

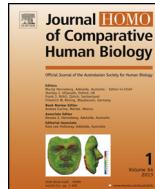


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An analysis of the origin of an early medieval group of individuals from Gródek based on the analysis of stable oxygen isotopes



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ABSTRACT

In the early Middle Ages, the region of the Cherven Towns, which is now located on both sides of the Polish–Ukrainian border, was fiercely contested by Slavs in the process of forming their early states. The main objective of the present study was to investigate the homogeneity of an early medieval population uncovered in that region, in the town of Gródek on the Bug River, by screening for non-local individuals. The origin of the studied skeletons was ascertained using analysis of oxygen isotopes in the phosphates isolated from bone tissue. In this paper, the isotope ratios obtained for samples collected from 62 human skeletons were compared to the background $\delta^{18}\text{O}$ (in precipitation water) from the regions of Kraków (south-eastern Poland), Lviv (western Ukraine), Brest (western Belarus), and Gródek, as well as to the ratios determined for the animals coexisting with the studied population. Proportions of oxygen isotopes obtained for all the studied individuals were found to be similar to those for the precipitation water and animals, which indicates the absence of bone fragments of individuals originating in other regions.

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S T R E S Z C Z E N I E

Tereny dawnych Grodów Czerwieńskich, które obecnie znajdują się na pograniczu Polski i Ukrainy, w początkach wieków średnich były przedmiotem rywalizacji Słowian formujących w tym czasie namiastki swojej państwowości. Nadrzędnym celem niniejszych badań było sprawdzenie jednorodności wczesnośredniowiecznej grupy, odnalezionej na stanowisku archeologicznym w Gródku nad Bugiem (w średniowieczu teren przynależący do Grodów Czerwieńskich), pod względem potencjalnych osobników pochodzenia nie lokalnego. Metodą wykorzystaną do ustalenia pochodzenia badanych osobników była analiza składu izotopowego tlenu w wyizolowanych fosforanach tkanki kostnej. W niniejszym opracowaniu, koncentrację izotopową tlenu otrzymaną dla próbek pobranych z 62 szkieletów ludzkich odniesiono do wartości $\delta^{18}\text{O}$ tła środowiskowego, które stanowiły woda opadowa (regiony: Kraków (Płd-wsch. Polska), Lwów (Zach. Ukraina), Brześć [Zach. Białorus] oraz Gródek) a także równoczesne zwierzęta współwystępujące z badana populacją. Wyniki niniejszych badań wskazują, że koncentracje izotopów tlenu uzyskane dla wszystkich badanych osobników zawierały się w wyznaczonym zakresie środowiskowym tak wody środowiskowej jak i analizowanej fauny, co może świadczyć o tym, że wśród analizowanych szczątków ludzkich nie było prawdopodobnie osobników pochodzenia nielokalnego przynajmniej w zakresie rozpatrywanych makroregionów.

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Introduction

In the early Middle Ages, Central and Eastern Europe saw the emergence of the foundations of many modern nations and their division into eastern Slavs (today's Belarusians, Russians and Ukrainians) and western Slavs (the Czechs, Poles, Slovaks, and Polabian Slavs). The proximity of Gródek and the Cherven Towns to the Polish-Ukrainian border gives rise to the question as to the ethnic character of this region in the early Middle Ages. It is difficult to conclusively ascertain the political status of the land along the middle Bug River prior to the formation of the Polish state as defined by the adoption of Christianity in 966 and the Christianization of Kievan Rus' in 988/989. The area was probably inhabited by the Lendians; however, some sources also mention the Buzhan, Dulebe, and Volhynian tribes ([Wołoszyn, 2012](#)).

According to historical data, the area under discussion most probably belonged to a region demarcated by a group of strongholds collectively known as the Cherven Towns (old East Slavic *grady chervenskie*). This term has derived from the oldest Ruthenian chronicle, "The Tale of Bygone Years". The Cherven Towns were contested by Poland and Kievan Rus' ([Franklin and Shepard, 1996](#)): in 981, the region was subjugated by Vladimir the Great, a Kievan prince (981–1015), and in 1018 it was conquered by the Polish king Bolesław Chrobry (992–1025). In 1031, the Cherven Towns once again came under Ruthenian rule. In the mid-14th century, Casimir the Great (Polish king, 1333–1370) incorporated the lands along the river Bug into Poland, including the Cherven Towns as well as present day south-western Ukraine as far as Podolia.

