CHILDHOOD DIET AND MOBILITYAT MEDIEVAL (1240s AD) SOLT-TÉTELHEGY, HUNGARY AS RECONSTRUCTED FROM STABLE CARBON, NITROGEN, AND OXYGEN ISOTOPE ANALYSIS

by

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A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Arts
in the Department of Anthropology
in the College of Sciences
at the University of Central Florida
Orlando, Florida

Spring Term
2015

ABSTRACT

Between 2005 and 2009, archaeologists excavated more than 100 skeletons from the medieval (1240s AD) Hungarian site of Solt-Tételhegy. Stable carbon and nitrogen isotope analyses were conducted on dental enamel and dentin from 24 individuals to examine their childhood diet. Although previous stable isotopic research has described the diet of medieval European peoples, this is the first such study on a medieval Hungarian population. The enamel $\delta^{13}C$ values range from -14.4‰ to -8.6‰, with a mean of -11.1‰, while the dentin $\delta^{13}C$ values range from -19.4‰ to -14.9‰, with an average of -17.4‰. These data indicate that C_3 plants were the main plant type consumed by the majority of this population, with the exception of a few individuals, who appear to have included C_4 plants in their diet. These results are to be expected, given the dominance of C_3 over C_4 plants in medieval Central Europe. Thus, based on historical and isotopic evidence, the outliers may have spent their childhoods elsewhere and later migrated into the Solt-Tételhegy area. The $\delta^{15}N$ values range from 9.5‰ to 11.6‰, with a mean of 10.6‰, indicating that animal protein was prevalent in the diets of the sample population. Despite clear signs of status differences indicated by burial location, stable nitrogen values also point to relatively egalitarian access to animal protein amongst the individuals. The enamel $\delta^{18}O_p$ values range from 23.6‰ to 27.2‰, with an average of 25.1‰, suggesting that multiple migrations occurred into the study site. The results of this study show that the dietary and mobility information gleaned from stable isotope analysis can be used to interpret the lifeways of archaeological peoples.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my family and friends for their encouragement in my academic endeavors, particularly this year. The support I have received from my parents, especially from my mother, has helped me in every way during graduate school, and I do not think I would have been as successful without it. I would like to thank my adviser and my committee members, Dr. Tosha Dupras, Dr. Lana Williams, and Dr. John Schultz, for their encouragement and input throughout my Master's coursework. I would not have gotten through it without them. Dr. Tosha Dupras has consistently made time to discuss my thesis with me, whether it was to troubleshoot mysteriously disappearing values on a scatterplot or to provide detailed comments on my drafts. She was so very patient with my edits and questions. Dr. Lana Williams supported and guided me from the beginning of my graduate studies, and I am as grateful for this now as I was when I started. Dr. John Schultz, too, has been instrumental, because his feedback, particularly on my term papers, has enabled me to grow significantly as a scientific writer. Likewise, this study would not have been possible without Dr. Erzsébet Fóthi at the Hungarian Natural History Museum in Budapest, and I thank her for allowing me to work on this remarkable sample and for the opportunity to forge research ties with the museum. I would also like to thank the Colorado Plateau Stable Isotope Laboratory at the University of Arizona and the Light Stable Isotope Mass Spectrometry Laboratory at the University of Florida for processing these samples so quickly.

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CHAPTER ONE: INTRODUCTION

Stable isotope analysis has been employed by bioarchaeologists since the early 1970s to understand the diet, nutritional health, weaning history, and migration patterns of both prehistoric and historic humans (Giblin 2009; Harrison and Katzenberg 2003; Macko et al. 1999; Schoeninger and Moore 1992). Although many authors have published on the diet of medieval Europeans, there is currently no stable isotopic research on the diet of ancient people from Hungary, particularly during the medieval period. As a result, the purpose of this pilot study is to ascertain the childhood diet of twenty-four individuals from medieval (1240s AD) Solt-Tételhegy (in southern Hungary), using stable carbon and nitrogen isotope analysis of dental enamel and dentin. This research will examine if sex and status influenced the diet of these people, as four of the individuals from the sample are thought to have occupied a higher rung in society due to their burial location (Fóthi and Bernert 2014). Additionally, the study highlights the probability that migration into the site occurred, using data from stable oxygen isotope analysis of enamel. Because there is a dearth of Central European stable isotope studies, the results from Solt-Tételhegy could serve as the springboard for further such research in Hungary and in other countries from the region. Dietary information from these areas will enrich the current understanding of how different medieval peoples lived in Europe, while also providing a comparison based on culture- and/or location-specific variables. Oxygen isotope information may begin to lay the foundation for future mobility studies in Hungary, by providing information of origin and mobility for the medieval peoples in this area.

Historical Background

The individuals analyzed in this research lived during the high medieval period of the Kingdom of Hungary, which existed from approximately 1000 AD to 1301 AD (Berend et al. 2013). This period is also referred to as the Árpádian dynasty, because its kings were the direct descendents of Árpád, the first ruler of the Hungarians (in the 9th and 10th centuries AD) (Engel 2001). During this time, Hungary was expanding to the east and south, specifically into the Balkans (Engel 2001), where the Hungarians encountered Bosnians, Bulgarians, Croats, Serbians, and later, Moravians. There was also turmoil, however, brewing in the region. King Béla IV had incurred the hatred of his subjects when he confiscated the lands his father had given to the nobles. This act would soon come back to haunt him. Meanwhile, the Mongols (Tatars) were moving increasingly closer to the country. Hungary received an influx of immigrants, who were fleeing from the impending invasion that had already ravaged parts of Eastern Europe (e.g., Ukraine) (Berend et al. 2013; Engel 2001; Molnár 2001). Because Béla IV allowed these foreigners (among them, the disruptive Cumans) entry, he continued to lose the support of his nobles and their knights, until conflict finally erupted in 1241 AD. A riot began against the Cumans, which coincided with the arrival of the Mongols into Hungary (Engel 2001). Without the nobles' troops, the king lacked an adequate defense against the invaders, and the Mongol army won a decisive victory against the Hungarian royal army at the Battle of Mohi in 1241 AD. Figure 1 shows a map of the Kingdom of Hungary in the 13th century AD following the Mongol invasion.

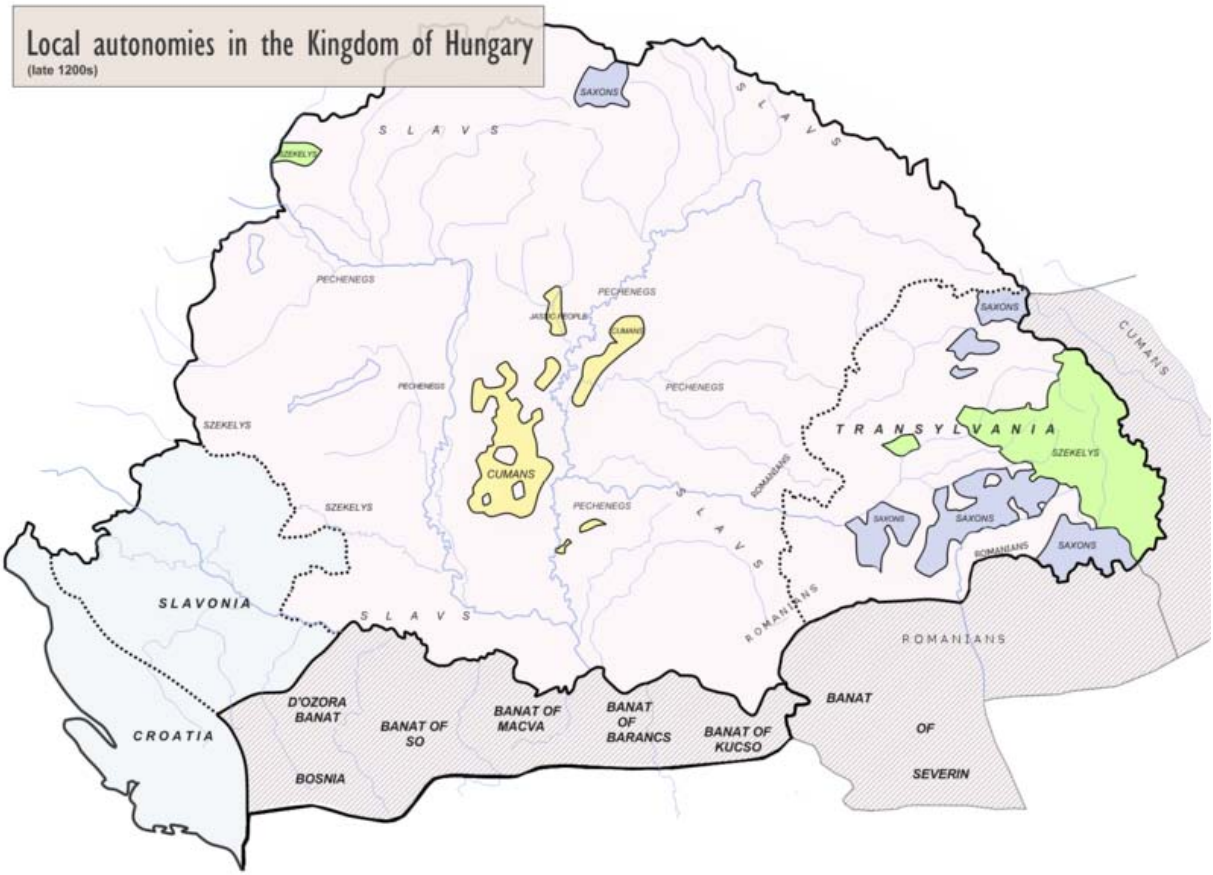

Figure 1. Map of the Kingdom of Hungary in the late 13th century AD (taken from http://commons.wikimedia.org/wiki/File:Hungary_13th_cent.png#/media/File:Hungary_13th_cent.png).

This defeat marked the beginning of a time of socioeconomic and political crisis for the medieval Hungarians. Villages disappeared (31 out of 43 in Orosháza), trade routes crumbled, and commerce virtually disappeared from entire regions (e.g., Bács and Ungvár). Parts of the Great Plain (*Alföld*), where the Mongols had camped for a year, were completely destroyed. Farmland that had been ravaged no longer yielded crops, causing widespread famine and social unrest. And although the war had claimed casualties, as had the resulting disease epidemics, the Mongols also took captives, leading to a population decline by about 15-20% (Engel 2001; Molnár 2001). Striving to rebuild his kingdom, Béla IV enacted drastic changes, one of which

was the formation of a new class of free peasant tenants (Engel 2001). Instead of working the land as serfs, they could now "rent" their own plots, which may have enabled them to improve their overall diet. Additionally, in an effort to repopulate Hungary, the king invited Germans, Poles, Romanians, and Moravians, along with other ethic peoples, to settle in the various regions (Berend et al. 2013; Molnár 2001). It is this last group, the Moravians, who are of particular importance to this research. The Moravians are a Slavic ethnic group that broke off from the Kingdom of Croatia to settle along the River Moravia in the 9th century AD (Bigoni et al. 2013; Róna-Tas 1999). They established Great Moravia, whose most important settlement was Mikulčice (Fig. 2). With multiple churches, burial grounds, and handicraft industries, it was both an administrative and a cultural center. The higher classes intermixed with the lower classes, as evidenced by the lack of social stratification of individuals interred in the churchyard (Bigoni et al. 2013). For whatever reason, it appears that some of the Moravians left Great Moravia and later inhabited parts of southern Hungary (Berend et al. 2013). It is from this group that part of this research sample most likely originates.

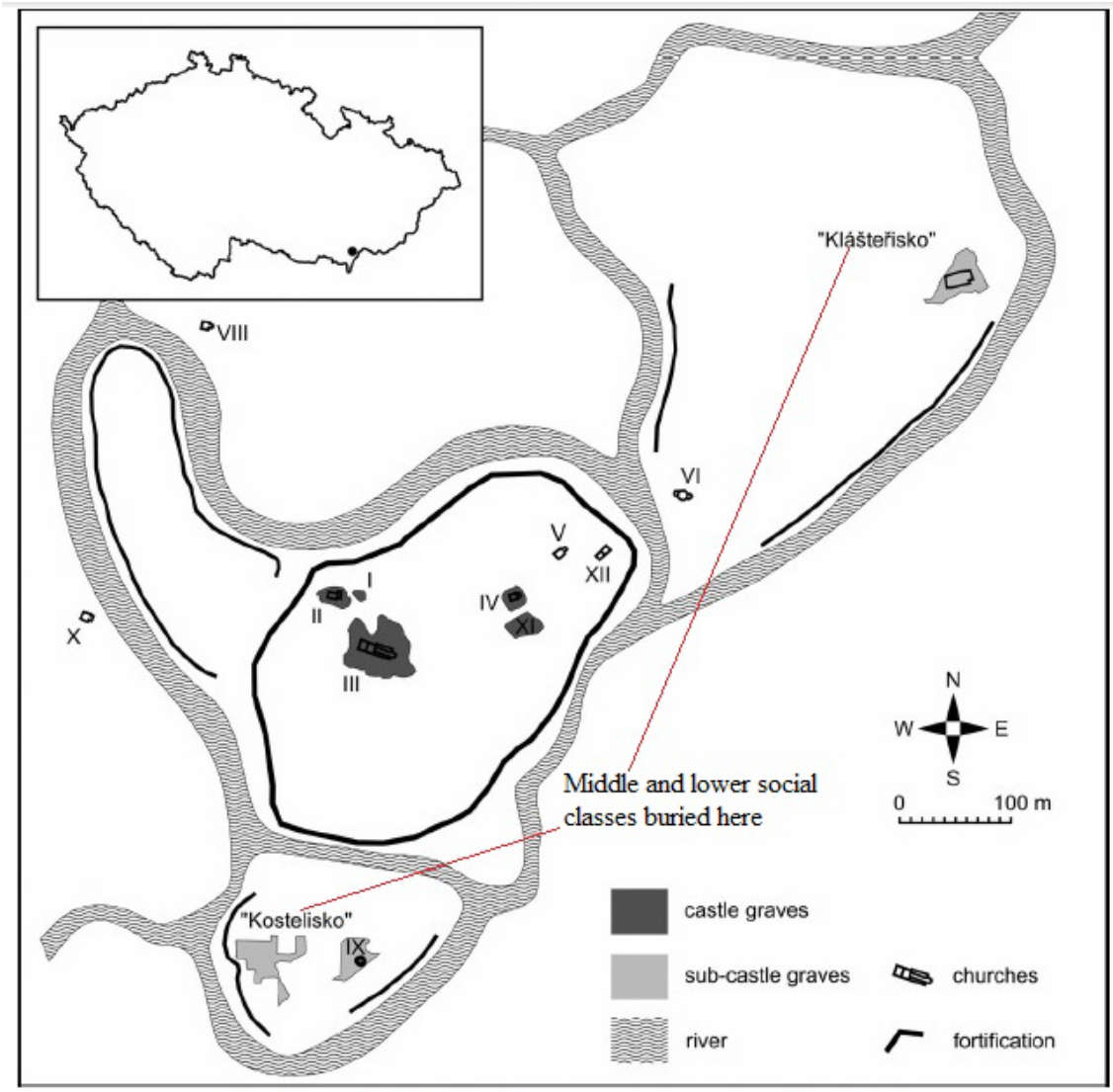

Figure 2. Map of Mikulčice in the 11th century AD (adapted from Bigoni et al. 2013).

Solt-Tételhegy is an archaeological site located in southern Hungary (Fig. 3), in a region known as the Southern Great Plain (*Dél Alföld*). The site has been known since at least the 1880s, when Aurél Török, dubbed the "father of Hungarian anthropology", began excavations there. He and the other archaeologists uncovered thousands of skulls, which are now stored in

the Anthropological Collection of the Hungarian Natural History Museum in Budapest (Szentpéteri 2009).

Figure 3. Map of present-day Hungary, with the study site of Solt-Tételhegy circled in red. Because medieval Hungary was larger, Solt-Tételhegy would have been in the center of the kingdom (adapted from http://commons.wikimedia.org/wiki/File:HU_counties_names.svg#/media/File:HU_counties_names.svg).

There are five primary medieval settlements, spanning 100 hectares, at Solt-Tételhegy: the *templomdomb* (hill-church) and *várdomb* (hill-fortress) to the north, a third on the east side, a fourth in the central part, and a fifth to the south (Szentpéteri 2009). The most intensive settlements were at the *templomdomb* and *várdomb*, but all five areas may have been larger and more densely populated than other contemporaneous settlements in the region. Such a cluster of

habitations, including at least two churches, was relatively rare in the region. Additionally, other archaeological evidence (e.g., well-constructed houses, high-quality decorative items, expensive grave goods, imported ceramics, and tax stamps) suggests a higher-status settlement. Therefore, medieval Solt-Tételhegy is comparable to Árpádian-period administrative centers, such as Bács.

Solt-Tételhegy's hill-church (Fig. 4) was used as a cemetery since the middle Bronze Age (by the Vatya culture), first as a pagan cemetery, and then as a Christian cemetery (Somogyvári 2014; Szentpéteri 2009). As such, the site contains artifacts and human remains from many different time periods, including the high medieval or Árpádian period (1000-1301 AD). During the middle Bronze Age (2200-1570 BC), trenches were dug and ramparts were constructed, the latter of which were fortified in the Middle Ages.

Figure 4. Aerial view of Solt-Tételhegy's *templomdomb*, or hill-church, prior to excavations in 2005 (adapted from Szentpéteri 2009; 2010).

It is thought by Fóthi and Bernert (2014) that some of the Moravians who left Mikulčice are buried at Solt-Tételhegy, and their skeletons are among the 108 excavated by archaeologist József Szentpéteri and his team in 2009. The builder of one of the churches and possibly three of

his family members may have been Moravians. They were interred inside the church itself, thus suggesting that they occupied a higher social status (Singman 2013). These four individuals are also included in the research sample.

The purpose of this research is threefold: 1) to examine the childhood diet of twenty-four inhabitants from medieval (1240s AD) Solt-Tételhegy, Hungary, 2) to identify migrants within the study population, and 3) to pinpoint as precisely as possible the geographic origins of the immigrants. In other words, what foods did the inhabitants of medieval (1240s) Solt-Tételhegy eat during childhood? Were there migrants within the study population? And, if so, where did the immigrants come from? Additionally, the influence of sex and status on diet is also discussed. Stable carbon and nitrogen isotope analyses from dental enamel and dentin were used to determine childhood diet, while stable oxygen isotope analysis from enamel was used to confirm childhood migration. This research is the first to apply stable isotope analysis to address childhood diet and mobility of a population from medieval Hungary. It is also unique in that it provides an isotopic comparison of the childhood diet of a medieval Hungarian population with that of contemporaneous European populations.

CHAPTER TWO: LITERATURE REVIEW

This chapter will provide a theoretical and methodological framework for stable isotope analysis as it applies to the reconstruction of diet. First, a brief explanation of the biochemistry of teeth will be provided. Next will follow a discussion on collagen and hydroxyapatite, followed by sections on stable carbon, nitrogen, and oxygen isotopes. Then the focus will shift to previous stable isotopic studies on medieval European diet. Finally, the chapter concludes with a brief assessment of the limitations of stable isotope analysis in bioarchaeology.

Teeth

Teeth, like bones, are composed of both organic and inorganic components. Covering each tooth is enamel, which is the hardest substance in the body. Enamel is 96% mineral (i.e. hydroxyapatite), while the remaining 4% is water and organic material (Busch et al. 2001; Holly 1991; Kohn et al. 1999; Leicester 1953). It is thickest at the cusp and thinnest at the cementoenamel junction (CEJ). Hydroxyapatite, which comprises most of enamel, is a crystalline calcium phosphate, so it is quite brittle and hard. Enamel's organic material is made up of two proteins: amelogenins and enamelins (Busch et al. 2001; Holly 1991).

Dentin lies just beneath enamel and is 70% inorganic, 20% organic (e.g., collagen), and 10% water. It is created by odontoblasts (i.e., tooth-forming cells) during dentinogenesis (Busch et al. 2001; Leicester 1953). Because it contains fewer minerals than enamel, dentin is softer, and its molecules are more loosely arranged, thus making it more susceptible to alteration or contamination of its biochemistry (Ambrose and Krigbaum 2003).

This study addresses childhood diet, so it is important to understand tooth formation. Since permanent first and second molars dominate the sample, they are the primary focus of this discussion. However, a brief explanation will be provided for deciduous second molars, as one individual is represented by this tooth. The deciduous second molar begins to form during the 18th-19th week *in utero* and is completely developed around 3 years of age (Holly 1991). Permanent teeth begin to form around the 20th week of prenatal development, but the majority of formation occurs postnatal. Maxillary first molars develop from birth to 9-10 years, and second molars develop from 2.5-3 years to 14-16 years. Mandibular first molars also form from birth to 9-10 years; second molars, from 2.5-3 years to 14-15 years (Holly 1991). The isotope values for enamel, however, will represent the age at which the crown develops. As elucidated by Dupras and Tocheri (2007), the crown of deciduous second molars begins to form before birth and is complete by 1 year of age. The crown of permanent first molars develops between 2 and 5 years, whereas the crown of permanent second molars forms between 4 and 6 years (Dupras and Tocheri 2007). Table 1 shows the developmental stages of permanent molars in greater detail.

Table 1. Developmental stages of permanent first and second molars (Dupras and Tocheri 2007; Holly 1991; Leicester 1953).

	Maxillary Teeth	
Developmental Stages	**First Molar**	**Second Molar**
Initial calcification	Birth	2.5-3 years
Crown completed	2.5-3 years	7-8 years
Root completed	9-10 years	14-16 years
	Mandibular Teeth	
Initial calcification	Birth	2.5-3 years
Crown completed	2.5-3 years	7-8 years
Root completed	9-10 years	14-15 years

Stable Isotopes

Before one can delve into stable isotope analysis, the basics must be understood. Isotopes are two or more alternative forms of an element, possessing the same number of protons and electrons but a different number of neutrons (DeNiro 1987). Different isotopes react at different rates, potentially leading to a difference in the isotopic ratios of the reactants and the products. This is called isotopic fractionation, and it is what makes the stable isotopic analysis of diet possible. The different reaction rates translate into different ratios of stable isotopes, enabling bioarchaeologists to determine if, for instance, a person's diet contained more terrestrial protein or marine protein. An important part of isotopic fractionation is that the isotopes with a lower atomic weight react more quickly in photosynthesis than those with a heavier weight, so they

will be more enriched at the end of the reaction (Wilson et al. 2007). For example, the carbon dioxide (CO_2) in the atmosphere is captured by terrestrial plants as $^{13}CO_2$ and $^{12}CO_2$ (Schoeninger 1995), which are then converted into the carbohydrates and proteins that herbivores and omnivores consume. By this point, the CO_2 isotopes have been fixated into ^{13}C and ^{12}C. Because ^{12}C is the lighter of the two, it will be more enriched at the end of photosynthesis. The opposite, however, occurs when plants are consumed by animals, leaving ^{13}C enriched instead (Katzenberg 2008). These carbon levels are then measured during stable isotope analysis to understand diet and nutritional health. Table 2 presents the relative terrestrial abundances of carbon and nitrogen isotopes.

