recorded. Thus, this method also is less time-consuming and does not require expensive equipment. Epoxy casts are typically viewed in low-magnification stereomicroscopy as a light source is tilted onto the cast (Williams and Holmes 2011). How the light refracts onto various features of the surface are counted and recorded. The various sizes of scratches are grouped in categories ranging from fine to hypercoarse while pits are categorized as small, large, or puncture (Semprebon *et al.* 2004, Teaford 2007c, Williams and Holmes 2011). Recorded data are then entered into a statistical program, such as SPSS. Various statistical tests (e.g. independent sample t-tests, ANOVA, discriminant function analysis) provide ways of making inferences about the data. For example, various trait frequencies of observed features on the enamel surface can carry information relating to many areas of interest, such as: diet, sex, and class (Semprebon *et al.* 2004). Though this method is faster than SEM, which allows for larger samples sizes, it does require a highly trained eye to accurately record enamel features (Teaford 2007c).

3.2.3 Microwear Texture Analysis

Microwear texture analysis is a fairly recent development in the field of dental anthropology. The texture analysis approach "combines white-light confocal microscopy… with scale-sensitive fractal analysis (SSFA)" (Ungar *et al.* 2008, Scott *et al.* 2012). Three-dimensional scans of the enamel surface provide repeatable measurements of features that can then be used to investigate dietary differences (Scott *et al.* 2012). Since texture analyses are repeatable, then recording enamel features are more accurate and decrease the rate of observer error. Microwear texture analysis, as a response to the limitations of SEM and low-magnification stereomicroscopy, takes less time and money and thus allows for the analysis of even larger samples (Ungar *et al.* 2008).

3.2.4 Limitations

Each method discussed above contains various drawbacks that are specific to that method. However, there are general limitations to dental microwear as well. One limitation is that microwear patterns can be caused either by direct or indirect effects of food (Teaford 2007a, Teaford 2007c). The most desired outcome is for all of the features in the enamel surface to be caused directly by food. However, this is not always the case. Abrasives on food can also indirectly cause similar microwear patterns. In non-human primates, abrasives could be grit on fruit or leaves (Ungar *et al.* 2006). In human populations, the situation can become more complex due to a variety of food preparation techniques, such as cooking food in the ashes of a fire pit or processing grain with a stone-grinding tool (Teaford 2007c). Here, the observed microwear patterns are caused by the preparation techniques rather than the foods themselves, which could influence results. Additionally, softer foods are unidentifiable in that they do not leave microscopic features on the enamel surface (Teaford 2007a). Though all of these factors seem to negatively influence the interpretation of observed microwear patterns, knowledge of a population's surrounding ecological conditions can alleviate some of these limitations.

3.3 Dental Macrowear

Dental macrowear is the loss of dental hard tissues during mastication as viewed at the macroscopic level (Schmidt 2010, Williams and Woodhead 1986). Various processes can create macrowear. One such process is abrasion, which is caused by particles in food that physically remove hard tissues. Another process is attrition, which is caused by tooth-to-tooth contact (Schmidt 2010). Attrition tends to create facets on the tooth cusps while abrasion tends to obliterate them. Enamel can also be eroded through chemical processes like acids (Williams and Woodhead 1986). Thus, removal of enamel through any of these methods can be termed as dental macrowear. Wear first begins by rounding and then flattening the cusps. Over an individual's lifetime, enamel can become thinned and the dentin underneath can become exposed.

The rate and morphology of enamel wear is not consistent among all human populations and is dependent upon a population's diet and their environmental setting (Molnar 1971, Molnar et. al 1972, Schmidt 1998). Macrowear can thus be used as an indicator of dietary differences between human populations. For example, people that reside in desert environments generally have a high amount of sand in their diet (Schmidt 2010). Sand, as an abrasive, can wear down enamel very quickly due to its hard composition subjecting individuals to heavy wear patterns. Thus, tooth enamel can wear down at various rates due food mastication, attrition, and/or exogenous abrasives over an individual's lifetime.

3.4 Oral Pathologies

Dental pathologies provide insight into a past population's behavior, living conditions, diet, and nutrition. As mentioned, dentition can resist most taphonomic processes better than the other tissues of the body, which allows researchers to analyze tooth wear, tooth decay, and periodontal diseases (Caselitz 1998, Strohm and Alt 1998, Shultz *et al.* 1998, Esclassan *et al.* 2009). The study of dental pathologies is an indirect way of gaining a better understanding of not only what foods people ate, but also how those foods affected their health. Several types of oral pathologies are particularly important in the reconstruction of past nutrition and diet, including caries, periodontal disease, opacities, and enamel hypoplasias.

Dental caries, also known as tooth decay, occur when the hard tissue of enamel is progressively destroyed due to plaque (bacterial infestation), dietary habits (e.g. continual consumption of sugar), or an absence of proper oral hygiene (Caselitz 1998). Decay first begins on the occlusal surface of enamel, then the bacteria travels down through the dentin and into the pulp cavity (Caselitz 1998). Once the enamel crown is destroyed, inflammation caused by bacteria can spread and often leads to periodontal (e.g. abscesses) or even lethal diseases (e.g. sepsis) (e.g. Shultz *et al.* 1998). Sugars and other carbohydrates are the most common culprits of dental caries (Caselitz 1998), and the frequency of caries increases with high levels of sugar in the diet (e.g. a maize based diet). Carious lesions are the result of lactic acid that erodes enamel (enamel breaks down at a pH between 4.0 and 5.5) and causes cavitation (Schmidt 1998). Caries can be found in all teeth, however they are usually found in molars because the grooves between cusps are perfect places for cariogenic food particles to become wedged. Characteristics of cariogenic foods are those that have a highly fermentable carbohydrate content and reduce the pH levels. Oral bacteria can then easily deposit lactic acid, which leads to the development of carious legions. Periodontal disease is another oral pathology, which is "characterized by vertical and horizontal loss of alveolar bone" (Strohm and Alt 1998). Periodontal disease typically occurs in adulthood after 30 years of age (Strohm and Alt 1998). An additional type of oral pathology is enamel opacity. Enamel opacities are opaque white patches that result from disturbances of mineralized zones beneath the surface and can often lead to caries (Hillson 1996, Shultz *et al.* 1998).

While caries, opacities, and periodontal diseases are more likely to affect individuals in adulthood, there are oral pathologies that affect children, such as enamel hypoplasias. Hillson (1996: 165) defines an enamel hypoplasia as a "deficiency of enamel thickness, disrupting the contour of the crown surface, initiated during enamel matrix secretion." The most common type of hypoplasias is a furrows defect, referred to as Linear Enamel Hypoplasia (LEH) (Hillson 1996). Several conditions have been attributed to hypoplasias; some include malnutrition, infectious diseases (e.g. measles), trauma, anemia, rickets, diarrhea, and diabetes (Schultz *et al.* 1998, Hillson 1996, Larsen 2002). Hypoplasias represent long-term stress episodes that can last months at a time. Enamel defects typically occur from one to four years of age during dental development. Defects are often associated with the high risks of morbidity related to weaning and supplementation (Larsen 2002). In times of stress, the body directs its energy to healing any ailments and consequently may cease enamel formation. And again, because teeth do not remodel, analyses of enamel hypoplasias, caries, periodontal diseases, or opacities can be useful indicators of periods of increased stress, malnutrition, and disease over an individual's lifetime.

3.5 Summary

Using multiple types of methods allows for a better reconstruction of ancient dietary patterns from archaeological human teeth recovered in archaeological contexts. That said, limitations associated with each of the various methods could affect the accuracy of results. By employing multiple methods some of these limitations can be avoided and a clearer understanding of diet and subsistence emerges. Stable isotope analyses can detect the diversity of diet. For example, certain sources of diet (e.g. marine or terrestrial) and the type of protein consumed can be identified. Dental microwear analyses provide a valuable compliment to stable isotope analyses because they assess dietary changes or habits that isotopes may not be able to distinguish. For example, microwear patterns may be able to differentiate the types of food found in C_3 or C_4 diets. However, neither dental microwear nor stable isotope analyses can assess nutrition in the diet. Oral pathologies can help fill in that missing information. Oral pathologies, like caries and hypoplasias, are particularly useful in evaluating stress and nutrition during childhood and how food is affecting enamel. These methods along with written sources and archaeological evidence can illuminate past diet, health, and disease.

4 RESEARCH DESIGN AND METHODS

Figure 2. Map of Holbæk, Denmark. Island names are italicized and Holbæk is in red.

4.1 Holbæk Archaeological Site, Ahlgade 15-17

Holbæk is located on the northeastern part of the region of Sjælland (or Zealand) (Fig. 2). The site of Ahlgade 15-17 lies on the north side of Holbæk's main street of Ahlgade. The cemetery associated with the church of St. Nicolai was excavated in 1985-1986 by the local Museum of Holbæk and the National Museum of Denmark (Asmussen 1997, Jørkov *et al.* 2009). The eastern part of the parish churchyard, St. Nicolai was found at the address number 15 and the medieval settlement was found at the address number 17. A large-scale excavation was launched in order to recover as many skeletons as possible (Asmussen 1997). Detailed archaeological and historical data from this Holbæk site have been recorded and published by Asmussen (1997).

The total area of the medieval settlement excavated was $75m^2$. This area was excavated to a depth of between 30 and 70 cm (Asmussen 1997: 188). The medieval settlement was dated from the late 12th century to the mid-15th century based upon cross-dating of the pottery in comparison to other Danish medieval sites (Asmussen 1997). Archaeological remains of houses from the later dates of the settlement suggest multiple buildings made up light half-timbered wattle and daub that rested on a foundation of stone with waste pits in the backyard area.

Only part of the original churchyard was excavated representing a total area of $480m^2$ (Asmussen 1997: 188). The eastern part of the cemetery was first used in the late 12th century and the western part in the early 13th century. The entire churchyard all together was abandoned in AD 1573 just after the reformation in Denmark marking the transition from Roman Catholicism to Lutheranism (Asmussen 1997: 188). Dates of the cemetery were based upon calibrated radiocarbon assays on skeletal material. Since marine foods composed a part of the diet, the reservoir effect was taken into account and dates were adjusted accordingly. Due to the close proximity of the burials and some bioturbation it was not possible to obtain an exact number of burials from the medieval cemetery, however, it was estimated that there were approximately 583 burials. From the skeletal material excavated, a minimum of 732 individuals was identified (Asmussen 1997: 42). The cemetery interments were not separated by sex or age. However, the under-representation of children should be noted since those buried in deeper layers of soil have deteriorated because their bones have not yet calcified (Asmussen 1997: 42).

There are six stratagraphic layers with level 1 being the oldest and level 6 as the most recent. A subjective assessment of the arm positions of 309 burials provided a chronological estimate for different time periods. It is really the arm position combined with the radiocarbon and stratagraphic data that allow for the assessment of dates. There were four most common types of arm positions – A (A1 and A2), B, C, and D. All radiocarbon dates for each burial type are based upon a few dated individuals. Burial type A (n=26) is radiocarbon dated to AD 1175 and continues to about AD 1300 (Asmussen 1997: 45). Burial type A has two subtypes, A1 and A2. Burial subtype A1 shows arms alongside the body while subtype A2 shows arms lying alongside the upper body with only the hands lying on the thighs. The most dominant burial type is B consisting of 183 graves. According to radiocarbon assays, burial type B began in the second half of the 13th century and continued into the 14th century and possibly may have been used until the abandonment of the cemetery (Asmussen 1997: 49). Here the forearms and hands were placed in the lap and the hands can either be close together or on top of each other. Burial type C had a total of 24 graves and is C-dated to the 14th and 15th century. Burial type C shows the hands placed on the mid torso. Burial type D (n=27) is radiocarbon dated to the 15th century and beginning of the 16th century. Burial type D shows forearms were placed on the upper body with the hands on the chest. The transitions during the medieval period between arm positions A through D occurred smoothly and did not begin or end abruptly, which is why some of the time periods overlap (Asmussen 1997: 189). Some individuals excavated showed a combination of the above burial types, though most of the individuals were found with one of the four burial types.

The four burial types were also noted in other Danish medieval cemeteries. Similar chronological timeframes were noted (Asmussen 1997) at the Æbelholt monastery cemetery in north Sjælland (AD 1175-1567) and burial types A and B found in Refshaleborgen cemetery in Lolland (AD 1000-1200). Additionally, these four burial types were identified at medieval cemeteries in Sweden (Helgeandshuset House Church cemetery AD 1300-1320), Norway (Olav's Church Cemetery in Trondheim AD 1100-1150), England (St. Helens Cemetery in York AD 950-1550) (Asmussen 1997). The various burial types contained some variation in styles and dates, though the burial types still followed the chronological order discussed above.

In addition to the burial customs discussed above in Ahlgade 15, bodies were typically wrapped in cloth and placed in a grave. Most of the burials would have had wooden coffins, but due to decay processes, the style cannot be discerned and all that remains are wood remnants. Some burials without coffins had stones placed around the body (Asmussen 1997: 57). All of the bodies were buried with their head to the west and a majority of them were lying in the supine position with their legs outstretched (Asmussen 1997: 43). The treatment of the dead is quite consistent throughout the cemetery with no distinctions between males, females, or non-adults. This consistency across the associated time periods suggests that during the Black Death in the mid-14th century, traditional treatment of the dead was likely maintained.

The most remarkable find in the cemetery were five burials containing scallop shells that had holes drilled into the base (Asmussen 1997: 139). The shells were found either placed in the middle of the chest or to the right side of the skeleton, which suggests that the shells could have been sewn on the cloth that wrapped the body. Three of the burials were males, and in the other two the sex could not be determined. The reason these scallop shells are so important is because they signify the pilgrimage individuals would take during the medieval period to Santiago de Compostela in Spain to visit the burial of the apostle Saint James. The few individuals from Holbæk apparently traveled the dangerous roads in the approximately 3,000km journey down to

Spain. The French in Spain would sometimes demand tolls to pass or pilgrims would suffer beatings for money (Rudolph 2004). Most pilgrims made the long journey to Santiago de Compostela for a miraculous cure, to fulfill a vow, or attain spiritual benefits (Rudolph 2004: 5). The collection of the scallop shell was the mark of the pilgrim.

Other archaeological material relevant to this study also includes the discovery of animal and fish bones as well as botanical remains. Most of the animal bones were recovered in the trash discarded from households in Ahlgade 17 (Asmussen 1997: 195). A large amount of the animal bones belonged to farm animals like goats, sheep, pigs, chickens, and some cattle. Remains of pens were also discovered for domesticated animals. Evidence of some various uses for domesticated animals other than for consumption include goat horns used to make combs and spoons, sheep for wool, and cats skinned for fur (Asmussenn 1997: 200). Fishing played a large role in Holbæk due to its close proximity to the fjord; a total of 3,843 fish bones were excavated at Ahlgade 15-17 that date from AD 1200 to 1400 (Asmussen 1997: 204). Burnt fish bones were also found. Freshwater and saltwater fish were both identified among the fish remains due to the brackish water in the Holbæk fjord, where the salt content is 20% of average marine salinity (Asmussen 1997: 204). Methods of fishing included line, nets, dragnets, and stationary netting. All of the fish caught in medieval Holbæk were from the inlet or the neighboring waters and appear to have been used for local consumption. No evidence of trade was found (Asmussen 1997). Several different types of grains were grown and cultivated in Holbæk, which include oats, wheat, rye, and barley (Asmussen 1997: 221). The most common archaeobotanical remains identified was oats whereas rye and barley were found in smaller quantities. Evidence of black henbane and motherwort were plants grown in the gardens that would have been used for medicinal purposes. Naturally growing plants (occasionally \ may have been cultivated according to some archaeobotanical remains) in the area that also contributed to medieval diet as spices or ingredients are cabbage, flax seed, blackberry, elderberry, hazel nuts, and sloe (a fruit).

