



## Preliminary evidence for medieval Polish diet from carbon and nitrogen stable isotopes

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### ABSTRACT

In this pilot study, stable carbon and nitrogen isotopes from bone collagen and apatite of skeletons from the 11th and 12th century cemetery in Giecz, Poland are interpreted. Isotope values from a small number of fish and animal bones from the same archaeological site are also examined. The goal of this research is to provide preliminary evidence of diet for a group of medieval Polish peasants, with particular emphasis on sex-based differences in diet. Results of isotope analyses suggest diet of this early medieval population was omnivorous and terrestrial-based. Fish bones sampled exhibit low  $\delta^{13}\text{C}$  ratios, and in half of the cases are significantly enriched in  $^{15}\text{N}$ , indicating they are freshwater species. Human bones do not reflect these signatures, suggesting freshwater fish were not a significant source of dietary protein at Giecz. The  $^{13}\text{C}_{\text{coll}}$  from some human bones is enriched beyond what might be expected from an exclusively  $\text{C}_3$  diet. Associated mammal bones do not exhibit similarly elevated  $\delta^{13}\text{C}_{\text{coll}}$  ratios, suggesting enrichment among humans is not due to consumption of animals foddered on  $\text{C}_4$  plants. Two possible sources of  $^{13}\text{C}_{\text{coll}}$  enrichment are marine fish in diet and direct consumption of a  $\text{C}_4$  plant, such as millet. The  $\delta^{13}\text{C}$  values obtained from bone apatite of a small subset of humans suggest that millet contributes to  $^{13}\text{C}_{\text{coll}}$  enrichment, although at least three individuals may have also consumed small amounts of marine fish. Sex-based differences in  $\delta^{15}\text{N}$  ratios indicate that men consumed relatively more animal products (meat or dairy) than did women. There is also a correlation between  $\delta^{13}\text{C}_{\text{coll}}$  and  $\delta^{15}\text{N}$  values in skeletons of men that is absent in women. These carbon and nitrogen isotope data are the first reported for any Polish population and contribute to a more complete picture of dietary adaptation and social organization in medieval Europe.

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### 1. Introduction

At the turn of the 10th century AD, populations in what is now Poland were in the midst of sociopolitical changes. Autonomous peoples united under the leadership of a single ruler who in AD 966 declared Christianity a national religion (Kurnatowska, 2002, 2003). These changes incorporated Poland into the broader European community, leading to intensified urbanization and wider communication networks. In this pilot study, carbon and nitrogen isotope analyses of skeletal materials from the 11th and 12th century cemetery at Giecz, Poland are reported in order to examine diet among a population immediately post-dating dramatic socio-political change.

Relationships between isotopes in human tissues and diet are well established and for 30 years isotopes have provided the most

direct tool for assessing diets of past populations (van der Merwe and Vogel, 1978). At the very foundation of human existence, diet influences diverse aspects of human behavior (Parker Pearson, 2003). Consequently, stable isotope studies in archaeological research have expanded to investigations of post-marital residence patterns (Tafari et al., 2006), sex- and age-based differences in diet (Ambrose et al., 1997; Herrscher et al., 2001; Katzenberg, 1993), and social stratification (Polet and Katzenberg, 2003; Richards et al., 1998). Although historical records from the medieval period are extant, they typically under-represent daily lives of individuals outside elite classes (Müldner and Richards, 2005; Polet and Katzenberg, 2003). Archaeological data are useful for supplementing records and adding undocumented context to interpretations of the past.

The use of isotope analysis to paleodietary studies derives from the fact that isotopic ratios of different types of food are preserved in the tissue chemistry of consumers. Carbon isotopes provide information about the ecosystem of a consumer, distinguishing between terrestrial versus marine niches, and between

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consumption of plants adapted for temperate versus arid environments. Nitrogen isotope ratios reveal information about an organism's trophic position in the local foodweb, distinguishing between herbivores, omnivores, and carnivores. Nitrogen isotopes are also sensitive to variations in local climate (Ambrose, 1991), soil condition (Britton et al., 2008), production systems (Bogaard et al., 2007) and consumer physiology (Ambrose, 1991; Fuller et al., 2005; Hobson et al., 1993), rendering their interpretation complex.

Isotope studies of medieval Europe have revealed important information on how food was distributed within populations, including differences in diet based on sex (Richards et al., 2006), status (Polet and Katzenberg, 2003) and age (Richards et al., 2002). These discrepancies are revealing of medieval attitudes regarding health and nutrition. Because certain foods (such as meat and animal products) were considered more prestigious than others during the medieval period (Dembińska, 1999), differences in diet can also reveal social stratification within a population. In addition to reconstructing diet, this study examines differences in men and women's diets in a subset of the medieval Polish peasantry.

The importance of fish as a food source has also been demonstrated isotopically in medieval Europe. Diachronic studies illustrate particularly well this change from earlier periods (Barrett and Richards, 2004; Müldner and Richards, 2007a,b; Salamon et al., 2008). Growing market economies, expanding trade networks and recently adopted Christian fasting may have contributed to high fish intake in Europe after AD 1000 (Barrett et al., 2004; McCormick, 2001; Müldner and Richards, 2005). This pilot study evaluates the importance of fish in diet at Giecz in a single period following Poland's Christianization (Kloczowski, 2000).

## 2. Biocultural context

Giecz is located in Greater Poland, the birthplace of the Polish state (Fig. 1). Until the middle of the 10th century Polish populations were organized by tribal affiliation and practiced regionally diverse forms of paganism (Barford, 2001). After political

consolidation by Prince Mieszko I in AD 966 Poland became a recognized, centralized Christian state.

Skeletal remains examined were excavated from an 11th and 12th century cemetery located adjacent to a fortified stronghold. This particular cemetery was chosen for isotope analysis because it dates to the period immediately following political and religious changes in Poland (Gieysztor et al., 1979). The individuals buried at the cemetery are believed to be peasants owing to their burial location outside the stronghold. Members of the social elite were likely buried inside the stronghold adjacent to the parish church, and are not investigated here. The cemetery investigated exhibits characteristics of Christian burials, including supination and orientation along an east–west axis (Daniell, 1998; Krysztofiak, 2008).

Diets of medieval European populations were dominated by grains along with vegetables such as peas and cucumbers (Dembińska, 1999; Singman, 1999). Carbonized remains of wheat, rye, barley and legumes are reported from culture layers of various early medieval archaeological sites in Greater Poland (Klichowska, 1972; Polcyn, 1994, 1995). Additionally, archaeobotanical investigations of contemporary sites at Giecz and Ostrów Lednicki also provide abundant evidence for millet cultivation. The most numerous and frequent remains are uncarbonized chaff, whereas charred grains are not as common. It is beyond doubt that millet cultivation played a major role in early medieval Poland and was an important part of its economy at the time. Although most indigenous and cultivated plants in Europe follow a C<sub>3</sub> photosynthetic pathway, a C<sub>4</sub> signature from millet must be borne in mind when interpreting diet isotopically. This may arise from direct consumption of millet in foods or beverages or indirectly via consumption of animals foddered on the grain.

Meat from terrestrial animals was an important food source in medieval Poland. In archaeozoological assemblages from contemporary Polish sites, cow and pig bones are equally common and account for approximately 80% of total assemblages. Sheep bones account for approximately 15% (Makowiecki, 2008). Fewer than 4% of total archaeozoological assemblages come from bones of fowl



Fig. 1. Map of Poland indicating Giecz and its surrounding medieval centers. All skeletal materials used in this study were obtained from Giecz (site Gz4).

including chicken, goose and duck (Makowiecki, 2006; Waluszewska-Bubiń, 1979). Wild species including deer and hare are also less common, accounting for fewer than 3% of total assemblages (Makowiecki, 2006). To what extent the peasantry had access to these resources is unclear. Medieval purchase records, which divide household meat purchases by the estimated number of occupants, have been used in Poland to estimate that people consumed about a half pound of terrestrial meat daily (Dembińska, 1999). Stable isotope data are used in this study to reveal more precisely how this bulk estimate amount was distributed within the peasantry.