Table 2. The relative terrestrial abundances of carbon and nitrogen isotopes (adapted from Katzenberg 2008).

Element	**Isotope**	**Abundance (%)**
Carbon	^{12}C	98.89
	^{13}C	1.11
Nitrogen	^{14}N	99.63
	^{15}N	.37

Stable isotope analysis has a long history in science, though not necessarily in bioarchaeology. In the early 20th century, chemists and geochemists began studying stable isotopes. In the 1970s, archaeologists followed, starting first with carbon isotopes, and then expanding to nitrogen, oxygen, strontium, hydrogen, and sulfur isotopes (Katzenberg 2008). Until the analysis of oxygen and strontium, diet studies dominated, but now migration and

mobility studies are becoming increasingly more common. Stable isotope analysis operates on two basic premises. First, that humans absorb the biochemical signatures of the foods they eat (Ambrose and Krigbaum 2003; Papathanasiou 2003; Richards and Hedges 1998). Second, that the natural abundance of isotopes in food varies according to the environments in which they are produced (Chenery et al. 2010). When humans eat or drink, the isotopic signatures in food and water are incorporated into their bones, teeth, soft tissues, hair, and nails, allowing for the reconstruction of diet, mobility, and nutritional health (Chenery et al. 2010; Papathanasiou 2003). Although bones, teeth, hair, and nails can all be sources for isotopic research, the analyses for this research focused on teeth.

Humans are what they eat, within reason. Isotopic compositions can differ based on the atmospheric and geochemical characteristics of their environments. According to van Klinken et al. (2000), there is greater variation among stable isotopic ratios in Africa, Asia, and the Americas than in Europe. This is because Europe has less resource diversity and thus less stable isotopic variation.

Stable isotopes are measured with gas isotope ratio mass spectrometers (IRMS). They are composed of an inlet, an ion source, a mass analyzer, and an ion collector (Katzenberg 2008). When a sample undergoes stable isotope analysis, there are four main steps. First, the sample becomes a gas and is ionized by the ion source. Second, the molecules enter a tube, and a magnet sorts the ionized molecules according to their mass. Next, the ions move into the ion collector and are measured. Finally, the two most plentiful isotopes (e.g., ^{12}C and ^{13}C) are compared with an international standard. These two isotopes will then become the isotope ratios used in stable

isotope studies, written as delta (δ) values in parts per mil (‰). The international standard used for $\delta^{13}C$ is Vienna Pee Dee Belemnite (VPDB), and for $\delta^{15}N$, it is atmospheric nitrogen (AIR). (Tykot 2006). The Vienna Standard Mean Ocean Water (VSMOW) has been the international standard used for $\delta^{18}O$ (Coplen 1994; Dufour et al. 2007), but it is now moving to VPDB.

Collagen

Much of the past and present stable isotopic research on prehistoric and historic humans has focused on collagen, primarily because of what it can tell bioarchaeologists about diet (Macko et al. 1999; Richards and Hedges 1998). Collagen is the organic (protein) component of tissues (Larsen 2002; Papathanasiou 2003). According to van Klinken (1999), carbon composes approximately 35% of collagen; nitrogen, approximately 11-16%. Since bone collagen is slow to turnover, the isotopic values reflect the average protein intake over the last ten or more years of a person's life (Chenery et al. 2010; Richards and Hedges 1998). Furthermore, because tooth dentin and different types of bone have varying collagen turnover times, researchers can examine an individual's diet at different stages of his or her life (Chenery et al. 2010). For example, stable isotopes extracted from dentin portray diet during childhood, as that is when tooth formation occurs, and there is little to no change in dentin structure after formation. Conversely, stable isotopes extracted from adult long bone shafts show diet during adolescence and adulthood (Chenery et al. 2010). As a result, it is possible to outline someone's nutritional history from birth to death using teeth and bones. Additionally, tissue turnover times depend on metabolic rates (Hedges and Reynard 2007; Tieszen et al. 1983). The quicker a tissue's metabolic rate, the faster

its turnover time. This explains why dentin has a slower turnover rate than bone, because it is not nearly as metabolically active (Hedges and Reynard 2007).

Collagen provides the carbon and nitrogen stable isotopes necessary for reconstruction of the protein portion of diet (Chenery et al. 2010; Papathanasiou 2003), and $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios from collagen are instrumental in determining the proportion of protein absorbed from plants and animals, respectively. They also shed light on the relative amounts of marine and terrestrial foods in the diet (DeNiro 1987; Papathanasiou 2003). As autotrophs, plants are the first step in food chains, so they set the carbon and nitrogen isotopic signatures for aquatic and terrestrial foods (DeNiro 1987).

Hydroxyapatite

As a phosphate mineral, hydroxyapatite is the inorganic component of bones and teeth (Ambrose and Krigbaum 2003). In teeth, it is found in enamel, which is the apatite source for this research sample. Like the collagen in dentin, enamel's apatite is an excellent indicator of an individual's diet as a child, because tooth enamel forms early in childhood and is not replaced after formation (Bentley 2006). However, unlike collagen, which reflects dietary protein, apatite reflects the carbohydrate portion of diet (Papathanasiou 2003). It is less susceptible to diagenetic alteration of its stable isotopes, due to the biochemical properties of tooth enamel. Tooth enamel is denser and harder than dentin, has larger phosphate crystals, and has less pore space, leading to greater resistance to post-depositional isotopic contamination (Bentley 2006; Dufour et al. 2007).

Carbon

Stable carbon isotope ratios ($\delta^{13}C$) are primarily used to distinguish between C_3 and C_4 plants, as well as between marine and terrestrial C_3 plant-based foods in temperate regions to which C_4 plants are not indigenous (Chenery et al. 2010; Giblin 2009; Müldner and Richards 2005; Papathanasiou 2003; Wilson et al. 2007). Carbon isotope ratios in terrestrial plants are influenced by multiple factors, such as the isotopic composition of atmospheric CO_2 when it is converted into plant carbon (DeNiro 1987; Wilson et al. 2007). However, as carbon passes from one trophic level to another (e.g., from plants to herbivores), isotopic fractionation is minimal. This means that the $\delta^{13}C$ values of animal tissues lie within 5‰ of the $\delta^{13}C$ values of the plants or animals they have consumed (DeNiro 1987).

Because the different plant types (e.g., C_3 vs. C_4) are so important to stable carbon isotope analysis, they merit closer inspection. Most food plants are C_3 plants, such as wheat, rye, barley, tubers (e.g., potatoes), legumes, nuts, and leafy greens. They grow in temperate regions, like Europe, the Middle East, and parts of Asia (DeNiro 1987; Mays 1997; Papathanasiou 2003). Interestingly, since bees eat the products of C_3 plants (e.g., nectar and pollen), honey has a similar $\delta^{13}C$ value to C_3 plants (DeNiro 1987). C_4 plants, on the other hand, thrive in tropical areas, like Africa and Southeast Asia. Maize, millet, and sugar cane are examples of C_4 plants (DeNiro 1987; Mays 1997), though only millet is applicable to this study. There is a third type of plant called CAM plants, but because their carbon isotopic signatures can resemble either C_3 or C_4 plants, it is generally not feasible to differentiate them (DeNiro 1987). C_3 plants have $\delta^{13}C$ values ranging between -33‰ and -22‰, with an average of -27‰, while C_4 plants have $\delta^{13}C$

values between -16‰ and -9‰, with an average of -12.5‰ (DeNiro 1987; Mays 1997). The differences between C_3 and C_4 plants do not end there. C_3 plants are depleted in ^{13}C by 5-15% relative to C_4 plants because of the various enzymes used to fix carbon (Macko et al. 1999). As Papathanasiou (2003) states, C_4 plants, unlike C_3 plants, fix nearly all available atmospheric CO_2, giving them greater, or enriched, ^{13}C values.

Marine plants are more isotopically enriched than terrestrial plants, because they use dissolved bicarbonate in the seawater, instead of atmospheric CO_2. In other words, their $\delta^{13}C$ values are about 7.5‰ less negative than those of land plants (DeNiro 1987; Papathanasiou 2003). Furthermore, $\delta^{13}C$ values of marine animals are roughly 5‰ more positive than those of terrestrial, temperate-climate animals (DeNiro 1987; Mays 1997; Papathanasiou 2003). Additional support for environmental influences on carbon is presented by Ambrose and Krigbaum (2003) and Richards et al. (2000), who assert that closed, humid forests create a "canopy effect," which leads to lower food web $\delta^{13}C$ values. Open, hot, and dry areas, on the other hand, have relatively high food web $\delta^{13}C$ values. Richards and Hedges (1998) state that humans with terrestrial diets from warm regions of Europe (e.g., the Mediterranean) have $\delta^{13}C$ values that are 1-2‰ more positive than those of humans from colder Europe. Finally, it is acknowledged that due to the increased burning of fossil fuels (e.g., coal and gasoline), pre-Industrial Revolution atmospheric and biological $\delta^{13}C$ ratios were more positive than today's ratios (DeNiro 1987; Mays 1997). Therefore, it is important to be aware of a sample's depositional environment when performing stable isotope studies.

A normal range for human bone/tooth $\delta^{13}C$ levels is -20.5‰ to -18.8‰, if the individuals consumed a diet of only C_3 plants (Chenery et al. 2010). Mays (1997) specifies that expected $\delta^{13}C$ values for bone/dentin collagen of humans consuming only C_3 plants, such as some medieval European peasants, are between -21‰ and -22‰. The author also explains that a diet consisting mostly of marine foods might yield collagen $\delta^{13}C$ levels of -12‰ to -13‰, as marine animals' carbon isotope values range between -17‰ and -18‰. These figures are supported by Papathanasiou (2003) and Richards and Hedges (1998), who found that humans eating only terrestrial C_3 plants have $\delta^{13}C$ values of about -20‰, whereas people consuming mostly marine resources have $\delta^{13}C$ ratios of nearly -12‰.

Because stable carbon isotopes are used to determine diet, including the protein proportions, they are inextricably linked with apatite and collagen (Papathanasiou 2003). This study, therefore, incorporates both.

Nitrogen

Nitrogen also conveys dietary information, though primarily via the trophic levels of organisms involved in a particular ecosystem's food web (Chenery et al. 2010; Richards et al. 2000; Wilson et al. 2007). Stable nitrogen isotope values allow bioarchaeologists to determine the relative importance of animals and plants in humans' diets (Chenery et al. 2010). On land and in water, $\delta^{15}N$ is enriched as nitrogen passes through the food chain from producers (plants) to consumers (animals and humans). Marine food chains are longer, which lead to greater ^{15}N enrichment (DeNiro 1987; Papathanasiou 2003). Macko et al. (1999) and Papathanasiou (2003) estimate this step-wise enrichment as being 2-3‰ more than the preceding level. Therefore,

humans who consume fewer marine resources, such as farmers, will have lower $\delta^{15}N$ values than those whose diets are rich in marine animals. Richards and Hedges (1998) place $\delta^{15}N$ levels at 5-12‰ and 12-22‰ for terrestrial-feeders and marine-feeders, respectively. Another reason marine ^{15}N is more enriched is due to the source of the nitrogen. In marine environments, bacterial denitrification (i.e., nitrate reduction) contributes most of the available nitrogen, while terrestrial nitrogen is produced by N_2 fixation. The former process creates more ^{15}N than does the latter process (Schoeninger and Moore 1992).

But marine foods are not the sole sources of higher $\delta^{15}N$ values. Animal protein in general, as opposed to plant protein, will contribute to higher nitrogen values, because it is higher in the food chain and is thus at a higher trophic level (Hedges and Reynard 2007; Reynard and Hedges 2008; Richards and Hedges 1998). As van Klinken et al. (2000) state, the increased $\delta^{15}N$ values seen in humans may also be partly explained by the "manuring effect." This occurs when $\delta^{15}N$ values in soil increase because of natural fertilizers, like animal feces, which are then incorporated into humans' plant and animal food sources.

Climate and precipitation, too, can affect stable nitrogen isotope values. Aridity, for example, may lead to $\delta^{15}N$ enrichment, as Ambrose (1991) argues. When aridity increases, so do $\delta^{15}N$ values. Herbivorous mammals were studied to determine that drought-tolerant animals had enriched nitrogen values, whereas water-dependent animals did not (Ambrose and DeNiro 1987). One possible explanation for this is that the drought-tolerant mammals excreted urea at a slower rate.

Another cause of elevated $\delta^{15}N$ values (in young children, at least) is breastfeeding (Dupras and Tocheri 2007; Dupras et al. 2001; Fuller et al. 2006; Richards et al. 2002). Babies who have been recently breastfed have higher nitrogen values than their mothers, since they occupy a higher trophic level, due to consumption of their mother's milk. Because dentin is slower to turn over than bone, the dentin formed during infancy will retain an enriched $\delta^{15}N$ value after weaning has occurred, though the values will decrease after a couple years. And since formation rates for teeth are known, it is possible to determine at what age weaning began.

The final two sources of nitrogen enrichment are nutritional stress and pathological conditions. As already discussed, diets high in protein result in higher $\delta^{15}N$ values, but the reverse can be true also (Hedges and Reynard 2007). If a person is severely protein-deficient, that can also lead to enriched nitrogen levels. Nutritional stress may result from many different reasons, such as metabolic disease (e.g., osteomalacia/rickets), cultural factors (e.g., unequal access to food), or environmental factors (e.g., famine). Some of these manifest in skeletal tissues, including teeth. Enamel hypoplasia, for example, is the incomplete formation of tooth enamel and is directly related to malnourishment and/or disease (Katzenberg et al. 1996; Polet and Katzenberg 2003). After nitrogen is absorbed into bodily tissues, some of it is used and some of it is excreted as urea. Positive nitrogen balance means that more nitrogen is consumed than excreted during tissue formation (Katzenberg and Lovell 1999). This could lead to lower $\delta^{15}N$ values. On the flipside, enriched $\delta^{15}N$ levels may stem from a negative nitrogen balance, which means that the organism's nitrogen consumption is insufficient. The body is then forced to scavenge protein from musculoskeletal tissues. And, like during isotopic fractionation, the lighter ^{14}N is excreted, while the heavier ^{15}N remains and is enriched. This is most apparent in tissues

with fast turnover rates; thus, even if individuals in the Solt-Tételhegy sample were ill or malnourished, their dentin collagen would probably not reflect it, unless the nutritional stress or pathological condition was present during tooth formation. Table 3 summarizes the factors that contribute to elevated $\delta^{15}N$ levels.

Table 3. Sources of nitrogen enrichment in humans.

Sources of $\delta^{15}N$ enrichment	**$\delta^{15}N$ values**	**Reference(s)**
Marine-based diet	17-20‰	DeNiro 1987; Macko et al. 1999; Papathanasiou 2003
Climate/precipitation	13-18‰	Ambrose 1991; Ambrose and DeNiro 1987
Breastfeeding	+2-3‰	Dupras and Tocheri 2007; Richards et al. 2002
Pathological/nutritional stress conditions	12.9‰	Hedges and Reynard 2007; Katzenberg et al. 1996; Katzenberg and Lovell 1999

Oxygen

Stable oxygen isotopes reflect climate and are one component of mobility studies (Chenery et al. 2010; Giblin 2009). They also provide information on population dynamics, habitat utilization by humans, and procurement origins for food and natural resources (Dufour 2007). As such, oxygen isotopes are useful in dietary studies, as well, because bioarchaeologists can determine the area from where a given group of people obtained its food. The $\delta^{18}O$ of skeletal phosphate is controlled by the isotopic composition of drinking water, which depends on the source of precipitation, distance from the coast, altitude, temperature of precipitation, evaporation rates, and local climate conditions (Chenery et al. 2010; Fricke et al. 1995; Tykot

2006; Wilson et al. 2007). In Europe, for instance, the average $\delta^{18}O$ of rainwater increases from east to west and north to south (Chenery et al. 2010).

Other factors, such as body mass and food source, are important, as well. Among most terrestrial vertebrates, there is an inverse relationship between body mass and oxygen. The $\delta^{18}O_p$ of larger animals is usually less affected by food consumption than the $\delta^{18}O_p$ of smaller animals (Daux et al. 2008; Fricke et al. 1995). However, food and water sources can often skew that relationship, because animals with low water turnover rates tend to receive more water from oxygen-enriched food sources than from drinking water. This means that large mammalian herbivores obtain up to 50% of their $\delta^{18}O_p$ from plants that are isotopically enriched, as opposed to animals that consume fewer super-hydrated (80-95% water by weight) plants.

Humans fall somewhere in the middle of this range, as they are omnivorous mammals of medium size with moderate water turnover rates (Daux et al. 2008). Because they consume fewer plants by body weight than do large herbivores, more of their $\delta^{18}O_p$ comes from drinking water. An added advantage that humans have over other animals is that they cook their foods. The $\delta^{18}O$ levels of cooked food are higher than those of drinking water, because while water boils, it evaporates and becomes ^{18}O-enriched. Furthermore, there are inevitable exchanges of water molecules between the cooking water and the water in the food. Foods that humans generally do not eat raw (e.g., meat, legumes, cereals, and fish) contribute significant amounts of oxygen-enriched water during cooking. With all these extra sources of enrichment, cooked food has $\delta^{18}O$ values that are similar to those of highly hydrated plants (Daux et al. 2008). Therefore, oxygen absorbed from cooked foods is more enriched than the oxygen in environmental water. This

translates to a maximum enrichment of 2‰ compared to drinking water (Daux et al. 2008; Fricke et al. 1995).

Measurements of $\delta^{18}O$ from tooth enamel provide a record of the climate in which a person was raised, as enamel forms during childhood and does not change thereafter (Fricke et al. 1995). But because oxygen undergoes fractionation due to metabolic processes, (Daux et al. 2008; DeNiro 1987), identification of migrants in a society is not always straightforward. Additionally, there is much variation in oxygen sources between individuals in a population. For example, Daux et al. (2008) state that isotopic fractionation between the water from cooked food and the water from the environment (e.g., from aquifers or rivers) is between 1.2‰ and 6.2‰, with the highest values belonging to vegetables. This makes establishing a local baseline difficult. However, higher $\delta^{18}O$ values generally suggest origins in warm, coastal, or arid environments (Chenery et al. 2010).

Brettell et al. (2012) studied stable oxygen and strontium isotope ratios from several Central and Western European archaeological sites to determine if migrations occurred into the areas. Although the majority of individuals from each of the sites was deemed to be local, approximately ten individuals total were almost certainly immigrants. Chenery et al. (2010) illustrated the diversity of a population from Roman Gloucester, England (2nd century AD), using $\delta^{18}O$ and strontium isotope values from human enamel apatite. They determined that most of the individuals spent their childhoods in the UK but that at least six migrated into the area from Continental Europe. Dufour et al. (2007) used stable oxygen isotope analysis to trace the origins of archaeological fish found in ancient Turkey, demonstrating that oxygen can be used to

construct geographical food webs. This is helpful if one is interested in the impact of trade on a particular population, and it is also applicable to medieval diet.

Medieval European Diet

Numerous studies have been undertaken on the diet of past humans. Bone stable isotope analysis of archaeological European remains has been used extensively to study the relative contributions of marine resources in medieval European diets. Mays (1997), for example, demonstrated that monastic diets included more marine resources than did the diets of laypeople. The nutritional history of medieval English peoples has been reconstructed to examine the effects of religion and status (Müldner and Richards 2005). Müldner and Richards (2007) also discovered that there was significant variation in marine animal consumption between males and females, as well as between the different social classes, in medieval York, England. Carbon and nitrogen stable isotope analysis has been used to determine that the diet of individuals in medieval Norwich contained a surprising amount of marine resources (20-30% of diet) and that pork may have been a high-status meat (Bayliss et al. 2004). Nitrogen stable isotopes have shed light on weaning ages in medieval Wharram Percy (Richards et al. 2002), as well as in medieval Fishergate House, York (Burt 2013). Stable isotopes have also demonstrated that the people interred in late medieval Orkney ate a marine-heavy diet, including seals, and that males consumed more marine mammals than did females (Richards et al. 2006).

Yoder (2010) studied the regional and temporal patterning of diet in medieval Danish peasant populations, with the conclusion that some regional, but no temporal patterning exists. Stable carbon and nitrogen isotopes have shown that there were clear status-based differences in

the diet of elites, monks, and peasants buried at the Cistercian monastery of Øm Kloster in Denmark (Yoder 2012). Stable isotopes have been used to understand dietary patterns, including sex-based differences in diet, from early-late medieval Sigtuna, Sweden (Kjellström et al. 2009). Also in Sweden, Linderholm and Kjellström (2011) discovered social differences in the diet of the residents of medieval Sigtuna.

Studying dental wear and caries, instead of stable isotopes, Esclassan et al. (2009) determined the dietary history of the inhabitants of medieval Vilarnau, France. In late medieval Koksijde, Belgium, social status was a likely cause of observed variations in human diet (Polet and Katzenberg 2003). Using stable carbon and nitrogen isotopes, Müldner et al. (2014) found that late medieval Belgians near the coast grazed their food animals on halophytic plants. The medieval cod (*Gadus sp.*) trade in Northwest Europe has been mapped using stable isotopes, indicating that fish from the region were consumed even in the UK (Barrett et al. 2008).

Additionally, stable isotopes have shown that male peasants consumed more animal products than did female peasants in medieval Giecz, Poland (Reitsema et al. 2010). Hakenbeck et al. (2010) used carbon and nitrogen stable isotopes to determine the diet of people living in medieval Bavaria, including sex-based dietary differences. Another study from medieval Germany (Weingarten) showed that different settlements had very different diets (Schutkowski et al. 1999). The diet of people living in early medieval Croatia (in Ravni Kotari) has been deduced with stable carbon and nitrogen isotope ratios (Lightfoot et al. 2012).

By comparing dentin and bone collagen, Reitsema and Vercellotti (2012) discovered that diet changed throughout the lifetime of the residents of medieval Trino Vercellese, Italy.

Additionally, the Church's impact on the diets of late medieval Italians was examined by Salamon et al. (2008).