All of the archaeological evidence from artifacts, human burials, along with faunal and botanical remains, begin to paint a picture of life in medieval Holbæk. Farming and fishing played large roles in their daily lives. One of the profound finds at Ahlgade 15-17 were the scallop shells in 5 of the burials. The individuals pilgrimage to Santiago de Compostela, Spain to visit the burial of the apostle Saint James and collect the scallop shells is really the only indication of Holbæk's contact with groups outside the region. These scallop shells could also suggest Holbæk's dedication to Christianity.

4.2 Materials and Methods

The skeletal collection chosen for this research was recovered from the medieval (AD 1200-1573) cemetery Ahlgade 15-17. Excavations at the site recovered 732 well-preserved individuals (Asmussen 1997), from which 70 individuals were chosen for this study. The University of Copenhagen in the Panum Institute houses the entire Holbæk skeletal collection. The individuals excavated represent the general public living in medieval Holbæk (Jørkov 2007). These individuals appear to have been fishermen, pastoralists, and craftsmen with no particular class distinction, who, according to the isotopic analyses, consumed a similar diet throughout their lives (Jørkov *et al.* 2009). All individual's sex and age are reported in Appendix A.

Dentition from 70 individuals from the medieval Holbæk site were analyzed and scored for microwear, macrowear, and caries in the collections department at the University of Copenhagen, Denmark. As this study is a complimentary analysis to Jørkov's (2007) isotopic study, it was appropriate to select the same individuals in order to better compare the existing isotopic data to the microwear, macrowear, and caries data collected in this study. Though Jørkov's (2007) study consisted of 74 individuals, five individuals were unavailable or did not have any teeth present (e.g. alveolar resorption). To obtain an even number of individuals, one individual was added to this research that was not in Jørkov's study (EG465) Sex and age were re-assessed by Jørkov (2007). Sex was determined based on morphological features on the skull and pelvis according to standards in Buikstra and Ubelaker (1994). Age estimation was determined by several skeletal locations, the pubic symphisis, auricular surface of the illium, and sternal rib ends (Jørkov 2007: 73).

Four groups of age ranges were included in this study and categorized by Jørkov (2007): non-adults (1-16 years old at death, N=25), young adults (ages 17-25 at death, N=14), middle-age adults (ages 26-45 at death, N=17), and older adults (ages 46+, N=14). In order to use age as a statistical category, median age was calculated for age ranges 17-25 and 25-45; for those aged 46+, the age 46 was used. These age values for each adult category were used only as a category references (Appendix A). Twenty-one of the individuals are female, twenty-four of the individuals are male, and twenty-five are unclassified. Those individuals unclassified are sub-adults and therefore cannot be identified skeletally as male or female. Jørkov (2007) intended to select a balanced number of individuals in both age and sex groups. These 70 individuals are a representative sample of the entire Holbæk cemetery assemblage, and by extension, the medieval Holbæk inhabitants.

4.2.1 Scoring Macrowear

Macrowear scores were assigned to each molar (M_3, M_2, M_1), premolar (P_2, P_1), canine (C), and incisor (I_2, I_1) using the Scott (1979) scoring system as outlined in Buikstra and

Ubelaker (1994). Scores were based on enamel loss and dentine exposure for both maxillary and mandibular dentition. The Scott (1979) scoring system assigns ordinal values between 1 and 10 for the occlusal surfaces of premolars, canines, and incisors. For each molar, these ordinal values are assigned to each occlusal quadrant. The four quadrant scores are summed to provide an overall tooth score between 4 and 40. Scores close to the value of 4 for molars and 1 for anterior teeth indicate little to no enamel loss, while scores approaching 40 for molars and 10 for anterior teeth indicate complete removal of the crown (Scott 1979). A score was not given to teeth fractured or destroyed by carious legions. Averages of first, second, and third molars, premolars, and anterior (canines and incisors) teeth were calculated (Appendix B). In order to assess wear patterns between anterior and posterior teeth, molar wear scores were calculated out of 40 and subsequently divided by 4 to obtain an average between 1 and 10. Thus, posterior teeth and anterior teeth could be directly evaluated statistically.

4.2.2 Scoring Dental Caries

Dental caries were also scored according to Buikstra and Ubelaker (1994). Each dental caries was recorded as:

1= occlusal surface

2= interproximal surfaces

3= smooth surfaces (buccal and lingual)

4= cervical caries at the CEJ

5= root caries

6= large caries

7= non-carious pulp exposure.

To simplify for statistical analysis, the total number of caries for each individual, regardless of location or type of caries, were calculated and reported in Appendix C.

4.2.3 Molding and Casting for Microwear Analysis

Each tooth was cleaned and molded for dental microwear analysis in the collections department at the University of Copenhagen. All teeth were first cleaned with acetone and cotton balls in order to remove any shellac or soil particles. When teeth were completely dry, the surface of both left first and second mandibular molars (M_1 and M_2) were molded with polyvinylsiloxane dental impression material (President Plus Jet Regular Body, Colténe/Whaledent Inc.). The molding material consists of a base and hardener that are mixed together with a caulk-like gun. The mixture was placed on the occlusal surface of each tooth to ensure all fissures and features were molded without air pockets. Approximately half of the tooth crown was covered with the mold mixture. For isolated teeth, a small amount (enough to cover the tooth) of mold mixture was applied to an aluminum foil surface. The isolated tooth was then placed, occlusal side down, into the mold and left to dry. After approximately 10 minutes, the mold was removed and labeled.

After all molds had been made, the casting process was completed in the Bioarchaeology Lab at Georgia State University in Atlanta, Georgia. A layer of lab putty (Colténe LAB-PUTTY base and hardener) was applied to the edge of molds to prevent liquid casting material from leaking while drying. Epoxy resin (Polytek Polypoxy 1010) was mixed with hardener (PolyCure 1212) at a ratio of 5:1 and stirred vigorously for five minutes. The resin mixture was spun in the centrifuge for approximately one minute at 4,000rpm. Since air bubbles in resin can obscure microwear features, pipettes were used to siphon the top layer of bubbles in each test tube. The resin was then dripped into each of the molds. It took approximately 24 hours for the resin mixture to fully dry and harden. The casts were then removed from the molds for analysis; none of the casts were cracked or broken.

4.2.4 Dental Microwear

The epoxy resin casts were analyzed at 35X magnification using a low-magnification stereomicroscope. Microwear features were identified within a standard counting square using an ocular reticle on the occlusal surface of the teeth. For standardization, the protoconid cusp was consistently used to identify microwear features on the mandibular molars. Since a few individuals had both mandibular molars missing either pre- or postmortem, several microwear features were identified on the protocone of maxillary first molars. Both enamel and dentin surfaces were analyzed for microwear features. While some teeth had only enamel or only dentin, some teeth had both enamel and dentin present and microwear was recorded on both surfaces.

A fiber-optic light source was cast across each tooth's occlusal surface at a shallow angle in order to highlight all microwear features. During the analysis, the light source would be adjusted to accent various features (Semprebon *et al.* 2004). Six variables were analyzed on both enamel and dentin surfaces; the respective numbers of fine, coarse, and hypercoarse scratches and of small, large, and puncture pits (Semprebon *et al.* 2004, Teaford 2007c, Williams and Patterson 2010). The features present in the ocular reticle ($0.4mm^2$) were counted and recorded. Microwear features were recorded on two different areas of the cusp (protoconid or protocone) and the average value was calculated for each feature (Appendix D). Areas of the tooth that appeared disturbed by postmortem taphonomic processes were avoided, such as areas that were cracked, broken, or matted. Criteria for identifying microwear features were recorded according to Semprebon *et al.* 2004. Fine scratches were narrow and very shiny, coarse scratches were also shiny but wider than fine scratches (typically only one side of the scratch would be refracted while the other side is dark), and hypercoarse scratches were deep and dark (Semprebon *et al.* 2004). Small pits were round and very shiny, large pits were deeper and darker than small pits but would refract a small amount of light, and puncture pits were the darkest and deepest (Semprebon *et al.* 2004). Dental microwear data will be used in this study to look for any differences between males, females, and non-adult diets rather than what specific microwear features say about diet.

4.2.5 Isotopic Data

The isotopic data for 69 individuals in this study were generated by Dr. Marie Louise Jørkov from the University of Copenhagen (Jørkov *et al.* 2007, 2009, 2010). As mentioned above, one individual (EG465) does not have isotopic data (Appendix E). Jørkov (2007) investigated intra-skeletal isotope variations between bone elements with different collagen turnover (femur, rib, petrous bone, teeth). Compact bone taken from the femoral mid-shaft has a turnover rate of approximately 10 years (Jørkov 2007: 37). Samples from the femur then provide isotopic ratios that infer diet of the last decade of life. Compact petrous bone in the cranium was also sampled. In contrast to femoral compact bone, the "endochondral layer which forms the main part of the capsule forms in uterus and is well ossified by the time of birth" (Jørkov 2007: 37). Therefore, the petrous bone does not remodel after the first two years of life; isotopic ratios then are useful for inferring diet during prenatal periods and the early stages of infancy. Another sampling site that provides information on childhood diet is dentin from teeth. Collagen from root dentin was sampled in one of the maxillary first molars, which should represent diet from around the age of 3-5 years (Jørkov 2007: 73). Trabecular bone taken from the ribs has a turnover rate of up to 3-5 years, with an even faster rate in infants and young adults (Jørkov 2007: 38). Samples from the rib provide isotopic ratios that are useful for inferring diet in the last several years of life. For the purposes of this study, only the isotopic data from the trabecular bone in the ribs were used in comparison with dental microwear and macrowear data. Since microwear has the "Last Supper Effect" (Grine 2007), in that dental microwear of the occlusal surface represents the last meal or several meals consumed, isotopic data from the bone with the fastest turnover rate would provide an estimate of diet composition closest in developmental time to the observed dental microwear patterns. Values of $\delta^{13}C$ and $\delta^{15}N$ from the collagen of trabecular rib bone were reported for all individuals.

5 STATISTICAL ANALYSES AND RESULTS

5.1 Statistical Methods

To better understand overall diet, consumption patterns, and teeth use-wear behavior, statistical analyses are employed to develop these associations. Statistical analyses of three primary sets of variables (microwear, macrowear, isotopes) serve as the mechanism for determining distinctions between diet, age, and sex. Analyses of variance tests (ANOVA) are utilized for the three primary variables to control for as many effects and their interactions as possible. An ANOVA compares the variability of values within groups (i.e. males, females, and non-adults) with the variability of values between groups. Specifically, an ANOVA compares the mean values for one variable between groups that are defined by another variable to see if there is significant variation in the former according to the latter. T-tests, principal component analyses, and Pearson correlations are also performed to further understand dietary and behavioral relationships between age or males, females, and non-adults. All data were assessed for normality.

5.2 Isotope Results

A Kolmogorov-Smirnov test was first performed on all isotope values ($\delta^{13}C$ and $\delta^{15}N$) to test for normality for the entire sample population (n =69). Both of the significance values for each $\delta^{13}C$ and $\delta^{15}N$ were greater than the α-level of 0.05 ($\delta^{13}C$ was 0.89 and $\delta^{15}N$ was 0.200). Thus, all of the isotope data are normally distributed. The following parametric tests were performed in the following sections: Pearson Correlation, T-tests, and ANOVA.

5.2.1 Pearson Correlation

A Pearson correlation test was performed to measure the relationship between $\delta^{13}C$ and $\delta^{15}N$ values (Table 1). Correlation tests measure the linear relationship between two variables. Both p-values in Table 1 are highly significant because they are less than the alpha level of 0.05. A scatter plot was created for $\delta^{13}C$ and $\delta^{15}N$ values to visually see the positive relationship (Figure 3). Thus, high values for $\delta^{13}C$ are associated with high values for $\delta^{15}N$ and vise versa with low values.

Table 1. Pearson Correlation of $\delta^{13}C$ and $\delta^{15}N$ values

Correlations

		$\delta^{13}C$	$\delta^{15}N$
$\delta^{13}C$	Pearson Correlation	1	.724**
	Sig. (2-tailed)		.000
	N	69	69
$\delta^{15}N$	Pearson Correlation	.724**	1
	Sig. (2-tailed)	.000	
	N	69	69

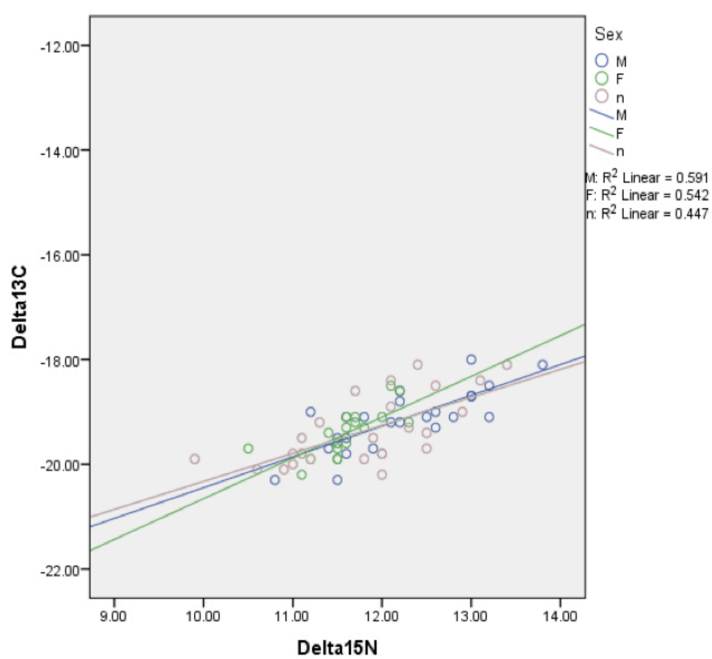

Figure 3. Scatter Plot of $\delta^{13}C$ by $\delta^{15}N$ values by Sex

The Pearson Correlation test suggests that there are no real differences between sex and non-adults. In order to detect if there were any differences in age for $\delta^{13}C$ and $\delta^{15}N$ values, scatter plots were created for $\delta^{13}C$ by age (Fig. 4) and $\delta^{15}N$ by age (Fig 5). $\delta^{13}C$ by age shows relatively consistent values through age and sex. There does not seem to be any groupings, $\delta^{13}C$ values remain quite uniform through the life of those individuals. $\delta^{15}N$ by age remains consistent for females and non-adults. $\delta^{15}N$ values for male individuals show an interesting distribution. There seem to be nine male individuals (EG581, EG339, EG202, EG140, EG399, EG52, EG203, EG185, EG71) that are grouped together apart from females, other males, and the rest of the sample population. The nine individuals are circled in red (Fig. 5).