Differential access to fish is also investigated. A freshwater lake existed near the site during medieval occupation and fish bones are often encountered during excavation. Fishhooks found at Giecz indicate that humans were exploiting aquatic resources. However, because most fish were more expensive than terrestrial meat during the medieval period (Dembińska, 1999), they may have been siphoned off by religious communities or the social elite and rarely consumed by the general populace (Makowiecki, 2001). Here, isotope evidence specifically assesses the relative importance of fish in peasant diet at Giecz.

### 3. Background of stable isotope theory

Isotopic values are expressed as a permil (‰) ratio of one of an element's isotopes to another in relation to a standard of known abundance (Vienna Pee Dee Belemnite for  $\delta^{13}\text{C}$  and AIR for  $\delta^{15}\text{N}$ ). Both carbon and nitrogen ratios are reported according to the equation [ $\delta = (R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}} \times 1000$ ].

#### 3.1. Nitrogen isotopes

An organism's  $\delta^{15}\text{N}$  ratio is related to its trophic position in the local food web: as nitrogen from food sources is ingested and incorporated into consumer tissues, the lighter isotope  $^{14}\text{N}$  breaks down more readily than  $^{15}\text{N}$  and is excreted with urea (Minawaga and Wada, 1984; Schoeninger and DeNiro, 1984). This leaves consumers' tissues enriched by approximately 3–5‰ compared to their diets throughout the food chain (Drucker and Bocherens, 2004).

Within terrestrial systems, many plants exhibit  $\delta^{15}\text{N}$  values of approximately 3‰. After trophic enrichment, herbivorous animals eating these plants exhibit  $\delta^{15}\text{N}$  values of 6–8‰ and carnivores exhibit values of approximately 9‰. Omnivores, including humans, typically exhibit intermediate values (Schoeninger and Moore, 1992). Although  $\delta^{15}\text{N}$  ratios evaluate the relative importance of animal protein in an organism's diet, they do not distinguish between different cuts of meat or between meat and dairy from the same animal.

The number of possible trophic positions is greater in aquatic foodwebs due to presence of zooplankton, zoobenthos, and insect prey at the base of the food chain (France, 1994). As a result,  $\delta^{15}\text{N}$  ratios of fish are often higher than those of terrestrial animals (DeNiro and Epstein, 1981), although fish may consume a diverse mixture of aquatic food sources and exhibit variable  $\delta^{15}\text{N}$  ratios. For example, the  $\delta^{15}\text{N}$  values of freshwater fish in Lake Baikal range from 7.3 to 13.7‰ although the majority falls between 10.0 and 12.5‰ (Katzenberg and Weber, 1999). Marine fish are also enriched compared to terrestrial animals: cod bone excavated from medieval Polish sites exhibit  $\delta^{15}\text{N}$  values of 10.7–13.2‰ (Barrett et al., 2008). After trophic enrichment, consumers of fish may exhibit  $\delta^{15}\text{N}$  enrichment beyond what could be expected from a terrestrial diet.

Despite these general trends,  $\delta^{15}\text{N}$  values of plants and animals are not identical across regions (DeNiro and Epstein, 1981). Other sources of variability besides diet influence  $\delta^{15}\text{N}$  ratios of plants and animals. These include climate (Ambrose, 1991), physiology

(Ambrose, 1991; Fuller et al., 2006) and subsistence techniques such as crop manuring or salt-marsh grazing (Bogaard et al., 2007; Britton et al., 2008). These variables generate inter-regional differences in human  $\delta^{15}\text{N}$  values that are not related to diet per se, which complicates isotopic comparisons of diet across populations. It is therefore important to establish a local baseline for human values which may be used as a point of comparison for estimating human diet. This local baseline should include associated plant and animal resources exploited by humans. Ideally, it also includes animals not consumed by humans, such as carnivores, to ascertain the end-member ratio of a truly carnivorous diet in the given environment.

#### 3.2. Carbon isotopes

The ratio obtained using carbon's two stable isotopes,  $^{12}\text{C}$  and  $^{13}\text{C}$ , is assessed to determine relative consumption of two classes of plants:  $\text{C}_3$  plants, including most vegetables, wheat, and barley, and  $\text{C}_4$  plants, including millet, maize, and other tropical grasses (Smith and Epstein, 1971). These two classes of plant are distinguished by different photosynthetic pathways through which carbon from the atmosphere is "fixed" in plant tissues (Bender, 1968). The major source of carbon for terrestrial ecosystems is atmospheric  $\text{CO}_2$ , with a  $\delta^{13}\text{C}$  ratio of approximately  $-8.0\text{‰}$  (Marino and McElroy, 1991). The photosynthetic pathway of  $\text{C}_3$  plants, the Calvin cycle, preferentially incorporates the lighter isotope  $^{12}\text{C}$  during metabolism and discriminates against  $^{13}\text{C}$ . Consequently,  $\text{C}_3$  plant tissues are considerably depleted compared to  $\text{CO}_2$ , exhibiting values of  $-20.0$  to  $-35.0\text{‰}$  (Katzenberg, 2000). The Hatch–Slack pathway, used by  $\text{C}_4$  plants to metabolize carbon, does not discriminate as stringently against the heavier isotope, leaving tissues  $^{13}\text{C}$ -enriched compared to  $\text{C}_3$  plants. The  $\delta^{13}\text{C}$  values of  $\text{C}_4$  plants range from  $-9.0$  to  $-14.0\text{‰}$  and do not overlap those of  $\text{C}_3$  plants (Katzenberg, 2000).

Marine plants metabolize carbon present in oceans via the  $\text{C}_3$  photosynthetic pathway. The major source of carbon in marine ecosystems is dissolved inorganic carbon (including carbonic acid and  $\text{CO}_2$ ), which in oceans worldwide exhibits an average  $\delta^{13}\text{C}$  value of approximately  $1.5\text{‰}$  (Hoefs, 2004). Particulate organic matter (including algae and detritus) is another source of carbon in marine environments with  $\delta^{13}\text{C}$  values generally ranging from  $-18.5$  to  $-22.0\text{‰}$  (Hoefs, 2004). The  $\delta^{13}\text{C}$  ratios of plants and animals occupying marine niches fall between these values, and marine fish  $\delta^{13}\text{C}$  values can range from approximately  $-11.0$  to  $-19.0\text{‰}$  (Barrett et al., 2008). In regions where  $\text{C}_4$  plants are demonstrably absent,  $\delta^{13}\text{C}$  enrichment thus suggests consumption of marine fish. In regions where  $\text{C}_4$  plants may have been present,  $\delta^{13}\text{C}$  ratios should be supplemented with other evidence (historical or archaeobotanical evidence and/or  $\delta^{15}\text{N}$  ratios) to identify marine fish in diet.

The  $\delta^{13}\text{C}$  composition of plants in freshwater ecosystems is highly variable. Unlike in terrestrial or marine environments where carbon derives primarily from a single source (atmospheric  $\text{CO}_2$  on land and dissolved carbonate in oceans), carbon composition in freshwater environments is heavily influenced by isotopic equilibration between water and atmosphere, and also by decomposing organic matter. The relative contribution of each variable to the overall isotopic values of bodies of freshwater depends largely on lake size and water turbulence (Dufour et al., 1999). Freshwater fish consequently exhibit a broad range of  $\delta^{13}\text{C}$  values, but studies suggest their values are usually depleted due to the low  $\delta^{13}\text{C}$  ratios of aquatic plants (Dufour et al., 1999; Pazdur et al., 1999). Depletion in  $\delta^{13}\text{C}$  ratios of human bone below what might be expected of a terrestrial diet (more negative than approximately  $-22.0\text{‰}$ , the low-end of what could be explained by a  $\text{C}_3$ -only terrestrial diet) suggests freshwater fish consumption.