The intricate and dynamic history of Poland's borderlands continues to be the subject of ethnological, historical, archaeological, and anthropological studies. It should be stressed that the ethnic interpretation of archaeological finds, which involves ascribing specific man-made items to ethnic groups, tribes, or nations, is now conducted with much greater caution than several decades ago. Indeed, this research area remains hotly debated by archaeologists ([Brather, 2004](#); [Curta, 2011](#); [Pohl, 2013](#)). The main goal of an anthropologist's work is to obtain as much knowledge as possible about

examined individuals or populations, with the most crucial and desired pieces of information concerning, *inter alia*, their geographic origin and migration paths. Traditional osteological methods used for such purposes include ancient DNA analysis, palaeoserological research, and determination of stable strontium and oxygen isotopes, which provide a valuable complement to skeletal analysis and lead to more reliable conclusions.

Using funds from the Leipzig Centre for the History and Culture of East Central Europe, an interdisciplinary attempt was made to answer the question whether any individuals of non-local origin were found in the area of the Cherven Towns. The stable isotope analysis applied in this study broadens the existing historical knowledge as it enables the verification of archaeological hypotheses as to the origin of the people from Gródek.

To date, stable isotope analysis has been conducted by numerous researchers around the world to elucidate the life of historical and prehistoric human populations. Several studies based on the use of stable oxygen isotopes have been carried out regarding populations of different continents; these include research by: White et al. (1998) and O'Brien and Wooller (2007) for North America; Wright and Schwarcz (1999) for Central America; Knudson (2009) for South America; Budd et al. (2004), Chenery et al. (2010), Daux et al. (2008), Lamb et al. (2014), McGlynn (2007), Prevedorou et al. (2010), Prowse et al. (2007), Roberts et al. (2013), and Szostek et al. (2014) for Europe; Dupras et al. (2001), Dupras and Tocheri (2007), and White et al. (2004) for Africa; and Shaw et al. (2010) for the Pacific islands.

The relative abundance of oxygen isotopes in bone tissue is strongly correlated with that in environmental water (Longinelli, 1984; Luz et al., 1984), and results from the fractionation caused by natural physical, chemical, and biological processes (Yurtsever, 1994). Analysis of the oxygen isotope ratio in skeletal fragments makes it possible to determine whether they are of local or non-local origin and can also show the direction and range of migration, as well as throw some light on the dynamics of mobility of entire human groups (Eerkens et al., 2013; Wright and Schwarcz, 1996). An important aspect of oxygen isotope analysis is the determination of the time of child weaning (Wright and Schwarcz, 1998) as well as the reconstruction of climatic changes over the centuries (Fricke and O'Neil, 1996; Huertas et al., 1995; Stephan, 2000).

In the hydrological system, spatial and temporal differences in the relative abundance of stable oxygen isotopes result from fractionation occurring via evaporation and condensation processes, which are highly dependent on climatic and geographical factors (Dansgaard, 1964; Gat, 1996; McGlynn, 2007). The lighter oxygen isotopes contained in water evaporate first, so the liquid phase contains a greater proportion of heavy isotopes. Furthermore, when the temperature decreases, air loses its ability to hold vapor and, in the process of condensation, the heavier isotopes are eliminated in the form of precipitation. However, the relative abundance of the ^{18}O isotope depends not only on the temperature, but also on the hydrological balance of the ecosystem. Thus, the oxygen isotope ratio in the environmental water is affected by factors such as altitude, temperature, latitude, and humidity in a given area (Craig, 1961; Kohn et al., 1996; Sponheimer and Lee-Thorp, 1999). It should be noted that at temperate and high latitudes, oxygen fractionation is strongly proportional to the temperature of the environment. This results in seasonal changes of the rainwater isotope ratio in a given region, with a decreased proportion of heavier isotopes in the colder months. The abundance of heavier isotopic fractions is also diminished at higher altitudes. A significant factor influencing the ratio of stable isotopes in environmental water is molecular exchange between surface water and water present in atmospheric air.