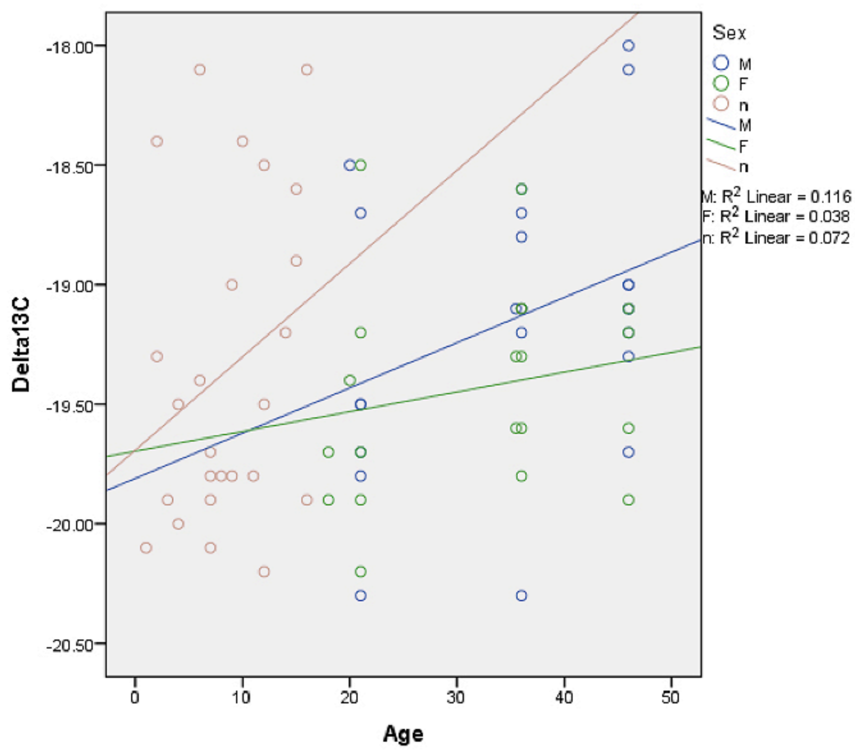

Figure 4. Scatter Plot of $\delta^{13}C$ by Age

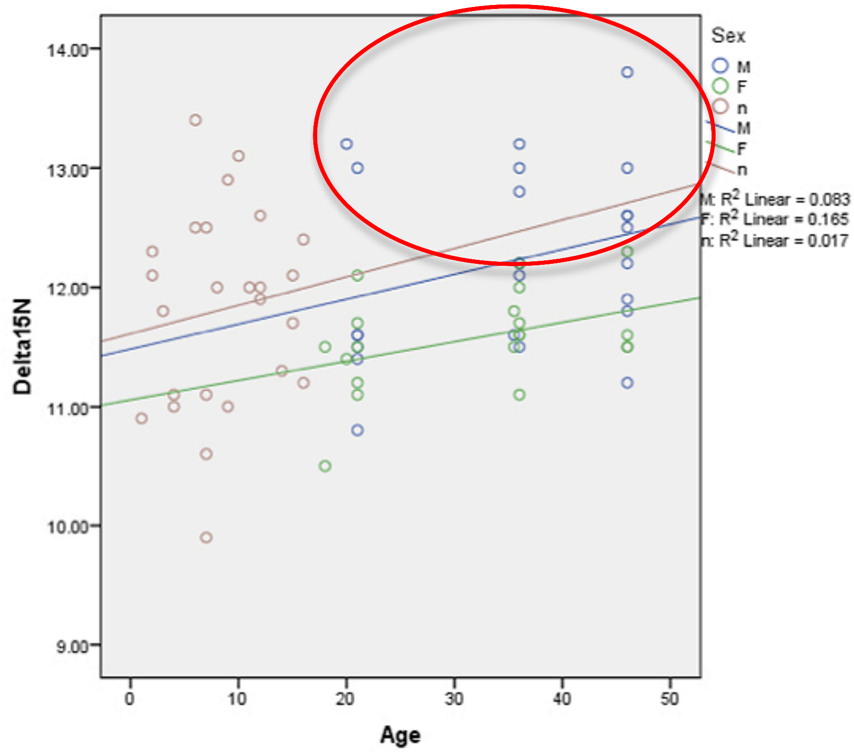

Figure 5. Scatter Plot of $\delta^{15}N$ by Age

5.2.2 Independent Samples T-tests

T-tests were also performed for $\delta^{13}C$ and $\delta^{15}N$ values to distinguish if any statistically significant differences exist in the diet between males and females. T-tests can only compare means between two groups, so the t-tests do not include non-adults. T-tests compare the mean of female isotope values for both $\delta^{13}C$ and $\delta^{15}N$ against the mean of male isotope values for both $\delta^{13}C$ and $\delta^{15}N$. A t-test was used to find differences in $\delta^{13}C$ and $\delta^{15}N$ values for all male and female individuals in the sample population (Table 2). The Levene's Test for Equal Variance shows equal variances for $\delta^{13}C$ and unequal variances for $\delta^{15}N$. The appropriate p-values for equal and unequal variances were chosen for both $\delta^{13}C$ and $\delta^{15}N$ values. The only significant isotope values are $\delta^{15}N$ in Table 2 ($p < 0.05$). This significant value suggests that males had higher $\delta^{15}N$ values in diet compared to females due to the higher mean in male $\delta^{15}N$ values.

Table 2. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values by Sex

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.492	.069	-	-
			-	-
$\delta^{15}N$	.004	.001	M	12.2208
			F	11.5700

Subsequent t-tests were run to further break down the significant $\delta^{15}N$ value in Table 2. Perhaps this dietary distinction between $\delta^{15}N$ values in males and females only occurred in certain age groups. Thus, three t-tests were performed for $\delta^{13}C$ and $\delta^{15}N$ values by age categories. The Levene's Test for Equal Variance shows equal variances for each of the three t-tests and the appropriate p-value was selected (Table 3, Table 4, Table 5). The first t-test shows isotopic values of select cases for ages 17-25 (Table 3). No significant differences were found between males and females in this age group. The second t-test shows isotopic values of select cases for ages 26-45 (Table 4). $\delta^{15}N$ values are significant different between males and females in this age group with higher values in males ($p < 0.05$). The third t-test shows isotopic values of select cases for ages 46+ (Table 5). No significant isotopic values were identified. From these three t-tests, the only age group that exemplified the t-test for all individuals (Table 2) was 26-45. Non-adults are tested in the following section because an ANOVA is required due to the varied ages.

Table 3. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values for Ages 17-25

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.435	.821	-	-
			-	-
$\delta^{15}N$	.582	.730	-	-
			-	-

Table 4. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values for Ages 26-45

T-test for Ages 26-45				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.813	.641	-	-
			-	-
$\delta^{15}N$	.152	.026	M	12.4286
			F	11.7000

Table 5. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values for Ages 46+

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.610	.126	-	-
			-	-
$\delta^{15}N$	.299	.122	-	-
			-	-

The subset of males (EG581, EG339, EG202, EG140, EG399, EG52, EG203, EG185, EG71) that were identified in Figure 5 of $\delta^{15}N$ by age are again distinguished here to see if they are statistically different in isotopic values from the rest of the population. The subset of male individuals (score = SM) are compared to females (score = F), the rest of the sample population (score = RSP), and other males (score = OM). The Levene's Test for Equal Variance shows equal variances for all three t-tests and thus equal variance p-values were assigned (Table 6, Table 7, Table 8). All of the p-values for each t-test are less than 0.05 and statistically significant. The significant values in all three tables confirm the dietary differences of the subset of males not only in $\delta^{15}N$ values but also in $\delta^{13}C$ values from females, the rest of the sample population, and other males. These specific male individuals are more enriched in $\delta^{15}N$ and $\delta^{13}C$ values according to their higher means.

Table 6. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values for Subset Males and Females

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.976	.000	SM	-18.7222
			F	-19.4350
$\delta^{15}N$	.735	.000	SM	13.0222
			F	11.5700

Table 7. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values for Subset Males and Rest of Sample Population

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.386	.001	SM	-18.7222
			RSP	-19.3917
$\delta^{15}N$	.091	.000	SM	13.0222
			RSP	11.7150

Table 8. T-test of $\delta^{13}C$ and $\delta^{15}N$ Values for Subset Males and Other Males

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
$\delta^{13}C$	.627	.003	SM	-18.7222
			OM	-19.4143
$\delta^{15}N$	.478	.000	SM	13.0222
			OM	11.6857

5.2.3 One-Way ANOVA

An ANOVA was required to test the $\delta^{13}C$ and $\delta^{15}N$ values for non-adults because of the varied ages of non-adults (age < 16). The results show no statistical significance in either $\delta^{13}C$ or $\delta^{15}N$ values (Table 9). Thus no significant dietary differences exist isotopically between non-adults. Sex-based diet variation cannot be tested for non-adults because no sex is attributed to them.

Table 9. ANOVA of $\delta^{13}C$ and $\delta^{15}N$ Values of Non-Adults by Age

ANOVA		
Variable	F	Sig.
$\delta^{13}C$	1.002	.505
$\delta^{15}N$	1.191	.390

In order to test whether isotopic indicators of diet changed over time, an ANOVA was performed between those individuals who can confidently be dated to pre-1350 (N=18) and to post-1350 (N=11) (Table 10). Each date category includes males, females, and non-adults. Dates were assigned from either the radiocarbon assays or arm positions or a combination of both. Neither mean $\delta^{13}C$ values nor mean $\delta^{15}N$ values appear to be significantly different among the two time periods ($p > 0.05$) (Table 10). The ANOVA suggests that diet before 1350 was similar to diet after 1350 when the bubonic plague hit Denmark, at least as is measurable isotopically. A scatter plot is provided for $\delta^{13}C$ and $\delta^{15}N$ values and plots the individuals dated before and after 1350 (Fig. 6). Individuals in the scatter plot are not in distinct groups and show a similar pattern in diet isotopically over time. However, there appears to be less variation in $\delta^{13}C$ values after 1350. Additionally, four of the identified subset of males were included in this analysis: two males (EG203 and EG185) in the pre-1350 category and two males (EG52 and EG71) in the post-1350 category. This tentatively indicates isotopically that diet of the subset of males also did not change over time.

Table 10. ANOVA of $\delta^{13}C$ and $\delta^{15}N$ Values for Individuals Pre-1350 and Post-1350

ANOVA		
Variable	F	Sig.
$\delta^{13}C$	.011	.918
$\delta^{15}N$	.834	.369

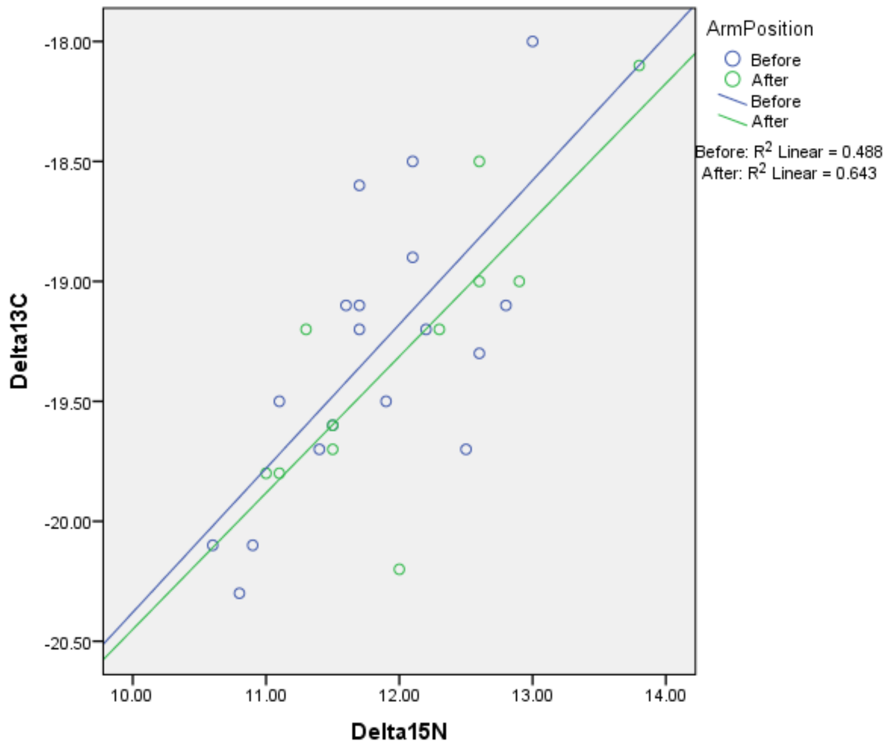

Figure 6. Scatter Plot of $\delta^{13}C$ by $\delta^{15}N$ values for Before and After 1350

5.3 Microwear Results

A Kolmogorov-Smirnov test was performed to test for normality in all of the microwear variables. Unfortunately, all of the significance values were greater than the α-level of 0.05. The data could not be log transformed due to the number of zeros in each microwear variable. Zeros are necessary since they distinguish microwear features not present on the occlusal surface from missing or otherwise unscorable tooth. No individuals were removed in order to maintain sample size. Though parametric tests are used for microwear analyses, non-parametric tests, like the Kruskal Wallis Test, are performed to detect if any differences arise. No differences are noted for microwear results.

5.3.1 One-Way ANOVA

A One-Way ANOVA was also performed for all microwear variables by sex (males and females) and non-adults (males score =M, female score=F, non-adult score =n) (Table 11). Since all non-adults cannot be distinguished as male or female, they were categorized together, which will also apply to all of the tests using non-adults reported in this chapter. The microwear variables include fine, coarse, and hypercoarse scratches, small, large, and puncture pit for both enamel and dentin. The ANOVA tested the entire sample of individuals (n = 70). All of the dentin variables (fine, coarse, hypercoarse scratches and small, large, puncture pits) were highly significant as well as small pits in the enamel because their p-values were less than 0.05 (Table 11). This suggests that there is significant between-group variation because the values were less than 0.05 for all dentin microwear variables. All of the statistically significant values are in Table 11.

Table 11. ANOVA of Microwear Variables by Sex and Non-Adults

ANOVA		
Variable	F	Sig.
Fine Scratch Enamel	1.330	.271
Fine Scratch Dentin	11.050	.000
Coarse Scratch Enamel	.418	.660
Coarse Scratch Dentin	9.647	.000
Hypercoarse Scratch Enamel	1.186	.312
Hypercoarse Scratch Dentin	5.657	.005
Small Pit Enamel	6.511	.003
Small Pit Dentin	12.651	.000
Large Pit Enamel	2.165	.123
Large Pit Dentin	11.857	.000
Puncture Pit Enamel	.033	.967
Puncture Pit Dentin	6.592	.002

The significant values in dentin variables are expected to produce between-group variation because non-adults do not have any dentin exposure. A Tukey post-hoc test was performed to see if only non-adults compared to males and females were statistically significant

(Table 12). Only the significant values from the ANOVA are reported. All of the significant values for dentin as well as small pit enamel are between the non-adults and males and non-adults and females. None of the males differ significantly from females. The only microwear variable that does not follow the same pattern as the others is puncture pit dentin where males do not differ significantly from non-adults.