Ratios of  $\delta^{13}\text{C}$  can be measured in bone collagen (reported as  $\delta^{13}\text{C}_{\text{coll}}$ ) or bone apatite ( $\delta^{13}\text{C}_{\text{ap}}$ ). Experimental evidence from controlled feeding experiments with rodents suggests that isotopes in bone collagen primarily represent a consumer's protein sources (Ambrose and Norr, 1993; Tieszen and Fagre, 1993). This is because bone collagen is formed from amino acids, many of which are essential and derive from ingested protein (Schoeller, 1999). However, 78% of carbon in bone derives from non-essential amino acids. These are typically obtained directly from dietary protein but in protein-deficient diets they may be assembled from other macronutrients (particularly carbohydrates) (Schwarcz, 2000). Isotopes in collagen therefore primarily, though not exclusively, represent dietary protein sources.

Apatite, the inorganic fraction of bone, is formed primarily from the major energy source in diet, carbohydrates, via dissolved bicarbonates in blood (Garvie-Lok et al., 2004). Although the isotopic integrity of enamel apatite is excellent, apatite in bone is more susceptible to diagenetic processes and alteration than collagen, including contamination by carbonates in the depositional environment, post-mortem recrystallization of apatite, and recrystallization or isotope exchange during sample preparation (Koch et al., 1997). Strategies for alleviating these problems do exist, such as consistent pre-treatment with 0.1 M acetic acid and restricting analyses to well-preserved bone (Koch et al., 1997; Nielsen-Marsh and Hedges, 2000a,b).

Because isotope values in apatite provide information on overall diet that may be masked in bone collagen, they are a valuable complement in isotope studies. Information on both protein and carbohydrates in diet helps distinguish between marine fish and  $\text{C}_4$  plants as possible sources of  $\delta^{13}\text{C}$  enrichment among consumers, or between consumption of animal products and of manured crops as sources of  $\delta^{15}\text{N}$  enrichment. In light of the complications associated with preservation and preparation of bone apatite (Koch et al., 1997; Nielsen-Marsh and Hedges, 2000a,b), meaningful information can only be obtained when samples are prepared carefully and interpreted cautiously.

The natural variations of  $\delta^{13}\text{C}$  values among plants and animals are maintained in the tissues of their consumer as carbon is incorporated up the food chain, but due to metabolic fractionation, there are predictable offsets between diet and consumer  $\delta^{13}\text{C}$  ratios. Consumer  $\delta^{13}\text{C}$  is generally enriched by +5.0‰ relative to plants consumed, and by +1.0‰ relative to animals consumed (DeNiro and Epstein, 1978; van der Merwe and Vogel, 1978; van Klinken et al., 2000). Between  $\delta^{13}\text{C}_{\text{ap}}$  and overall diet there is an offset of +9.4 to 9.7‰ (Ambrose and Norr, 1993; DeNiro and Epstein, 1978; Kellner and Schoeninger, 2007). By accounting for these relationships, it is possible to backtrack from a consumer's  $\delta^{13}\text{C}$  ratios and determine the isotope ratios of foods consumed.

Kellner and Schoeninger (2007) previously demonstrated the relative clarity with which a regression of  $\delta^{13}\text{C}_{\text{coll}}$  against  $\delta^{13}\text{C}_{\text{ap}}$  from experimental studies can sort isotope ratios of consumers into particular spectra of diets. These authors used previously published data from controlled feeding experiments to calculate regression lines of a  $\text{C}_3$  protein diet, a marine protein diet, and a  $\text{C}_4$  protein diet with 100%  $\text{C}_3$  and 100%  $\text{C}_4$  energy end-points. The experimental data produced regression lines with  $r^2$  values of 0.95, 0.90 and 0.85, respectively. When archaeological data are plotted in a similar manner these linear relationships are apparent, although not as strong as the experimental data, due in part to the confounding digestive physiology of large ruminant animals present in human diet. The model is nevertheless argued to be more accurate than using collagen, apatite, or collagen-apatite spacing relationships alone in reconstructing past diet (Kellner and Schoeninger, 2007). In this study, the model is used to supplement and evaluate interpretations drawn primarily from collagen data.

#### 4. Materials

Skeletal materials in this pilot study were excavated at site Gz4 between 1999 and 2006. Skeletons of over 270 individuals have been excavated from the cemetery, all of which were buried during the 11th and 12th centuries. Individuals are believed to be peasants, as members of the elite were likely buried within the stronghold near the parish church. Exact dates of individual burials within this time frame are unknown. A subset of 12 men and 12 women was selected for analysis in this preliminary investigation. This was deemed the minimum necessary to yield statistically meaningful results for the population in question, although a much larger sample is necessary to represent dietary behaviors of the whole medieval Polish peasantry. Immature individuals were excluded from the sample, and adults were sampled from among the best-preserved remains as assessed visually. Samples of apatite were prepared from 8 individuals for which an adequate amount of bone remained after collagen analysis, including 5 males and 3 females.

Only rib sections were sampled from humans, which have an estimated turnover rate of approximately 30 years (Stenhouse and Baxter, 1977). Stable isotopes in rib are thus representative of what individuals ate during the last decades of their lives.

Also sampled are the associated bones of cow, pig, sheep, and deer, animals known to have been consumed in medieval times (Dembińska, 1999; Makowiecki, 2008). Four vertebrae from unidentified species of fish were also analyzed. Faunal remains were retrieved from dirt filling the graves, therefore it is possible they were deposited during an earlier occupation of the site (8th and 9th centuries) and removed and used as backfill when the burials were interred (11th and 12th centuries). Despite this, it is likely that earlier faunal samples could provide an accurate baseline given that they are local specimens.

#### 5. Methods

Human and herbivore collagen samples were prepared according to Ambrose (1990). Small chunks of bone were cleaned of dirt and visible contaminants with a scalpel and/or forceps and ground to a coarse powder. The inorganic component of bone was removed by soaking powdered bone for 20 min in 1.0 M HCl to solubilize minerals. These were flushed away in a 60 mL glass frit filter funnel.

Recovered fish bones were more delicate than those of humans and terrestrial animals. When subjected to the same preparation protocol they yielded unacceptably low amounts of collagen for analysis. For these, a revised protocol was used (Ambrose et al., 1997; Ambrose, pers. comm.) in which bone was crushed to just 1 mm and demineralized in a more dilute solution of HCl (0.2 M) for longer periods of time (24–48 h).

Demineralized residues were soaked overnight in 0.125 M NaOH to remove lipids and other contaminants. These were then rinsed repeatedly in the filter funnel. Using a water bath, remaining residues were heated in centrifuge tubes for 10 h in a dilute HCl solution (pH  $\approx$  3) at 90–95 °C to solubilize collagen. This breaking down of tightly wound collagen tendrils separates any remaining contaminants. Finally, the "hot collagen broth" (Ambrose, 1990) was filtered through the coarse glass frit in the filter funnel, and the filtrate lyophilized for at least 24 h. Freeze-dried samples were completely homogenized by hand grinding with an agate mortar and pestle.

Collagen samples were analyzed on a Costech Elemental Analyzer coupled to a Finnigan Delta IV Plus stable isotope ratio mass spectrometer under continuous flow using a CONFLO III interface in the Stable Isotope Biogeochemistry Laboratory at The Ohio State University. One triplicate and two duplicate samples were run (analytical error listed in Table 2). Stable carbon

( $\delta^{13}\text{C}$  = permil deviation of the ratio of  $^{13}\text{C}:^{12}\text{C}$  relative to the Vienna Pee Dee Belemnite Limestone standard) and stable nitrogen ( $\delta^{15}\text{N}$  = permil deviation of  $^{15}\text{N}:^{14}\text{N}$  relative to AIR) measurements were made where repeated measurements of the USGS24 and IAEA1 standards were  $\pm 0.06\text{‰}$  for  $\delta^{13}\text{C}$  and  $\pm 0.17\text{‰}$  for  $\delta^{15}\text{N}$ .