Finally, not all stable isotope studies are completed on human bones and teeth. Some projects use animal skeletal material. For example, Halley and Rosvold (2014) compared the stable carbon and nitrogen values of pigs (*Sus scrofa*) from medieval Norway with those of other northwestern European countries to better understand human stable isotope ratios and thus diet. A study from Poland (Kałdus) utilized animal bone collagen and apatite to chronicle the human-environment interactions that occurred during the medieval period (Reitsema et al. 2013). A summary of the medieval European diet studies described in this section is shown in Table 4.

Table 4. Summary of medieval European diet studies.

Author(s)	**Time and Place**	**Material(s)**	**Results**
Barrett et al. 2008	9th-15th centuries AD. Arctic Norway, North Sea, Kattegat, and Baltic Sea	Cod (*Gadus sp.*) bone collagen	Cod was traded over very long distances in Northern and Western Europe.
Bayliss et al. 2004	10th-14th centuries AD. Central Norwich, England	Human bone collagen	Diets contained large amounts of marine resources. Pork may have been high-status food.
Burt 2013	14th-15th centuries AD. Fishergate House, York, England	Human bone collagen	Weaning complete by 2 years.
Esclassan et al. 2009	12th-14th centuries AD. Villarnau, France	Human dental wear and caries	Tooth loss caused by deep caries, attrition, periodontitis, and trauma. Females had more caries than males.
Hakenbeck et al. 2010	Early medieval. Bavaria	Human bone collagen	Limited marine resources. Significant sex-based dietary differences.
Halley and Rosvold 2014	1300-1400 AD. Bergen, Norway; NW Europe	Pig (*Sus scrofa*) bone collagen	Pigs from Bergen consumed marine protein.

Author(s)	Time and Place	Material(s)	Results
Kjellström et al. 2009	800-1500 AD. Sigtuna, Sweden	Human bone collagen	High-status individuals ate more animal protein. Females had more homogenous diets.
Lightfoot et al. 2012	800-1000 AD. Ravni Kotari, Croatia	Human bone collagen	Marine component of diet was lost, and C_4 plants were added to diet.
Linderholm and Kjellström 2011	Medieval (after 10th century AD). Sigtuna, Sweden	Human bone collagen	Significant status-based differences in diet.
Mays 1997	10th-15th centuries AD. Northeast England	Human bone collagen	Primarily terrestrial diets, but monastic diets included more marine resources than those of laypeople.
Müldner and Richards 2005	12th-15th centuries AD. Northern England	Human bone collagen	Diet of terrestrial, freshwater, and marine foods. Potential evidence of fasting.
Müldner and Richards 2007	13th-16th centuries AD. Fishergate, York, England	Human bone collagen	Significant sex- and status-based variation in consumption of marine resources.
Müldner et al. 2014	1st-15th centuries AD. Flemish coastal plain, Belgium	Herbivore bone and dentin collagen	Inhabitants regularly employed salt marsh grazing of their livestock.
Polet and Katzenberg 2003	12th-15 centuries AD. Dunes abbey in Koksijde, Belgium	Human and animal bone collagen	Mostly terrestrial diets, some marine resources. Dietary differences may be status-based.
Reitsema and Vercellotti 2012	8th-13th centuries AD. Trino Vercellese, Italy	Human bone and dentin collagen	Diets changed throughout lifetime. There were differences based on sex and status.
Reitsema et al. 2010	11th-12th centuries AD. Giecz, Poland	Human bone collagen and apatite	Male peasants ate more animal protein than did female peasants.
Reitsema et al. 2013	10th-11th centuries AD. Kałdus, Poland	Animal bone collagen and apatite	Extensive use of manure as fertilizer. Fish caught from several ecological niches.
Richards et al. 2002	10th-16th centuries AD. Wharram Percy, England	Human bone and dentin collagen	Weaning complete by 2 years of age.

Author(s)	Time and Place	Material(s)	Results
Richards et al. 2006	800-1200 AD. Newark Bay in Orkney, Scotland	Human bone collagen	Individuals showed heavy consumption of marine foods, with males consuming more than females.
Salamon et al. 2008	1300-1500 AD. Rome, Italy	Human bone and dentin collagen	Marine resource consumption increased due to religious dietary restrictions.
Schutkowski et al. 1999	6th-8th centuries AD. Weingarten, Germany	Human bone collagen	Significant dietary differences were observed between settlements.
Yoder 2010	1100-1500 AD. Øm Kloster, Viborg, and Ribe in Denmark	Human bone collagen and apatite	There was regional but no temporal patterning of diet.
Yoder 2012	Medieval (approximately 1100-1500 AD). Øm Kloster, Denmark	Human bone collagen and apatite	There were status-based differences in diet at the Cistercian monastery.

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While all of these are excellent studies that cover various diet-related topics in the Middle Ages, most of them are clustered around the UK or in Northern Europe. There is a paucity of stable isotope research on the rest of Europe, particularly on Central Europe, during this time period. Only one published work about stable isotope research in Hungary exists, but it focuses on mobility in Neolithic-Copper Age (4500 BC) Hungary, instead of on medieval diet or mobility (Giblin 2009). Lightfoot et al.'s (2012) study from medieval Dalmatia, Croatia is currently the most applicable to this research, as Croatia neighbors Hungary and may have had comparable baseline stable isotopic (e.g., carbon and nitrogen) values.

Limitations of Stable Isotopes in Bioarchaeology

Stable isotope analysis has certainly enriched bioarchaeological studies, but there are limitations that must be taken into account. Depending on the temporal setting of the samples, results may be affected by the post-Industrial Revolution introduction of fossil fuels (Katzenberg 2008). Similarly, stable isotope values can be altered by certain environmental factors, such as climate and source of precipitation (Ambrose and Krigbaum 2003).

While collagen is a crucial part of stable isotope research, it has limitations, as well. It is especially susceptible to diagenetic alteration, which leads to contamination and/or replacement of biogenic stable isotopes (Macko et al. 1999). The older the sample, the more likely that the collagen will hydrolize, denature, or dissolve away (Lee-Thorp 2000). Cleaning procedures in weak acid solutions (e.g., hydrochloric acid solution) are effective in removing surface diagenetic isotopes, but if they have been incorporated deeper, they may skew results. For example, diagenetic dentin carbon can make it appear that the individual consumed more plant protein than he or she actually did.

As Daux et al. (2008) elucidate, establishing a local baseline for oxygen is difficult for several reasons. Multiple environmental factors, such as source of precipitation and evaporation rates, impact the oxygen levels in surface water. Many variables also affect the oxygen isotope values found in human skeletal tissues. Enrichment occurs between the uptake of $^{18}O_{dw}$ and the measurement of $\delta^{18}O_p$, and oxygen isotopic fractionation occurs when food is cooked. These changes vary depending on the type of food consumed, as well as the initial ^{18}O levels of the raw food and cooking water.

CHAPTER THREE: MATERIALS AND METHODS

Samples from Solt-Tételhegy

Between 2005 and 2009, József Szentpéteri led multiple excavations at Solt-Tételhegy (Figs. 5-6). In total, 125 skeletons were recovered and are currently housed in the Anthropology Collection at the Hungarian Natural History Museum in Budapest. The individuals in this study are among the 108 skeletons discovered at the northern edge of the site in 2009. A map of the excavation area is provided in Figure 7. Before proceeding with this chapter, it is important to discuss the previous anthropological research conducted on these individuals.

Figure 5. Photograph of the excavation of the Árpádian/medieval cemetery (image courtesy of J. Szentpéteri).

Figure 6. Photograph of a skeleton interred near the medieval church (image courtesy of J. Szentpéteri).

Figure 7. Excavation map of the cemetery (upper) and the church (lower) at Solt-Tételhegy (courtesy of J. Szentpéteri).

Out of the 125 skeletons, 39 belonged to juveniles, which, according to Fóthi and Bernert (2014), is lower than the expected number. Furthermore, infants under 1 year were missing from the cemetery. This could be due to various reasons, such as the faster decomposition of infant

bones or different funeral practices for infants (Fóthi and Bernert 2014; Szentpéteri 2014). In contemporaneous cemeteries, babies were usually interred in shallower graves, increasing the potential for environmental degradation of their comparatively small and thin bones. Another possibility is that excavation of the cemetery is not yet complete and the infant skeletons are buried in one section. Among the skeletons, there were 47 adult females and 35 adult males. It is noteworthy that between the ages of 15 and 24 years, the mortality rate for adult females was higher than for adult males, perhaps due to deaths during miscarriage, pregnancy, or childbirth. Mortality rates for females peaked at 30-34 years, with as many as 1/4 of the females dying in that age range. Males, too, died most often in middle adulthood, despite few skeletal injuries to suggest accidental or violent deaths (Fóthi and Bernert 2014). The average height for males was 168 cm; for females, 155 cm.

There appear to be two distinctive skull shapes in the sample population. The majority (77%) of individuals have long, narrow skulls, with a moderately high brain case and a tall, thin face, as seen in Figures 8-9. The remaining 23% have hyperbrachycranic skulls, which are characterized by a short, wide brain case and a narrow forehead (Figs 10-11). These hyperbrachycranic skulls suggest origins in the Balkans or the Dinaric Alps (Fóthi and Bernert 2014). The hyperbrachycranic individuals are also taller, with a male (ST 304) reaching 177 cm and a female (ST 300/I) reaching 161.2 cm. The hyperbrachycranic individuals were interred inside a Gothic church, while all members of the first group were buried outside the church. Although the cemetery outside the church was used by various social statuses, ethnicities, and nationalities, most of the individuals were shorter in stature and had longer skulls (Fóthi and Bernert 2014). Based on skull shape, size, and measurements, the individuals found inside the

church (i.e., the hyperbrachycranic individuals) most closely resemble contemporaneous people from Mikulčice, Czech Republic. Significantly, the most populous ethnicity that lived in Mikulčice were the Moravians.

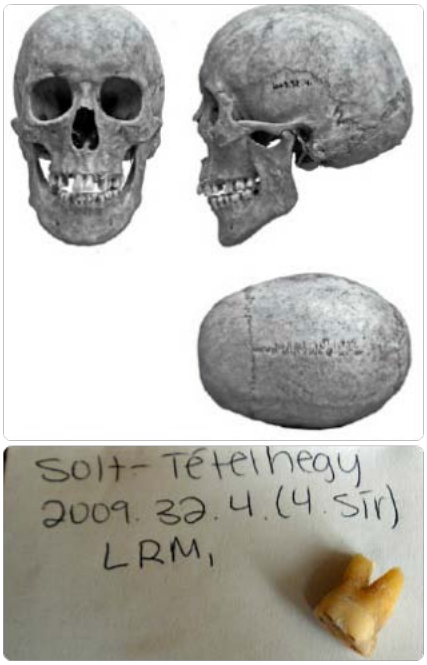

Figure 8. Skull of male (ST 4) excavated from grave 4 in the cemetery (Fóthi and Bernert 2014) and the tooth sample extracted from it (photograph taken by A. Gugora 2014). Note the longer and narrower brain case.

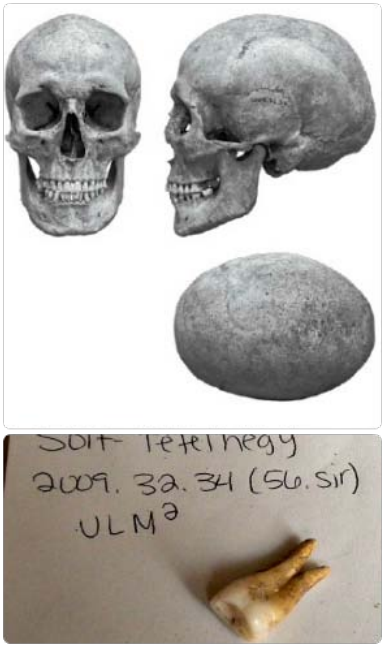

Figure 9. Skull of male (ST 56) excavated from grave 56 in the cemetery (Fóthi and Bernert 2014) and the tooth sample extracted from it (photograph taken by A. Gugora 2014). Again, note the longer and narrower brain case.

Figure 10. Hyperbrachycranic skull of male (ST 304) buried inside the medieval church (Fóthi and Bernert 2014). Note the shorter and wider brain case.

Figure 11. Hyperbrachycranic skull of female (ST 300/I) buried inside the medieval church (Fóthi and Bernert 2014). Again, note the shorter and wider brain case.

Materials

This research sample consists of either 1st or 2nd molars (mandibular or maxillary) from 24 individuals excavated from Solt-Tételhegy's hill-church in 2009. Twelve teeth are from adult males, ten teeth are from adult females, and two teeth are from juvenile individuals whose sex could not be determined (Table 5 and Figs. 12-13). As such, one deciduous molar is present (ST 121/I), while the remaining 23 are permanent molars. The samples were collected at the Hungarian Natural History Museum in Budapest on June 16-17, 2014 using dental pliers. A photograph of each tooth was taken before and after extraction, with relevant site information included. Molars were chosen because they have the largest surface area and contain abundant dentin and enamel from which stable isotopes could be analyzed.

Table 5. Study samples from medieval Solt-Tételhegy, Hungary.

Sample ID	Tooth	Sex	Age (years)	Burial Location
ST 2009.32.4 (4)	LRM1	Male	30-39	Cemetery
ST 2009.32.21 (31)	LLM2	Male	25-29	Cemetery
ST 2009.32.34 (56)	ULM2	Male	40-49	Cemetery
ST 2009.32.35 (57)	LLM1	Male	30-34	Cemetery
ST 2009.32.38 (60)	LRM1	Male	25-29	Cemetery
ST 2009.32.47 (69/I)	LRM1	Male	40-44	Cemetery
ST 2009.32.55 (82)	LRM1	Female	25-34	Cemetery
ST 2009.32.65 (94)	LRM2	Male	35-39	Cemetery
ST 2009.32.55 (95)	LRM1	Male	25-34	Cemetery
ST 2009.32.68 (97)	LRM1	Female	15-17	Cemetery
ST 2009.32.69 (98)	URM1	Female	15-17	Cemetery
ST 2009.32.75 (113)	LRM1	N/A	13-14	Cemetery
ST 2009.32.76 (114)	LLM1	Female	30-39	Cemetery
ST 2009.32.78 (116/I)	LLM1	Female	35-39	Cemetery
ST 2009.32.83 (121/I)	LRM2 (dec.)	N/A	7-8	Cemetery
ST 2009.32.84 (122/I)	LRM1	Female	30-34	Cemetery
ST 2009.32.91 (128)	URM1	Male	35-39	Cemetery
ST 2009.32.100 (145/I)	ULM2	Female	35-39	Cemetery
ST 2009.32.107 (158)	LLM1	Female	30-34	Cemetery
ST 2009.32.109 (167)	LLM1	Male	35-39	Cemetery
ST 2009.32.118 (284)	ULM1	Female	35-39	Church
ST 2009.32.119 (300/I)	LLM2	Female	45-54	Church
ST 2009.32.120 (300/II)	URM2	Male	40-49	Church
ST 2009.32.121 (304)	LRM1	Male	40-44	Church

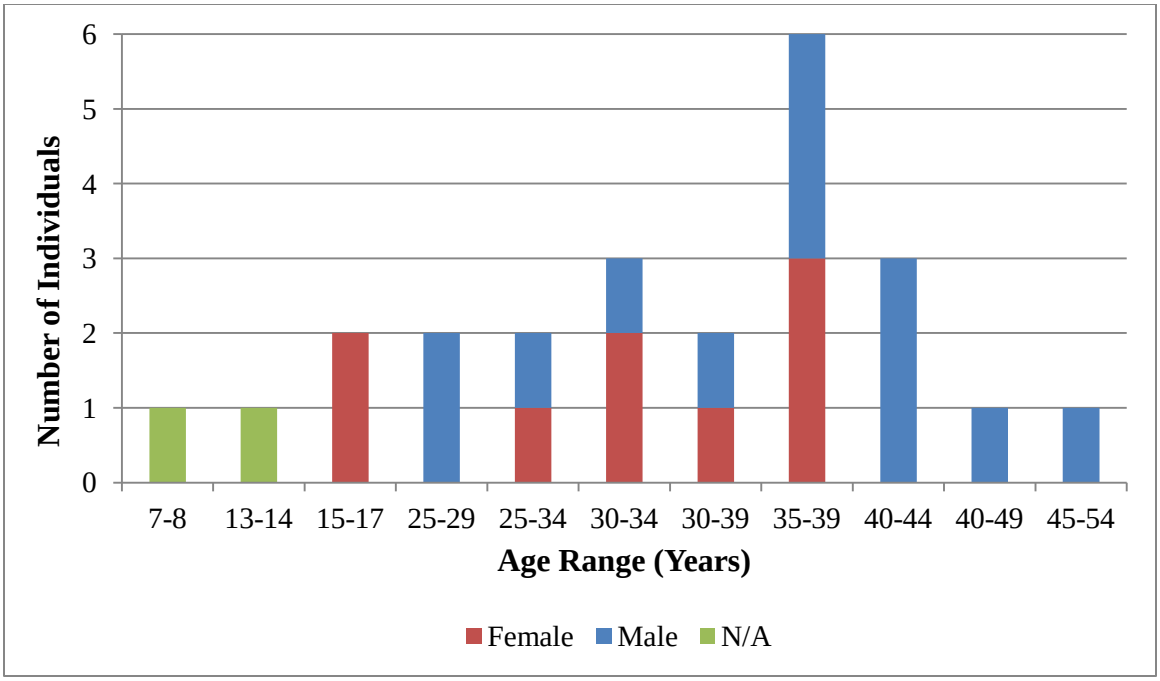

Figure 12. Graph showing the distribution of age (years) and sex from the sample population.

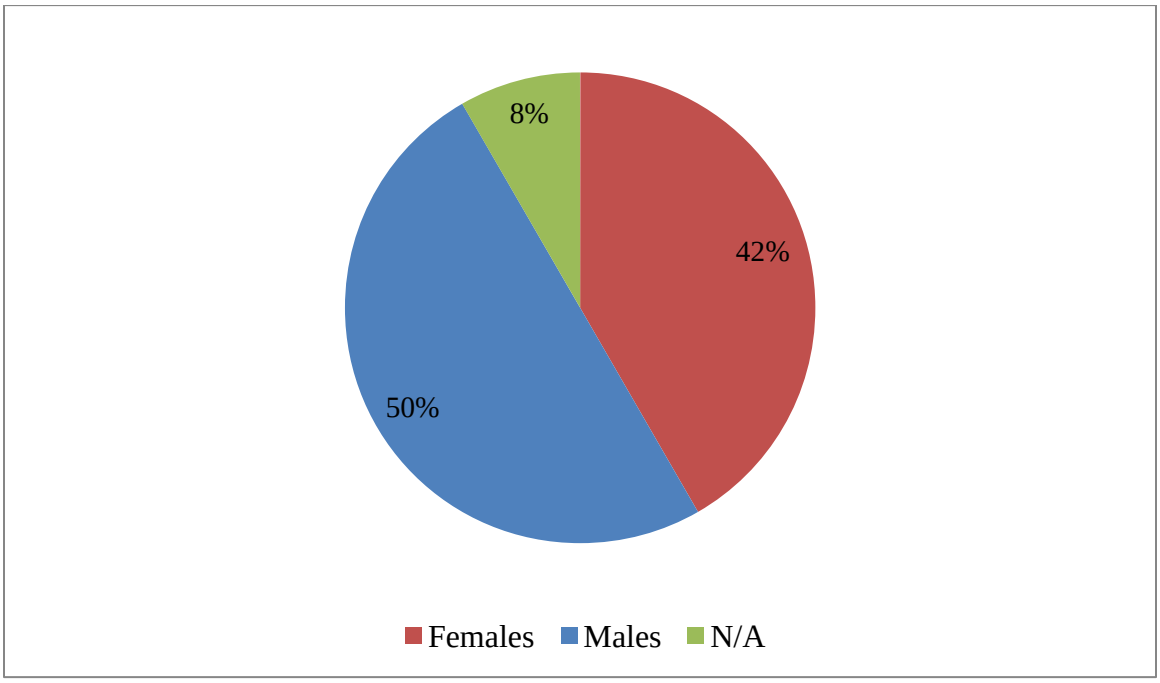

Figure 13. Pie chart with the percentage of sexes in the sample population.

The teeth were in excellent condition, considering the time period and the age of the individuals, with minimal occlusal wear. This ensured that the molars would yield plenty of dentin and enamel. Plaque and calculus were also minimal, as were caries, which only seven individuals demonstrated. Plaque, calculus, and caries were removed using a dental pick and were stored in their respective tooth's plastic sample collection bag. Additionally, the skulls were in good condition, displaying little to no skeletal degradation. The alveolar processes remained intact enough that extracting the teeth sometimes proved difficult. As a result, if the integrity of the mandible or maxilla was deemed to be in jeopardy, another skull with slightly looser dental alveoli was selected. Furthermore, either all or the majority of teeth were still present, whether in the skull or in the grave, suggesting that tooth loss during life was not rampant.

Methods

Using procedures outlined on UCF's Bioarchaeology Lab Protocol sheets (2014, adapted from Longin 1971), collagen was extracted from tooth dentin, while apatite was taken from enamel. The entire extraction process lasted 79 days, not counting the amount of time it took the mass spectrometry labs to analyze the stable isotopes.

Collagen

To clean the teeth, they were first rinsed with de-ionized water in an ultrasonicator machine (Fisher Scientific FS30) until the water was clear and debris-free. The molars were allowed to dry overnight in the oven (Precision Scientific Co. Thelco Model 4) at 60º C. The dentin was manually separated from the enamel, broken into smaller chunks, weighed, and placed into 10 mL glass culture test tubes. Each sample was then immersed into 2 mL of 2%

hydrochloric acid (HCl) solution, which was changed and agitated daily for approximately 2 months, until the dentin demineralized and only a "ghost" or pseudomorph remained.

The demineralized dentin was rinsed 3 times with distilled water and placed into 2 mL of .5 M sodium hydroxide (NaOH) for 20 minutes, while being agitated every 5 minutes. Afterwards, the samples were spun down at 2400 rpm for 10 minutes in a centrifuge (Thermo Scientific Sorvall ST40), and the NaOH cycle was repeated until the solution was clear in color. The NaOH was then removed, and the samples were rinsed at least 5 times in de-ionized water so that the pH reached 7±1. The NaOH step is important because it removes trace elements and/or contaminants that could lead to diagenetic alteration.

Next, 2 mL of .25 M HCl acid solution was added, the samples were spun down, and the acid was removed. Distilled water was added to bring the pH to between 2.5 and 3. The collagen was solubilized by heating it in 2 mL of de-ionized water, after which the test tubes were sealed and baked at 90º C for 24 hours in the Fisher Scientific Isotemp oven. Samples were then transferred into empty glass dram vials (weighed beforehand) to bake uncovered at 60º C for 24-48 hours, until the water evaporated and only collagen remained. The samples were weighed, and the percent yields were calculated using Equation 3.1:

$$\text{collagen yield (\%)} = \left(\frac{\text{collagen weight (g)}}{\text{dry sample weight (g)}}\right) \times 100 \qquad (3.1)$$

The final step was to send the samples to the Colorado Plateau Stable Isotope Laboratory (CPSIL) to stable carbon and nitrogen isotope analysis with the use of a mass spectrometer.