Table 12. Tukey Post-Hoc of Microwear Variables by Sex and Non-Adults

Tukey Post-Hoc				
Variable	(I) Sex	(J) Sex	Mean Difference (I-J)	Sig.
Fine Scratch Dentin	M	F	1.2649	.410
		n	4.3125*	.000
	F	M	-1.2649	.410
		n	3.0476*	.007
	n	M	-4.3125*	.000
		F	-3.0476*	.007
Coarse Scratch Dentin	M	F	.3720	.669
		n	1.7358*	.000
	F	M	-.3720	.669
		n	1.3638*	.006
	n	M	-1.7358*	.000
		F	-1.3638*	.006
Hypercoarse Scratch Dentin	M	F	-.0149	.999
		n	.9175*	.013
	F	M	.0149	.999
		n	.9324*	.015
	n	M	-.9175*	.013
		F	-.9324*	.015
Small Pit Enamel	M	F	-.6667	.887
		n	-4.5867*	.004
	F	M	.6667	.887
		n	-3.9200*	.020
	n	M	4.5867*	.004
		F	3.9200*	.020
Small Pit Dentin	M	F	1.4375	.954
		n	3.7642*	.000
	F	M	-1.4375	.954
		n	2.3267*	.000
	n	M	-3.7642*	.000
		F	-2.3267*	.000
Large Pit Dentin	M	F	-.2024	.954
		n	2.7100*	.000

	F	M	.2024	.954
		n	2.9124*	.000
	n	M	-2.7100*	.000
		F	-2.9124*	.000
Puncture Pit Dentin	M	F	-.2262	.212
		n	.2500	.128
	F	M	.2262	.212
		n	.4762*	.002
	n	M	-.2500	.128
		F	-.4762*	.002

5.3.2 Independent Samples T-test

An independent samples t-test was performed to see if there were any significant differences between the subset of nine male individuals (EG581, EG339, EG202, EG140, EG399, EG52, EG203, EG185, EG71) and the rest of the sample population according to microwear patterns (Table 13). The results, summarized in Table 13, suggest there are no significant differences in microwear patterns between the subset of males and all other individuals since none of the p-values less than 0.05. Thus, the subset of males and all other individuals (adult and non-adult) likely had similar macrowear patterns.

Table 13. T-test of Microwear Variables for Subset of Males and Rest of Sample Population

T-test		
Variable	F	Sig.
Fine Scratch Enamel	1.330	.683
Fine Scratch Dentin	11.050	.202
Coarse Scratch Enamel	.418	.670
Coarse Scratch Dentin	9.647	.153
Hypercoarse Scratch Enamel	1.186	.371
Hypercoarse Scratch Dentin	5.657	.096
Small Pit Enamel	6.511	.083
Small Pit Dentin	12.651	.485
Large Pit Enamel	2.165	.115
Large Pit Dentin	11.857	.110
Puncture Pit Enamel	.033	.311
Puncture Pit Dentin	6.592	.486

5.3.3 Discriminant Function Analysis (DFA)

A DFA is a multivariate tool that identifies which variables are separating individuals across the y-axis and the x-axis. The purpose of this test is to look for polarizations between sexes and/or individuals and to also see if there are any other groupings other than sex or age. Groups are not predetermined by DFA. A DFA was performed for all of the microwear variables (the grouping variable). Function 1 in the structure matrix describes the x-axis while function 2 describes the y-axis (Table 14). Values in the structure matrix closer to 1 or -1 describe the various positive and negative aspects of both the y-axis and the x-axis. For example, small pit dentin is .639 in function 1 and describes the microwear patterns for individuals who reside on the positive side of the x-axis. A scatter plot was created to visually see what microwear variables separate individuals according to the structure matrix and locate groupings and polarizations (Fig. 7).

Table 14. Structure Matrix of Microwear Variables

Structure Matrix

Variables	Function	
	1	2
SmallPitDentin	.639*	-.363
LargePitDentin	.627*	.261
FineScratDentin	.608*	-.212
CoarsScratDentin	.574*	-.095
SmallPitEnamel	-.473*	.007
HyperScratDentin	.436*	.135
LargePitEnamel	-.255*	-.217
FineScratEnamel	-.208*	-.108
CoarsScratEnamel	.119*	-.037
PuncPitEnamel	-.032*	-.026
PuncPitDentin	.389	.614*
HyperScratEnamel	.077	.419*

The x-axis of figure 7 shows non-adults separated from males and females, more or less. There are still some males and females grouped in with non-adults. The distinction between non-adults and males and females is driven by dentin exposure. All of the positive values in the structure matrix for function 1 are dentin microwear variables and subsequently most males and females reside on the positive side of the x-axis. Enamel microwear, particularly small pit, large pit, and coarse scratches characterize the negative side of the x-axis where the non-adults reside. The few males and females who occupy the negative side of the axis with non-adults will have more enamel.

The y-axis of figure 7 shows quite a few individuals clustered around zero with no distinct groupings. However, there is a very general trend for some females to occupy the slightly more positive side of the y-axis while some males seem to occupy the slightly more negative side. The negative variables in the structure matrix are small pit and fine scratch dentin and large pit enamel (Table 14). The positive variables are large pit, hypercoarse scratch dentin, and puncture pit dentin and hypercoarse scratch enamel. It seems that the deeper types of microwear (i.e. large pits, hypercoarse scratches, puncture pits) characterize those females on the farther positive side and the more shallow types of microwear (i.e. small pits and fine scratches) seem to characterize those males on the far negative side of the y-axis (Fig. 7). Again, while there are no distinct groupings between males and females there are some notable trends between sexes and individuals.

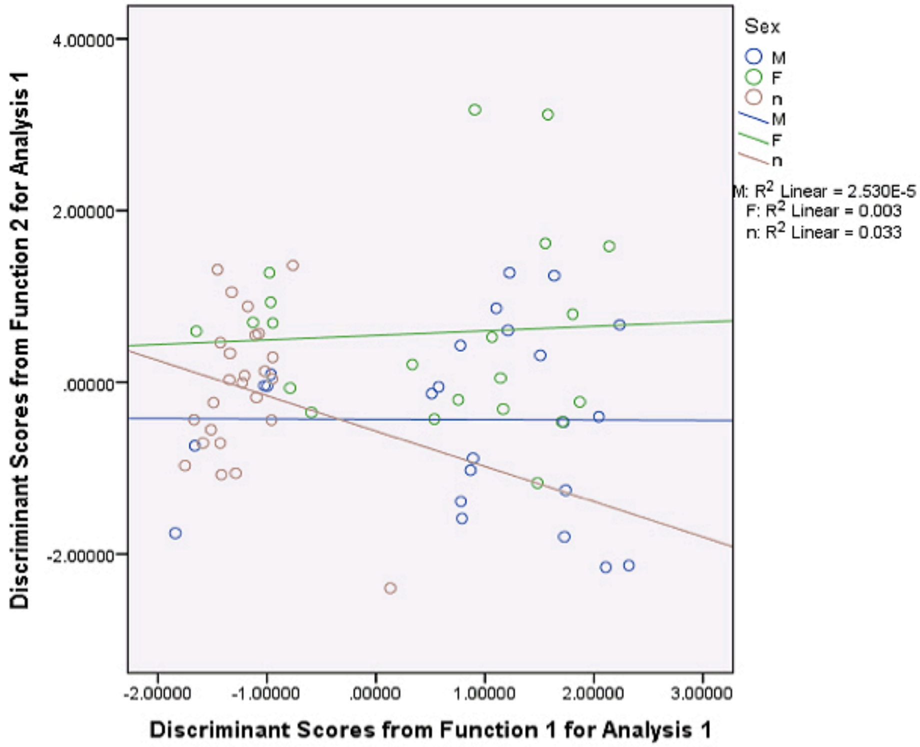

Figure 7. Scatter Plot of Microwear Variables from Structure Matrix

5.3.4 Regression Results

Regression analyses estimate the relationships among variables. Regressions performed with microwear variables are intended to answer more methodological questions. Enamel and dentin, though materially different, generally produce similar microwear features. Significant p-values suggest that as microwear on enamel increases so does microwear on dentin. P-values that are not significant suggest that microwear features follow separate trajectories. This premise is tested here with a regression test between enamel and dentin for each microwear feature (Table 15). Only individuals were included in the analysis with microwear recorded on both enamel and dentin, this excluded all non-adults (n=45). From the regression results, none of the p-values were less than 0.05, and thus are not significant. Therefore, microwear features on enamel follow different trajectories than microwear features on dentin for this sample population.

Table 15. Regression Test for Microwear Features on Enamel and Dentin

Regression		
Variable	F	Sig.
Fine Scratch Enamel and Dentin	.871	.360
Coarse Scratch Enamel and Dentin	2.813	.106
Hypercoarse Scratch Enamel and Dentin	.001	.975
Small Pit Enamel and Dentin	.187	.669
Large Pit Enamel and Dentin	.311	.582
Puncture Pit Enamel and Dentin	.195	.663

5.4 Macrowear Results

The Kolmogorov-Smirnov test was used to test for normalcy of all macrowear variables for the entire sample population (n=70). Similar to microwear variables, there were no significant values for any of the macrowear variables, even with scores removed for non-present teeth. However, to maintain the high sample size in testing between groups by sex and age, ANOVA and Independent Sample T-tests were conducted with no elimination of individuals. Because these tests assume normal distributions, the Kruskal Wallis Test was performed alongside ANOVAs to see if there were any notable differences between the parametric and non-parametric tests. No differences were found.

5.4.1 One-Way ANOVA

A one-way ANOVA test was run to detect if there were any statistical differences between the means of males, females, and non-adults groups (males score =M, female score=F, non-adult score =n) for all macrowear variables (Table 16). The ANOVA tested the entire sample of individuals (n=70). From the ANOVA results, all macrowear averages were statistically significant ($p < 0.05$) (Table 16). This suggests that there is significant between-group variation because all of the values were less than 0.05 ($p = .000$) for all macrowear variables. The Tukey post-hoc test was performed to compare all possible combinations of group differences (Table 17). It was found that the primary differences in macrowear variables were between non-adults and females and non-adults and males, similar to the microwear Tukey post-hoc results (Table 12). These results were expected due to the cumulative effect of occlusal wear, whereby less wear would be expected on non-adult teeth compared to adult teeth. Additionally, none of the values between males and females were statistically significant.

Table 16. ANOVA of Macrowear Variables by Sex and Non-Adults

ANOVA		
Variable	F	Sig.
Average M3 Score	13.934	.000
Average M2 Score	12.375	.000
Average M1 Score	42.110	.000
Average Premolar Score	20.534	.000
Average Anterior Score	14.110	.000

Table 17. Tukey Post-Hoc of Macrowear Variables by Sex and Non-Adults

Tukey Post-Hoc				
Variable	(I) Sex	(J) Sex	Mean Difference (I-J)	Sig.
Average M3 Score	M	F	.2128720	.946
		n	3.0498958*	.000
	F	M	-.2128720	.946
		n	2.8370238*	.000
	n	M	-3.0498958*	.000
		F	-2.8370238*	.000
Average M2 Score	M	F	.1998512	.944
		n	2.6592083*	.000
	F	M	-.1998512	.944
		n	2.4593571*	.000
	n	M	-2.6592083*	.000
		F	-2.4593571*	.000
Average M1 Score	M	F	1.1104911	.134
		n	4.7920625*	.000
	F	M	-1.1104911	.134
		n	3.6815714*	.000

	n	M	-4.7920625*	.000
		F	-3.6815714*	.000
Average Premolar Score	M	F	-.2521429	.850
		n	2.3510000*	.000
	F	M	.2521429	.850
		n	2.6031429*	.000
	n	M	-2.3510000*	.000
		F	-2.6031429*	.000
Average Anterior Score	M	F	-.1398810	.937
		n	1.7425000*	.000
	F	M	.1398810	.937
		n	1.8823810*	.000
	n	M	-1.7425000*	.000
		F	-1.8823810*	.000

5.4.2 Independent Samples T-tests

T-tests were performed to see if there were any statistically significant differences between male (score=M) and female (score = F) macrowear averages for each macrowear variable (e.g. AvgM3Score). T-tests compare the mean of female macrowear averages for each macrowear variable against male macrowear averages for each macrowear variable. All of the t-tests only include male and female adults since non-adults do not have an age category attributed to them. Levene's test was used to assess the homogeneity of variances between all macrowear variables. All of the values are greater than 0.05, thus equal variances are assumed. The results of the t-test show no significant differences between sex in any macrowear variables since the p-value is greater than 0.05 (Table 18). This test confirms the ANOVA macrowear results and the DFA (Table 14 and Fig. 7) microwear results that males and females do not significantly differ in occlusal macrowear.

Table 18. T-test of Macrowear Variables by Sex

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean

Average M3 Score	.941	.800	-	-
			-	-
Average M2 Score	.876	.778	-	-
			-	-
Average M1 Score	.191	.114	-	-
			-	-
Average Premolar Score	.154	.596	-	-
			-	-
Average Anterior Score	.589	.779	-	-
			-	-

5.5 Macrowear and Isotope Results

While macrowear and isotope analyses have been described in the above sections, this section aims to further interpret diet from macrowear scores. Several ANOVAs and t-tests are performed to detect whether macrowear variables are associated with isotope values. These tests can help better understand if rapid wear of teeth are due to diet or something else.

5.5.1 One-Way ANOVA

In order to assess if macrowear scores are associated with dietary variables for all individuals (n=70), an ANOVA was performed for both $\delta^{13}C$ by macrowear (Table 19) and $\delta^{15}N$ by macrowear (Table 20). Firstly, the ANOVA for $\delta^{13}C$ by macrowear contains no significant values for any of the macrowear averages ($p > 0.05$) (Table 19). Secondly, the ANOVA for $\delta^{15}N$ by macrowear contains only one significant value for $\delta^{15}N$ by Average Anterior Score ($p < 0.05$) (Table 20). The remaining p-values for $\delta^{15}N$ by macrowear variables are not significant ($p> 0.05$). Isotope values for $\delta^{13}C$ and $\delta^{15}N$ do not seem to be directly correlated with most wear on anterior and posterior teeth, except for $\delta^{15}N$ values by anterior teeth.

Table 19. ANOVA of $\delta^{13}C$ Values by Macrowear Variables for All Individuals

ANOVA		
Variable	F	Sig.
$\delta^{13}C$ by Average M3 Score	.532	.958
$\delta^{13}C$ by Average M2 Score	1.112	.399
$\delta^{13}C$ by Average M1 Score	1.569	.178
$\delta^{13}C$ by Average Premolar Score	1.261	.247
$\delta^{13}C$ by Average Anterior Score	1.173	.322

Table 20. ANOVA of $\delta^{15}N$ Values by Macrowear Variables for All Individuals

ANOVA		
Variable	F	Sig.
$\delta^{15}N$ by Average M3 Score	.405	.993
$\delta^{15}N$ by Average M2 Score	.892	.638
$\delta^{15}N$ by Average M1 Score	1.590	.171
$\delta^{15}N$ by Average Premolar Score	.895	.656
$\delta^{15}N$ by Average Anterior Score	1.777	.049

Two additional ANOVAs (Tables 21 and 22) were performed for $\delta^{13}C$ and $\delta^{15}N$ values by macrowear variables, however these tests excluded non-adults, since most of the heavy wear on teeth occurs in adulthood. In further speculation of the results in Tables 19 and 20, these ANOVAs test if mean isotopic data significantly vary according to macrowear scores. The ANOVA for $\delta^{13}C$ by macrowear contains no significant variation according to any of the macrowear scores ($p > 0.05$) (Table 21),. This result follows the same pattern as the ANOVA performed above for all individuals (Table 19). The ANOVA for $\delta^{15}N$ by macrowear contains one marginally significant value for mean $\delta^{15}N$ by Average Anterior Score ($p=.056$) (Table 22). 95% confidence is perhaps not as strong as originally thought in Table 20 with a stronger significance in mean $\delta^{15}N$ by Average Anterior Score. Also, as average wear scores increase from 1 to 10, mean values of $\delta^{15}N$ do not steadily increase. If that had been the case, significant enriched $\delta^{15}N$ values of males could have been associated with having higher rates of wear. Instead, those with higher wear scores appear to only have slightly higher mean $\delta^{15}N$ values than those with low scores.