Despite a relatively small sample, D'Agostino's K-squared test demonstrates that both  $\delta^{13}\text{C}_{\text{coll}}$  and  $\delta^{15}\text{N}$  are normally distributed in the human sample ( $\text{KSQ} = 0.4, 4.0$ ). Parametric statistics including linear regressions and one- and two-tailed Monte Carlo tests, appropriate for small sample sizes and ordinal data, are used to evaluate data. One-way ANOVAs are employed when an alternate hypothesis predicts a difference between groups, and two-way ANOVAs are used when a difference between two groups is unclear. Data are reported with means, standard deviations ( $\pm 1\sigma$ ), and ranges.

Apatite was extracted according to Garvie-Lok et al. (2004). Approximately 1 g of bone remaining from collagen preparation was ground by hand with a ceramic and an agate mortar and pestle. To remove the organic fraction, bone powder was soaked for 48 h in 10 mL 2% NaOCl solution, replacing solutions every 12 h. Powders were rinsed with multiple changes of distilled, deionized water. Diagenetic carbonates were removed by soaking powder for 4 h in 50 mL 0.1 M acetic acid, a concentration shown to minimize alteration caused by diagenesis or sample preparation (Garvie-Lok et al., 2004; Koch et al., 1997; Nielsen-Marsh and Hedges, 2000a,b). Halfway through acid treatment, bone powder in solution was exposed to vacuum to ensure thorough interaction between sample and acid. Samples were dried for up to 48 h in a fume hood and homogenized in an agate mortar and pestle.

A 75–95  $\mu\text{g}$  subsample was analyzed for  $\delta^{13}\text{C}_{\text{ap}}$  using an automated Carbonate Kiel device coupled to a Finnigan Delta IV Plus stable isotope ratio mass spectrometer in the Stable Isotope Biogeochemistry Laboratory at The Ohio State University. Samples were acidified under vacuum with 100% ortho-phosphoric acid, the resulting  $\text{CO}_2$  cryogenically purified, and delivered to the mass spectrometer. One sample (20/02) run in duplicate produced identical  $\delta^{13}\text{C}$  values. The standard deviation of repeated measurements of a limestone internal standard (NBS-19) was  $\pm 0.02\text{‰}$  and of a biogenic calcite standard (sclerosponge skeleton) was  $\pm 0.01\text{‰}$ .

Apatite and collagen  $\delta^{13}\text{C}$  from the 8 individuals for whom both are available are plotted in a simple linear regression. The scatter is superimposed on regression lines developed in Kellner and Schoeninger (2007) to visualize and identify protein and energy sources in diet at Giecz.

## 6. Results

According to criteria outlined in Ambrose (1990) for detecting diagenesis, all samples are in excellent condition (Tables 1 and 2). Collagen quality indicators measured include %C, %N and atomic C/N ratios (van Klinken, 1999).

Mammal samples exhibit a  $\delta^{13}\text{C}$  range of  $-21.9$  to  $-20.5\text{‰}$  with an average value of  $-21.4 \pm 0.6\text{‰}$ . Nitrogen isotope ratios range from 5.8 to 6.8 $\text{‰}$  with an average value of  $6.3 \pm 0.4\text{‰}$  (Fig. 2 and Table 1).

Both the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of fish sampled for this study are highly variable (Table 1). Fish bones exhibit a  $\delta^{13}\text{C}$  range of  $-26.5$  to  $-24.5\text{‰}$  and an average of  $-25.5 \pm 1.0\text{‰}$ . Values of  $\delta^{15}\text{N}$  show the widest variation, ranging from 6.4 to 12.3 $\text{‰}$  with an average of  $9.6 \pm 2.7\text{‰}$ . Among fish, less positive  $\delta^{15}\text{N}$  ratios associated with more negative  $\delta^{13}\text{C}$  ratios and more positive  $\delta^{15}\text{N}$  with less negative  $\delta^{13}\text{C}$  ratios (Fig. 2).

**Table 1**  
Faunal data.

ID number	Sample type	Bone	Nitrogen [%]	Carbon [%]	C:N ratio	$\delta^{15}\text{N}_{\text{Air}}$ (‰)	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰) bone collagen
F154/03	Fish	Vert	14.1	39.3	3.3	6.4	-26.5
F273/03	Fish	Vert	13.3	38.1	3.3	8.3	-26.4
F295/05	Fish	Vert	13.9	39	3.3	12.3	-24.7
F63/05	Fish	Vert	14	39.3	3.3	11.2	-24.5
S00/04	Ovicapridae	Phalanx	13.9	38.2	3.2	6.5	-21.9
D00/02	Cervidae	Hoof	14.8	40.5	3.2	6	-21.6
C00/03	<i>Bos</i> sp.	Talus	14.2	39	3.2	6.8	-21.6
P00/01	<i>Sus</i> sp.	Phalanx	14.3	39.2	3.2	5.8	-20.5

$\delta^{13}\text{C}$  ratios from human bones are presented in Table 2. These range from  $-19.4$  to  $-18.0\text{‰}$  with an average of  $-18.9 \pm 0.4\text{‰}$ . Men's and women's mean  $\delta^{13}\text{C}_{\text{coll}}$  ratios are  $-18.8\text{‰}$  and  $-19.0\text{‰}$  respectively. This difference is not statistically significant (Monte Carlo, one-tail;  $p = 0.13$ ) (Fig. 3 and Table 2).  $\delta^{13}\text{C}_{\text{ap}}$  values exhibit a small range of  $-11.5$  to  $-12.7$  which may suggest little influence of sample alteration through diagenesis or preparation. The mean for  $\delta^{13}\text{C}_{\text{ap}}$  values is  $-12.0 \pm 0.5\text{‰}$ , 6.9 $\text{‰}$  higher than  $\delta^{13}\text{C}_{\text{coll}}$  mean.

Unlike in  $\delta^{13}\text{C}_{\text{coll}}$  values, sex-based differences in  $\delta^{15}\text{N}$  values are apparent. The overall range of  $\delta^{15}\text{N}$  values is 7.9–10.3 $\text{‰}$ ; the average  $\delta^{15}\text{N}$  value among men is  $9.6 \pm 0.4\text{‰}$ , whereas the average among women is  $8.8 \pm 0.5\text{‰}$ . This 0.8 $\text{‰}$  difference between the groups is significant (Monte Carlo, one-tail;  $p = 0.001$ ). There are no significant differences across age groups for either  $\delta^{15}\text{N}$  or  $\delta^{13}\text{C}$  values.

Carbon and nitrogen from collagen are modestly correlated among men (Fig. 3). About 54% of  $\delta^{13}\text{C}_{\text{coll}}$  variation in men is explained by corresponding variations in  $\delta^{15}\text{N}$  (linear regression;  $r^2 = 0.54$ ). Among women, this relationship is absent ( $r^2 = 0.05$ ).

## 7. Discussion

### 7.1. Faunal samples

All four terrestrial mammals exhibit  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values within the range of exclusive  $\text{C}_3$  feeders. There is no reason to suspect these animals were not locally raised or fed non-local resources. The possibility of non-contemporaneity is nevertheless an important one, as non-contemporaneous animals could exhibit isotope variations due to environmental changes (van Klinken et al., 2000) or changes in subsistence technologies (Bogaard et al., 2007; Britton et al., 2008; Pechenkina et al., 2005). A larger faunal sample is necessary to strengthen conclusions about human diet made based on these animals.

The sample comprises both wild (deer) and domesticated (pig, cow, sheep) taxa, yet shows little variation for either  $\delta^{13}\text{C}$  or  $\delta^{15}\text{N}$ . A preliminary conclusion is that domestic animals sampled here were not foddered with any type of  $\text{C}_4$  plant that would have enriched their  $\delta^{13}\text{C}$  values. Subtracting the effects of trophic level enrichment from  $\delta^{13}\text{C}$  values obtained from these animals it is inferred that local plant resources, though not sampled, have  $\delta^{13}\text{C}$  values of around  $-26.0\text{‰}$ , and  $\delta^{15}\text{N}$  values around 3.0 $\text{‰}$ . Such values are expected in a  $\text{C}_3$  environment (Schoeninger and Moore, 1992). Ideally, a greater number of faunal samples would be used to establish dietary baselines for humans.