The primary aim of this study was to examine the homogeneity of origin of an early medieval population from Gródek on the Bug River. We do not endeavour to address the question as to whether the region of the Cherven Towns was pre-Polish or pre-Ruthenian in character, but rather to separate the local individuals buried in Gródek from any non-local ones. The examined site is located in the east of Poland, near the Ukrainian border.

Site and sample description

Gródek is a small town in Lublin Province in the east of Poland (coordinates: $50^{\circ}47'55''\text{N}, 23^{\circ}56'54''\text{E}$, 185 m.a.s.l.). It lies on the Bug River, which demarcates the Polish-Ukrainian border, near the

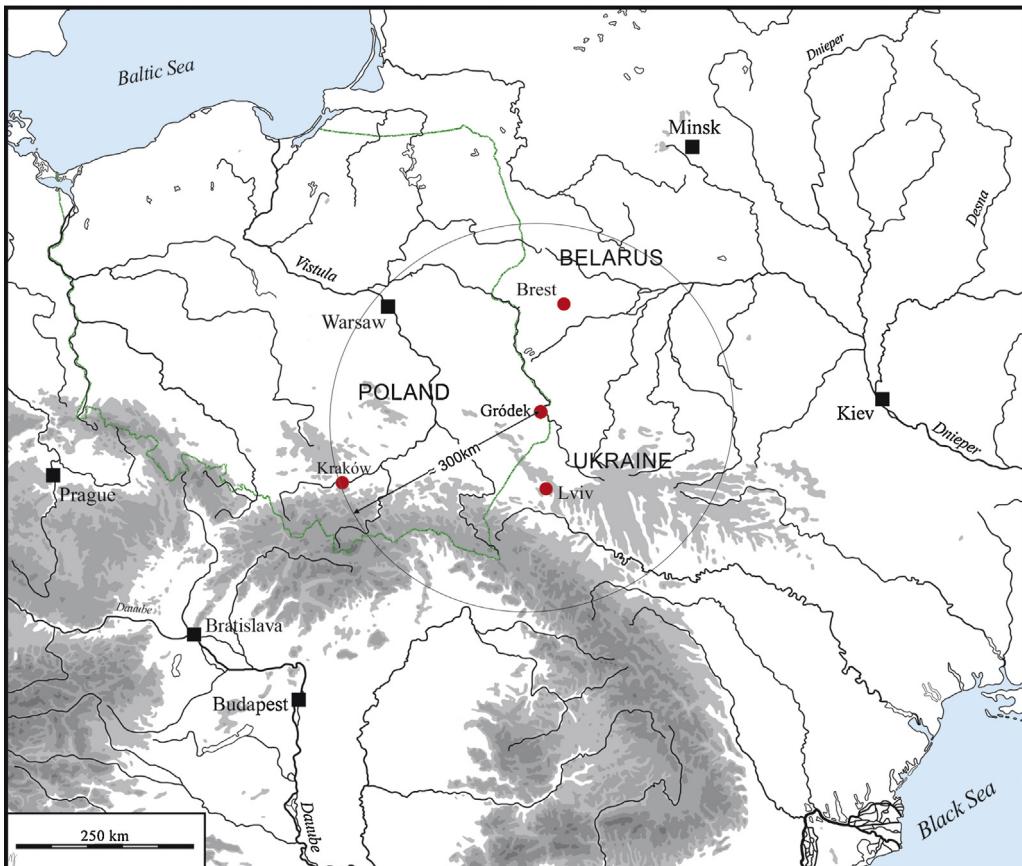


Fig. 1. Location of the Gródek settlement.