Table 21. ANOVA of $\delta^{13}C$ Values by Macrowear Variables for All Adults

ANOVA		
Variable	F	Sig.
$\delta^{13}C$ by Average M3 Score	.770	.734
$\delta^{13}C$ by Average M2 Score	1.835	.205
$\delta^{13}C$ by Average M1 Score	1.429	.349
$\delta^{13}C$ by Average Premolar Score	1.010	.503
$\delta^{13}C$ by Average Anterior Score	1.358	.271

Table 22. ANOVA of $\delta^{15}N$ Values by Macrowear Variables for All Adults

ANOVA		
Variable	F	Sig.
$\delta^{15}N$ by Average M3 Score	.795	.709
$\delta^{15}N$ by Average M2 Score	1.113	.482
$\delta^{15}N$ by Average M1 Score	.767	.720
$\delta^{15}N$ by Average Premolar Score	.773	730
$\delta^{15}N$ by Average Anterior Score	2.199	.056

5.5.2 Independent Samples T-tests

In further speculation of the significant value in Table 20 of $\delta^{15}N$ by Average Anterior Score, the subset of nine male individuals (EG581, EG339, EG202, EG140, EG399, EG52, EG203, EG185, EG71) are considered here to see if their average macrowear scores are significantly different, similar to the isotope t-tests in section 5.1.2. The subset of male individuals (score = SM) is compared to females (score = F), the rest of the sample population (score = RSP), and other males (score = OM) in three independent samples t-tests. Levene's test was used to assess the homogeneity of variances between all macrowear variables (Table 23). All of the values are greater than 0.05, except for average M3 scores. The appropriate sig (2-tailed) value is used according to equal or unequal variances assumed. Two of the five macrowear variables have p-values less than 0.05 (Table 23). Average M1 and anterior score are both statistically significant for macrowear variables in comparison to the rest of the population. Additionally, the subset of males also significantly vary in the M1 score and approach significance in the average M2 score. From each of their means, the subset of males has higher macrowear scores than the rest of the sample population in their first molars and anterior teeth.

The significant value of anterior scores helps to further interpret the significant anterior score by $\delta^{15}N$ values in the ANOVAs of the previous section. These nine adult males in the subgroup are significantly different from females, other males, and the rest of the sample population isotopically (Table 6, Table 7, Table 8). Table 23 shows that their anterior and first molar wear scores also significantly differ from the rest of the sample population, which also confirms the ANOVA (Table 20) that average anterior wear scores are associated with diet. The ANOVAs from the previous section included all individuals (Tables 19 and 20) and all adults (Tables 21 and 22) with marginally significant values for average anterior wear scores. The interpretive significance of average anterior wear scores emerges in this subset of males (Table 23). The t-test results for subset of males compared to females and subset of males compared to other males are not provided in a table because none of them were statistically significant.

Table 23. T-test of Macrowear Variables by Subset Males and Rest of Sample Population

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Sex	Mean
Average M3 Score	.044	.251	-	-
			-	-

Average M2 Score	.978	.070	-	-
			-	-
Average M1 Score	.168	.013	SM	6.797222
			RSP	4.312500
Average Premolar Score	.135	.155	-	-
			-	-
Average Anterior Score	.786	.029	SM	4.266667
			RSP	3.022131

5.6 Microwear and Isotope Results

Similar to macrowear and isotope results in the previous section, microwear features were also analyzed along with isotope values to determine whether microwear patterns are correlated with diet. Two one-way ANOVAs were performed to see if all of the microwear variables in enamel and dentin were associated with $\delta^{13}C$ and $\delta^{15}N$ values. The first test of $\delta^{13}C$ values by all microwear variables had no significant variables (Table 24). The second test evaluated $\delta^{15}N$ values against all microwear values and also had no significant variables (Table 25). None of the p-values were less than 0.05 and therefore not significant. The ANOVAs conducted for isotope values and microwear variables indicated that diet is not associated with microwear patterns.

Table 24. ANOVA of $\delta^{13}C$ Values by Microwear Variables

ANOVA		
Variable	F	Sig.
$\delta^{13}C$ by Fine Scratch Enamel	1.059	.427
$\delta^{13}C$ by Fine Scratch Dentin	1.051	.436
$\delta^{13}C$ by Coarse Scratch Enamel	.664	.870
$\delta^{13}C$ by Coarse Scratch Dentin	1.036	.452
$\delta^{13}C$ by Hypercoarse Scratch	.845	.676

Enamel		
$\delta^{13}C$ by Hypercoarse Scratch Dentin	.723	.814
$\delta^{13}C$ by Small Pit Enamel	1.309	.214
$\delta^{13}C$ by Small Pit Dentin	1.147	.340
$\delta^{13}C$ by Large Pit Enamel	1.162	.326
$\delta^{13}C$ by Large Pit Dentin	.865	.652
$\delta^{13}C$ by Puncture Pit Enamel	.577	.935
$\delta^{13}C$ by Puncture Pit Dentin	.625	.902

Table 25. ANOVA of $\delta^{15}N$ Values by Microwear Variables

ANOVA		
Variable	F	Sig.
$\delta^{15}N$ by Fine Scratch Enamel	1.041	.439
$\delta^{15}N$ by Fine Scratch Dentin	1.614	.087
$\delta^{15}N$ by Coarse Scratch Enamel	1.236	.268
$\delta^{15}N$ by Coarse Scratch Dentin	.586	.908
$\delta^{15}N$ by Hypercoarse Scratch Enamel	.843	.657
$\delta^{15}N$ by Hypercoarse Scratch Dentin	.681	.829
$\delta^{15}N$ by Small Pit Enamel	1.175	.315
$\delta^{15}N$ by Small Pit Dentin	1.186	.306
$\delta^{15}N$ by Large Pit Enamel	.732	.779
$\delta^{15}N$ by Large Pit Dentin	.833	.668
$\delta^{15}N$ by Puncture Pit Enamel	1.265	.246
$\delta^{15}N$ by Puncture Pit Dentin	1.238	.266

5.7 Dental Caries Results

5.7.1 Pearson Correlation Test

A Pearson correlation was run to analyze the linear relationship between diet ($\delta^{13}C$ and $\delta^{15}N$ values) and number of caries (Table 26). The p-values for both number of caries by $\delta^{13}C$ values (.967) and number of caries by $\delta^{15}N$ values (.982) are greater than 0.05, and thus are not significant. This correlation suggests that tooth caries prevalence is not significantly correlated with diet as is measurable by isotopic analysis. Thus, dental caries were not likely caused by what was consumed but by other factors that can influence tooth decay over time.

Table 26. Pearson Correlation of Number of Caries by $\delta^{13}C$ and $\delta^{15}N$ Values

Correlations

		Number of Caries	$\delta^{13}C$	$\delta^{15}N$
Number of Caries	Pearson Correlation	1	-.005	-.003
	Sig. (2-tailed)		.967	.982
	N	70	69	69
$\delta^{13}C$	Pearson Correlation	-.005	1	.724**
	Sig. (2-tailed)	.967		.000
	N	69	69	69
Delta15N	Pearson Correlation	-.003	.724**	1
	Sig. (2-tailed)	.982	.000	
	N	69	69	69

5.7.2 Spearman's Correlation Test

A Spearman's nonparametric correlation was performed between average macrowear scores with the prevalence of caries because the macrowear scores are ranked data (predetermined ordinal values were assigned to the rates of wear). A Spearman's correlation does not assume a linear relationship between the two variables. The weakly positive p-values in Table 27 suggest that as macrowear scores increase (except for Average M2 Scores) the prevalence of caries also increases.

Table 27. Spearman's Correlation between Macrowear Variables and Caries Prevalence

Correlations

			Number of Caries
Spearman's rho	AvgM3Score	Correlation Coefficient	.305
		Sig. (2-tailed)	.010
		N	70
	AvgM2Score	Correlation Coefficient	.188**
		Sig. (2-tailed)	.119
		N	70
	AvgM1Score	Correlation Coefficient	.434**

		Sig. (2-tailed)	.000
		N	70
	AvgPremolScore	Correlation Coefficient	.455**
		Sig. (2-tailed)	.000
		N	70
	AvgAnteriorScore	Correlation Coefficient	.269**
		Sig. (2-tailed)	.024
		N	70
	NumberCaries	Correlation Coefficient	1.000*
		Sig. (2-tailed)	.
		N	70

5.7.3 Independent Samples T-test

Similar to the t-test performed in Table 10 to see if diet changed over time isotopically, a t-test is used here to test if caries prevalence changes over time: pre-1350 (N=18) and post-1350 (N=11) (Table 28). A change in caries prevalence could suggest some dietary changes that are not measurable isotopically. The Levene's Test for Equal Variance shows equal variances for caries prevalence and the appropriate p-value was selected. The p-value is greater than 0.05 and thus not significant. The t-test results suggest that caries prevalence before 1350 is not significantly different than after 1350. Therefore, the tests run for both isotopic data and caries prevalence agree that no shift likely occurred after 1350.

Table 28. T-test of Caries Prevalence for Individuals Pre-1350 and Post-1350

T-test				
Variable	Levene's Test for Equal Variance Sig.	Sig. (2-tailed)	Period	Mean
Number of Caries	3.139	.339	-	-
			-	-

6 DISCUSSION AND CONCLUSION

6.1 Findings

The isotopic results met my expectations and reflected Jørkov's (2007) isotope analysis. Results suggest isotopic diversity in diet that was relatively uniform throughout life. The positive correlation between $\delta^{13}C$ and $\delta^{15}N$ values suggested that those individuals who consumed a diet enriched in $\delta^{13}C$ also consumed foods enriched in $\delta^{15}N$ and vice versa. From the distribution in the scatter plot (Fig. 3), $\delta^{15}N$ values have a 4‰ range that indicate consumption of different protein sources. $\delta^{15}N$ values are between 10‰ and 14‰, which suggests the protein sources to be terrestrial and freshwater fish on different trophic levels. The results of these isotopic indicators of diet are supported by archaeological finds of numerous animal and fish bones at the site of Ahlgade 15-17. The primary animals recovered were domesticated chickens, sheep, goats, pigs, and some cattle (Asmussen 1997). Individuals in medieval Holbæk may have had more access to animal meat from their own farms. Holbæk was a small community that may not have participated in trade with outside regions, as measured archaeologically (import or export) (Asmussen 1997: 213). Freshwater fish consumed at Holbæk were pike, carp, and perch. The brackish waters that surround the country of Denmark contain depleted $\delta^{13}C$ values in comparison to saltwater. These depleted $\delta^{13}C$ values then move up the food chain (Jørkov 2007). Freshwater fish, like those listed above, migrated into the brackish waters of Denmark, which could explain why such enriched $\delta^{15}N$ values suggest freshwater fish consumption. High $\delta^{15}N$ values also support historical records of increased consumption of fish in medieval diet due to restrictions on meat by the church (especially during Lent) (Asmussen 1997: 213).

From the distribution in the scatter plot (Fig. 3), $\delta^{13}C$ values have a 2.5‰ range that indicates a mainly a C_3 diet. The various types of C_3 grains that were grown and cultivated in

Holbæk include oats, wheat, rye, and barley (Asmussen 1997: 221). The most widely cultivated grain was oat, which was used for animal feed and for human consumption (usually made into porridge). Other types of C_3 foods locally grown and occasionally cultivated were cabbage, blackberries, nuts (unspecified), and elderberry (Asmussen 1997). Thus, the archaeobotanical finds at Ahlgade 15-17 concur with the variation of $\delta^{13}C$ values. Additionally, many of the foods consumed at Holbæk could easily be stored. For instance, fish could be dried or smoked, cabbage could be stored in a cellar, and many of the fruits like blackberry and elderberry could be dried, picked in vinegar, or turned into wine (Pearson 1997). During the medieval period, desirable foods would have been those that could be stored for winder months or in case of famine.

Interestingly, I expected there to be no significant differences between males and females; however, males were found to be significantly more enriched in $\delta^{15}N$ values than females (Table 2). The distribution of $\delta^{15}N$ values also suggests more variation in male diet, which was between 11‰ and 14‰ (a range of 3‰). Female diet showed a tighter distribution around 11.5‰ and 12.5‰ (a range of 1‰). Thus, males were likely consuming a more varied diet of terrestrial and marine foods. Deep sea fishing became popular in the medieval period (Enghoff 1996) and through archaeological and isotopic evidence fishing appeared to have also been common in Holbæk. Perhaps fishermen out at sea had more access to fish on different trophic levels. Furthermore, typical male roles in the medieval period were as the intensive agricultural labor on farms (Esclassan *et al.* 2008: 295). Women prepared the meals and ate smaller amounts of food than men. Women were considered to be smaller in size compared to males and thus required less food, which may also reflect less variety in foods as well (Pearson 1997). A study by Boldsen (1991) of dental attrition rates in medieval Danes in Tirup, Denmark indicated a quicker rate of attrition in males than in females and considers increased consumption in males to cause these wear differences. Furthermore, it seems that this difference between males and females is only significant in the age category of 26-45. Perhaps adults in those ages were responsible for a large part of the agricultural labor in the fields cultivating oats and barley. Those males may have then required more variety in their consumption essential proteins (animal and fish meat) to maintain sufficient energy levels. These dietary distinctions may not only indicate different consumption patterns between males and females, but also perhaps behavioral differences.

Temporal differences were also considered in this study by analyzing change in diet isotopically before and after AD 1350. I can accept my hypothesis that no shift in diet likely occurred from pre- to post- plague. Diet appears to have remained quite consistent throughout the medieval period in Denmark with no change in dietary resources as measured by isotopic signatures. These results are surprising given the historical evidence of a change in foodways and agricultural systems. However, the lack of a shift in diet coincides with Yoder's (2010) isotopic analyses of three medieval sites in medieval Denmark whose residents also did not experience a diet shift after AD 1350. Both this study and Yoder's study show that a change in agricultural systems does not always indicate a dietary change as well. Smaller variations of diet may have shifted during the medieval period that isotopes would not be able to measure.