Apatite

Apatite extraction is less time-consuming than collagen extraction, though the first few steps are shared. The teeth were first cleaned in distilled water with an ultrasonicator machine, and they were left to dry overnight in the oven at 60º C. Afterwards, the enamel was manually separated from the dentin and subsequently ground into a fine powder (approximately 180 microns in size), using a steel mortar and pestle. About 20-30 mg of the powdered enamel were weighed out and placed into 2 mL plastic, capped sample tubes.

Then .04 mL of 2% sodium hypochlorite solution per mg of sample was added to the enamel in each of the plastic tubes, after which the bleach solution was left to sit for 24 hours. The next day, the bleach was removed. The samples were rinsed 5 times in de-ionized water, with the help of a centrifuge at 2400 rpm for 5-10 minutes to compact the powder. This step ensured that none of the sample was pipetted out with the liquid.

Next, .04 mL of .1 M acetic acid solution per mg of sample was added to each tube. The uncapped samples were covered with plastic wrap and allowed to stand at room temperature for 4 hours, after which they were again rinsed 5 times with distilled water following the same procedure as for the removal of the bleach. The bleach and acetic acid solutions are essential, because they remove any possible contaminants that could interfere with the stable isotopic values. At this time, it was crucial that all the water was pipetted out, since the tubes were covered with a Kimwipe and placed in the freezer until completely frozen. If any water were to have remained in the sample tube, isotopic exchange could have occurred between the carbonate and the water, which might have skewed results.

Once the samples were frozen, they were freeze-dried for 1-2 days. As the name implies, this process has 2 steps: first, the samples were frozen around -60º C, and then they were dried with the help of a vacuum. By this stage, the powdered enamel has become apatite. Finally, the dried samples were weighed, and the percent yields were calculated using Equation 3.2:

$$\text{Apatite yield (\%)} = \left(\frac{\text{treated sample (mg)}}{\text{untreated sample (mg)}}\right) \times 100 \qquad (3.2)$$

The last step was to send the dentin samples to the Colorado Plateau Analytical Laboratory at Northern Arizona University to undergo mass spectrometry. Stable carbon isotopes were measured in the samples with gas isotope-mass spectroscopy, using a Delta V Advantage Mass Spectrometer, with a Carlo Ebra NC2100 Elemental Analyzer. The enamel samples were sent to the Light Stable Isotope Mass Spectrometry Laboratory at the University of Florida for stable oxygen isotope analysis.

CHAPTER FOUR: RESULTS

This chapter describes the results of the stable isotope analyses for the Solt-Tételhegy sample, including preservation and any differences in isotopic values based on age, sex, tooth type, and burial location. The level of preservation is determined through carbon (%C) and nitrogen (%N) concentrations, collagen yields (%), C:N ratios, and apatite yields (%). Due to inadequate sample size (n=24), no statistical tests were performed. It is important to remember that because the stable isotope analyses employed teeth, not bone, the results reflect childhood, not adulthood, diet.

Sample Preservation

Teeth, like bone, are vulnerable to microbes and post-depositional processes that may degrade the organic (collagen) and mineral (hydroxyapatite) portions of teeth. This can lead to diagenetic alteration of their stable isotopes and, therefore, potentially skewed results.

Collagen

The carbon and nitrogen isotopes extracted from dentin collagen are particularly at risk of diagenesis, because dentin's biochemical structure is less compacted than that of enamel. As a result, there are larger spaces between the molecules into which microbial contaminants may embed themselves. Preservation for dentin collagen was assessed using carbon (%C) and nitrogen (%N) concentrations, collagen yields (%), and C:N ratios. Table 6 presents the stable carbon and nitrogen isotope results from dentin collagen, as well as the levels of preservation.

Table 6. Stable carbon and nitrogen isotope results from dentin collagen for the Solt-Tételhegy samples.

Sample ID	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	%C	%N	Collagen Yield (%)	C:N
ST 2009.32.4 (4)	-17.2	10.5	41.8	15.3	14.8	3.19
ST 2009.32.21 (31)	-17.8	10.8	42.2	15.2	12.1	3.22
ST 2009.32.34 (56)	-17.7	10.2	46.9	16.9	16.7	3.22
ST 2009.32.35 (57)	-17.5	10.2	50.5	18.3	14.5	3.22
ST 2009.32.38 (60)	-17.2	10.9	39.7	14.2	8.2	3.24
ST 2009.32.47 (69/I)	-16.3	10.7	41.4	15.0	11.5	3.21
ST 2009.32.55 (82)	-17.0	10.0	42.5	15.6	15.7	3.19
ST 2009.32.65 (94)	-17.2	10.2	42.4	15.4	15.4	3.20
ST 2009.32.66 (95)	-19.4	11.5	39.2	14.2	10.3	3.21
ST 2009.32.68 (97)	-16.8	11.6	40.6	14.7	15.1	3.22
ST 2009.32.69 (98)	-17.0	11.0	39.6	14.4	9.0	3.20
ST 2009.32.75 (113)	-17.3	10.6	43.1	15.6	15.3	3.22
ST 2009.32.76 (114)	-18.9	11.3	41.2	15.0	17.1	3.20
ST 2009.32.78 (116/I)	-14.9	11.0	41.8	15.0	16.8	3.23
ST 2009.32.83 (121/I)	-17.4	10.3	42.6	15.6	17.7	3.19
ST 2009.32.84 (122/I)	-16.0	10.5	42.1	15.4	18.1	3.19
ST 2009.32.91 (128)	-17.8	10.6	42.4	15.4	16.9	3.21
ST 2009.32.100 (145/I)	-17.1	11.6	42.3	15.2	16.1	3.23
ST 2009.32.107 (158)	-16.5	10.6	41.0	15.9	16.0	3.22
ST 2009.32.109 (167)	-17.0	10.0	41.1	14.9	17.2	3.21
ST 2009.32.118 (284)	-17.7	10.2	40.9	14.8	14.8	3.22
ST 2009.32.119 (300/I)	-18.4	10.7	42.3	15.4	16.4	3.21
ST 2009.32.120 (300/II)	-18.4	9.5	42.0	15.2	17.9	3.21
ST 2009.32.121 (304)	-18.1	10.2	42.7	15.5	17.7	3.21
Minimum	-19.4	9.5	39.2	14.2	8.2	3.19
Maximum	-14.9	11.6	50.5	18.3	18.1	3.24

The first measures of tooth preservation are carbon and nitrogen concentrations within the sample collagen. These levels are determined from the amount of CO_2 and N_2 in the collagen, using a mass spectrometer. As written by Ambrose (1990), modern collagen should contain 15.3-

47% carbon and 5.5-17.3% nitrogen, but these ranges are deemed applicable to archaeological collagen, as well. Only one sample from this study (ST 57, with %C=50.5 and %N=18.3) showed a %C and a %N outside the acceptable range (Figs. 14-15). However, because these values are only slightly greater than the accepted ranges, they are still adequate for the purpose of this study. As expected, there is a strong linear relationship between the carbon and nitrogen concentrations for this sample (Fig. 16).

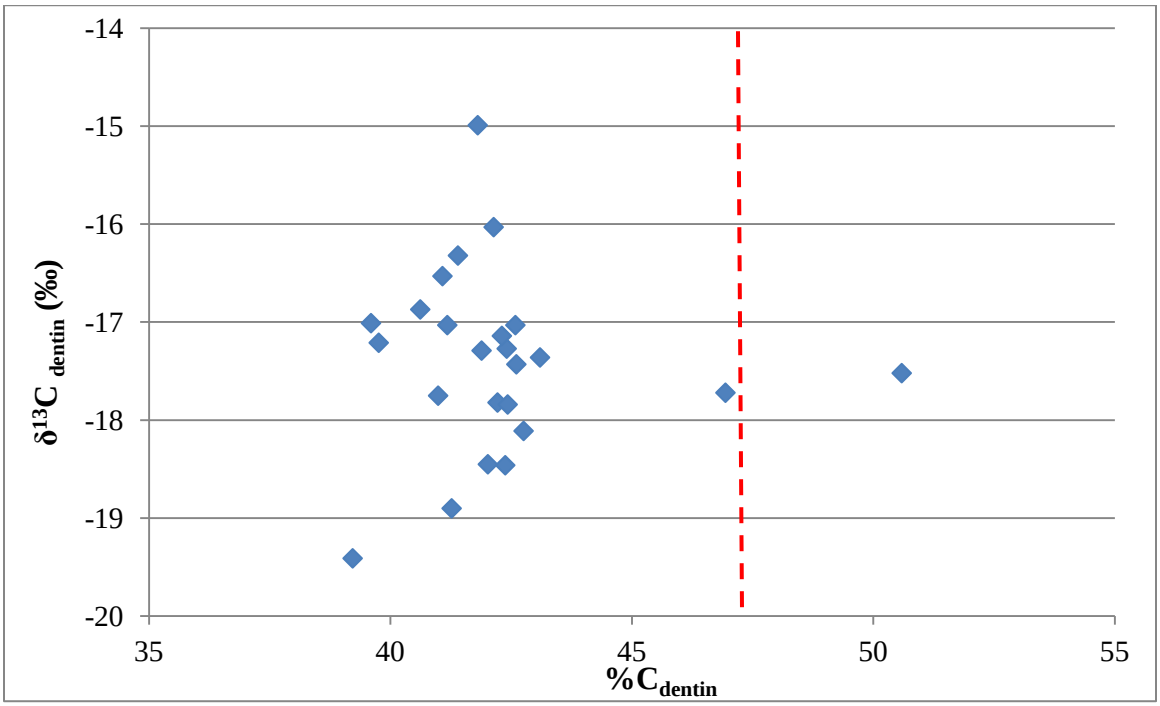

Figure 14. Graph of the carbon weight percentage (% C) and $\delta^{13}C$ (‰) values from dentin collagen. The red dotted line indicates the maximum cut-off for acceptable collagen preservation at 47%.

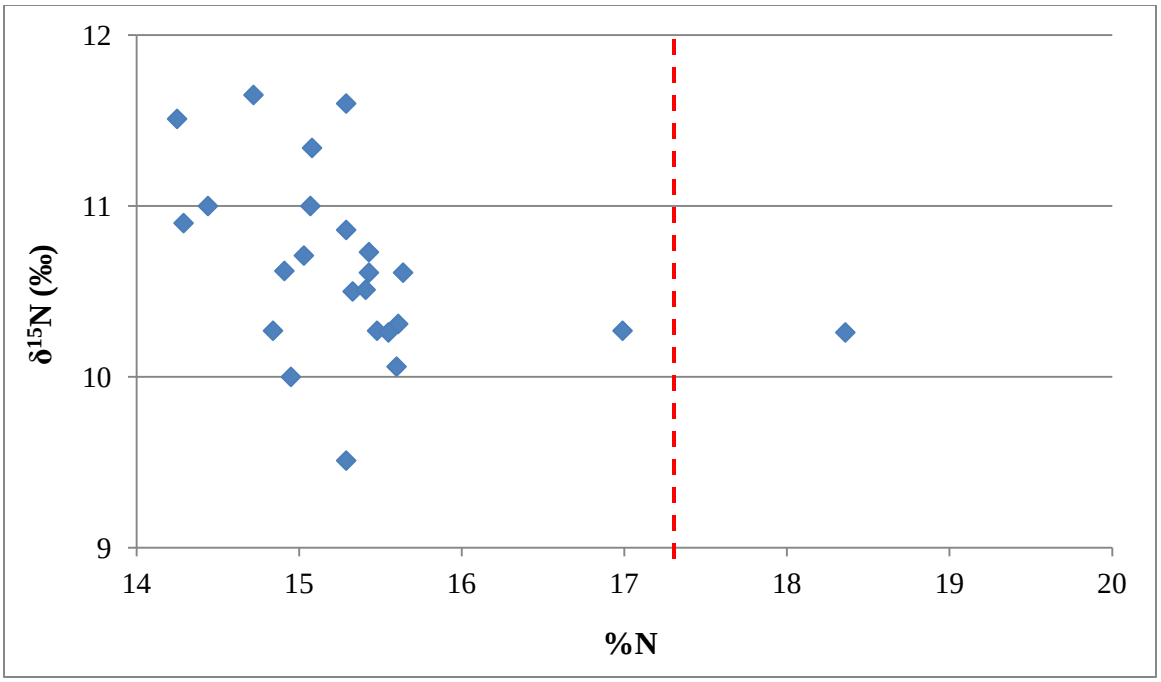

Figure 15. Graph showing the nitrogen weight percentage (%N) and $\delta^{15}N$ (‰) from dentin collagen. The red dotted line shows the maximum cut-off for acceptable collagen preservation at 17.3%.

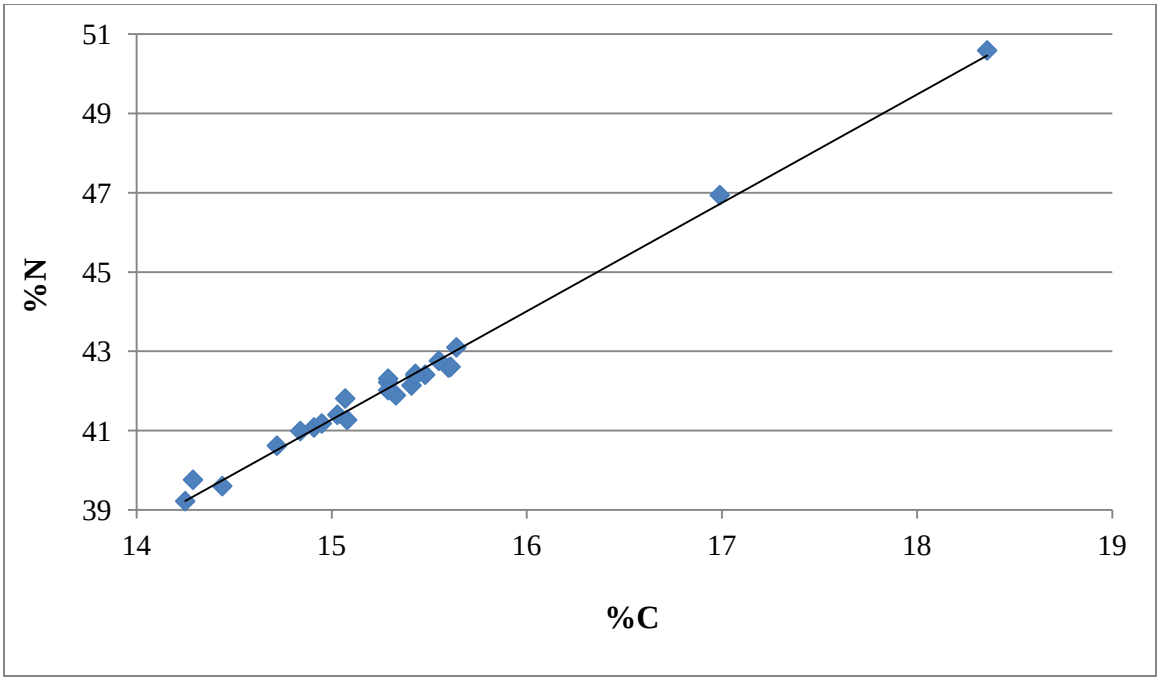

Figure 16. Graph depicting the linear relationship (with a trend line) between the carbon weight percentage (%C) and the nitrogen weight percentage (%N) from dentin collagen samples.

Collagen yield is the proportion of extracted collagen to the initial dentin. It is calculated using Equation 4.1:

$$\text{collagen yield (\%)} = \frac{\text{collagen weight (g)}}{\text{dentin dry weight (g)}} \times 100 \qquad (4.1)$$

According to DeNiro (1985), Ambrose (1990), and van Klinken (1999), an acceptable collagen yield for archaeological skeletal material is at least 2%. All samples in this study exhibit collagen yields above 2% and can thus be considered well-preserved. One sample is slightly over the acceptable range for %C and %N, but it is still deemed to be well-preserved.

Because archaeological samples are at greater risk of diagenetic alteration of their stable isotopes than are modern samples, a correction factor must be applied to calculate the atomic

carbon to nitrogen (C:N) ratio. As adapted from Katzenberg (2008), the ratio is calculated using Equation 4.2:

$$\text{atomic C:N} = \frac{14}{12} \times \left(\text{weight \%} \ \frac{\text{C}}{\text{N}}\right) \qquad (4.2)$$

This formula is also necessary because mass spectrometers calculate weight ratios of carbon to nitrogen that are lighter by a factor of 14/12 than the ratios put forth by DeNiro (1985). Thus, the C:N ratio must be adjusted to account for this discrepancy. Well-preserved archaeological samples have C:N ratios between 2.9 and 3.6 (DeNiro 1985). All samples from Solt-Tételhegy fall within this range (Fig. 17), even the sample that is slightly outside the acceptable range for %C and %N.

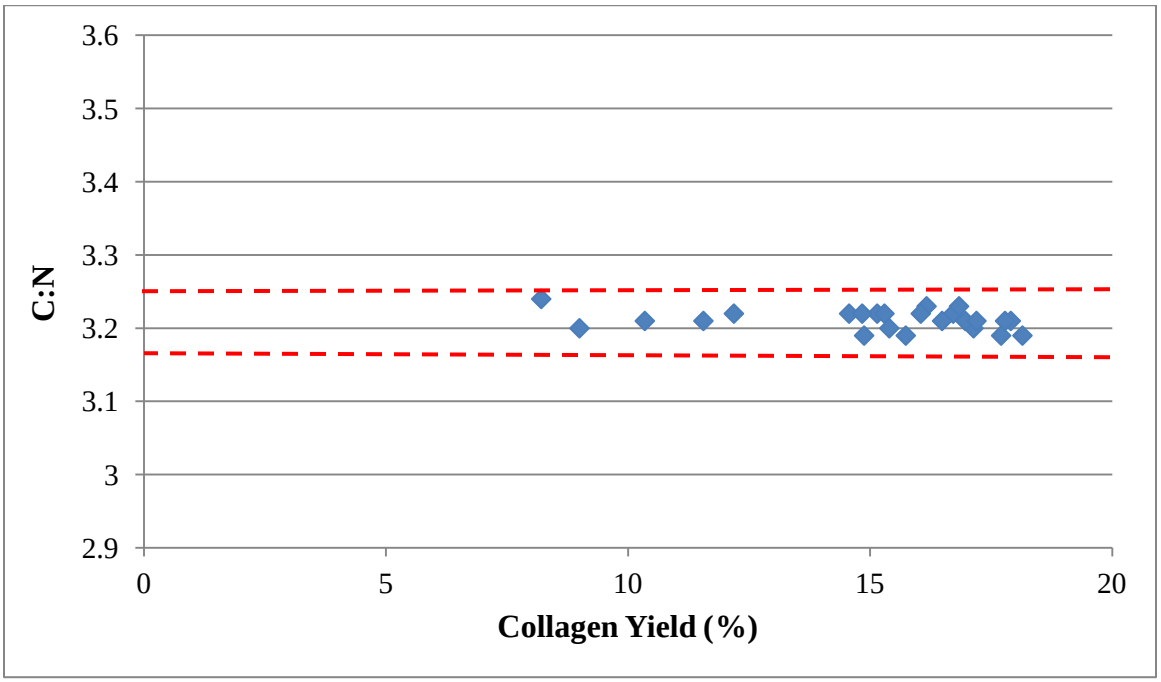

Figure 17. Graph depicting the collagen yield vs. the C:N ratio from dentin. The red dotted lines show that the sample falls within the acceptable C:N range.

Apatite

Because tooth enamel is nonporous, unlike dentin, it is less subject to diagenetic alteration of its stable isotopes. Table 7 presents the stable carbon and oxygen isotope results from enamel apatite. If one considers that a yield of 2% is sufficient for isotope analysis (DeNiro 1985; Ambrose 1990; van Klinken 1999), then the apatite yields for this sample, which are all greater than 50%, indicate that the teeth are very well-preserved. Apatite yield is the proportion of extracted apatite to the dry enamel and is calculated using Equation 4.3:

$$\text{apatite yield (\%)} = \frac{\text{apatite weight (mg)}}{\text{dry enamel weight (mg)}} \times 100 \qquad (4.3)$$

Table 7. Stable carbon and oxygen isotope results from enamel apatite for the Solt-Tételhegy samples.

Sample ID	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Apatite Yield (%)
ST 2009.32.4 (4)	-11.4	24.5	94.5
ST 2009.32.21 (31)	-11.9	23.7	75.6
ST 2009.32.34 (56)	-11.4	23.6	92.4
ST 2009.32.35 (57)	-10.8	24.3	91.1
ST 2009.32.38 (60)	-11.0	25.5	92.3
ST 2009.32.47 (69/I)	-9.8	24.6	92.0
ST 2009.32.55 (82)	-10.1	25.4	91.2
ST 2009.32.65 (94)	-11.3	24.3	92.9
ST 2009.32.66 (95)	-14.4	25.4	92.3
ST 2009.32.68 (97)	-11.2	25.1	91.4
ST 2009.32.69 (98)	-10.1	24.8	91.9
ST 2009.32.75 (113)	-11.6	26.3	90.7
ST 2009.32.76 (114)	-13.2	25.3	90.6
ST 2009.32.78 (116/I)	-10.2	24.6	93.4
ST 2009.32.83 (121/I)	-9.6	25.0	92.7
ST 2009.32.84 (122/I)	-10.4	25.0	90.6
ST 2009.32.91 (128)	-11.1	27.2	87.1
ST 2009.32.100 (145/I)	-9.6	25.1	92.9
ST 2009.32.107 (158)	-9.3	25.0	69.2
ST 2009.32.109 (167)	-8.6	24.8	93.6
ST 2009.32.118 (284)	-10.8	24.8	93.4
ST 2009.32.119 (300/I)	-12.6	26.6	93.2

Sample ID	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	Apatite Yield (%)
ST 2009.32.120 (300/II)	-12.9	26.3	71.6
ST 2009.32.121 (304)	-12.3	N/A	93.2
Minimum	-14.6	23.6	69.2
Maximum	-8.6	27.2	94.5

Diet

Stable carbon and nitrogen isotope analysis was conducted on teeth from 24 individuals from Solt-Tételhegy, Hungary to examine childhood diet. Carbon and nitrogen isotope ratios are given in the standard delta (δ) notation, in per mil (‰).