confluence with its tributary, the Huczwa River (Fig. 1). Between 1952 and 1955, the Cherven Towns Archaeological Station of the Institute for Material Culture History, Polish Academy of Sciences (now the Institute of Archaeology and Ethnology, PAN) conducted excavations in Gródek (Wołoszyn, 2012). The site included the area of a fortified settlement, which constituted part of a large (approx. 15 ha) settlement complex. The excavated area of 1075 m² revealed 469 human skeletons. Excavations provided evidence for a wide array of human activity, including remains from the early Stone Age/Neolithic (Funnel Beaker Culture) and the Bronze Age (Lusatian Culture), graves from the Roman period, a cemetery and residential and agricultural buildings from the early Middle Ages, 17th century farm buildings, as well as trenches from World Wars I and II (Kuśnierz, 2010, 2012).

At the archaeological site, three layers of settlement were distinguished:

Layer I – A thin layer of topsoil (0.30–0.35 m).

Layer II – Remains of an early medieval settlement as well as early modern graves and court buildings (17th century). The majority of human skeletons were found in this layer.

Layer III – Remains of a settlement dated to approx. 9th to mid-13th century (Kuśnierz, 2006).

The cemetery from which the studied skeletons were taken was established in the town square after the settlement's collapse in the mid-13th century. However, the relics dated to the 11th–13th

century found in the graves indicate that the cemetery had been used for up to 200 years prior to that (see Kuśnierz, 2010, 2012).

Material and methods

Human and animal samples

The cemetery from which the analyzed material was obtained was located in the north-eastern area of the town square. The explored part of the cemetery consisted of 466 graves, 42 of which contained some burial goods. Almost all skeletons were placed with the heads westwards, in accordance with the beliefs of the Catholic religion. The dead were in the supine position with their arms crossed or extended along the body. Samples of 62 skeletons (27 males and 35 females) were collected for isotope analysis, with only 4 accompanied by grave goods. The sex of the individuals, as well as their age at death, was assessed by generally accepted methods, analyses and anatomical skeleton descriptions (Buikstra and Ubelaker, 1994; Ubelaker, 1984). Detailed data concerning the age and sex of the examined individuals as well as animal species from the Gródek archaeological site are presented in Table 1.

In the process of collecting material for isotope analysis, bones with signs of antemortem mechanical damage and those belonging to individuals exhibiting possible evidence of infectious diseases were excluded. Samples of femoral compact bone were collected from each skeleton. Several skeletons (and in particular that from grave 232) bore marks of multiple injuries, e.g., in the form of cuts most probably sustained in a fight. Analysis of grave density and location showed that most of the burials were located in the north-eastern part of the cemetery.

In order to determine the background ratio of stable oxygen isotopes, we used reference material consisting of animal bones originating from the studied environment as well as data concerning the isotope ratio in the environmental water. In the case of animals, the relative abundance of isotopes was established based on analysis of 8 samples collected from the long bones of even-toed ungulates (order Artiodactyla), such as domestic pigs, wild boars, goats/sheep, and cows. As far as water is concerned, there are no ongoing studies monitoring oxygen isotope ratios in environmental water in this part of eastern Poland. Therefore, we used data on the relative abundance of stable isotopes in precipitation water from three measuring stations close to Gródek such as Kraków, Lviv, and Brest, obtained from the databases of the Global Network of Isotopes in Precipitation (GNIP) and the International Atomic Energy Agency (IAEA). Additionally, isotope data for Gródek computed using the Online Isotopes in Precipitation Calculator (OIPC) enabled a comparison of the microregion with the three macroregions in terms of isotope ratios.

Analytical procedure

FTIR analysis

In order to control for the state of preservation of human and animal skeletons, diagenetic indicators were determined based on spectroscopic bands using Fourier transform infrared spectrometry (FTIR). These data were obtained for hydroxyapatites in each examined bone sample by means of a procedure devised by Wright and Schwarcz (1996).

The resulting bands presented the characteristics of phosphate and carbonate groups in bone apatite and were used to calculate the crystallinity index and carbonate-to-phosphate ratio. The crystallinity index (CI) was calculated according to the equation:

$$CI = \frac{(A_{565} + A_{605})}{A_{595}}$$

where A – absorbance in the infrared region; 565, 605 – two wavelengths absorbed by the PO_4 group (Wright and Schwarcz, 1996).