From the isotope analyses, a subset of males were discovered to be not only significantly different isotopically (both in $\delta^{13}C$ and $\delta^{15}N$ values) from females, other males, and the rest of the sample population (Fig. 5), but also in their average macrowear scores for first molars and anterior teeth (Table 23). Given the marginally significant relationship between anterior macrowear and $\delta^{15}N$ values, this suggest that these males had proportionally more high-trophic level protein in their diets and what looks like to be differences in anterior tooth wear. These two results in combination can be interpretively meaningful in that they distinguish this group of males. These nine adult males (EG581, EG339, EG202, EG140, EG399, EG52, EG4203, EG185, EG71) have age ranges from their early twenties to the late forties and fall generally into the age range category of significant isotopic values (Table 4). Several possibilities could explain these males. They may have had specialized roles in the Holbæk like as craftsmen or fishermen, which would have provided them access to differential resources. Otherwise, perhaps they were recent immigrants to the area before they died and that is why their isotopic signatures do not match the rest of the population in Holbæk, though it is then interesting that these immigrants were only males and no females. Another likelihood includes a more elite status of males in the community like a medieval guild. This subset of males was eating more or different foods that created significantly greater wear on their anterior teeth and first molars. Average anterior scores by $\delta^{15}N$ values (Table 20) correlated with isotopic indicators of diet, though it is interesting that the p-value for average anterior score by $\delta^{13}C$ values was not significant when these males were also highly enriched in $\delta^{13}C$ values as well (Tables 6, 7, and 8). The wear on these adult males' anterior teeth possibly indicates some use-wear in connection with consuming terrestrial animals and freshwater fish. Perhaps these men were fishermen and used their anterior teeth as tools out at sea that also encouraged different consumption patterns. Furthermore, two of these males could confidently be dated pre-1350 and two males post-1350. All four males were included in the temporal analysis looking for change in isotopic indicators of diet over time. With no suggested differences, this also suggests that the significantly different dietary patterns of these males also probably did not change over time. Since burials at Ahlgade 15-17 did not provide any indication of class distinctions or social differences, it is difficult to positively say who these males were or where they came from. This discovery can be considered even more profound in the light of sex differences in microwear and macrowear.

The lack of meaningful statistical significance in all results of microwear and macrowear tests between sex and age confirms my hypothesis that overall males, females, and non-adults probably used their teeth in analogous ways (Tables 11 and 15). A similar study of medieval populations in Aebelholt and Naestved, Denmark also showed no significant differences between males and females in dental attrition (Lunt 1978). Though this may seem surprising since dietary differences were found between males and females isotopically, it is better understood once microwear and macrowear were analyzed in relation to diet. Essentially, does diet explain the observed enamel wear and microwear patterns? The answer appears to be no. Heavy wear (with the exception of marginally significant average anterior wear in $\delta^{15}N$ values) in adult teeth is not correlated with isotopic indicators of diet (Tables 19, 20, 21, and 22). Thus, my expectation was met in that wear patterns in teeth were not related to diet isotopically and do not differ between males or females. Medieval food processing techniques can likely explain this phenomenon.

During the medieval period, grinding cereals introduces dirt and rock particles from the grinding stone into flour for making bread. The extent of tooth wear in Holbæk could indicate high and regular consumption of grain that was heavily contaminated with abrasives from millstones and significantly contributed to loss of enamel (Asmussen 1997). Danish medieval diet was based primarily on grains and bread (approximately one kilogram per day) and could make up about seventy percent of total peasant food intake (Boldsen 1991, Esclassan *et al.* 2008). Thus, abrasives from millstones in food were likely the contributing factor to such extensive wear rather than the food itself. Moreover, early adult wear scores are very high (Appendix B), which suggests rapid wear on the occlusal surface of teeth very quickly in life.

During the medieval period in Holbæk, once the first molar reaches occlusion it only took about 8-10 years for wear to reach the enamel-dentin junction (Asmussen 1997: 284). Such extensive wear thus also increases with age.

Another non-diet related factor that is known to have contributed to tooth substance loss in Holbæk was using teeth for holding nails or other tools, possibly by a craftsman (Asmussen 1997: 284). One such individual (EG266), not included in the sample population for this study, shows signs of teeth used as tools for either material processing or for holding tools. Evidence of this kind of occupation was also found in medieval Kent, England (Turner and Anderson 2003). Marked dental abrasion to the maxillary teeth of an adult male in Kent also shows occupational activity, possibly a carpenter, who held iron nails between the teeth. Perhaps this highly specialized occupation was only afforded to selected individuals.

Another factor that is detrimental to dental hard tissues is the erosive effect of acid in beer or wine. Beer and wine were consumed in large amounts in some medieval regions of Denmark. Medieval beer is generally considered to have higher acidic values but limited information is known about the actual pH values (Ganss *et al.* 2002: 59). Though individuals in Holbæk had access to the ingredients for fermentation to make beer (like milk from cows), whether they actually made beer is unknown. All of these factors (i.e. abrasives, occupation, and acidic foods) together could contribute to a substantial loss of enamel.

Microwear patterns were also not correlated with diet in medieval Holbæk, as expected (Table 24, Table 25). Unless grit in diet is the culprit of patterns observed on enamel and dentin surfaces, the only other suggestion could be use-wear or material processing. If only abrasives were creating microwear patterns than it would be expected that a majority of the features found on the occlusal surface would be deeper features like hypercoarse scratches and puncture pits.

However, that is not the case. Most of the first molars had a variety of different types of microwear ranging from fine and small to hypercoarse and large (Appendix D). Additionally, a trend between some males and females was noted in the principal component analysis (Fig. 7). Some males appear to have had more shallow types of microwear features on the occlusal surface like fine scratches and small pits while some females had more deep types microwear features like hypercoarse scratches and puncture pits. Since microwear patterns are not correlated with diet this trend could be considered as possible use-wear differences in the teeth of some individuals, which also confirms my hypothesis that some use-wear differences existed between males and females. The various daily activities of females that are not typically performed by males, like cooking and food processing, could possibly produce different microwear patterns. While this slight difference in some males and females suggests a possible trend in behavior there are no distinct or real groups between males and females in microwear or macrowear patterns. The lack of differences between sex identified in microwear or macrowear analyses indicate that abrasives from millstones were the primary producers of these wear patterns since neither microwear nor macrowear were correlated with diet. Males were consuming a wider variety of foods than females according to the isotope results though these suggested different diets between males and females would not have contributed to differential microwear patterns.

Though microwear and macrowear were not associated with diet, interestingly neither was dental caries (Table 26). Caries prevalence was not correlated with isotopic indicators of diet, which was unexpected because of a diet high in grain consumption. Though individuals in Holbæk are relatively low sugar diets, grains are cariogenic foods that can also contribute to tooth decay. Though interstingly, this result supports archaeological finds of numerous fish bones at Ahlgade 15-17 (Asmussen 1997). A diet consisting of fish increases the levels of fluoride in saliva, which helps prevent tooth decay. Specifically, fluoride is a base that inhibits bacterial enzymes from demineralizing enamel and enhances remineralization (Featherstone 1999). An analysis of the concentration of fluoride in tooth enamel from Holbæk showed a raised level in comparison to other medieval Danish and Swedish populations (Asmussen 1997: 293). Thus, a rich fish diet coupled with low intake of sugars (not cane sugar) likely facilitated better dental health of individuals at Holbæk. Though the prevalence of caries was very low in Holbæk, dental caries were still observed in teeth and were possibly caused by plaque build-up and lack of dental hygiene.

Two studies (Esclassan *et al.* 2009, Varrela 1991) on medieval populations also suggested that considerable enamel loss due to abrasives from grain ground on millstones to aid in caries prevention. Esclassan *et al.* (2009) studied dental caries and tooth wear from a medieval population from southwest France (12th-14th centuries). Results indicate a high degree of dental wear and a lower presence of dental caries in both men and women. Food particles are unable to become wedged in tooth grooves to deposit lactic acid in teeth with high rates of wear. A similar distribution of caries and increased dental wear can also be observed in a medieval population in Finland (Varrela 1991). However, caries prevalence has a slightly positive relationship with macrowear scores indicating that as macrowear scores increase so do the number of caries (Table 27). I suggest that these results point to an age related effect where independent of rates of dental wear, without proper hygiene and tooth decay preventative care, will result in tooth decay as an individual gets older. Holbæk still seems to follow a similar trend found in other medieval populations. A diet consisting of fish coupled with rapid loss of dental tissues through harsh abrasives in flour left little room for dental caries to form on enamel.

Caries prevalence over time, similar to isotopic analyses over time, showed no significant change from before AD 1350 to after AD 1350 (Table 28). Dental caries probably remained consistently low in Holbæk throughout the medieval period. Since a significant change in diet did not occur as well, fluoride levels in individuals from fish consumption also likely remained high and continued to prevent tooth decay. Furthermore, no change in caries prevalence also suggests no change in diet on a more subtle level. A decrease, for instance, of cariogenic foods (e.g. grains) to eating more foods like meat could result in even lower prevalence of caries.

Aside from diet and dental wear in medieval Holbæk, a methodological analysis was also conducted between the microwear features of enamel and dentin. It was found that the microwear features on enamel follow different trajectories than microwear features on dentin (Table 15). Enamel and dentin, while both very heterogeneous tissues, are structurally different. Enamel is generally tougher than dentin because 85% to 92% of enamel is composed of mineral with some organic matter and 30-40 nm of hydroxyapatite crystals (Lucas 2004: 26). Dentin is 48% mineral with organic collagen fibers and has only 2-3nm of hydroxyapatite crystals (Lucas 2004: 27). Other studies have also suggested the fundamental differences in composition of dentin and enamel (Burak *et al.* 1999, Ranjitkar *et al.* 2008). Perhaps different diets and foods (e.g. hard versus soft foods) impact enamel and dentin differently. Enamel is more likely to suffer microfractures than dentin due to its high mineral content (Lucas 2004). The high consumption of grain in Holbæk contaminated with abrasives from millstones may have fractured enamel while leaving features in dentin. Dentin and enamel under pressure of a coarse diet that contributes to a high degree of wear may leave distinctive microwear features. Burak *et al.* (1999:886) conducted an experimental study of human dentin and observed differences in enamel and dentin wear rates at different loadings and thus, structural factors of the two dental tissues affect human tooth-wear processes. The results of this study concur with Burak *et al.* (1999) and advocate for further research on how microwear patterns influence enamel and dentin. Microwear patterns should not be assumed to be the same on enamel and dentin in every population. The well-preserved teeth from individuals at Holbæk provide an excellent first step into this research.

6.2 Conclusion

Using multiple types of analyses has allowed for a better reconstruction of past dietary patterns and behaviors in medieval Holbæk, Denmark. Previous stable isotope analyses conducted by Jørkov (2007) detected the sources of diet to be mixed terrestrial C_3 and marine foods. Dental microwear and macrowear analyses were valuable tools for assessing some plausible dietary habits, such as the erosive effects of abrasives from millstones that were not distinguishable through isotopes analyses. Furthermore, both analyses were able to shed light on some possible behavioral trends between males and females, such as occupational differences. Dental microwear, macrowear, and stable isotope analyses do not have the capabilities to assess nutrition. Thus, the inclusion of dental caries analyses were particularly useful in evaluating how the elements of food (particularly fluoride) could influence overall dental health. This study aimed to provide a complimentary analysis to Jørkov's (2007) initials study comparing medieval Holbæk to Iron Age Denmark. With the implementation of additional analyses (microwear, macrowear, and dental caries), this research has not only corroborated isotopic analyses, but also discovered additional information about various dietary habits and behavioral patterns of individuals who lived in medieval Holbæk (AD 1200 -1573). Some of the inferred behavior and lifestyles in Holbæk (e.g. teeth used to hold nails) has also been found in other Danish medieval populations (Barrett *et al.* 2011, Boldsen 1991, Esclassan *et a.* 2008, Ganss *et al.* 2002, Mays 1999, Turner and Anderson 2003, Yoder 2010). This project contributes to the overall understanding of diet and subsistence in medieval Europe. Dental microwear analyses have not been conducted before this study in any medieval human populations in Denmark, nor in Scandinavia. The contributions of this study have also been able to support archaeological finds at Ahlgade 15-17. Evidence of available food in the archaeological record does not directly indicate it was consumed on a regular basis as part of diet. Now, the connection has been strengthened between the recovered fish bones and high consumption of freshwater fish through isotope and dental caries analyses. Stable isotope, dental microwear and macrowear, and dental caries analyses of individuals spanning four centuries compared with historical sources and archaeological discoveries provided a more cohesive reconstruction of dietary habits, health, and behavior of medieval Danes in Holbæk, Denmark.

6.3 Future Research

The research presented here provides additional insight into dietary and behavioral patterns of medieval Danish Holbæk individuals and contributes to the understanding of dental macrowear, microwear, and dental pathologies in bioarchaeological populations. Additional applications of dental microwear in other medieval populations in Denmark, perhaps from a more urban population, would provide comparative data to better understand the diversity of the medieval Danish diet. Holbæk was a small countyside town with no evidence of trade or much contact with other Danish towns. A comparison of Holbæk data with dental microwear and macrowear analyses of other populations may provide more insight into medieval Danish teeth wear patterns, trade networks (if any not detected in the archaeological record), and food preparation. Continued analysis of the variation in microwear should be done to see if the use-wear patterns of men and women observed in this study is exclusive to Holbæk. Another interesting avenue of research would be to create a model using the various arm positions in burials of each individual to estimate temporal paleodemographic rates using a probability density function (Weise and Boldsen 2013). Essentially, archaeological data would provide a proxy for changes in population size in medieval Holbæk. From this model, pre- and post-plague time periods could be compared to analyze how the Black Death may have impacted the lives of those living in Holbæk. These additional avenues of research can place Holbæk in the broader context of medieval Europe by elucidating variation in diet and masticatory behavior that can be used to infer broader patterns of behavior and health during a dynamic and tumultuous period of European history.

REFERENCES

Adamson MW. 2004. Food in medieval times. Westport, CT: Greenwood Press.

Ambrose SH, Buikstra J, Krueger HW. 2003. Status and gender differences in diet at Mound 72, Cahokia, revealed by isotopic analysis of bone. *Journal of Anthropological Archaeology*. 22: 217-226.

Anderson DE, Goudie AS, and Parker AG. 2007. Global Environments through the Quaternary: Exploring Environmental Change. Oxford: Oxford University Press.

Antoine, Daniel (2008) The Archaeology of "Plague." *Med Hist Suppl*. (27): 101–114.

Asmussen E., editor. 1997. Ahlgade 15–17, Holbæk. En arkæolo- gisk og historisk undersøgelse fra 1200 til nutiden. Aarbøger for Nordisk Oldkyndighed og Historie 1994–95. København: Det Kongelige Nordiske Oldskriftselskab.

Baker G, Jones LHP, and Wardrop ID. 1959. Cause of wear in sheep teeth. *Nature*. 184:1583-4.

Barrett JH *et al.* 2011. Interpreting the expansion of sea fishing in medieval Europe using stable isotope analysis of archaeological cod bones. *Journal of Archaeological Science.* 38: 1516-1524.

Bennike P, Lewis ME, Schutkowski H, and Valentin F. 2005. Comparison of child morbidity in two contrasting medieval cemeteries from Denmark. *Am J Phys Anthropol.* 128:734-746.

Boldsen JL. 1991. Ageing and dental attrition in a medieval rural Danish population. *International Journal of Anthropology* 6:217-224.

Boldsen JL. 2005b. Leprsosy and mortality in the medieval Danish village of Tirup. *Am J Phys Anthropol.*. 126:159-168.

Buikstra JE, Ubelaker DH. 1994. Standards for Data Collection from Human Skeletal Remains. Fayetteville, Arkansas: Arkansas Archaeological Survey Report Number 44.

Burak N, Kaidonis JA, Richards LC, Townsend TC. 1999. Experimental studies of human dentine wear. *Archives of Oral Biology*, 44:885-887.