Collagen

The $\delta^{13}C$ values plotted against $\delta^{15}N$ values are shown in numerous figures that are differentiated by age, tooth type, sex, and burial location. Figure 18 depicts the relationship between carbon and nitrogen isotope values. Figure 19 plots dentin carbon isotope values against median age. Figure 20 shows nitrogen isotope values against median age, while Figure 21 plots dentin carbon and nitrogen against each other. For Figures 19-21, tooth type has been included as an additional variable. As shown in the graphs, the $\delta^{13}C$ ratios range from -19.4‰ to -14.9‰, with a mean of -17.4‰, and the $\delta^{15}N$ ratios range from 9.5‰ to 11.6‰, with a mean of 10.6‰. The $\delta^{13}C$ values are relatively evenly distributed, except for two outliers, -19.4‰ (ST 95) and -14.9‰ (ST 116/I), which are both first molars, as seen in Figure 19. The $\delta^{15}N$ values appear to be more strongly affected by tooth type. The only sample with a value less than 10‰ (ST 300/II, at 9.5‰) came from a second molar, which forms later during tooth development than the first molar. One second molar (ST 145/I, at 11.6‰) also has a value greater than 1‰, as well as three

first molars (ST 114, at 11.3‰; ST 95, at 11.5‰; and ST 94, at 11.6‰). For the graphs that include median age, it is important to remember that the median age applies only to the age at which the individual died, not to the age of tooth formation.

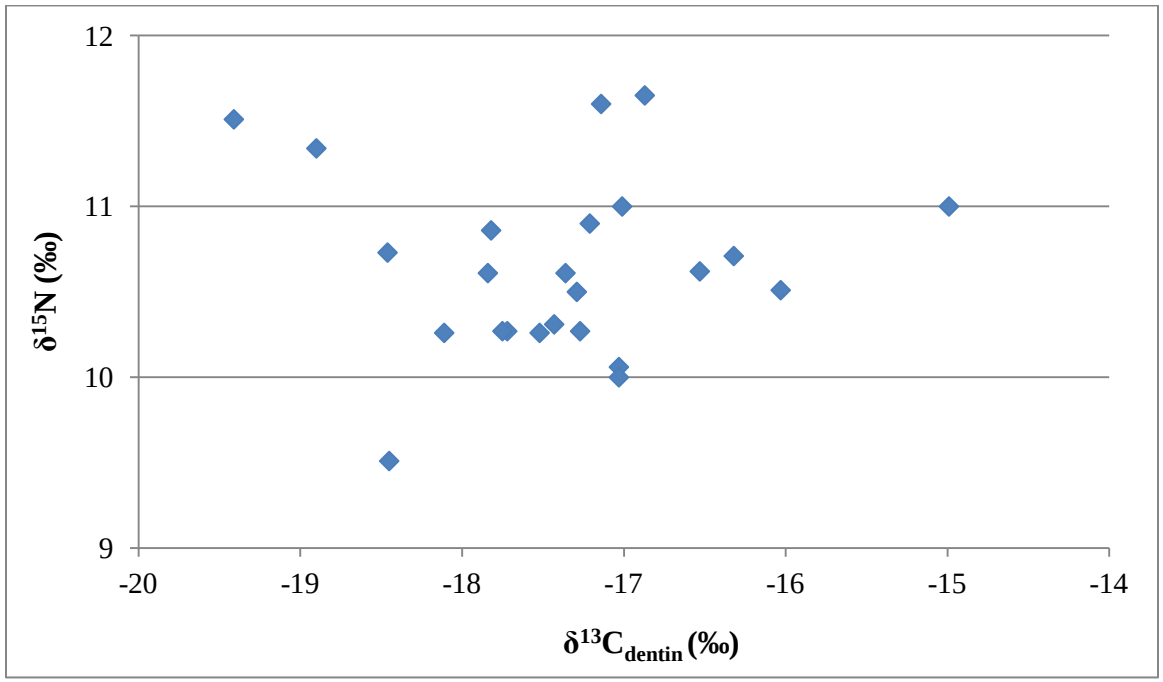

Figure 18. Graph depicting $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) from dentin collagen.

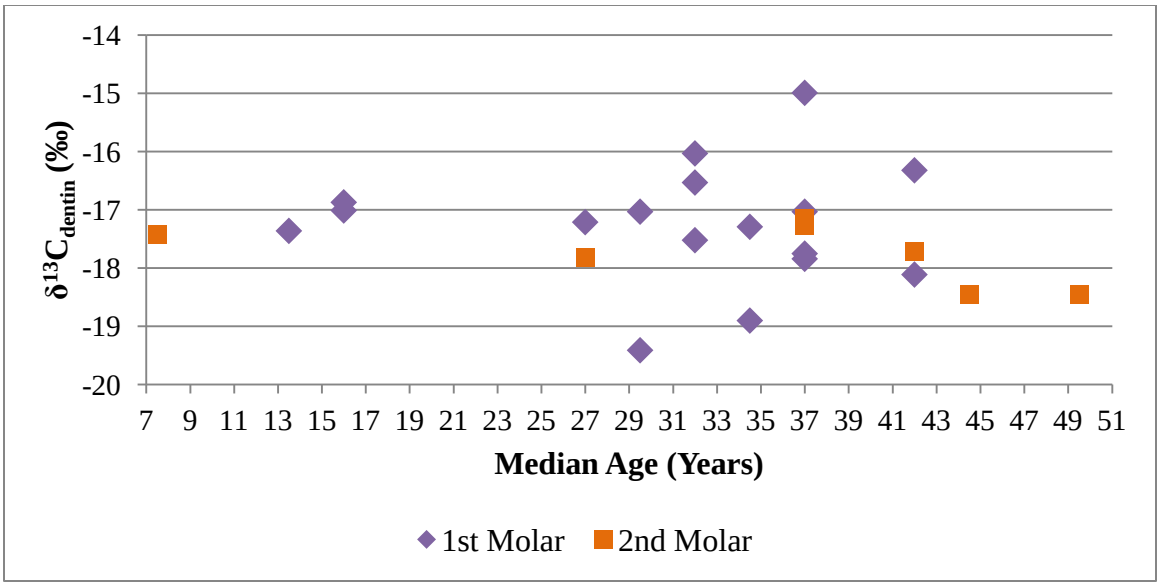

Figure 19. Graph showing the relationship between median age (years) and $\delta^{13}C$ (‰) from dentin collagen. The results are sorted by tooth type.

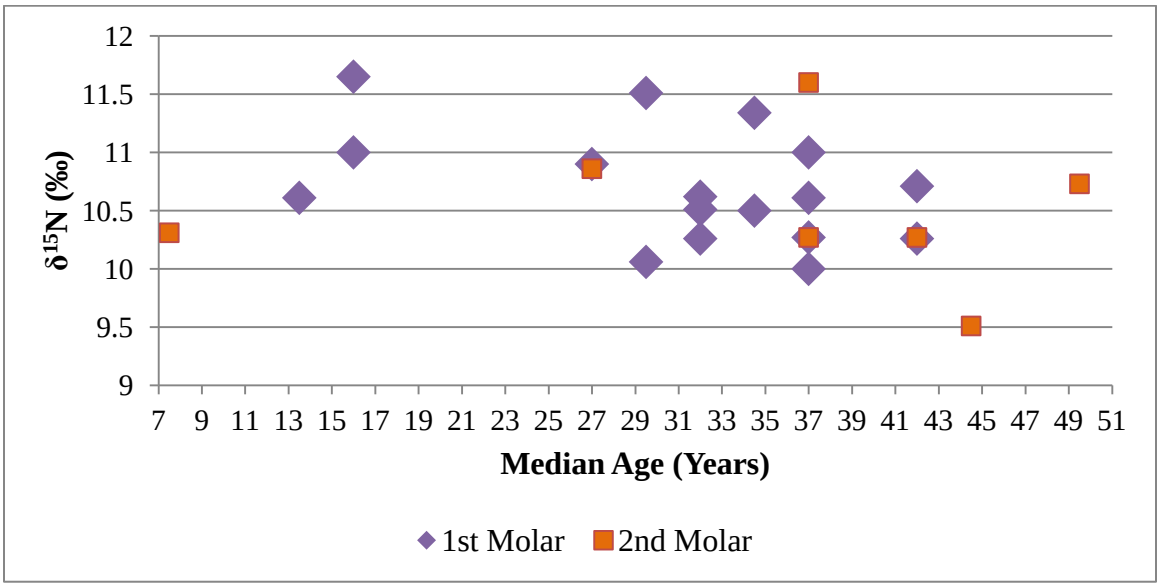

Figure 20. Graph depicting the relationship between median age (years) and $\delta^{15}N$ (‰) from dentin collagen. The results are sorted by tooth type.

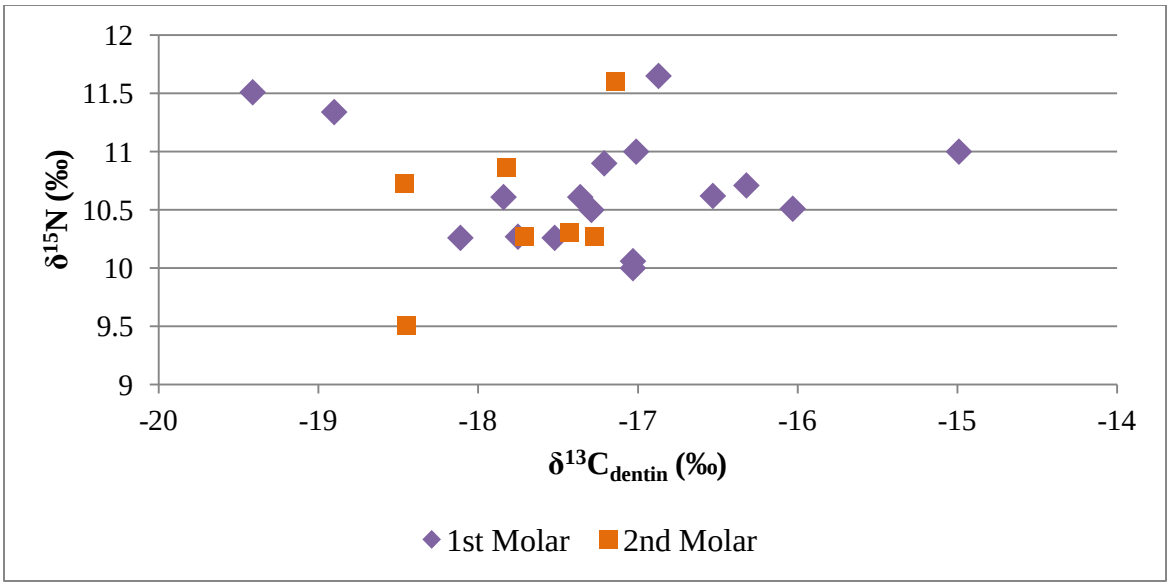

Figure 21. Graph comparing $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) from dentin collagen. The results are differentiated by tooth type.

Figure 22 depicts dentin $\delta^{13}C$ against $\delta^{15}N$, sorted by sex. The majority of individuals are clustered in the center of the graph, but the highest dentin $\delta^{13}C$ (ST 116/I, at -14.9‰) and $\delta^{15}N$ (ST 97, at 11.6‰) values belong to females; the lowest (ST 95, at -19.4‰ and ST 300/II, at 9.5‰, respectively), to males.

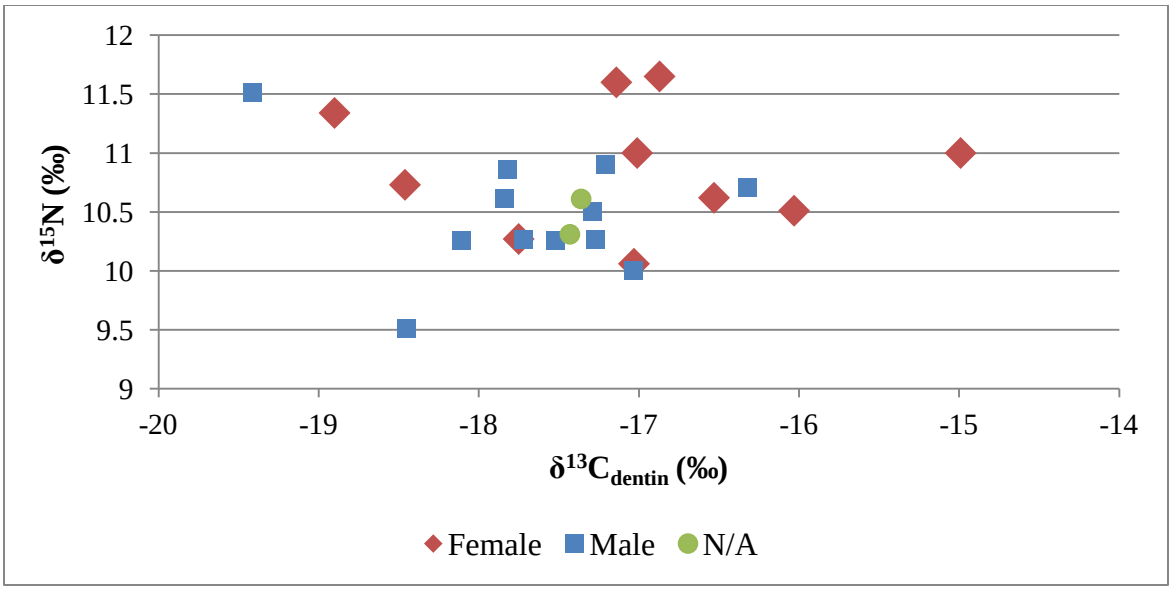

Figure 22. Graph comparing $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) from dentin collagen. The results are sorted by sex.

Of the 24 individuals in this study sample, 20 were buried in a cemetery surrounding a Gothic church, while four were buried inside the church itself. Figure 23 compares stable carbon and nitrogen isotope values based on burial location. The majority of samples are evenly distributed, but there are clear outliers among the carbon ($\delta^{13}C$= -19.4‰ and -14.9‰) and nitrogen ($\delta^{15}N$= 9.5‰, 11.3‰, 11.6‰, and 11.6‰) isotopes. It appears that this variation is affected by burial location, as the lowest $\delta^{15}N$ value came from an individual buried inside the church and the highest from outside it. Additionally, it should be noted that both the lowest and the highest $\delta^{13}C$ values were found in individuals interred in the cemetery.

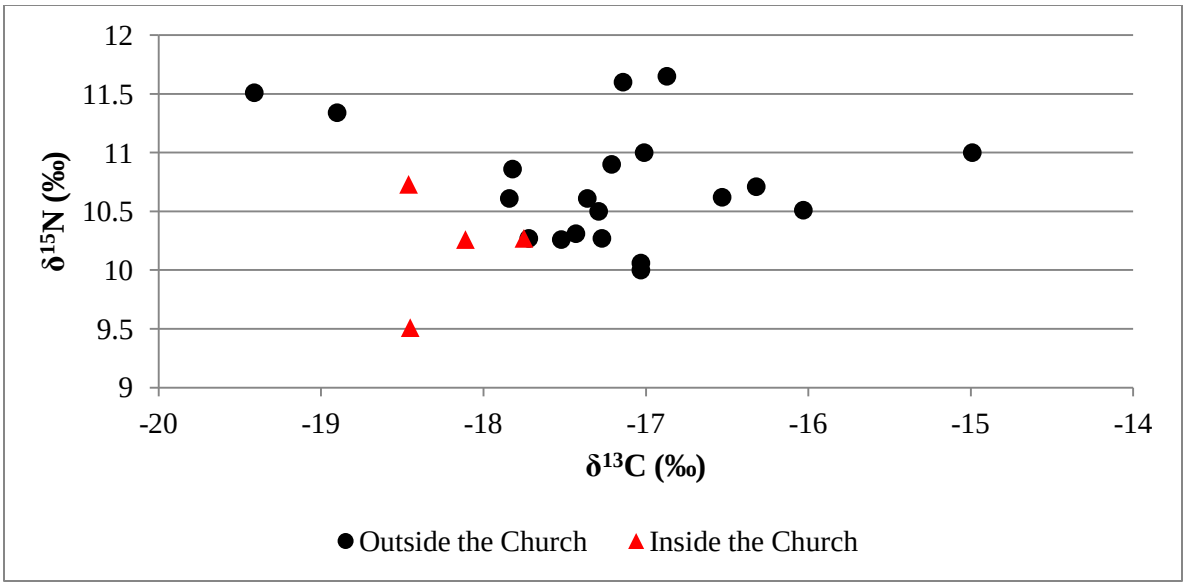

Figure 23. Graph comparing $\delta^{13}C$ (‰) and $\delta^{15}N$ (‰) from dentin collagen. The results are distinguished by burial location.

The percentage of C_4 plants consumed by each individual in the sample can be calculated using White and Schwarcz's (1989) formula, shown in Equation 4.4:

$$\text{percentage } C_4 = \frac{(\delta_c - \delta_3 + \Delta_{dc})}{(\delta_4 - \delta_3)} \times 100 \qquad (4.4)$$

where δ_c= the sample's $\delta^{13}C$ value, Δ_{dc}= the isotopic fractionation between diet and individual (-5), δ_3= the average $\delta^{13}C$ value of C_3 plants (-26‰), and δ_4= the average $\delta^{13}C$ of C_4 plants (-9‰). However, this study modifies the equation to better suit the sample population. Instead of using White and Schwarcz's (1989) δ_4 value, van der Merwe's (1982) value of -12.5‰ is preferable, because corn, a C_4 plant from the Americas, was not consumed in Europe during the 1200s AD. Therefore, the new formula can be seen in Equation 4.5:

$$\text{percentage } C_4 = \frac{(\delta_c - (-26) + (-5))}{(-12.5 - (-26))} \times 100 \qquad (4.5)$$

Table 8 presents the dentin $\delta^{13}C$ values and the estimated percentage of C_4 plants (PC_4) consumed by each individual in the sample. The percentage of C_4 plants eaten range from 11.7% to 44.5%, with an average of 26.7%.

Table 8. Values for dentin $\delta^{13}C$ and percentage of C_4 plants (PC_4) in the diet of the research sample, sorted from lowest to highest PC_4 value.

Sample ID	$\delta^{13}C_{dentin}$ (‰)	PC_4 (%)	Sex	Tooth
ST 95	-19.4	11.7	Male	M1
ST 114	-18.9	15.5	Female	M1
ST 300/I	-18.4	18.8	Female	M2
ST 300/II	-18.4	18.8	Male	M2
ST 304	-18.1	21.4	Male	M1
ST 128	-17.8	23.4	Male	M1
ST 31	-17.8	23.5	Male	M2
ST 284	-17.7	24.0	Female	M1
ST 56	-17.7	24.3	Male	M2
ST 57	-17.5	25.7	Male	M1
ST 121/I	-17.4	26.4	N/A	M2
ST 113	-17.3	26.9	N/A	M1
ST 4	-17.2	27.4	Male	M1
ST 94	-17.2	27.6	Male	M2
ST 60	-17.2	28.0	Male	M1
ST 145/I	-17.1	28.6	Female	M2
ST 82	-17.0	29.4	Female	M1
ST 167	-17.0	29.4	Female	M1
ST 98	-17.0	29.5	Female	M1
ST 97	-16.8	30.5	Female	M1
ST 158	-16.5	33.1	Female	M1
ST 69/I	-16.3	34.6	Male	M1
ST 122/I	-16.0	36.8	Female	M1
ST 116/I	-14.9	44.5	Female	M1

Figures 24, 25, and 26 show the dentin $\delta^{13}C$ versus $\delta^{15}N$ values with the percentages of C_4 plants consumed by the people in this sample, differentiated by sex, tooth type, and burial location, respectively. Nine individuals had diets comprised of <25% C_4 plants, and 15 individuals had diets that included between 25% and 50% C_4 plants. No one from the population consumed

between 50% and 75% C_4 plants or >75% C_4 plants. There appears to be only a moderate relationship between sex and the percentage of C_4 plants consumed, with the majority of females eating between 25-50% C_4 plants. Males, however, are relatively evenly distributed. Most of the first molars fall into the 25-50% C_4 range, while the second molars are more evenly distributed, as Figure 25 displays.

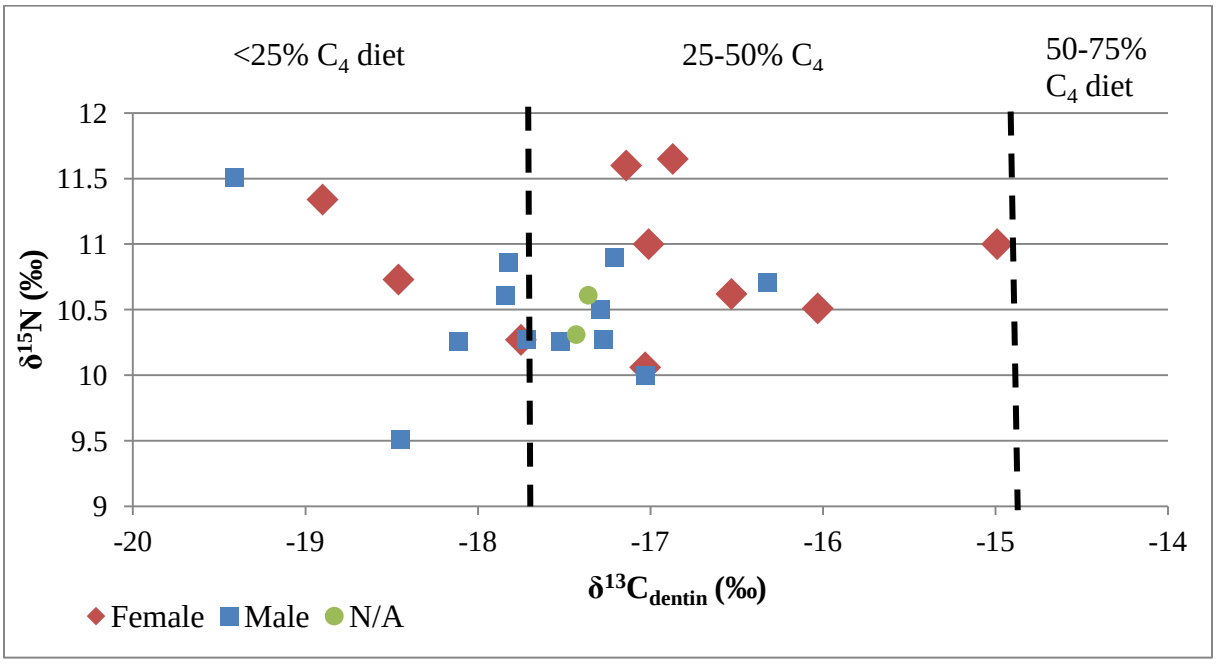

Figure 24. Graph showing the percentage of C_4 plants consumed in relation to dentin $\delta^{13}C$ (‰) versus $\delta^{15}N$ (‰) values. The results are sorted by sex.