Table 1

Age at death, sex, diagenetic change analysis results (Cl and CO_3/PO_4), and oxygen isotope composition for human and animal skeletons from Gródek on the Bug River.

No	Burial number	Sex	Age ^a	Cl index	CO_3/PO_4 ratio	$\delta^{18}\text{O}$	Grave contents
<i>Human bone samples</i>							
1	11	F	Mt	3.19	0.29	18.72	Glass bracelet fragment, 3 decorative copper fragments from a diadem
2	33	M	Mt	3.36	0.26	16.07	
3	35a	F	Ad	3.46	0.22	16.40	
4	35b	F	Ad	3.37	0.20	15.04	
5	38			3.28	0.30	15.38	
6	45	M	Ad	3.28	0.27	16.02	
7	46	M	Sn	3.26	0.30	16.46	
8	53	F	Mt	3.09	0.36	15.37	
9	56	F	Ad	3.11	0.21	16.20	
10	60	M	Ad	3.22	0.27	14.21	
11	65	M	Mt	3.05	0.42	16.38	
12	81	M	Mt	3.25	0.29	16.98	
13	84	F	Ad	3.44	0.20	17.21	
14	87	F	Mt	2.68	0.52	16.43	
15	88	M	Ad	3.12	0.34	17.74	
16	89	F	Mt	2.64	0.61	17.22	
17	90	F	Ad	3.83^x	0.25	18.07	
18	115	M	Ad	2.75	0.27	17.60	
19	116	M	Mt	3.22	0.23	19.09	
20	126	M	Mt	3.12	0.45	16.01	
21	133	M	Ad	2.58	0.54	17.95	
22	139	M	Mt	2.74	0.46	17.04	
23	143	F	Sn	2.77	0.58	16.77	
24	145	M	Mt	3.24	0.26	16.54	
25	148	M	Mt	3.23	0.26	14.99	
26	156	M	Mt	2.68	0.56	18.40	
27	164			3.24	0.24	17.92	
28	167	F	Mt	2.91	0.36	15.57	
29	170	F	Mt	3.25	0.27	16.39	
30	179	M	Ad	3.00	0.45	17.10	
31	190	F	Ad	2.82	0.47	17.11	
32	227	F	Ad	3.17	0.34	17.34	
33	232	M	Mt	3.12	0.29	18.24	
34	233b	F	Sn	2.56	0.60	16.23	
35	238	F	Mt	2.81	0.51	17.47	
36	245	M	Mt	2.17	0.53	15.85	
37	249	M	Mt	2.83	0.46	14.96	
38	250	F	Ad	2.09	0.64	16.62	2 S-shaped temple rings
39	263	F	Ad	3.25	0.36	16.85	
40	280	M	Mt	2.76	0.50	17.42	
41	283	M	Mt	2.81	0.40	16.98	
42	290	F	Sn	2.70	0.43	15.73	Glass bracelet fragment
43	292	F	Ad	2.81	0.39	14.47	
44	304	M	Mt	3.23	0.41	15.14	
45	310	F	Ad	2.67	0.59	16.96	
46	318	F	Ad	2.60	0.62	19.20	
47	328	M	Ad	3.37	0.25	16.08	
48	333	M	Ad	3.54	0.25	16.75	
49	339	F	Ad	2.76	0.52	16.62	
50	346	F	Mt	3.26	0.33	14.10	
51	353	M	Ad	3.21	0.25	14.63	
52	368	F	Mt	2.95	0.39	17.48	
53	371	M	Mt	3.13	0.34	16.56	
54	393	F	Ad	2.55	0.64	15.75	
55	400	M	Mt	3.58	0.22	14.53	

Table 1 (Continued)