Caselitz P. 1998. Caries – Ancient Plague of Humankind. In *Dental Anthropology: Fundamentals, Limits, and Prospects.* Alt KW, Rösing FW, Teschler-Nicola M, eds. Austria: Springer-Verlag/Wien, pp. 203-226.

Covert HH, Kay RF. 1981. Dental microwear and diet- implications for determining the feeding behaviors of extinct primates, with a comment on the dietary pattern of *Sivapithecus*. *Am J Phys Anthropol.* 55: 331-336.

Dahlback G. 2003. The towns. In *The Cambridge History of Scandinavia*. Helle K, ed. Cambridge: Cambridge University Press, pp. 611-634.

Dahlberg AA, Kinzey WG. 1962. Etude microscopique de l'abrasion et de l'attrition sur la surface des dents. *Bulletin du Groupement International pour les Recherches Scientifique en Stomatologie.* 5: 242-251.

DeWitte, SN. 2009. The effect of sex on risk of mortality during the Black Death in London, A.D. 1349-1350. *Am J Phys Anthropol.* 139: 222-234.

Enghoff IB. 1996. A medieval herring industry in Denmark and the importance of herring in Eastern Denmark. *Archaeofauna* 5:43-47.

Esclassan R, Grimoud AM, Ruas MP, Donat R, Sevin A, Astie F, Lucas S, Crubezy E. 2009. Dental caries, tooth wear and diet in an adult medieval (12th-14th century) population from mediterranean France. *Archives of Oral Biology*. 54:287-297.

Featherstone, JDB. 1999. Prevention and reversal of dental caries: role of low level fluoride. *Community Dentistry and Oral Epidemiology*. 27: 31-40.

Ganss C, Klimek J, Borkowski N. 2002. Characteristics of tooth wear in relation to different nutritional patterns including contemporary and medieval subjects. *Eur J Oral Sci*. 110: 54-60.

Gordon KD and Walker AC. 1983. Playing "possum": a microwear experiment. *Am J Phys Anthropol.* 60: 109-112.

Gowland, R.L., and Chamberlain, A.T. (2005) Detecting plague: palaeodemographic characterisation of a catastrophic death assemblage. *Antiquity*, 79 (303). pp. 146-157.

Grine FE. 1977. Analysis of early hominid deciduous molar wear by scanning electron microscopy: a preliminary report. *Proceedings of the Electron Microscopy, Society of South Africa*. 7: 157-158.

Grine FE. 2007. Introduction to Dentition and Diet. In *Dental Perspectives on Human Evolution.* SE Bailey and JJ Hublin, eds. New York: Springer- Verlag, pp 291-302.

Hanawalt BA. 1993. Growing up in medieval London. New York: Oxford University Press.

Helm S, Prydsø U. 1979. Assessment of age at death from mandibular molar attrition in Medieval Danes. Scand. J. dent. Res., 87: 79-90.

Hillson S. 1996. Dental Anthropology. Cambridge: Cambridge University Press.

Hoffman, E. 1981. The unity of the kingdom and the provinces in Denmark during the Middle Ages. In *Danish Medieval History: New Currents*. Skyum-Nielsen N, Lund N, eds.

Copenhagen: Museum Tusculanum Press, pp. 95-108.

Hogue SH, Melsheimer R. 2008. Integrating dental microwear and isotopic analyses to understand dietary change in east- central Mississippi. *J Archaeolog Sc.* 35: 228-238.

Jørkov ML. 2007. Drinking With the Rich and Dining With the Poor in Roman Iron Age Denmark: A Dietary and Methodological Study Based on Stable Isotope Analysis. Dissertation. Institute of Forensic Medicine, Copenhagen University.

Jørkov ML, Heinemeier J, Lynnerup N. 2007. Evaluating bone collagen extraction methods for stable isotope analysis in dietary studies. *Journal of Archaeological Science.* 34: 1824-1829.

Jørkov ML, Heinemeier J, Lynnerup N. 2009. The petrous bone – a new sampling site for identifying early dietary patterns in stable isotopic studies. *Am J Phys Anthropol.* 138:199-209.

Jørkov ML, Jorgensen L, Lynnerup N. 2010. Uniform diet in a diverse society. Revealing new dietary evidence of the Danish Roman Iron Age based on stable isotope analysis. *Am J Phys Anthropol.* 143: 523-533.

Katzenberg AM. 2011.The ecological approach: understanding past diet and the relationship between diet and disease. In *A Companion to Paleopathology*. AL Grauer, ed. Wiley-Blackwell, Inc., Ch. 6.

Kelly, J. 2005. The Great Mortality: An Intimate History of the Black Death, The Most Devastating Plague of All Time. New York: Harper Perennial.

Kristensen HK. 1988. A Viking-period and medieval settlement at Viborg Sonderso, Jutland. *Journal of Danish Archaeology* 7:191-204.

Krueger HW, Sullivan CH. 1984. Models for carbon isotope fractionation between diet and bone. In *Stable Isotopes in Nutrition. American Chemical Society Symposium Series.* Turnlund, JE and Johnson PE, Eds. 258: 205-222.

Larsen, CS. 2002. Bioarchaeology: The lives and lifestyles of past people. *Journal of Archaeological Research.*10: 119-166.

Lauring P. 1976. A History of the Kingdom of Denmark. Copenhagen: Host & Son.

Lunt, DA. 1978. Molar Attrition in Medieval Danes. In *Development, Function, and Evolution of Teeth*. PM Butler and KA Joysey, eds. New York: Academic Press, pp. 465-481.

Mays S. 1999. A biomechanical study of activity patterns in a medieval human skeletal assemblage. *International Journal of Osteoarchaeology* 9:68-73.

Møller-Christensen V, and Faber B. 1952. Leprous changes in a material of medieval skeletons from the St. Georges Court, Naestved. *Acta Radiologica* 37:308-317.

Müldner G, Richards MP. 2005. Fast or feast: reconstructing diet in later medieval England by stable isotope analysis. *J Archaeol Sci.* 32:39–48.

Nielsen J. 2011. Does human sexual dimorphism influence fracture frequency, types, and distribution? *Anthropological Review*. 74: 13-23.

Organ JM, Teaford MF, Larsen CS. 2005. Dietary inferences from dental occlusal microwear at mission San Luis de Apalachee. *Am J Phys Anthropol*. 128: 801-811.

Pearson KL. 1997. Nutrition and the early medieval diet. *Speculum* 72:1-32.

Pérez-Pérez A, Espurz V, Castro JM, Lumley MA, Turbon D. 2003. Non-occlusal dental microwear variability in a sample of Middle and Late Pleistocene human populations from Europe and the Near East. *Journal of Human Evolution*. 44: 497-513.

Peters CR. 1982. Electron-optical microscopic study of incipient dental microdamage from experimental seed and bone crushings. *Am J Phys Anthropol.* 57: 283-301.

Poulsen B. 1997. Agricultural Technology in Medieval Denmark. In *Medieval Farming and Technology: The Impact of Agricultural Change in Northwest Europe.* Astill G and Langdon J, eds. Netherlands: Koninklijke Brill, pp. 115-146.

Price TD, Nielson JN, Frei KM, Lynnerup N. 2012. Sebbersund: isotopes and mobility in an 11^{th}-12^{th} c AD Danish Churchyard. *Journal of Archaeological Science*. 39: 3714-3720.

Puech PF. 1979. Diet of Early Man: Evidence from Abrasion of Teeth and Tools. *Curr Anthropol*. 20: 590-592.

Puech PF, Prone A. 1979. Mechanical process of dental wearing down by abrasion, reproduced by experimentation and applied to fossil man and his paleoecological surroundings. *CR Acad Sci D Nat.* 289: 895.

Ranjitkar S, Kaidonis JA, Townsend GC, Vu AM, Richards LC. 2008. An in vitro assessment of the effect of load and pH on wear between opposing enamel and dentine surfaces. *Archives of Oral Biology*, 53:1011-1016.

Rasmussen P, Olsen J. 2009. Soil erosion and land-use change during the last six millennia recorded in lake sediments of Gudme Sø, Fyn, Denmark. *Geological Survey of Denmark and Greenland Bulletin*. 17: 37-40.

Rensberger JM. 1978. Scanning electron microscopy, of wear and occlusal events in some small herbivores. In *Development, Function, and Evolution of Teeth*. PM Butler and KA Joysey, eds. New York: Academic Press, pp. 415-438.

Rose JC, Ungar PS. 1998. Gross dental wear and dental microwear in historical perspective. In *Dental Anthropology: Fundamentals, Limits, and Prospects*. Alt KW, Rosing FW, Teschler-Nicola M, eds. New York: Springer, pp. 349-386.

Rudolph C. 2004. Pilgrimage to the End of the World: The Road to Santiago de Compostela. Chicago: The University of Chicago Press.

Sawyer B, and Sawyer P. 1993. Medieval Scandinavia from conversion to reformation. Minneapolis: University of Minnesota Press.

Sawyer P. 1986. Early fairs and markets in England and Scandinavia. In *The Market in History*. Anderson BL and Latham AJH, eds. Dover, NH: Croom Helm, pp. 59-78.

Schmidt CW. 1998. Dietary Reconstruction in prehistoric humans from Indiana: an analysis of dental macrowear, dental pathology, and dental microwear. Dissertation. Purdue University.

Schmidt CW. 2010. On the relationship of dental microwear to dental macrowear. *Am J Phys Anthropol*. 142: 67-73.

Schmidt CW. 2001. Dental microwear evidence for a dietary shift between two nonmaize- reliant prehistoric human populations from Indiana. *Am J Phys Anthropol*. 114: 139-145.

Scott EC. 1979. Dental scoring technique. *Am J Phys Anthropol.* 2:43-69

Scott RS, Teaford MD, Ungar PS. 2012. Dental microwear texture and anthropoid diets. *Am J Phys Anthropol*. 147: 551-579.

Semprebon GM, Godfrey LR, Solounias N, Sutherland MR, Jungers WL. 2004. Can low magnification stereomicroscopy reveal diet? *J Hum Evol.* 47: 115-144.

Steenstrup, CHR. 1914. The Medieval Popular Ballad. Boston: Ginn and Company.

Teaford MF. 2007a. What Do We Know and Not Know about Dental Microwear and Diet? In *Evolution of the Human Diet:The Known, Unknown, and the Unknowable*. Ungar PS, ed. Oxford: Oxford University Press, pp 106-131.

Teaford MF. 2007b. What Do We Know and Not Know about Diet and Enamel Structure? In *Evolution of the Human Diet:The Known, Unknown, and the Unknowable*. PS Ungar, ed. Oxford: Oxford University Press, Pp 56-76.

Teaford MF. 2007c. Dental Microwear and Paleoanthropology: Cautions and Possibilites. In *Dental Perspectives on Human Evolution: State-of-the-Art Research in Dental Paleoanthropology.* Bailey SE, Hublin JJ, eds. New York: Springer- Verlag, pp 345-368.

Teaford MF, Lytle JD. 1996. Brief Communication: diet- induced changes in rates of human tooth microwear: a case study involving stone- ground maize. *Am J Phys Anthropol.* 100: 143-147.

Teaford MF. 1991. Dental microwear: what can it tell us about diet and dental function. *Advances in dental anthropology*, 341-356.

Turner G, Anderson T. 2003. Marked Occupational Dental Abrasion from Medieval Kent. *International Journal of Osteoarchaeology.* 13: 168-172.

Ungar PS, Grine FE, Teaford MF, El Zaatari S. 2006. Dental microwear and diet in African early *Homo*. *J Hum Evol*. 50: 78-95.

Ungar PS, Scott RS, Scott JA, Teaford MT. 2008. Dental microwear analysis: historical perspectives and new approaches. In *Technique and Applications in Dental Anthropology.* JD Irish and GC Nelson, eds. Cambridge: Cambridge University Press, Pp 389-425.

Varrela TM. 1991. Prevalence and distribution of dental caries in a medieval population in Finland. *Archives of Oral Biology*, 36: 553-559.

Walker A, Hoeck HN, Perez L. 1978. Microwear of mammalian teeth as an indicator of diet. *Science*. 201: 908-910.

Walker PL. 1976. Wear striations on the incisors of cercopithecoid monkeys as an index of diet and habitat preference. *American Journal of Physical Anthropology*. 45: 299-308.

Weise S, Boldsen JL. 2013. Hands Up! Estimating paleodemographic rates from archeological data. American Association of Physical Anthropologists Abstract: pp. 287.

Williams FL, Holmes NA. 2011. Evidence of terrestrial diets in Pliocene Eurasion Papioins (Mammalia: Primates) inferred from low-magnification stereomicroscopy of molar enamel use-wear scans. *PALAIOS.* 26: 720-729.

Yoder, C. 2006. The Late Medieval Agrarian Crisis and the Black Death Plague Epidemic in Medieval Denmark: A Paleopathological and Paleodietary Perspective. Dissertation, Texas A&M University, Texas.

Yoder, C. 2012. Let them Eat Cake? Status-based differences in diet in medieval Denmark. *Journal of Archaeological Science*. 39: 1183-1193.

Yoder, C. 2010. Diet in Medieval Denmark: a regional and temporal comparison. *Journal of Archaeological Science*. 37: 2224-2236.