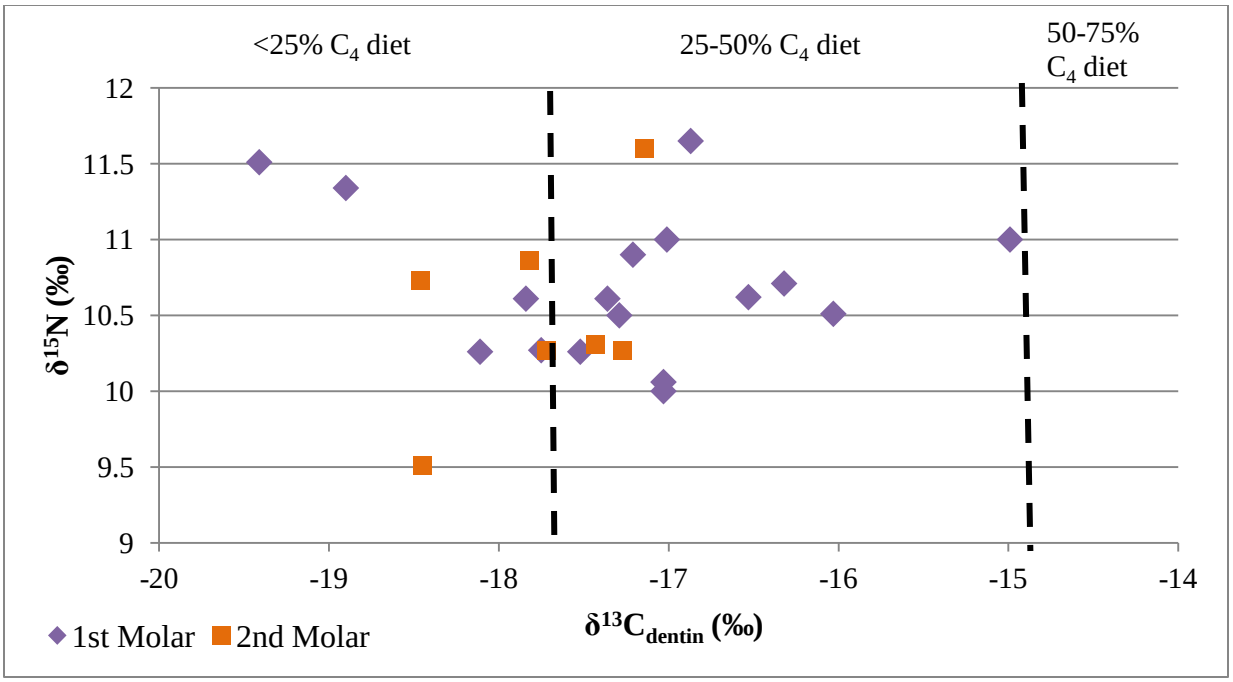

Figure 25. Graph showing the percentage of C_4 plants consumed in relation to dentin $\delta^{13}C$ (‰) versus $\delta^{15}N$ (‰). The results are distinguished by tooth type.

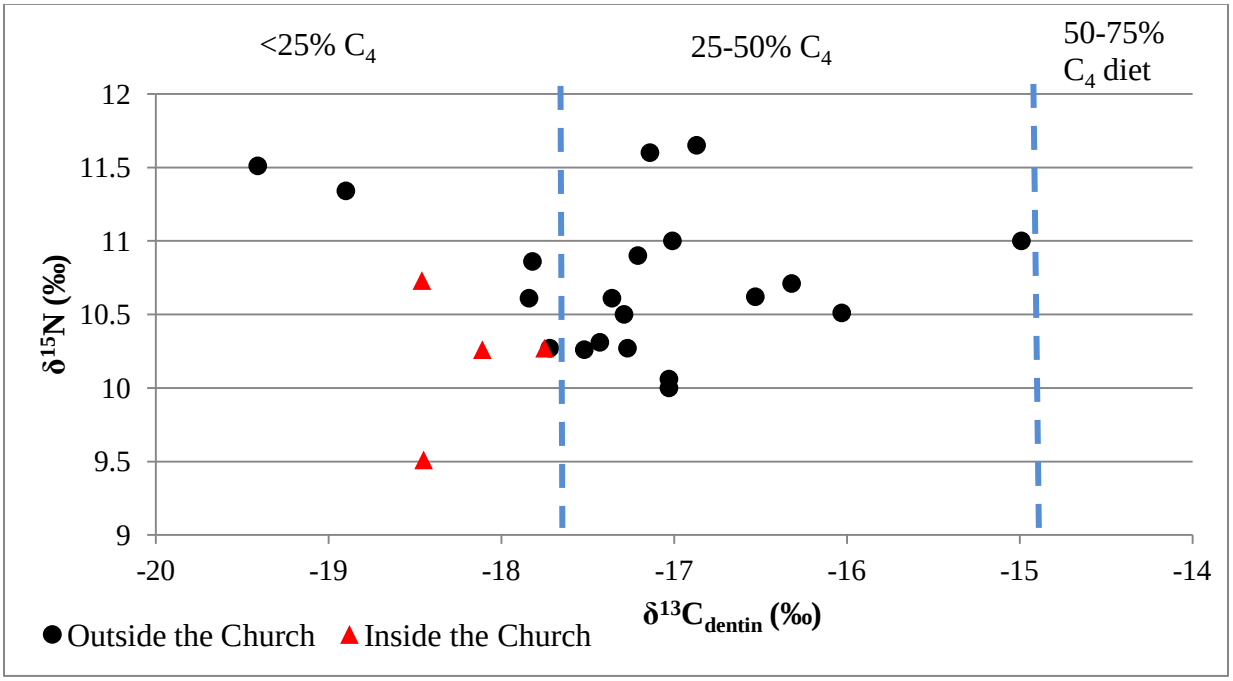

Figure 26. Graph depicting the percentage of C_4 plants consumed in relation to dentin $\delta^{13}C$ (‰) versus $\delta^{15}N$ (‰). The results are sorted by burial location.

The creation of a food web was not possible for this sample, because there is currently no stable isotope data for flora or fauna from medieval Hungary.

Apatite

Figure 27 depicts the relationship between median age and carbonate isotope values, differentiated by tooth type. The enamel $\delta^{13}C$ ratios range from -14.4‰ to -8.6‰, with a mean of -11.1‰. The values are relatively scattered, with just one obvious outlier ($\delta^{13}C$= -14.4‰), in a first molar. However, another first molar ($\delta^{13}C$ = -8.6‰) is the only tooth with a carbonate isotope value greater than -9‰.

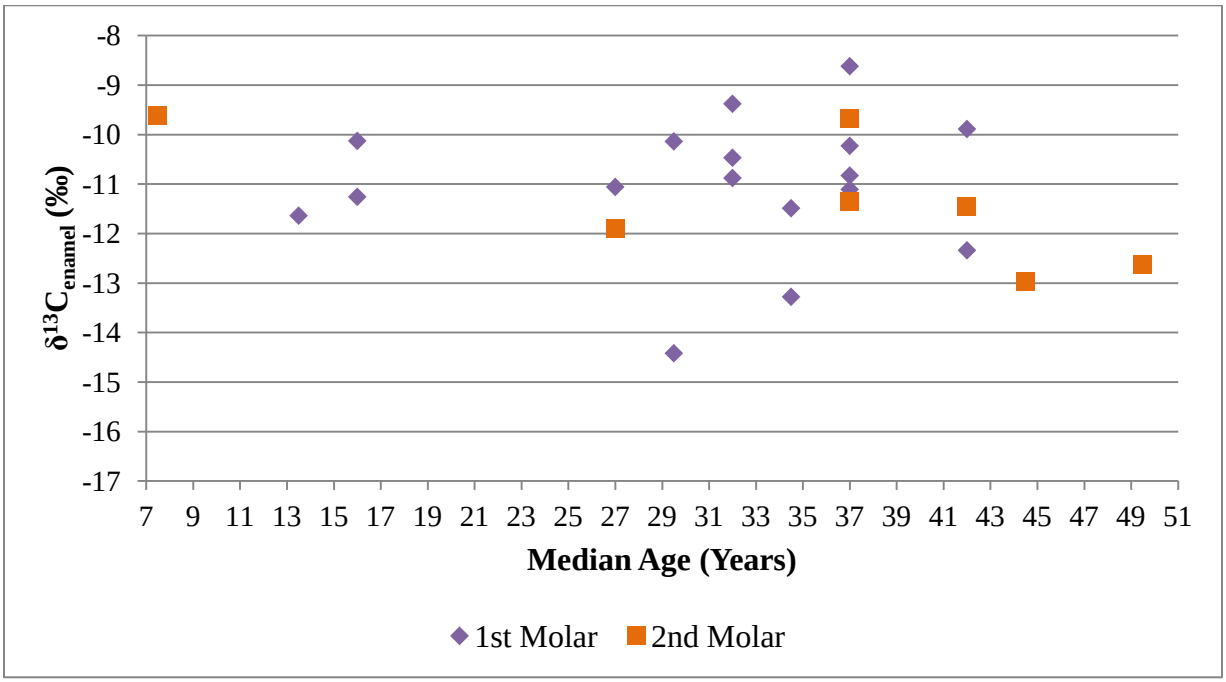

Figure 27. Graph of the relationship between median age (years) and $\delta^{13}C$ (‰) from enamel apatite. The results are distinguished by tooth type.

When examining stable carbon isotope values from enamel, Figure 28 shows that there are sex-based differences. Although most of the values are clustered between -12‰ and -9‰,

three values stand out. Males display both the lowest (-14.4‰) and highest (-8.6‰) values, while a female has the next lowest (-13.2‰) carbonate value.

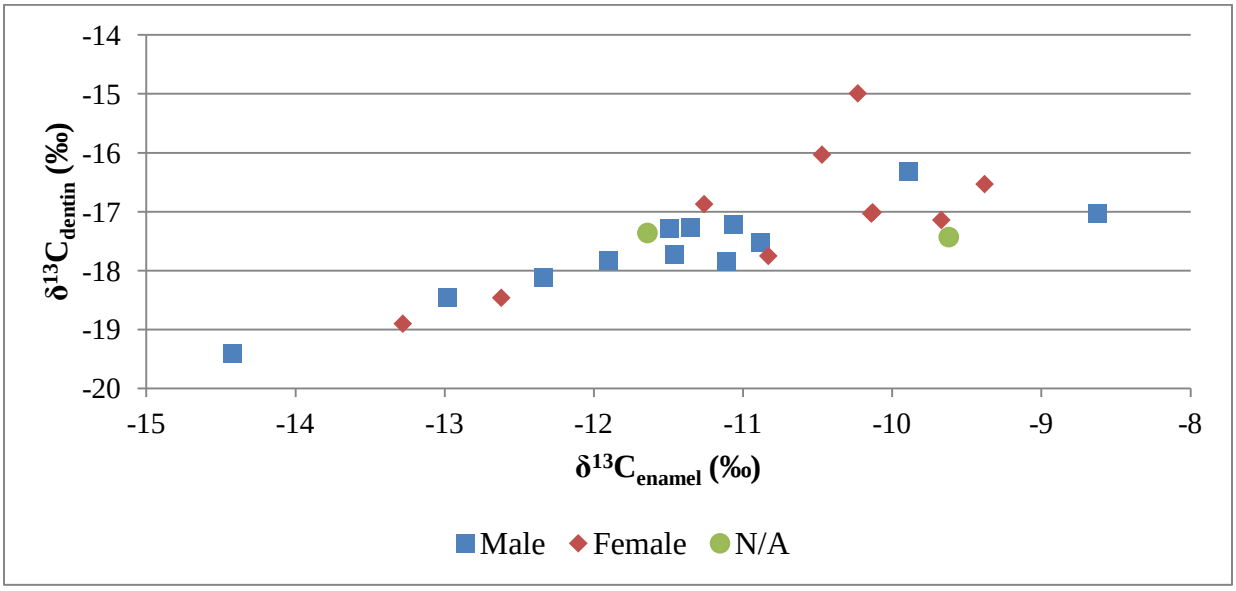

Figure 28. Graph depicting differences in $\delta^{13}C$ (‰) from enamel apatite (carbonate) and $\delta^{13}C$ (‰) from dentin collagen. The results are differentiated by sex.

The effect of burial location on enamel carbon values can be seen in Figure 29. The lowest (-14.4‰) and highest (-8.6‰) enamel $\delta^{13}C$ values came from individuals buried in the cemetery outside the church. The values of three people interred inside the church cluster between -13‰ and -12‰, while a fourth is an outlier at -10.8‰.

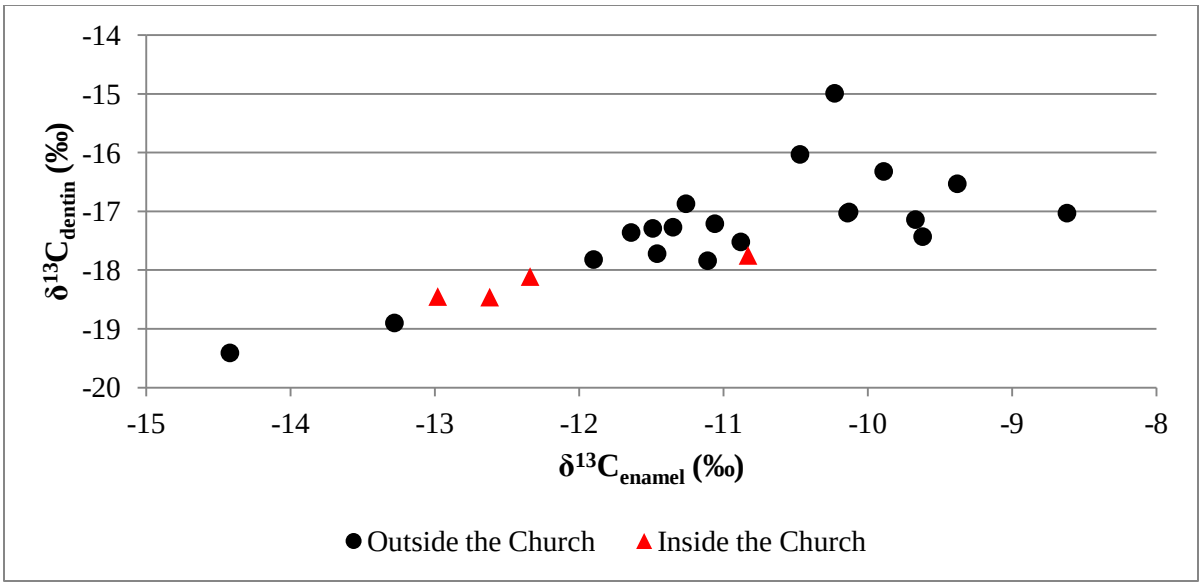

Figure 29. Graph showing differences in $\delta^{13}C$ (‰) from enamel apatite (carbonate) and $\delta^{13}C$ (‰) from dentin collagen. The results are distinguished by burial location.

Origins and Mobility

Stable oxygen isotope analysis was performed on enamel apatite from 24 individuals from Solt-Tételhegy, Hungary to determine if childhood migration into the study site occurred. Oxygen isotope values are written in standard delta (δ) notation, in per mil (‰), and in VSMOW. Results for only 23 samples, instead of the full 24, are reported, because one sample (ST 304) was unfortunately lost during stable isotope analysis. The values range between 23.6‰ and 27.2‰, with an average of 25.1‰. Table 9 shows the stable oxygen isotope ratios of 23 individuals from the study sample.

Table 9. Stable oxygen isotope results for Solt-Tételhegy, reported in VSMOW.

Sample ID	**$\delta^{18}O$ (‰)**
ST 2009.32.4 (4)	24.5
ST 2009.32.21 (31)	23.7
ST 2009.32.34 (56)	23.6
ST 2009.32.35 (57)	24.3
ST 2009.32.38 (60)	25.5
ST 2009.32.47 (69/I)	24.6
ST 2009.32.55 (82)	25.4
ST 2009.32.65 (94)	24.3
ST 2009.32.66 (95)	25.4
ST 2009.32.68 (97)	25.1
ST 2009.32.69 (98)	24.8
ST 2009.32.75 (113)	26.3
ST 2009.32.76 (114)	25.3
ST 2009.32.78 (116/I)	24.6
ST 2009.32.83 (121/I)	25.0
ST 2009.32.84 (122/I)	25.0
ST 2009.32.91 (128)	27.2
ST 2009.32.100 (145/I)	25.1
ST 2009.32.107 (158)	25.0
ST 2009.32.109 (167)	24.8
ST 2009.32.118 (284)	24.8
ST 2009.32.119 (300/I)	26.6
ST 2009.32.120 (300/II)	26.3

Figure 30 depicts median age versus $\delta^{18}O$ from enamel apatite, with tooth type as an additional variable. The lowest (ST 56, at 23.6‰) and highest (ST 128, at 27.2‰) values are seen in 1st molars. Several first molars also appear to cluster between 24‰ and 26‰, with ratios from second molars showing greater overall variation.

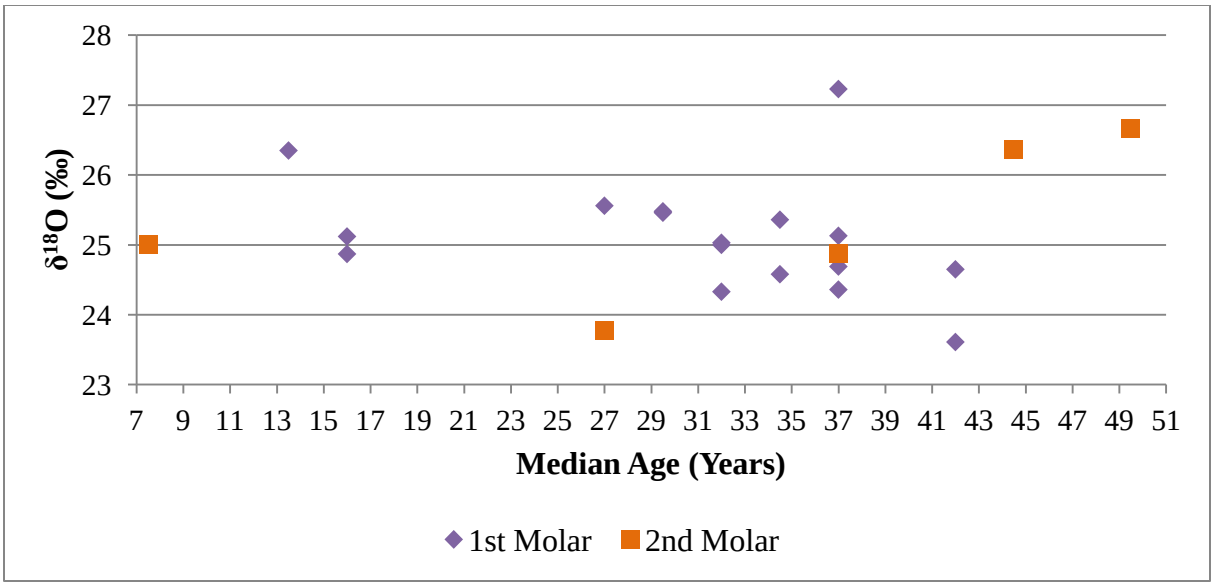

Figure 30. Graph showing the relationship between median age (years) and $\delta^{18}O$ (‰) from enamel apatite. The results are differentiated by tooth type.

The relationship between enamel $\delta^{13}C$ (‰), $\delta^{18}O$, and sex is shown in Figure 31. Most of the oxygen isotope values for males and females lie between 24‰ and 26‰, but there are a few obvious outliers, the most extreme belonging to males (at 23.6‰ and 27.2‰). There are also two clear outliers among the females (at 25.3‰ and 26.6‰), as well as a large gap between the two juveniles whose sex could not be determined. There appears to be a relationship between carbon and oxygen, since moderate-high isotope values for carbon (-12‰ to -9‰) seem to correlate with moderate values for oxygen (24-26‰). Of course, this is not true for all samples. An intermediate $\delta^{13}C$ (-11.1‰) value has a high $\delta^{18}O$ (27.2‰) value, and an intermediate $\delta^{18}O$ (25.4‰) ratio has a very low $\delta^{13}C$ (-14.4‰) ratio. It is noteworthy that these carbon and oxygen values belong to males.

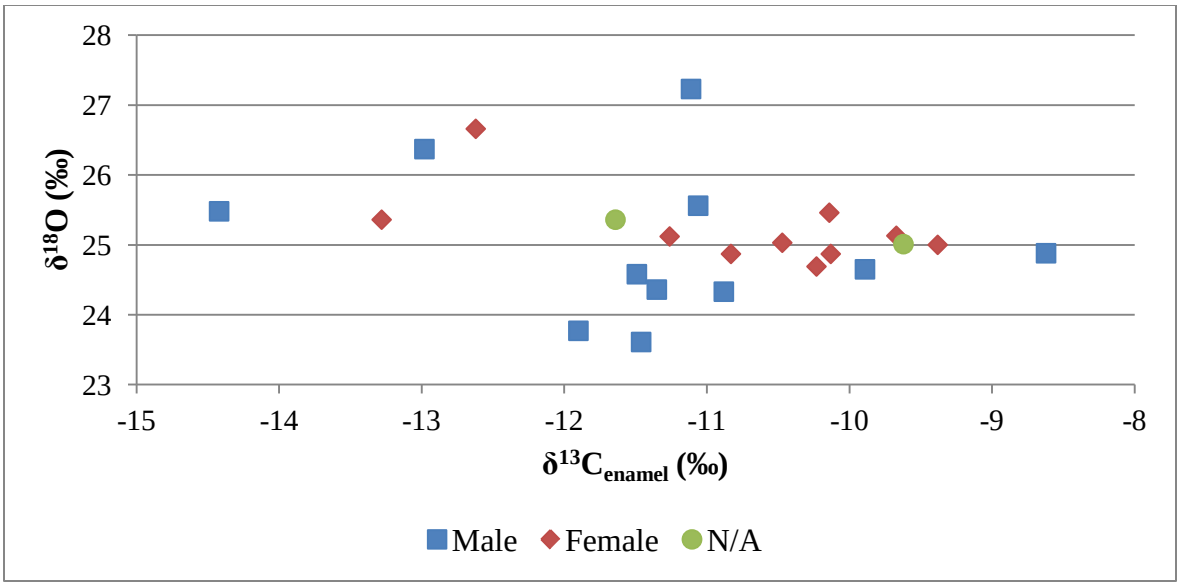

Figure 31. Graph comparing $\delta^{13}C$ (‰) and $\delta^{18}O$ (‰) from enamel apatite. The results are sorted by sex.