Species of fish sampled in this study are unidentified. However,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values may help identify their ecological niches. It is inferred that these samples are from freshwater environments because of their conspicuously negative  $\delta^{13}\text{C}$  signatures. Within freshwater systems, depleted  $\delta^{13}\text{C}$  values as light as  $-34.0\text{‰}$  are

**Table 2**  
Archaeological human data.

ID Number	Bone	Sex	Nitrogen (%)	Carbon (%)	C:N Ratio	$\delta^{15}\text{N}_{\text{Air}}$ (‰)	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰) bone collagen	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰) bone apatite	Age
Human samples									
17/02D	Rib	F	14.9	40.8	3.2	9	-19.4	-12.4	35–45
08/02	Rib	F	14.5	39.9	3.2	9.3	-19.4		50–59
14/02	Rib	F	14.1	38.5	3.2	7.9	-19.2		40–49
51/99	Rib	F	14.4	39.7	3.2	9.1	-19.2		40–50+
12/03	Rib	F	13.9	38.3	3.2	9.1	-19.1		35–49
34/99A	Rib	F	14.7 ± 0.14 <sup>a</sup>	40.3 ± 0.51 <sup>†</sup>	3.2	8.4 ± 0.26 <sup>a</sup>	-19 ± 0.03 <sup>a</sup>	-12.3	35–49
39/99	Rib	F	14.6	40.3	3.2	9	-18.9	-12.6	40–49
02/02	Rib	F	14.9	41	3.2	9.1	-18.9		35–44
20/02	Rib	F	13.4 ± 0.08 <sup>b</sup>	36.7 ± 0.01 <sup>b</sup>	3.2	8.5 ± 0.01 <sup>b</sup>	-18.9 ± 0.01 <sup>b</sup>	-12.7 ± 0.0 <sup>b</sup>	40–45
10/03	Rib	F	14.7	40.2	3.2	8.7	-18.8		50–59
42/99	Rib	F	15.1	41.2	3.2	8.5	-18.6		40–45
17/06	Rib	F	12.8 ± 0.19 <sup>b</sup>	35 ± 0.49 <sup>b</sup>	3.2	8.9 ± 0.03 <sup>b</sup>	-18.5 ± 0.01 <sup>b</sup>		30–45
75/01	Rib	M	14.5	39.9	3.2	8.9	-19.3	-11.6	20–25
04/06	Rib	M	14.6	40	3.2	9.1	-19.3		25–30
36/03	Rib	M	14.4	39.8	3.2	9.2	-19		35–45
31/99	Rib	M	14.4	39.6	3.2	10	-19		40–50+
81/01	Rib	M	14.7	40.4	3.2	9.5	-19		35–39
08/05	Rib	M	15	41.4	3.2	9.6	-18.9		35–44
37/99	Rib	M	14.2	38.9	3.2	9	-18.9		40–45
02/03	Rib	M	13.5	37.1	3.2	9.4	-18.7		30–49
54/99	Rib	M	14.2	39.5	3.2	9.8	-18.7		40–45
80/01A	Rib	M	14.8	40.7	3.2	10.3	-18.4	-11.7	45–59
16/02	Rib	M	14.8	40.6	3.2	10.3	-18.2	-11.5	35–45
14/05	Rib	M	15	41.1	3.2	9.9	-18	-12.1	40–45

<sup>a</sup> Indicates triplicate measurement.

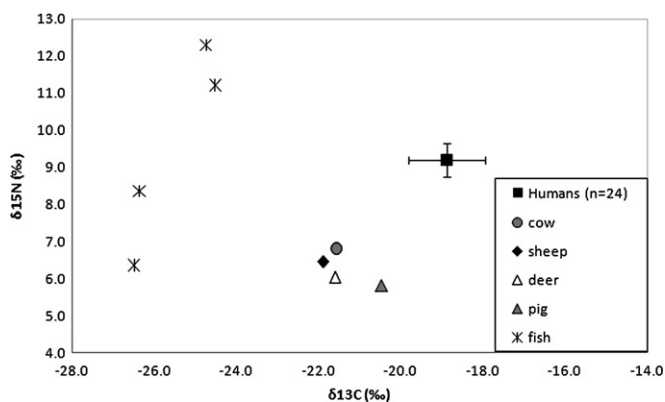
<sup>b</sup> Duplicate measurement.

indicative of pelagic environments, while values closer to  $-26.0\text{‰}$  are associated with littoral environments (France, 1995). Furthermore, greater enrichment of  $\delta^{15}\text{N}$  is expected of piscivores and planktivores, whereas detritivores exhibit lower values (Katzenberg and Weber, 1999). Considering their isotopic signatures, two samples (F 295/05 and F 63/05) may be littoral fish occupying high trophic positions such as pike or perch, known to have been consumed by Polish populations during the medieval period (Dembińska, 1999; Makowiecki, 2001). The other two samples (F 154/03 and F 273/03) may be littoral detritivores, such as bass or burbot. High isotopic variability observed in fish bones at Giecz illustrates the importance of analyzing local samples when considering freshwater fish as a potential dietary resource. None of the fish sampled in this study are marine species, although this does not imply that marine fish were not a part of the local economy.

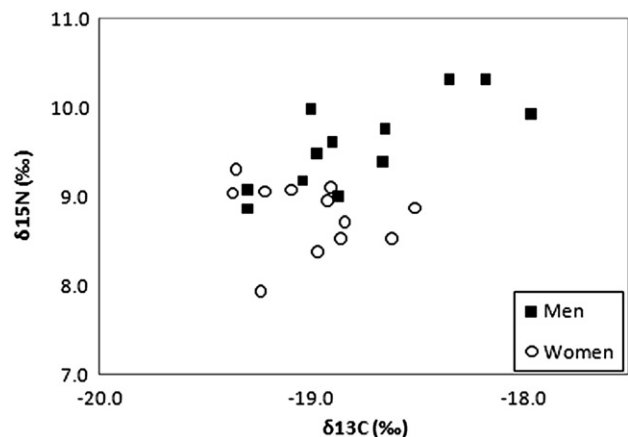
## 7.2. Human samples

Isotope ratios obtained from humans at Giecz suggest an omnivorous diet. Values are not highly variable, exhibiting a  $\delta^{13}\text{C}$  range of  $1.4\text{‰}$  and a  $\delta^{15}\text{N}$  range of  $2.4\text{‰}$ . This suggests that, although small, the sample may adequately encapsulate the dietary habits of the sub-population buried at site Gz4.

Both  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values are within the range expected for a population obtaining most of its dietary protein from terrestrial (not aquatic) sources. The difference of  $2.9\text{‰}$  between the means of animal and human  $\delta^{15}\text{N}$  values suggests that human  $\delta^{15}\text{N}$  ratios are accounted for by the animal values plus expected trophic level enrichment resulting from their consumption (Schoeninger and Moore, 1992). Human tissues do not reflect the conspicuously negative  $\delta^{13}\text{C}$  values of fish sampled at Giecz, indicating that freshwater fish were not a significant dietary resource for this population.



**Fig. 2.** Human (mean ± 1σ) and animal bone collagen isotope data from Giecz, Poland. A wide separation between human and fish values suggests a terrestrial-based diet. Human carbon values are enriched compared to herbivore values suggesting consumption of a C<sub>4</sub> plant.



**Fig. 3.** Carbon and nitrogen isotope ratios of collagen from men ( $n = 12$ ) and women ( $n = 12$ ) at Giecz. Carbon and nitrogen values exhibit a positive correlation among men but not among women. Women's nitrogen values are markedly lower than those of men.