APPENDICES

Appendix A

Individual	Sex	Age	Reference Age	Individual	Sex	Age	Reference Age
EG246	F	26-45	36	EG339	M	17-25	21
EG195	F	18	-	EG86	n	7	-
EG267	M	26-45	36	EG78	F	26-45	36
EG209	F	46	46	EG75	n	4	-
EG324	F	26-45	36	EG223	n	7	-
EG217	F	26-45	36	EG555	n	15	-
EG52	M	46+	46	EG199	n	7	-
EG399	M	26-45	36	EG140	M	26-45	36
EG208	M	26-45	36	EG465	F	18	-
EG567	F	17-25	21	EG124	n	2	-
EG179	M	46+	46	EG116	M	17-25	21
EG329	M	17-25	21	EG159	n	6	-
EG323	F	26-45	36	EG138	n	1	-
EG397	F	20	-	EG160	F	46+	46
EG143	F	17-25	21	EG113	F	46+	46
EG141	M	46+	46	EG155	n	9	-
EG202	M	26-45	36	EG542	n	12	-
EG581	M	20	-	EG461	n	12	-
EG203	M	46+	46	EG206	n	16	-
EG162	F	26-45	36	EG591	M	17-25	21
EG185	M	46+	46	EG438	n	9	-
EG410	M	17-25	21	EG71	M	46+	46
EG420	F	26-45	36	EG101	M	17-25	21
EG371	M	46+	46	EG163	n	10	-
EG194	M	46+	46	EG295	F	17-25	21
EG390	F	17-25	21	EG368	F	46+	46
EG193	M	26-45	36	EG222	n	16	-
EG450	M	26-45	36	EG80	n	8	-
EG145	n	3	-	EG115	n	6	-
EG70	M	46+	46	EG436	n	11	-
EG114	F	17-25	21	EG598	n	14	-
EG408	n	12	-	EG153	M	26-45	36
EG237	n	4	-	EG456	n	2	-
EG90	n	7	-	EG599	F	26-45	36
EG165	n	15	-	EG613	F	46+	46

Appendix B

All Macrowear Data						
Individual	AvgM3 Score	AvgM2 Score	AvgM1 Score	AvgM1 Score	AvgPremol Score	AvgAnterior Score
EG246	1	2.5625	3.75	3.75	2.25	2.5
EG195	1	1.875	3.5	3.5	2	2.5
EG267	7.425	8.3125	9	9	4	3.3
EG209	2.5	7.075	8.25	8.25	6	5.75
EG324	4.125	5.3125	7.125	7.125	3.4	2.5
EG217	1	4.125	8	8	3.9	3.75
EG52	0	4.125	6.5	6.5	4.5	4.6
EG399	3	4.625	5.925	5.925	2.25	5.7
EG208	1.625	3	4.625	4.625	2.9	3.75
EG567	1.8125	2.625	3.675	3.675	2.75	3.4
EG179	6.4	9.4	10	10	7.5	6.8
EG329	2.06	3.5	6.425	6.425	2.7	4
EG323	10	8.25	9.25	9.25	5.75	6.25
EG397	1	1.75	3.625	3.625	2	2.5
EG143	1.125	3.375	4.4	4.4	2.6	2.9
EG141	2	0	9	9	5.75	6.8
EG202	0	2.875	5.5	5.5	3	5.3
EG581	0	2.5	4.175	4.175	2.25	3
EG203	7.75	8.25	8.56	8.5625	4.75	4.2
EG162	3.125	4	6.175	6.175	3.4	4
EG185	6.25	6.125	9	9	3.6	3
EG410	1.25	3.75	5.325	5.325	2	2.4
EG420	2.25	4.425	7.575	7.575	4.6	6.6
EG371	4.575	6.75	9	9	4.5	4.2
EG194	4	5.075	6.25	6.25	3	2
EG390	1.125	3.625	4.56	4.5625	2.12	2.7
EG193	1	3.825	7	7	3.25	4.75
EG450	5.057	5.5	8.0625	8.0625	3.75	3.5
EG145	0	2	8	2	0	1.4
EG70	4.375	5.5	7	7	2.75	2
EG114	0	2.5	3.75	3.75	2	2
EG408	1	1	1.75	1.75	1	1.4
EG237	0	2.25	2.0625	2.0625	0	2
EG90	0	3	2.18	2.1875	0	1.6
EG165	0	1.375	3.25	3.25	1.75	2.6
EG339	0	2.1875	4.1875	4.1875	2	1.8
EG86	0	3	1.1875	1.1875	0	2.6
EG78	3	3.75	5.625	5.625	2.25	2.7
EG75	0	0	0	0	2.25	2.3

(continues onto next page)

Individual	AvgM2 Score	AvgM2 Score	AvgM1 Score	AvgM1 Score	AvgPremol Score	AvgAnterior Score
EG223	0	6	2.125	2.125	0	3.4
EG555	0	1	1.875	1.875	1.75	2.5
EG199	0	3	1	1	0	2.3
EG140	7.375	6.25	9.5	9.5	4.5	6
EG465	1.125	2.75	3.1825	3.8125	2	2.6
EG124	0	1.825	2.175	2.175	0	2.25
EG116	1	3.25	5.5	5.5	2.75	2
EG159	0	2.75	1.125	1.125	0	2.7
EG138	0	1	2.1875	2.1875	0	1.4
EG160	0	4.5	0	0	5.8	7
EG113	8.125	8.875	8.875	8.875	5.5	4
EG155	0	4.75	1	1	0	2.25
EG542	1	1.325	1.5	1.5	1	1.7
EG461	0	1	2.125	2.125	1	1.7
EG206	1	1.75	3.6875	3.6875	2.1	2.2
EG591	0	1	1.925	1.925	1	1.75
EG438	0	1	2.5	2.5	5.5	2
EG71	5.5	7.425	7.825	7.825	4.4	4.8
EG101	2.75	3.125	5.125	5.125	1.9	2.25
EG163	0	0	1.325	1.325	5	1.5
EG295	1	1	2.5	2.5	1.75	1.9
EG368	3.825	4	4.8125	4.8125	3	3.5
EG222	0	1.1875	1.75	1.75	1.5	2
EG80	0	2.25	1.25	1.25	0	1.4
EG115	0	4	2.25	2.25	0	2.7
EG436	1	1	2.175	2.175	1	1.7
EG598	0	1.75	3.375	3.375	2	1.7
EG153	3.625	3.875	4.825	4.825	2	2.4
EG456	0	1	1.25	1.25	0	1.5
EG599	8	9.375	8.375	8.375	7	7.1
EG613	7.75	6.5	9.25	9.25	6.1	5.8

Appendix C

All Dental Caries Data			
Individual	Number of Caries	Individual	Number of Caries
EG246	2	EG339	3
EG195	0	EG86	0
EG267	2	EG78	1
EG209	4	EG75	0
EG324	0	EG223	0
EG217	1	EG555	2
EG52	1	EG199	0
EG399	0	EG140	5
EG208	2	EG465	0
EG567	1	EG124	0
EG179	2	EG116	1
EG329	4	EG159	0
EG323	0	EG138	0
EG397	4	EG160	0
EG143	1	EG113	2
EG141	2	EG155	0
EG202	0	EG542	0
EG581	0	EG461	0
EG203	0	EG206	0
EG162	0	EG591	0
EG185	1	EG438	1
EG410	0	EG71	0
EG420	2	EG101	1
EG371	0	EG163	1
EG194	5	EG295	0
EG390	0	EG368	0
EG193	1	EG222	1
EG450	0	EG80	0
EG145	0	EG115	0
EG70	0	EG436	0
EG114	0	EG598	1
EG408	0	EG153	1
EG237	0	EG456	0
EG90	1	EG599	1
EG165	0	EG613	2

Appendix D

All Microwear Data												
Individual	FS Enam	FS Dent	CS Enam	CS Dent	HS Enam	HS Dent	SP Enam	SP Dent	LP Enam	LP Dent	PP Enam	PP Dent
EG246	6.5	4.5	6.5	3	0	0	4	6	3	1.5	1	0
EG195	8	0	2.5	0	1	0	11.5	0	2	0	1.5	0
EG267	0	14	0	2	0	1	0	8	0	3	0	0
EG209	0	6.5	0	2	3	3	0	4	0	2.5	0	1.5
EG324	0	1.5	0	0	0	4	0	7	0	7	0	1.5
EG217	0	6	0	0	0	2	0	3	0	1.5	0	0.5
EG52	11	0	2.5	2	3	2.5	0	8	3	4	1	0
EG399	10	2.5	5	2	0	4	5.5	5.5	1	2.5	0	0
EG208	14	3	1	0	0	4.5	5	3.5	3.5	3.5	0	0
EG567	0	6	3.5	1.5	0	0.5	9.5	0	4	8.5	0	0
EG179	0	8	0	2.5	0	0	0	3	0	2.5	0	1
EG329	12.5	11	2.5	2.5	0.5	0	7	6	2	0	0	0
EG323	0	13.5	0	2	0	1	0	1.5	0	5	0	0.5
EG397	18	0	2.5	2.5	0.5	3.5	0	2	1	10	0	1
EG143	4.5	2.5	3.5	3	0.5	0	7.5	0	1.5	5	0	2
EG141	0	6.5	0	2.5	0	0	0	7	0	2.5	0	0
EG202	4.5	1	5	4	0	1	5.5	5	2.5	3.5	0	1
EG581	7	0	2	3	1.5	0	2.5	2.5	3	10	0	0.5
EG203	0	10	0	2.5	0	0.5	0	2.5	0	2.5	0	0
EG162	8.5	1	2.5	4	0.5	1.5	13.5	4	2	3	0	0
EG185	0	14	0	0	0	2	0	3.5	0	2	0	0
EG410	12.5	2.5	4	3	1	2	6.5	3	2.5	2	0	1
EG420	9.5	6.5	3.5	3	3	0	1.5	6	5	2.5	0.5	0
EG371	4	3	1.5	1.5	1	0.5	10.5	5.5	0	2.5	0	0
EG194	3.5	0	3.5	5.5	1.5	0	3	6	0	1.5	0	0
EG390	10.5	0	1	0	2	0	5.5	0	0	0	0	0
EG193	11.5	6.5	4	1.5	0	0	5.5	3	2	7.5	0.5	1
EG450	8	6.5	2.5	0.5	1	3	1	7.5	3.5	2	0	0
EG145	7.5	0	0.5	0	2	0	5.5	0	4.5	0	0	0
EG70	4.5	4	6	6.5	0	0	3.5	10	2.5	2.5	0	0
EG114	9.5	0	4.5	0	1.5	0	0	0	7	0	0	0
EG408	4	0	3	0	0	0	6.5	0	7.5	0	1	0
EG237	8	0	2	0	0	0	8.5	0	1.5	0	0	0
EG90	10	0	1	0	0	0	19	0	0.5	0	0	0
EG165	13	0	0.5	0	0	0	14.5	0	1.5	0	0.5	0
EG339	4.5	0	4	0	0	0	3	0	4	0	1	0
EG86	12.5	0	0	0	0	0	6	0	3	0	0	0

(continues onto next page)

Individual	FS Enam	FS Dent	CS Enam	CS Dent	HS Enam	HS Dent	SP Enam	SP Dent	LP Enam	LP Dent	PP Enam	PP Dent
EG78	13	2.5	2.5	3	0	0	7.5	3.5	1.5	3.5	0	0.5
EG75	7.5	0	1	0	0	0	11.5	0	7.5	0	0.5	0
EG223	8	0	1.3	0	0	0	10	0	6.5	0	1	0
EG555	14.5	0	0.5	4	0	0.5	6.5	8.5	4	1	0	0
EG199	7.5	0	2	0	1	0	19.5	0	1.5	0	0	0
EG140	15	0	0	0	0	0	9	0	9.5	0	0	0
EG465	3.5	0	0.5	0	1.5	0	16.5	0	4	0	0	0
EG124	9.5	0	3	0	0	0	4	0	2.5	0	1	0
EG116	9	0	0.5	0	0	0	8.5	0	5	0	0	0
EG159	2	0	2	0	2.5	0	11.5	0	5	0	0	0
EG138	3	0	1	0	0	0	5	0	4	0	0	0
EG160	21.5	0	4	0	0.5	0	12	0	5	0	0	0
EG113	4	7	3	4	3.5	0	1	4	7	4.5	2	0.5
EG155	13	0	0.5	0	0	0	19.5	0	3	0	0	0
EG542	11.5	0	2	0	0	0	6.5	0	8	0	1	0
EG461	1	0	4	0	0.5	0	9.5	0	5.5	0	0	0
EG206	15	0	3	0	0	0	9.5	0	4	0	0	0
EG591	11.5	0	2.5	0	0	0	6.5	0	1	0	0	0
EG438	13	0	3	0	0	0	13.5	0	9	0	1	0
EG71	5.5	7.5	0	3.5	1	1	6.5	0	7	9.5	0.5	1.5
EG101	8.5	0	3.5	0	0	0	10.5	0	5	0	2	0
EG163	6	0	0	0	3.5	0	10.5	0	5	0	0	0
EG295	15	0	2	0	2	0	14	0	4.5	0	0.5	0
EG368	10.5	0	1.5	0	1.5	0	11.5	0	2.5	0	0	0
EG222	7.5	0	3	0	0	0	4.5	0	3	0	0	0
EG80	9.5	0	2.5	0	0	0	6	0	1	0	0	0
EG115	12	0	1.5	0	1.5	0	10.5	0	3	0	0	0
EG436	8.5	0	3	0	2.5	0	7	0	2.5	0	0	0
EG598	14	0	0.5	0	1	0	5	0	0	0	0	0
EG153	6.5	3.5	1	0.5	0	0.5	13.5	9	0.5	2.5	0	0
EG456	6	0	3.5	0	0	0	5.5	0	2.5	0	1.5	0
EG599	0	1.5	0	4	0	3.5	0	5.5	0	6	0	0.5
EG613	0	5	0	0	0	1	0	9.5	0	1.5	0	1.5

Figure headers are abbreviated as follows: Enam = Enamel, Dent = Dentin, FS = Fine Scratch, CS = Coarse Scratch, HS = Hypercoarse Scratch, SP = Small Pit, LP = Large Pit, and PP = Puncture Pit.

Appendix E

All Isotope Data			
Individual	Element	$\delta^{13}C$ (‰, vPDB)	$\delta^{15}N$ (‰, vAIR)
EG246	Rib	-19.3	11.8
EG195	Rib	-19.7	10.5
EG267	Rib	-19.1	11.6
EG209	Rib	-19.9	11.5
EG324	Rib	-19.6	11.5
EG217	Rib	-18.6	12.2
EG52	Rib	-18.1	13.8
EG399	Rib	-18.7	13
EG208	Rib	-19.2	12.1
EG567	Rib	-19.9	11.2
EG179	Rib	-19	11.2
EG329	Rib	-19.5	11.6
EG323	Rib	-19.1	12
EG397	Rib	-19.4	11.4
EG143	Rib	-20.2	11.1
EG141	Rib	-19.1	12.5
EG202	Rib	-19.1	13.2
EG581	Rib	-18.5	13.2
EG203	Rib	-18	13
EG162	Rib	-19.8	11.1
EG185	Rib	-19.3	12.6
EG410	Rib	-19.7	11.4
EG420	Rib	-19.3	11.6
EG371	Rib	-19.1	11.8
EG194	Rib	-19.7	11.9
EG390	Rib	-19.7	11.5
EG193	Rib	-18.6	12.2
EG450	Rib	-18.8	12.2
EG145	Rib	-19.9	11.8
EG70	Rib	-19.2	12.2
EG114	Rib	-18.5	12.1
EG408	Rib	-19.5	11.9
EG237	Rib	-19.5	11.1
EG90	Rib	-19.9	9.9
EG165	Rib	-18.9	12.1
EG339	Rib	-18.7	13
EG86	Rib	-20.1	10.6
EG78	Rib	-19.6	11.6
EG75	Rib	-20	11

(continues onto next page)

Individual	Element	$\delta^{13}C$ (‰, vPDB)	$\delta^{15}N$ (‰, vAIR)
EG223	Rib	-19.7	12.5
EG555	Rib	-18.6	11.7
EG199	Rib	-19.8	11.1
EG140	Rib	-19.1	12.8
EG124	Rib	-19.9	11.5
EG116	Rib	-18.4	12.1
EG159	Rib	-20.3	10.8
EG138	Rib	-19.4	12.5
EG160	Rib	-20.1	10.9
EG113	Rib	-19.6	11.5
EG155	Rib	-19.1	11.6
EG542	Rib	-19.8	11
EG461	Rib	-20.2	12
EG206	Rib	-18.5	12.6
EG591	Rib	-18.1	12.4
EG438	Rib	-19.8	11.6
EG71	Rib	-19	12.9
EG101	Rib	-19	12.6
EG163	Rib	-19.5	11.5
EG295	Rib	-18.4	13.1
EG368	Rib	-19.2	11.7
EG222	Rib	-19.2	12.3
EG80	Rib	-19.9	11.2
EG115	Rib	-19.8	12
EG436	Rib	-18.1	13.4
EG598	Rib	-19.8	12
EG153	Rib	-19.2	11.3
EG456	Rib	-20.3	11.5
EG599	Rib	-19.3	12.3
EG613	Rib	-19.1	11.7