Figure 32 shows burial location as it affects enamel $\delta^{13}C$ (‰) and $\delta^{18}O$ (‰) values. Although four individuals were actually interred inside the church, stable oxygen isotope data for one of them (ST 304) could not be reported due to sample loss during stable isotopic analysis. However, two of the three reported church burials show very different carbon and oxygen results than those from the cemetery. They are less enriched in enamel $\delta^{13}C$ but more enriched in $\delta^{18}O$. There are outliers among the cemetery burials, as well. One individual is quite enriched in oxygen, while two have much more negative carbon values than the others. It should also be noted that the highest and lowest $\delta^{18}O$ values belong to individuals buried outside the church.

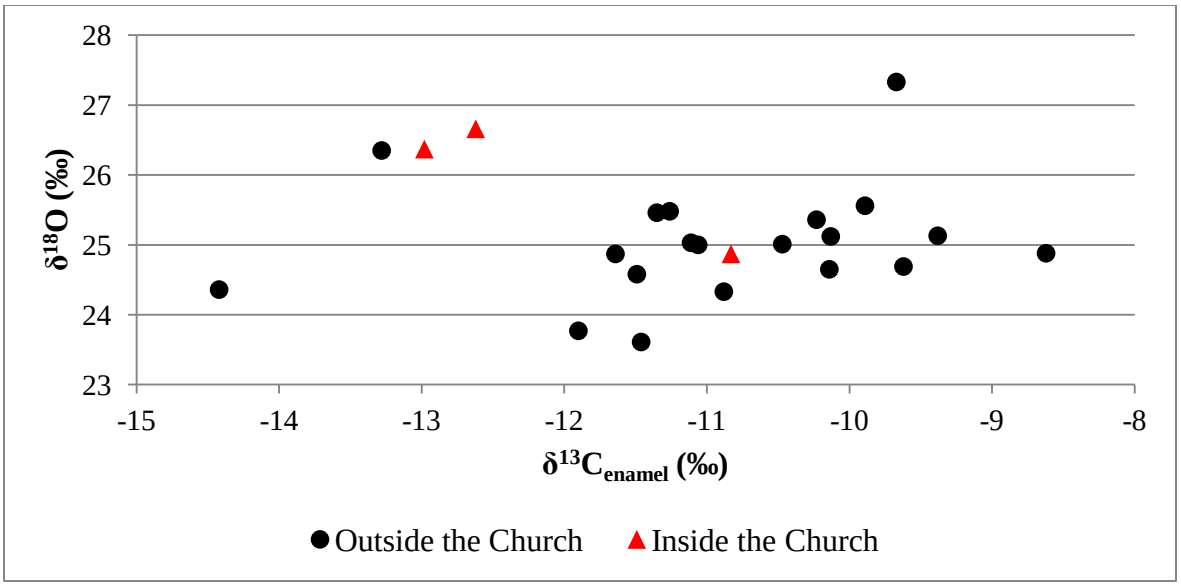

Figure 32. Graph showing $\delta^{13}C$ (‰) versus $\delta^{18}O$ (‰) from enamel apatite. The results are distinguished by burial location.

CHAPTER FIVE: DISCUSSION

This chapter provides an in-depth examination of the study's results within the historical background of the research site. The diets of the individuals are analyzed and compared to the diets of contemporaneous populations from Europe. Migration is also discussed, and stable oxygen isotope levels are compared with populations from other parts of Europe.

General Diet in Medieval Hungary and East-Central Europe

Land was extremely important in early medieval Hungary, as it not only provided food for humans and herd animals, but possession of it also determined one's place in the social hierarchy. In the 1200s AD, land was the sole means of acquiring noble status in Hungary, and after the Mongol invasion of 1241 AD, even free peasants could farm their own land (Engel 2001). Since medieval Hungary, especially eastern and southern Hungary, was sparsely inhabited, there was plenty of viable farmland. Forests were cleared, and during the first half of the 13th century, the method of agriculture changed to a system of land rotation (Berend et al. 2013). This meant that plots of land were farmed for 3-5 years, after which they were allowed to rest and new plots were utilized. Any uncultivated land was devoted to ungulate grazing (Berend et al. 2013; Engel 2001).

As with most of medieval Europe, Hungary primarily cultivated C_3 cereal crops. Wheat was planted on the central lands, while barley, rye, oats (which are native to Central Europe), and millet (a C_4 plant native to Europe) grew on the periphery lands (Adamson 2004; Berend et al. 2013). Solt-Tételhegy is located in present-day southern Hungary (in the Southern Great Plains), but it would have been more central in the Middle Ages, since the Kingdom of Hungary was

much larger. Wheat would have been the most common grain grown in the region. In fact, historical sources state that by the early 13th century AD, cereal cultivation was prevalent across the plains. Yields increased from about double to triple, or even quadruple, the amount of grain sowed (Berend et al. 2013). Cereals, however, were not the only food plants that grew in the region. Apples, cherries, sour cherries, peaches, watermelons, peas, onions, beans, lentils, hazelnuts, and walnuts were also staples in the diets of medieval Hungarians (Adamson 2004; Berend et al. 2013). Fruits and vegetables were important, and some of the most lucrative agricultural advances came from the Benedictine monasteries. They introduced intensive garden cultivation, including orchards and vineyards, leading to the increasing importance of wine and viticulture. This led to more local and international trade, with grain, wine, live animals (e.g., oxen, pigs, and sheep), fruit, honey, salted fish, and salt being the main trade goods (Berend et al. 2013).

Meat, though less plentiful than C_3 plants in the diet, was consumed with relative regularity, and, at the time, animal husbandry played a more significant role in East-Central Europe than in Western Europe (Berend et al. 2013). Livestock and other food animals were either kept alongside farmlands in villages, annually on pastures, or seasonally on pastures. Cattle, sheep, goats, pigs, and horses were the most important animals, for both food and labor, and cow bones comprise up to 60% of zooarchaeological remains in many settlements (Berend et al. 2013). Small ruminates, such as goats and sheep, were the most common animals raised in villages, as they do not require vast pastures, unlike cows and horses. Poultry appears to have been less popular, making up only 1-8% of zooarchaeological assemblages (Berend et al. 2013), but bird bones are also less sturdy than mammal bones and may not have survived as well. While

hunting was considered a sport for nobles and royals, wild game actually contributed very little to overall meat consumption (Adamson 2004). Animals like boar, venison, hare, pheasant, and pigeon were eaten mostly during feasts, while domesticated animals (e.g., chickens, cows, pigs, and sheep) were preferred for everyday meals. Hungary is also home to many lakes and rivers, and because of this, freshwater fish, particularly carp and trout, constituted a large part of the medieval diet (Adamson 2004; Berend et al. 2013).

Diet and Stable Isotopes

According to archaeological and historical sources, it appears that medieval Hungarians generally had sufficient food. They were not plagued by famine or resource shortages, except in exceptional circumstances (e.g., during and directly after the Mongol invasion). Contrary to popular opinion, medieval Europeans as a whole were neither limited nor nutritionally-impoverished in their selection of foods. As previous studies have demonstrated (Adamson 2004; Berend et al. 2013; Hakenbeck et al. 2010; Richards et al. 2006), most social classes were able to procure a relatively wide array of plant foods. The lower classes had access to dietary basics, such as bread, dairy, meat (usually cheap cuts), eggs, produce, and preserved fish. Based on the minimal tooth wear observed on the older individuals from Solt-Tételhegy (in their 40s), *their* diet, at least, did not appear to have included much grit.

C_3 and C_4 Plant Consumption

Both collagen and apatite contribute stable carbon isotopes. Humans who consume a diet of terrestrial C_3 plants, with few to no C_4 plants, are expected to have dentin $\delta^{13}C$ values between -19‰ and -22‰ (Mays 1997; Papathanasiou 2003; Richards and Hedges 1998). C_3 plants have

more negative stable carbon isotope ratios than do C_4 plants, so they will result in more negative $\delta^{13}C$ values in humans (DeNiro 1987; Mays 1997). From the medieval Solt-Tételhegy sample, only one (ST 95 at -19.41‰) individual fits this trend, while the rest of the population falls within the -18‰ to -14‰ range. All individuals displayed C_3 plant percentages higher than 50%, with most being above 70%. These values indicate that C_3 plants were the dominant produce but that C_4 plants constituted an average of 26.7% of the diet. The enamel $\delta^{13}C$, or carbonate, values support the dentin carbon values. Most of the population consumed more C_3 plants than C_4 plants, with the probable exception of four individuals, whose carbonate $\delta^{13}C$ ratios range from -9.6‰ to -8.6‰. All others are either intermediate between C_3 and C_4 values or are closer to C_3 values. This holds true for other medieval European populations, as well, because C_3 plants were the most plentiful edible plant type in Europe. Cereal crops, such as wheat, barley, oats, and rye, were the primary C_3 foods, but legumes, root vegetables, cabbages, onions, and various fruits were also consumed, though probably in reduced quantities (Adamson 2004; Berend et al. 2013). Grains were popular due to their many uses. They could be baked into breads; cooked into soups, stews, porridges, and potages; mixed into batters; or brewed into beers. They were also usually cheaper than the more vitamin- and fiber-rich vegetables (Adamson 2004). As for C_4 plants, the most likely species eaten by the study sample is millet, because it has been cultivated in Europe since at least 2000 BC (Adamson 2004). C_4 plant consumption varies, with the highest percentage belonging to a female (ST 116/I, at 44.5%) and the lowest belonging to a male (ST 95, at 11.7%). Both of these individuals were buried in the cemetery outside the church, so they were presumably from the same ethnic group and from a similar social status. This dietary difference could be attributed to various causes, including status- and sex-based causes.

Historically, millet has been associated with lower-status diets and was used as animal fodder (Dupras and Tocheri 2007; Reitsema and Vercellotti 2012). Thus, the individuals with higher levels of millet consumption could have occupied a slightly lower rung in society, or they may not have been able to afford C_3 cereals. It is also possible that they had more access to millet than to other grains or vegetables, simply because they grew up in areas with high millet cultivation, like the Slavic areas of East-Central Europe (Berend et al. 2013; Lightfoot et al. 2012). Sex may play a role, since more females than males show PC_4 levels ranging from 25% to 50%. Female children, for whatever reason, could have been preferentially fed millet. Weaning, however, could have contributed to the increased PC_4 levels, as well. In historical societies, millet, mixed with goat's milk, cow's milk, sheep's milk, or water, was a popular weaning food (Dupras and Tocheri 2007; Dupras et al. 2001; Fuller et al. 2006), so the individuals with high C_4 plant percentages could be displaying weaning signals. Support for the weaning hypothesis is lent by the observation that the majority of high PC_4 levels come from 1st molars. A final possibility to explain the differences in C_4 plant consumption is that millet was used as an illness or a convalescence food by the residents of medieval Solt-Tételhegy, like it was by Roman-era Egyptians (Dupras 2015, personal communication). If the individuals with high C_4 plant consumption had a chronic illness or nutritional deficiency during dental crown formation, their $\delta^{15}N$ values may be enriched. Two females do indeed show a positive correlation between high nitrogen isotope and high PC_4 levels, so they may have been given millet specifically to aid in recovery from their illness.

A common $\delta^{15}N$ estimate for terrestrial feeders is between 5‰ and 12‰, while for marine feeders, it is 12-22‰ (Richards and Hedges 1998). The values from Solt-Tételhegy fall

strictly within the terrestrial feeders range, despite historical sources stating that moderate amounts of freshwater and marine fish were consumed by medieval Hungarians. With the highest $\delta^{15}N$ value at 11.6‰, the study population evidently did not consider fish to be an important part of its diet. Instead, it is likely that the individuals absorbed protein from terrestrial plants and animals, such as small ruminates (e.g., goats and sheep), chickens, and cows. Pigs were eaten in medieval Hungary, but secondarily to ruminates (Adamson 2004; Berend et al. 2013). Because pigs are generally omnivorous, like humans, they occupy a higher trophic level than do herbivorous food animals and thus contribute higher $\delta^{15}N$ values to their consumers. For example, residents of medieval Norwich showed potential signs of heavy pork consumption, as their nitrogen isotope values were very enriched (Bayliss et al. 2004). However, the $\delta^{15}N$ values of this sample are consistently lower than Bayliss et al.'s (2004) values, suggesting that pigs were not as prevalent in the diet. The inhabitants of Solt-Tételhegy consumed a moderate amount of animal protein during their childhood, but it is likely that much of their childhood dietary protein came from plants.

Diet and Tooth Type

Because this study utilizes teeth, only childhood diet is reflected; however, because tooth developmental rates are well known, it is possible to determine the approximate age at which the individuals were consuming the bulk of their research-relevant diet.

The lowest and highest dentin $\delta^{13}C$ values are from first molars, which are fully formed between 9 and 10 years, as are the lowest and highest enamel $\delta^{13}C$ ratios. For the most part, the first molars have greater dentin and enamel carbon isotope enrichment. This could indicate

retained weaning signals, a weaning effect, or the presence of weaning foods, such as cow's milk or millet. Infants who are weaning display greater dentin carbon and/or nitrogen isotope values, as they occupy a higher trophic level than other humans, due to consumption of their mother's milk (Dupras and Tocheri 2007; Dupras et al. 2001). One reason why first molars are a better marker for breastfeeding and weaning is that they develop before second molars do; thus, they ultimately contain more protein during infancy than second molars (Richards et al. 2002). One second molar, however, also shows an enriched $\delta^{15}N$ ratio, which could be the result of a pathological condition. But without examining the individual's bones, this remains mere conjecture.

Social Influences on Diet

As several stable isotopic studies have demonstrated, diet and social life are inextricably linked in medieval Europe. Males tended to consume more animal protein than females, because they were deemed to be higher in the social hierarchy and because they usually engaged in more demanding physical activity (Reitsema et al. 2010; Richards et al. 2006). At the same time, male children were often valued above female children (Reitsema et al. 2010). Medieval Solt-Tételhegy, however, does not appear to conform to these trends. Rather, it is females, not males, who have the highest dentin carbon isotope values, as well as the most enriched nitrogen isotope values. This indicates that most female children ate as much animal protein as male children. Why this is the case is as yet unclear. Perhaps some of the families with female children could better afford meat and non-starchy vegetables. Or perhaps female children were simply exposed to more protein as a result of aiding their mothers in food preparation, as suggested by Reitsema

and Vercellotti (2012). Additionally, it has been documented in both historical and modern societies that females tended to snack throughout the day, due to their proximity to food (Larsen 1997). Another possibility, however, is that female children were fed higher-quality diets to ensure they survived to reproductive age.

Solt-Tételhegy also differs from many other medieval settlements in its relatively egalitarian access to food and meat in particular. Although there are outliers among enamel $\delta^{13}C$, dentin $\delta^{13}C$, and $\delta^{15}N$ isotope values, social status does not appear to explain this. The four individuals who were interred inside the church were likely more privileged than those buried outside it, especially considering one of them was involved in its construction, yet their stable isotope values are not necessarily more enriched. In fact, the lowest $\delta^{15}N$ value belongs to one of the males excavated from beneath the church. Furthermore, most of the individuals buried in the cemetery display more enriched $\delta^{15}N$ values, suggesting that higher status did not always equate with preferential access to animal protein. If Solt-Tételhegy really was an Árpádian-period administrative center, it was wealthier than many other contemporaneous settlements in Hungary (Szentpéteri 2014). It is therefore possible that, by default, its residents enjoyed a more comfortable lifestyle with higher-quality food resources. Alternatively, the individuals buried in the cemetery could span multiple social classes, some higher and some lower, though all were probably less affluent than the individuals interred inside the church. Thus, differences in wealth and access to animal and plant protein may have existed amongst those interred in the cemetery.

The final social characteristic that will be discussed is religion. Strict fasting laws imposed by the Catholic Church prohibited the consumption of mammalian protein on nearly

half the days of the year (Kjellström et al. 2009; Müldner and Richards 2007; Salamon et al. 2008). To combat this, medieval peoples incorporated fish into their diets. Solt-Tételhegy's inhabitants do not show overly depleted carbon or nitrogen values, but neither are they as enriched as other medieval European populations (e.g., Swedish). Szentpéteri (2014) writes that most Árpádian-period settlements in Hungary lacked a church, but Solt-Tételhegy had at least two. The church in which four individuals were interred had existed in some form or another since the middle Bronze Age (Somogyvári 2014; Szentpéteri 2014), so when Hungary eschewed paganism in favor of Christianity in 1000 AD, the villagers were subject to the Church's fasting restrictions. Furthermore, the town had two religious buildings by the 1200s AD, suggesting that, on the surface, at least, the residents adhered closely to Catholic dietary directives. This may partly explain why, despite evidence of status and wealth (e.g., tax stamps, imported ceramics, high-quality artifacts, and egalitarian access to food), the research population has lower $\delta^{15}N$ values than medieval sites in Northern Europe (e.g., Sigtuna, Sweden). Two other religious explanations for the relatively low nitrogen isotope levels are Islam and Judaism. Despite the official dominance of Christianity, medieval Hungary was home to many Muslims and Jews, because the kingdom was especially accepting of them (Berend et al. 2013). Neither faith allows its adherents to consume pork, which is a high trophic-level protein. This could also account for the individuals with low $\delta^{15}N$ values. It is therefore possible that Jews, Muslims, or both lived in medieval Solt-Tételhegy.

Diet and Illness

When a person is suffering from illness or malnourishment, one of the side effects is a negative nitrogen balance, wherein the body is not absorbing enough nitrogen. To compensate, the body cannibalizes protein from musculoskeletal tissues, leading to the excretion of ^{14}N and the absorption and subsequent enrichment of ^{15}N (Katzenberg and Lovell 1999). Negative nitrogen balance may possibly explain why two females from medieval Solt-Tételhegy have higher $\delta^{15}N$ values than males. If these female children were chronically ill or experiencing chronic nutritional stress during dental crown formation, their bodies could have been thrown into negative nitrogen balance. The fact that a female also had the highest PC_4 consumption lends further support to this idea, since millet may have been used as an illness food. However, until pathological data is acquired for this sample, the link between nitrogen enrichment, millet, and pathological/nutritional stress is merely conjecture.

Diet and Migration

Comparisons between the study population's oxygen isotope values can be made with those of contemporaneous populations elsewhere in Europe. Solt-Tételhegy's $\delta^{18}O$ values are enriched by approximately 5‰ in comparison to the various Eurasian countries (e.g., Belgium, Germany, and Iran) reported by Daux et al. (2008), and at least 4‰ greater than the values determined by Brettell et al. (2012) for medieval France and Germany. It is therefore likely that the sample population was consuming more ^{18}O-enriched food and water during childhood than were other Eurasian populations. Table 10 provides the $\delta^{18}O$ values (‰) found by Brettell et al. (2012) and Daux et al. (2008).

Table 10. Summary of the stable oxygen isotope results from Brettell et al. (2012) and Daux et al. (2008).

Authors	**Sites**	**$\delta^{18}O$ (‰)**
Brettell et al. (2012)	Kent, UK	17.6-18.8
	Hannover-Anderten, Germany	16.9-17.9
	Sannerville and Giberville, France	17.4-18.2
Daux et al. (2008)	Brussels, Belgium	15.9-17.5
	Bordeaux, Le Tholy, and St. Amand, France	16.2-18.3
	Flossenbürg, Germany	Mean: 16.4
	Athens, Greece	Mean: 16.9
	Kermanshah, Iran	17.6-18.4

If skull shape is the sole determining factor, there appear to be two separate ethnic groups, which are conveniently differentiated by burial location, as well. The first group consists of the individuals buried outside the church, who have a longer and narrower brain case. The second group is comprised of individuals interred inside the church, with hyperbrachycranic (shorter and wider) skulls. However, stable oxygen isotope values introduce the possibility of multiple ethnicities and/or nationalities arriving in medieval Solt-Tételhegy from Central Europe, Eastern Europe, the Mediterranean, and even the Middle East.

Although the baseline $\delta^{18}O$ levels used in this study are modern, it is nevertheless possible to compare these values with the research sample's $\delta^{18}O$ values. All of the $\delta^{18}O$ are above 23.6‰ but below 28‰. Thus, as Figures 33-34 show, no individuals migrated from Northern Europe or Russia. It is also unlikely that anyone travelled from the British Isles. Instead, since the majority of the values range from 24-25‰, these individuals were most likely born in Central and Eastern Europe (Fig. 35). This is to be expected, as early medieval Hungary

was a veritable melting pot of Central and Eastern European ethnicities, including Germans, Slavs (e.g., Moravians from present-day Czech Republic), and the native Hungarians.

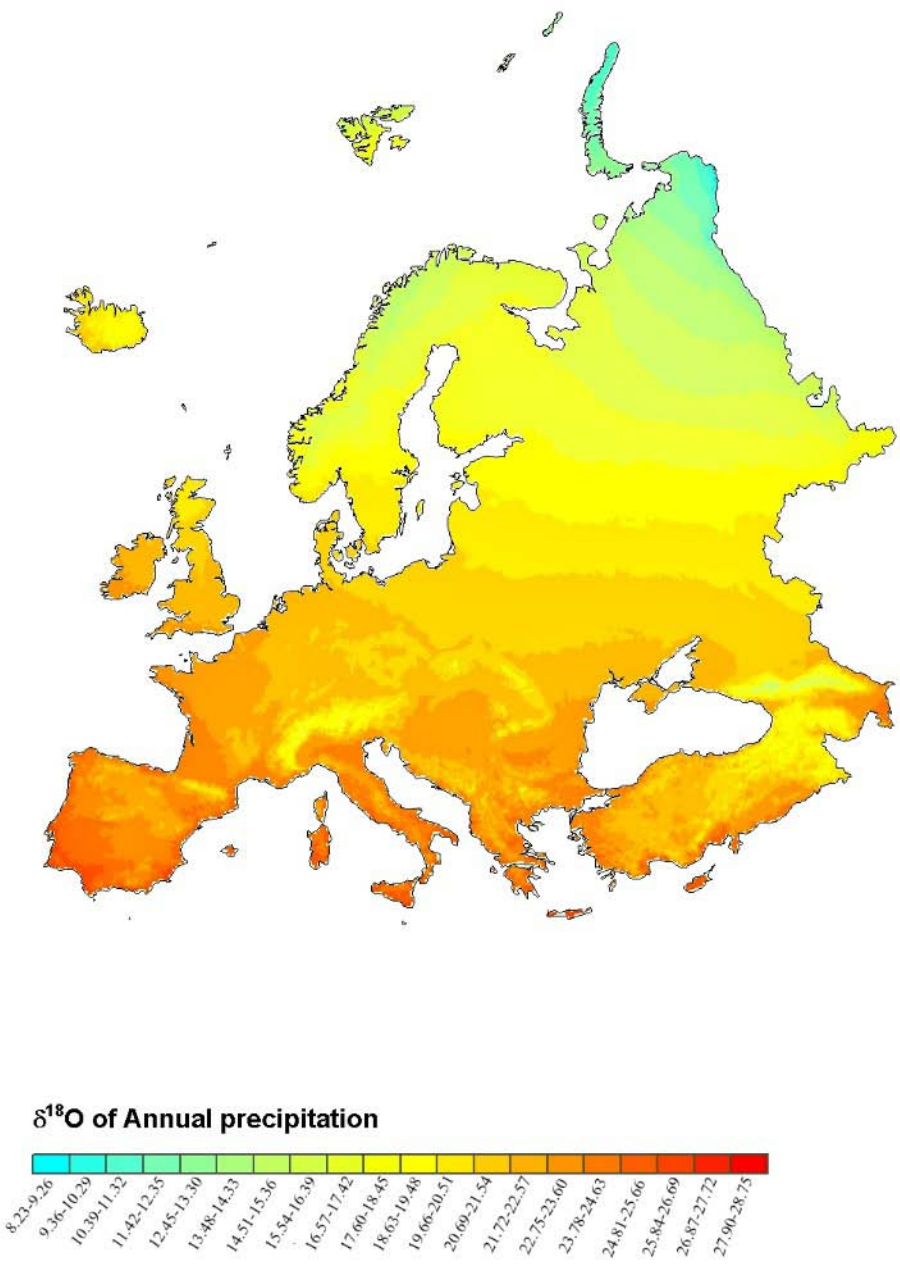

Figure 33. Oxygen isoscape map of Europe, with the $\delta^{18}O$ values (‰) of annual precipitation reported in VSMOW (adapted from waterisotopes.org).