For comparison, isotope data from other medieval European populations are displayed in Fig. 4. These populations consumed diets similar to that at Giecz, but were selected to illustrate particular differences and similarities among them. For example, the lack of significant amounts of fish in diet at Giecz is highlighted by comparisons with two populations exhibiting clear isotopic signals of fish: a medieval Belgian population which consumed freshwater species (Polet and Katzenberg, 2003) and a medieval Swedish population which consumed marine species (Kosiba et al., 2007). In both populations,  $\delta^{15}\text{N}$  ratios are considerably higher than in the Giecz sample. Conversely, terrestrial diets of a medieval German population (Schutkowski et al., 1999), a medieval English population (Fuller et al., 2003; Richards et al., 2002), and a series of Austrian groups from the Iron Age (Le Huray and Schutkowski, 2005) exhibit  $\delta^{15}\text{N}$  ratios similar to those at Giecz. These comparisons suggest that the people at Giecz were not heavily reliant on marine fish.

As Christianity was introduced throughout Europe, a number of medieval groups incorporated substantial quantities of fish into their diets, possibly to accommodate religious fasts (Barrett and Richards, 2004; Müldner and Richards, 2005; Salamon et al., 2008). For a total of 182 days each year, including Wednesdays, Fridays and Lent, meat, dairy and eggs were proscribed by the medieval Church (Woolgar, 2000). In Poland, the Lenten season was more than three weeks longer than this, beginning on the 10th Sunday before Easter rather than on Ash Wednesday (Kloczowski, 2000). Fish, unlike terrestrial meat, was permitted during fasts and for those adhering to Christian customs would have been the only available source of animal protein during much of the year. Such a drastic dietary restriction may leave an isotopic signature in human bone. That fish do not contribute significantly to human bone isotope ratios at Giecz may indicate the population did not observe Christian fasts, although East–West burials organized in distinct rows (Kryzstofiak, 2008) do suggest adherence to at least one Christian convention.

Alternatively, fish may have been an expensive commodity at Giecz that was reserved for the social elite and/or clergy (Dyer, 1988; Müldner and Richards, 2005). Giecz was located at the confluence of major exchange routes during the early medieval period (Kryzstofiak, 2008) and fish could also have been traded

away for a reasonable profit rather than consumed locally. Also, due to the high cost of fish, individuals sampled in this study may indeed have observed Christian fasts, but replaced meat with more affordable, terrestrial protein from cheese, eggs, and milk. However, all protein sources were considered luxury items in the early medieval period (Bennett, 1996; Makowiecki, 2006) and according to historical records, the Polish Church proscribed all terrestrial animal products during fasts, including dairy products (Dembńska, 1999; Kloczowski, 2000). Future isotopic analyses of bones from elite burials in the separate parish cemetery at Giecz would clarify a status-based distribution of fish.

Human  $\delta^{13}\text{C}$  values fall within the expected range of a population consuming both  $\text{C}_3$  and  $\text{C}_4$  resources (Schoeninger and Moore, 1992), but are closer to values expected for a purely terrestrial  $\text{C}_3$  foodweb. The majority of human diet appears to have comprised  $\text{C}_3$  plants such as wheat and vegetables. However, a smaller portion of isotopically enriched foods has caused enrichment of human values over those of sampled animals (Fig. 2) and of other populations consuming  $\text{C}_3$  resources alone (Fig. 4).  $\text{C}_4$  enrichment could arise from consumption of marine fish, consumption of millet, or consumption of animals foddered on millet.

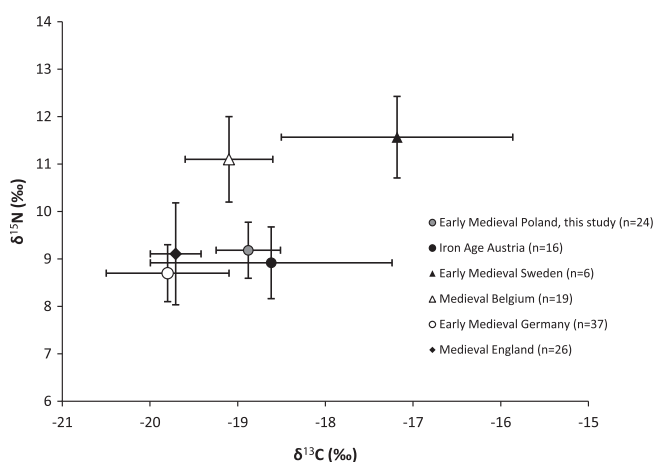
Although marine fish could have been imported to Giecz from the Baltic Sea and preserved by salting or pickling, the low human  $\delta^{15}\text{N}$  ratios already discussed indicate that protein sources at Giecz were largely terrestrial. Expected  $\delta^{15}\text{N}$  ratios for populations consuming fish are several permil higher than those obtained in this study (Fig. 4). The  $\delta^{13}\text{C}$  enrichment among consumers of marine fish such as the Swedish population investigated by Kosiba et al. (2007) is also considerably higher than enrichment observed at Giecz. If marine fish's high  $\delta^{15}\text{N}$  values were cancelled by low  $\delta^{15}\text{N}$  values from terrestrial protein or legumes at Giecz, more variation among human isotope ratios could be expected. Furthermore, the quantities of these resources would have to be great to cancel out all but the smallest contributions of fish with high  $\delta^{15}\text{N}$  ratios to diet.

Human bone may also become indirectly enriched in  $^{13}\text{C}$  via consumption of animals foddered on  $\text{C}_4$  plants. Animals sampled in this study do not exhibit a  $\text{C}_4$  signature (Fig. 2), but it is possible that they date to another period during which different foddering strategies were employed. It is also possible that  $\text{C}_4$  signature reached humans indirectly from millet-consuming animals not sampled in this study, such as rabbits, chickens or wild fowl.

Direct consumption of millet by humans is a more parsimonious explanation for  $\delta^{13}\text{C}$  enrichment at Giecz. Although animal products are protein-rich and consequently over-represented as dietary components by isotopes from bone collagen, plants are not invisible (Richards, 2000). Proso millet contains 11.6% protein by dry weight (Kalinova and Moudry, 2006; Serna-Saldivar et al., 1991). For comparison, eggs are 12–13% protein by weight, and vegetables and fruits are often less than 1% protein (Watt and Merrill, 1975). Protein from millet and other cereals can influence isotope ratios in bone collagen, albeit not as strongly as animal protein. A small difference in isotope ratios caused by a plant might thus indicate quite high amounts of that plant's consumption.

Early isotopic evidence of millet consumption in Europe comes from Slovenia and Austria ca. 800 and 400 BC (Le Huray and Schutkowski, 2005; Murray and Schoeninger, 1988), and Serbia ca. AD 250 and AD 400 (Bonsall et al., 2004). The paucity of isotope evidence suggests that millet was not a significant source of protein for people in medieval times, but this may not be the case.

In Poland, pollen and carbonized seeds of proso millet have been recovered from several sites dating to as early as the 5th century AD (Barford, 2001; Jarosińska, 1994; Latalowa et al., 2003), and medieval documents suggest millet was a staple of medieval Polish



**Fig. 4.** Bone collagen isotope ratios from Giecz are compared to five other European populations for which isotopic dietary analyses are previously published. Diet at Giecz most closely resembles those of several Iron Age populations in Austria (shown together) which comprise terrestrial  $\text{C}_3$  resources as well as millet (Le Huray and Schutkowski, 2005). In comparison, populations from early medieval Germany (Schutkowski et al., 1999) and medieval England (Fuller et al., 2003; Richards et al., 2002) represent exclusively  $\text{C}_3$  diets with no input from fish. Both the medieval Belgian population (Polet and Katzenberg, 2003) and the early medieval Swedish population (Kosiba et al., 2007) consumed diets including aquatic resources.

cuisine (Dembińska, 1999). Ale and beer were brewed from millet during the medieval period in Poland, although barley, oats, rye, and wheat were also typical ingredients (Dembińska, 1999). Millet may have also had non-dietary importance as part of burial rituals to deter vampires (Barber, 1988), a concern that escalated among Slavic peoples as Christian customs demanded corpses be buried rather than cremated (Barford, 2001).

### 7.3. $\delta^{13}\text{C}$ ratios in apatite

To test dietary inferences based on collagen data, we calculated a regression of  $\delta^{13}\text{C}_{\text{ap}}$  and  $\delta^{13}\text{C}_{\text{coll}}$  values determined for 8 individuals for whom both were available (Fig. 5). These data points were superimposed on regression lines developed by Kellner and Schoeninger (2007) using experimental studies. Although these regression lines are less precise when used to interpret archaeological data, we use this model to illustrate and inform interpretations based on collagen data.

Isotope values from Giecz plot near the line representing a  $\text{C}_3$  protein diet, which corroborates conclusions drawn from collagen values. However, data points of three individuals (80/01A, 16/02 and 14/05) are shifted slightly to the right of this line. These individuals also exhibit three of the four highest  $\delta^{15}\text{N}$  values obtained in this study (the fourth among these, 31/99, was not sampled for apatite data). All three are male. Although these data points may still be within the range of  $\text{C}_3$  protein diets as determined by Kellner and Schoeninger, their rightward shift, along with their elevated  $\delta^{15}\text{N}$  values, suggests that these three individuals may indeed have consumed small amounts of marine fish or  $\text{C}_4$ -foddered animals. This information adds to what could be discerned using  $^{13}\text{C}_{\text{coll}}$  values alone, although a larger data set including apatite values of fauna is necessary to confirm the role of fish in diet at Giecz.

It should be noted that data points representing Giecz do not plot at the base of the  $\text{C}_3$  protein regression line, as would be expected for a population whose dietary energy comes only from  $\text{C}_3$  plants. Rather, they lie toward the midpoint of the line, suggesting that dietary sources of energy at Giecz were  $\delta^{13}\text{C}$ -enriched. This substantiates evidence from collagen for direct millet consumption by humans at Giecz. If the  $\delta^{13}\text{C}$  enrichment were due only to indirect millet consumption via animals foddered on millet or to marine fish consumption, the  $\text{C}_4$  signature would be visible in dietary protein. That is, the data points would be located at the base

of the regression line, but shifted to the right. The fact that the data points lie toward the middle of the  $\text{C}_3$  protein line indicates that at least some of the  $\text{C}_4$  signature is from a dietary energy source, such as carbohydrates derived from millet. This could be in the form of either food or drink.

These isotopic data supporting direct consumption of millet by humans at Giecz are limited in scope, yet corroborate extensive archaeobotanical evidence of millet throughout Central Europe (Le Huray and Schutkowski, 2005; Polcyn, 2002; Rösch et al., 1992; Schutkowski et al., 1999). We conclude that millet was most likely a significant dietary resource for medieval human populations in Poland, although only a larger sample of humans and animals will confirm this. These results should be borne in mind when interpreting human diet elsewhere in Europe where millet is typically unexpected.

### 7.4. Sex-based differences in isotope signatures

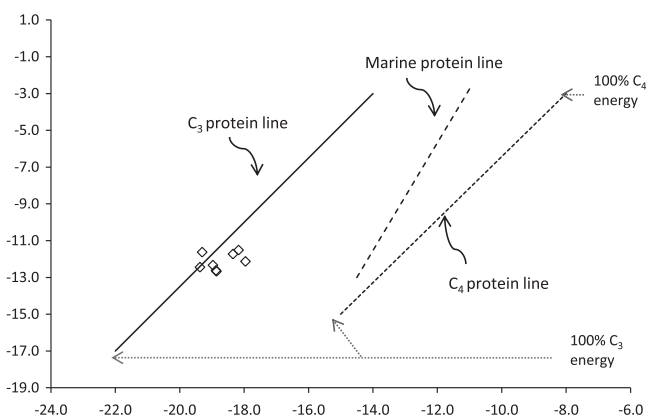
When considering dietary differences between the sexes during the medieval period, the question is not if social roles of men and women differed, which is known to be the case from historical records. The question rather is how extreme were these social differences, and whether they led to differential access to more highly valued foods. Attributing sex-based differences in  $\delta^{15}\text{N}$  enrichment to gender inequalities is a straightforward answer, but may not adequately surmise the situation. Indeed, the lowest  $\delta^{15}\text{N}$  value exhibited among women does not indicate a vegetarian diet due to deprivation of animal products proscribed by social rank, although local plants have not been directly sampled. Rather, it indicates consumption of relatively less meat than the average male. Other valid explanations should be explored.

Different diets may result from a sexual division of labor characteristic of the medieval period. Women's activities may have led them to consume more  $\text{C}_3$  plants than males in the course of daily activities, for example by contacting and consuming  $\text{C}_3$  plants while selling and buying them at markets or tending household gardens. Men may have accessed more meat purchasing it from "hucksters" in town or when dining in taverns. This model links dietary differences to complementary tasks performed by men and women, but does not imply social inequalities.

A sexual division of religious activities could account for sex-based differences in meat consumption (Bynum, 1987). Christianity was a factor in the lives of individuals living at Giecz during the 11th and 12th centuries and fasting was encouraged by the Church, if not rigorously enforced. Fasting may have been more carefully observed by women than by men in medieval society: "Since late medieval spirituality valued both renunciation and service, each gender renounced and distributed [charitably] what it most effectively controlled: men gave up money, property, and progeny; women gave up food" (Bynum, 1987: 193). If women observed half of a year's worth of fasting days that men did not, it could explain difference in  $\delta^{15}\text{N}$  values detected here.

A third explanation draws from medieval ideologies about the natures and constitutions of men and women, and the corresponding dietary needs of both sexes (Müldner and Richards, 2007a,b). For example, medieval culinary records (cookbooks, diaries, and memoirs) suggest that "... 'heavy food,' especially meat, was seen as more appropriate for men and lighter food for women, in part because meat had, for a thousand years, been seen as an aggravator of lust" (Bynum, 1987: 191). These beliefs do not necessarily imply that men and women were socially unequal, although they do reveal wariness about female promiscuity.

Fuller et al. (2004) proposed a physiological explanation for lower  $\delta^{15}\text{N}$  values among women. Pregnancy causes  $\delta^{15}\text{N}$  in hair of modern pregnant women to be depleted by 0.5–1.0‰. Bone, which



**Fig. 5.** A regression of  $\delta^{13}\text{C}$  ratios from bone apatite and collagen of 8 individuals from Giecz is superimposed over regression lines developed by Kellner and Schoeninger (2007). The lines represent diets based on three different primary sources of protein ( $\text{C}_3$ , marine, and  $\text{C}_4$  protein). The end points of each line represent diets based exclusively on one of two different primary sources of energy ( $\text{C}_3$  and  $\text{C}_4$ ). The location of Giecz data points indicates a diet of primarily  $\text{C}_3$  protein with a mixture of  $\text{C}_3$  and  $\text{C}_4$  energy sources.



remodels at an increased rate during gestation and lactation, may demonstrate a similar effect (Fuller et al., 2006). Müldner and Richards (2007b) suggest this remodeling may not be active enough to leave an isotopic trace in bone collagen after so short a time. That the trend is not universal also cautions against physiology as an explanation per se. However, it warrants a more detailed investigation at Giecz, especially in light of the fact that only  $\delta^{15}\text{N}$  values – not  $\delta^{13}\text{C}$  values – differ by sex.

Finally, differences in meat consumption can result from pervasive gender inequalities. If men and women were differentially valued in medieval society, high quality foods such as meat could have been available to men and withheld from women. A pecking order has been described in which food literally traveled down the table from individuals of higher to lesser rank: in medieval Poland, “the husband and male members of the family ate together first; the wife and other females ate together after the men finished” (Dembińska, 1999: 49–50). Socially structured pecking orders may have led to limited meat available to those eating last, particularly women and children.

Responding to their powerlessness in medieval society, women may have willingly abstained from food, thereby asserting control over their own lives. Discussing anorexia nervosa during the medieval period, Bynum (1987) notes that food and food preparation were the only realms of society in which women were master. She proposes that self-deprivation provided women with a sense of autonomy otherwise unavailable to them.

These factors may all have contributed in part to observed sex-based differences in  $\delta^{15}\text{N}$ . Comparison of isotope data to other lines of evidence, such as skeletal indicators of health and disease or a similar investigation of the social elite and clergy, could help clarify the cause of the isotopic differences observed here.