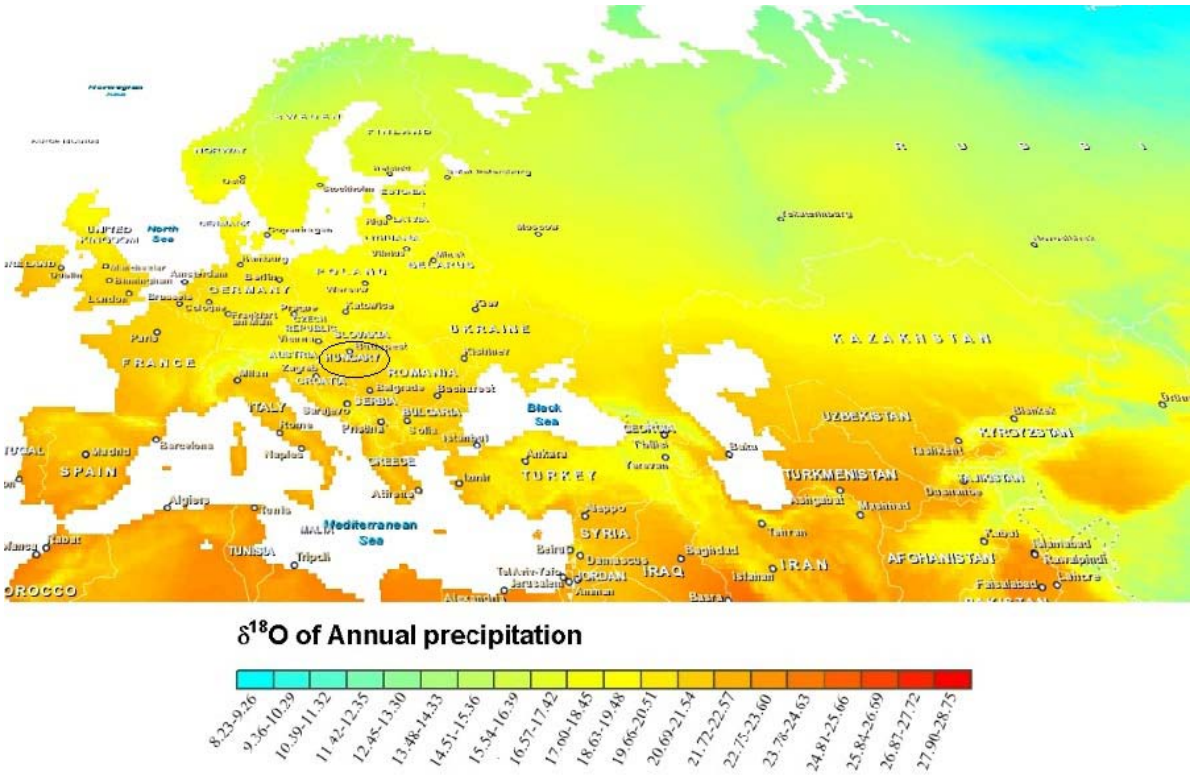

Figure 34. Oxygen isoscape map of Eurasia, with the $\delta^{18}O$ values (‰) of annual precipitation reported in VSMOW. Hungary has been circled in black (adapted using ArcGIS from waterisotopes.org).

Moravian Migration

After the Moravians left the Kingdom of Croatia in the 9th century AD, many of them eventually settled in Hungary (Berend et al. 2013; Róna-Tas 1999) and likely in Solt-Tételhegy, as well. They are a Slavic people, so they are related to the indigenous inhabitants of the Balkans and the Dinaric Alps, who often exhibit hyperbrachycranic skulls with a short, wide brain case and a narrow forehead. Significantly, the four individuals interred inside the church also display these skeletal characteristics, while the people buried in the cemetery have a longer, narrower brain case and a taller, thinner face. There were evidently at least three separate ethnic groups living in the study site, one of which potentially consisted of Moravians who migrated into the

settlement. Further support may be lent by church enamel $\delta^{13}C$ values (-12.9‰, -12.6‰, and -12.3‰) that differ by at least 1‰ from those buried in the cemetery. The individuals inside the church also fall on the lower end of the PC_4 range, indicating that C_4 plants did not constitute a large part of their childhood diets, unlike many of the people buried outside the church. A possible explanation for this observation is that the hyperbrachycranic group (i.e., buried inside the church) grew up elsewhere, perhaps where millet was not widely cultivated, before migrating into Solt-Tételhegy later in life.

However, based on the stable oxygen isotope results (Table 11), this hypothesis does not seem to hold up, for two reasons. First, the $\delta^{18}O$ value for one of the hyperbrachycranic individuals (ST 284, a female) is about 2‰ less than the values of the two remaining church-buried individuals (a female and a male), which are grouped close together. Second, most of the population, including ST 284, has similar enough oxygen isotope ratios that they form a cluster, while two cemetery and two church burials are obvious outliers. Therefore, it is unlikely that all the hyperbrachycranic individuals migrated into the settlement. A possible explanation is that the hyperbrachycranic individuals constitute a separate genetic ethnic group: Moravian, whose members may have grown up in very different places. Two of them, ST 300/I and ST 300/II, entered Solt-Tételhegy in their late teens or early adulthood. ST 284, on the other hand, was probably born there, and her parents or grandparents may have been migrants into the site. Though all three individuals were buried inside the church, that does not necessarily mean they belonged to the same family. The clustered male (ST 300/II) and female (ST 300/I) could be related (e.g., siblings), and the lone female (ST 284) could be related to the fourth person (a

male) excavated from the church's interior. Unfortunately, $\delta^{18}O$ data for this individual is not available, due to sample loss during stable oxygen isotope analysis.

Table 11. The $\delta^{18}O$ values (‰) for the research sample, reported in VSMOW.

Sample ID	**$\delta^{18}O$ (‰)**
ST 2009.32.4 (4)	24.5
ST 2009.32.21 (31)	23.7
ST 2009.32.34 (56)	23.6
ST 2009.32.35 (57)	24.3
ST 2009.32.38 (60)	25.5
ST 2009.32.47 (69/I)	24.6
ST 2009.32.55 (82)	25.4
ST 2009.32.65 (94)	24.3
ST 2009.32.66 (95)	25.4
ST 2009.32.68 (97)	25.1
ST 2009.32.69 (98)	24.8
ST 2009.32.75 (113)	26.3
ST 2009.32.76 (114)	25.3
ST 2009.32.78 (116/I)	24.6
ST 2009.32.83 (121/I)	25.0
ST 2009.32.84 (122/I)	25.0
ST 2009.32.91 (128)	27.2
ST 2009.32.100 (145/I)	25.1
ST 2009.32.107 (158)	25.0
ST 2009.32.109 (167)	24.8
ST 2009.32.118 (284)	24.8
ST 2009.32.119 (300/I)	26.6
ST 2009.32.120 (300/II)	26.3

It is also important to note that two individuals from the cemetery display outlying $\delta^{18}O$ ratios. The first, ST 113, is considered an outlier simply because it is nearly identical to one of the church-burial's (ST300/II) values, suggesting a common geographical origin. The second cemetery burial will be discussed in the next subsection. From these observations, it is possible that multiple, short-distance migrations occurred into the area. Thirteenth century Solt-Tételhegy

was a large settlement, perhaps even an administrative center. It is therefore conceivable that people from different parts of East and Central Europe moved there for work or other reasons. Furthermore, people from the Balkans and the Dinaric Alps, such as the hyperbrachycranic Moravians, evidently also came to Solt-Tételhegy. One of these individuals may have even spent her childhood there. This should come as no surprise, though, considering Hungary's long history of diversity. During the Middle Ages, Germans, Poles, and Slavs were all frequent immigrants into the country, and it appears that genetic Moravians lived and died in Solt-Tételhegy, as well.

Other Migrations

Medieval Solt-Tételhegy was situated near a prominent and extensive trade route. As Figure 35 depicts, this trade route intersected with others throughout Eurasia, leading to the inevitable commingling of different peoples. Additionally, the Kingdom of Hungary was at the crossroads of the east and west, of Islam and Christianity. Its ethnic and religious tolerance attracted Jewish and Muslim immigrants alike, who were not always welcome in Central or Western Europe (Berend et al. 2013). Orosháza, in eastern Hungary, was particularly popular, but whether or not Solt-Tételhegy was, as well, is uncertain.

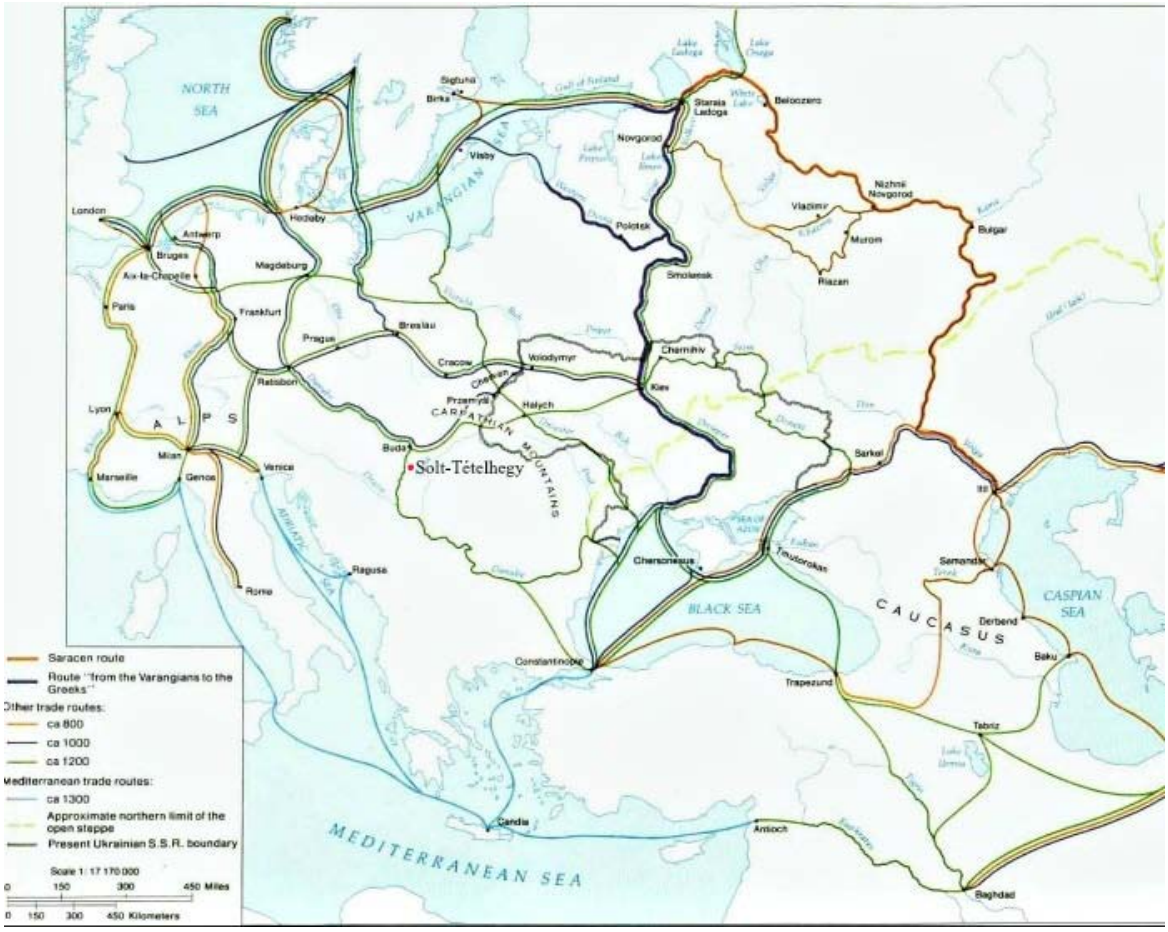

Figure 35. Map of the trade routes in medieval (800-1300 AD) Europe, with the study site denoted by the red marker (adapted from sumy.net.ua).

Four individuals with $\delta^{18}O$ values between 26‰ and 27‰ appear to have migrated very great distances (Fig. 36). Italy and Spain are possibilities, but so are parts of the Middle East (e.g. Arabia and lower Iran) and potentially even North Africa (e.g., Morocco). Based on historical sources, though, Muslim immigrants are more likely than Mediterranean peoples. At 27.2‰, the cemetery-burial ST 128, has the highest $\delta^{18}O$ value. However, it is significant that two purported Moravians (ST 300/I and ST 300/II) also have very enriched oxygen isotope levels (26.6‰ and 26.3‰, respectively). The Balkans are nowhere near the areas that display $\delta^{18}O$ values of 26‰, so these genetically-Dinaric people seemed to have spent their childhoods in the Mediterranean

or the Middle East, before migrating to Solt-Tételhegy. Were they the children of Slavic merchants, who travelled with their parents? Or had their families been living in the Mediterranean or Middle East for generations by the time they were born? At this point, there is insufficient evidence to explain their migration history.

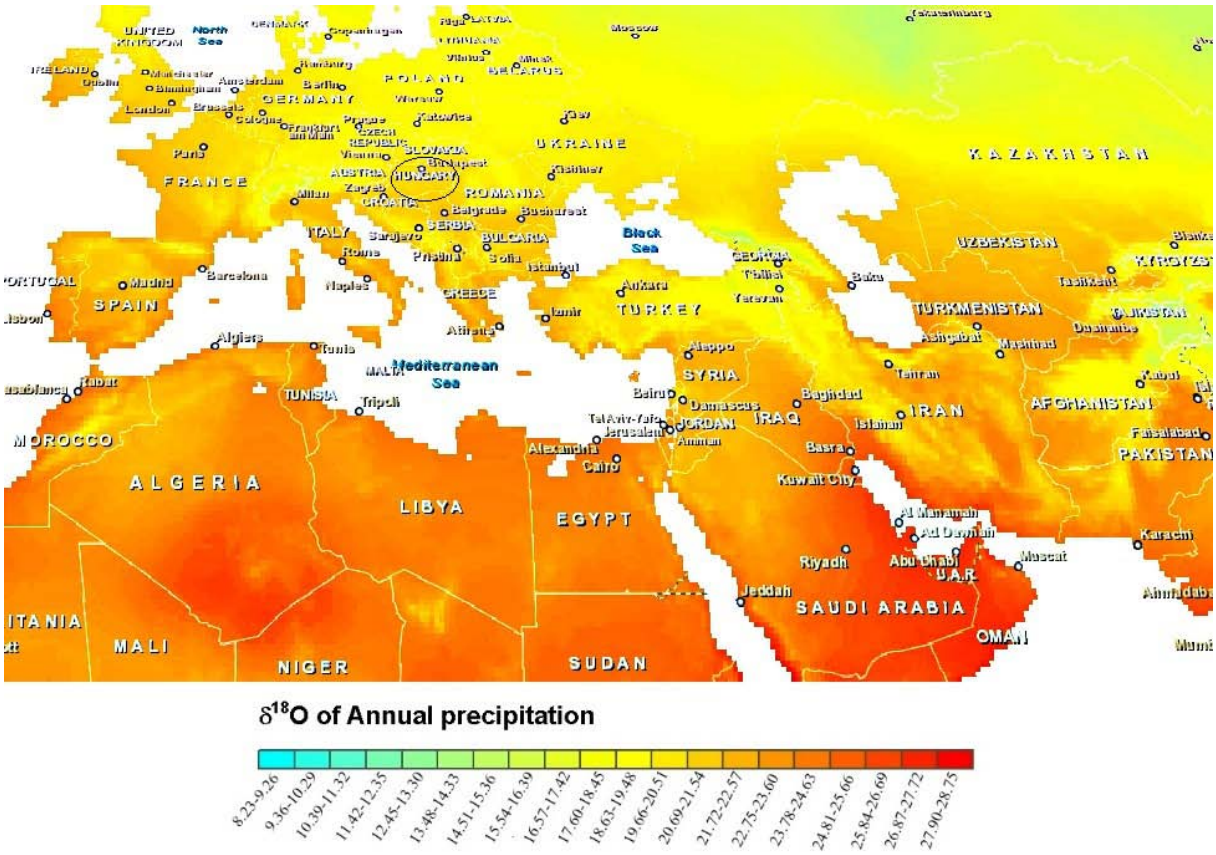

Figure 36. Oxygen isoscape map focused on Europe, North Africa, and the Middle East. The $\delta^{18}O$ values (‰) of annual precipitation are reported in VSMOW. Hungary has been circled in black (adapted using ArcGIS from waterisotopes.org).

Prevalence of Migration amongst C_3 vs. C_4 Plant-eaters

The majority of individuals who display mid to high C_4 plant consumption (between 25-50% of diet) appear to be native to Hungary, or to East-Central Europe, at the very least. This

supports historical accounts that East-Central Europe grew an abundance of C_4 plants, such as millet, as alternatives to C_3 cereal crops or as a weaning food. However, C_4 plants were grown outside of East-Central Europe, as well. One individual whose $\delta^{18}O$ value suggests a geographic origin in the Mediterranean or in traditionally-Islamic lands has a PC_4 of 26.9%. The remaining three long-distance migrants, also either Mediterranean or Islamic peoples, show some of the lowest percentages. If one considers that most modern millet is cultivated in semi-arid regions, such as Africa or the Middle East, this finding is surprising. Additionally, the two lowest percentages of C_4 plant consumption are observed in East-Central Europeans. Various explanations could account for the limited inclusion of C_4 crops in these individuals' diets, but perhaps the most likely is that they may have been a status- or sex-based food.

CHAPTER SIX: CONCLUSIONS

This research addressed questions of childhood diet and mobility of a medieval population from Hungary. It provided preliminary insight into the childhood diets of at least three different ethnic groups from 1240s AD Solt-Tételhegy, Hungary. Migrations into the site were also discussed, as were the most probable geographic origins, and thus ethnicities, of the immigrants. Furthermore, the influence of sex and status was examined, and comparisons were drawn between Solt-Tételhegy and other medieval European sites.

According to historical documents, archaeobotany, and stable isotope analysis, the sample population enjoyed a diet relatively abundant in both plant and animal foods. There was no consistent pattern in diet based on sex, and social status did not affect diet in the expected manner, as several individuals buried in the cemetery outside the church displayed greater carbon and nitrogen isotope enrichment than those interred inside the church. Weaning signals may also be present in first molars, while a pathological condition could explain the enrichment seen in one second molar.

Stable dentin carbon analysis suggests that primarily terrestrial C_3 plants comprised the individuals' plant-protein quota. The average percentage of C_4 plants consumed was only 26.7%. However, C_4 plants, most likely millet, comprised nearly 50% of one individual's diet. There appears to be a link between C_4 plant consumption and sex, as the highest percentage belonged to a female (44.5%), while the lowest percentage belonged to a male (11.7%). Stable enamel carbon analysis, too, depicts a diet rich in temperate C_3 plants, with varying levels of C_4 plant consumption.

Stable nitrogen analysis shows that the residents consumed a moderate amount of animal protein, though this varies by individual. However, because $\delta^{15}N$ levels are not overly enriched, they most likely consumed more plants than animal products. Additionally, it does not appear that marine resources were included in the diet. Unlike many contemporaneous European populations, the sample from Solt-Tételhegy does not depict consistent sex- or status-based patterns in $\delta^{15}N$ values, though the differences do not conform to trends seen elsewhere in medieval Europe.

Stable oxygen isotope analysis appears to support the osteological observation that at least three separate genetic ethnic groups are present in the study sample. One of these groups is probably Moravian, another is likely native Hungarians (and therefore native East-Central European), while the third could be either Mediterranean or Muslim. Although the precise origin of the individuals cannot be determined with the data available, it is nevertheless clear that several independent migrations occurred into Solt-Tételhegy.

This study is important to anthropology and to bioarchaeology. There currently exists no other stable isotopic research on the people of medieval Hungary and only a few from East-Central Europe in general. This analysis is a springboard for other stable isotope projects in Hungary and in the region, and it also contributes to the larger body of stable isotopic studies on medieval Europe. Additionally, most dietary isotopic research focuses on bones, rather than on teeth, and thus on adulthood diet, instead of on childhood diet. In that respect, too, this study is important.

Future Directions

This sample has the potential to yield a wealth of other information. It presents the opportunity to pursue a nutritional profile for the entire lifespan, by combining stable isotope analysis on both teeth (childhood diet) and bones (adulthood diet). Although the individuals with enriched nitrogen ratios were likely consuming more protein, their values may also be attributed to nutritional stress or to pathological conditions, particularly if their skeletons display signs of either. Further migration studies are also possible. Comparing the stable oxygen isotope values from this sample to those from medieval Moravian settlements, such as Mikulčice, could pinpoint the geographical origins of Solt-Tételhegy's Slavic group. Likewise, $\delta^{18}O$ comparisons with Arabic, Iranian, or Mediterranean peoples may yield more precise conclusions about the childhood homelands of the long-distance migrants.

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