An explanation may be sought for the correlation between  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  ratios restricted in this study to men. Murray and Schoeninger (1988) observed a similar trend in their reconstruction of a terrestrial-based diet in Iron Age Slovenia, which could not be explained based on the available data. At Giecz, the trend may suggest that men consumed a small amount of marine protein that women did not, or animals foddered on millet (including those unsampled, such as hare). However, it should be stressed that men's  $\delta^{13}\text{C}_{\text{coll}}$  ratios are *not* statistically different from those of women, and in no sampled individuals are  $\delta^{15}\text{N}$  ratios high enough to evoke marine fish as more than a sporadic dietary resource.

The correlation between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  ratios among men may indicate that among males, consumption of animal products corresponds with millet-eating. This explanation evokes sex-specific dietary preferences. *Farcimina*, blood sausage stuffed with millet grits, is a staple of traditional Polish cuisine also popular in the medieval period (Dembińska, 1999). Medieval texts and ethnographic evidence indicate that millet gruels and porridges regularly complemented boiled or roasted meat as side dishes, and millet fried in butter was a daily staple (Dembińska, 1999). The particular dishes in which meat and dairy went hand-in-hand with millet could have been more commonly consumed by men, explaining the isotopic correlation.

The relationship may also indicate alcohol consumption accompanying meat consumption. Individuals consuming the most animal products may have done so at local taverns, where they also consumed drinks fermented from millet. Drinking ale during the medieval period was not restricted to taverns alone. In a world where milk was more often used for making cheese and water was frequently polluted, ale consumption was commonplace (Bennett, 1996). Be they peasant or nobility, adult or child, male or female, the average person consumed a quart of ale a day during the medieval period in England (Bennett, 1996). This may have been enough to influence human isotopic values, although protein

content of beer is low. Modern beverages show a clear isotopic separation between beer brewed from  $\text{C}_3$  versus  $\text{C}_4$  plants (means of  $-25\text{‰}$  and  $-19\text{‰}$ , respectively) (Brooks et al., 2002). The isotopic effects of beverages should be studied to confirm whether ale consumption, in conjunction with meat consumption, could be responsible for a correlation between  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  in human bone.

## 8. Conclusions

Residents of Giecz consumed an omnivorous diet that included significant amounts of animal protein. Most plants consumed were  $\text{C}_3$  crops such as wheat, barley, and vegetables. Isotopic evidence suggests that the population also consumed  $\text{C}_4$  plants, most likely millet. Marine fish may have been consumed, although any contribution to overall diet was not great and may have been restricted to men. Sex-based differences in diet are observed. These include greater consumption of animal products by men than by women, and a correlation between  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of men.

Millet consumption in Poland during the 11th and 12th centuries is an important observation setting Giecz apart from other Northern European groups. Researchers who do not anticipate isotopically heavy plant resources attribute  $\delta^{13}\text{C}$  enrichment to consumption of marine foods, especially in the absence of complementary  $\delta^{15}\text{N}$  data (Johansen et al., 1986; Mays, 1997; van der Merwe and Vogel, 1978) or to immigration from warmer climates (Richards et al., 1998). These assumptions may be unnecessary if millet was present in the local diet. It is therefore necessary to establish where and when millet was consumed in Europe and not to assume exclusively  $\text{C}_3$  diets.

Isotope ranges among humans are within those expected for a terrestrial diet. Any contribution of marine fish to diet was slight despite archaeological provenience of fish bones. If future studies confirm these results in a larger sample, it could suggest that fish were not replacing meat during Christian fasts. An alternate interpretation is that fish were caught, but were sold or traded away rather than consumed, or were consumed by the social elite who should be the subject of further investigation.

Apatite data used to supplement  $\delta^{13}\text{C}$  ratios in collagen generally support these conclusions. However, combined evidence from  $\delta^{15}\text{N}$ ,  $\delta^{13}\text{C}_{\text{coll}}$  and  $\delta^{13}\text{C}_{\text{ap}}$  values for three individuals makes a better case for marine fish consumption than could be gleaned from collagen data alone. The model developed by Kellner and Schoeninger (2007), although imperfect when interpreting archaeological samples, provides a simple and compelling way to better visualize diet using  $\delta^{13}\text{C}_{\text{coll}}$  and  $\delta^{13}\text{C}_{\text{ap}}$  values in tandem. When used within a framework established through archaeozoological and historical records, this method can tease apart the subtle influences on human's isotope ratios, such as low or irregular consumption of millet and fish.

These data suggest that women and men did not have similar access to all food resources during the medieval period, as evidenced by significantly higher  $\delta^{15}\text{N}$  ratios among men. This may be due to a sexual division of labor, social attitudes about gender and food in the medieval period, or sex-based inequalities. A physiological effect in which women's  $\delta^{15}\text{N}$  values are depleted during gestation may also cause this small but significant difference. Furthermore, while men and women do not differ in terms of their  $\delta^{13}\text{C}_{\text{coll}}$  values, men exhibit a positive correlation between  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}_{\text{coll}}$  that is absent in women. Sex-based differences in dining behavior could have caused this trend, for example men dining outside the home more often than women and eating particular dishes combining meat with millet more regularly. A larger human sample must be studied before this trend can be attributed to marine fish consumption, as the majority of males sampled here exhibit low  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}_{\text{coll}}$  ratios that appear to be terrestrial.

Interestingly, two trends – the correlation between  $\delta^{13}\text{C}_{\text{coll}}$  and  $\delta^{15}\text{N}$  and consumption of millet – suggest similarity between Giecz and the Iron Age populations examined by Le Huray and Schutkowski (2005) and Murray and Schoeninger (1988) rather than other medieval groups. In the former study, which included 16 Hallstatt individuals from northern Austria,  $\delta^{15}\text{N}$  values were terrestrial (mean = 8.9‰). The  $\delta^{13}\text{C}_{\text{coll}}$  values ranged from  $-20.1\text{‰}$  to  $-14.8\text{‰}$ , and millet consumption was evoked when  $\delta^{13}\text{C}_{\text{coll}}$  values exceeded  $-18.0\text{‰}$ . The study by Murray and Schoeninger included 20 individuals buried in Slovene tumuli, also dating to the Hallstatt period. There, human  $\delta^{15}\text{N}$  values were also terrestrial (mean = 9.4‰) and  $\delta^{13}\text{C}_{\text{coll}}$  values ranged from  $-20.0$  to  $-13.0\text{‰}$ . Isotope ratios at Giecz fall within these ranges, although  $\delta^{13}\text{C}_{\text{coll}}$  at Giecz is at the lighter end. The authors of both Iron Age studies point to paleobotanical evidence of millet consumption in Central Europe to explain  $\delta^{13}\text{C}_{\text{coll}}$  enrichment. Similar evidence for millet cultivation exists in Poland (Latalowa et al., 2003; Polcyn, 2002) but is not observed in Western Europe during the medieval period. At Giecz, cultural affinities with other Central and Eastern European (i.e., Slavic) populations may have influenced dietary decisions more strongly than the sociopolitical influences reaching from Western Europe at the time. The data sets from both Polish and Iron Age populations are nevertheless limited.

This pilot study illustrates how individualized isotope profiles complement historical and archaeological data to explore invisible behaviors such as sex-based differences, religious practices, and other dietary behaviors. Future research at Giecz should include a broader sample of animals and humans, ideally incorporating members of the clergy and social elite buried elsewhere at the site. Archaeological research in Europe has demonstrated that although a lack of material culture causes medieval diversity to be relatively under-appreciated, this period in Europe's history was not a homogenous cultural event. Compared to the amount of anthropological research that has been published about Western European populations, Eastern Europe's archaeological past is less well-known, and future studies of Poland and its surrounding areas will indicate how applicable Western European models of medieval life are to European populations overall. More isotope studies of diet will also help illustrate how tribal populations of Slavs transitioned into a modern, Christian world, and will provide information on the extent of human adaptability in complex social contexts.

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