No	Burial number	Sex	Age ^a	Cl index	CO ₃ /PO ₄ ratio	δ ¹⁸ O	Grave contents
56	439	M	Mt	3.88^x	0.20	18.16	
57	441	M	Mt	2.64	0.55	16.22	
58	442	F	Mt	2.60	0.54	17.02	Silver temple ring, 2 bronze buttons, fabric fragment
59	444	M	Ad	2.58	0.65	18.26	
60	445	M	Juv	2.68	0.74^x	16.23	
61	453	M	Mt	3.36	0.26	17.12	
62	458	M	Mt	3.45	0.19	16.20	
No	Burial number	Species		Cl index	CO ₃ /PO ₄ ratio	δ ¹⁸ O	
<i>Animal bone samples</i>							
63	G01	<i>Bos taurus</i>		3.26	0.36	16.84	
64	G02	<i>Sus domesticus</i>		3.81^x	0.45	12.19	
65	G03	<i>Sus scrofa</i>		3.32	0.30	12.57	
66	G06	<i>Bos taurus</i>		3.10	0.32	15.09	
67	G07	<i>Capra/Ovis</i>		3.33	0.32	18.52	
68	G08	<i>Capra/Ovis</i>		3.28	0.31	18.22	
69	G09	<i>Sus domesticus</i>		3.03	0.40	14.00	
70	G11	<i>Bos taurus</i>		3.18	0.36	16.83	

^a Ad – young adult, Mt – mature adult, Sn – Senile.

Bold^x – diagenetically altered material.

The phosphate-to-carbonate ratio (CO₃/PO₄) indicates the degree of contamination of biogenic apatites by exogenous carbonates. It is expressed by the following formula:

$$\frac{C}{P} = \frac{A[1415]}{A[605]}$$

where A[x] – band absorbance in the region x [cm⁻¹]; [1415], [605] – bands characteristic of PO₄ and CO₃ groups, respectively.

Oxygen isotope analysis

Analysis of stable oxygen isotopes was carried out for phosphate groups isolated from bone hydroxyapatites according to the procedure proposed by O'Neil et al. (1994). A ground bone sample was cleaned to remove organic material and other possible contamination by means of sodium hypochlorite (NaOCl), followed by sodium hydroxide (NaOH). In order to release phosphate groups from hydroxyapatite, samples were incubated in hydrofluoric acid (HF). After adding another substrate in the form of silver nitrate (AgNO₃), silver phosphate crystals were obtained (Ag₃PO₄), which were used directly to measure isotope proportions according to the method developed by Lécuyer et al. (2007), in an isotope mass spectrometer operating in the continuous flow mode coupled with an elementary microanalyzer and gas chromatograph. Measurements of oxygen isotopes in bone samples were conducted at the Institute of Radioisotope Applications, Silesian University of Technology in Gliwice.

The results of spectrometric analysis were expressed in the form of delta notation, where the oxygen isotope ratio in an examined sample was compared with the same parameter for a laboratory standard (NIST 120c). In our calculations, the reference value for NIST 120c in relation to the Vienna Standard Mean Ocean Water (VSMOW) scale was δ¹⁸O, which equaled 21.7 per thousand, with measurement uncertainty being 0.17. Oxygen isotope level (δ¹⁸O) is measured with regard to a standardized sample of clean ocean water (VSMOW), and expressed by the formula:

$$R = \frac{\text{amount of } ^{18}\text{O}}{\text{amount of } ^{16}\text{O}} \quad \delta^{18}\text{O}_{\text{sample}} = \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} * 1000$$

Results and discussion

Diagenesis

Qualitative and quantitative evaluation of the chemical composition of a non-contaminated tooth or bone sample provides information about its biogenic tissue structure. In the case of analysis of archaeological skeletal material, we should take into account the influence of the burial environment, which may lead to recrystallization of biological apatite, possibly affecting isotopic analysis. For that reason, diagenetic alteration analysis was performed for all studied individuals from the excavated site in Gródek, using FTIR and with the results expressed as the CI index and the CO_3/PO_4 ratio (Fig. 2a and b).

The average values obtained for all human samples are $\text{CI} = 3.02$ and $\text{CO}_3/\text{PO}_4 = 0.37$. Changed bone tissue is characterized by a more organized, less tense crystal structure with larger crystals, regardless of whether diagenesis occurred due to long exposure in a grave or was caused by high temperature,

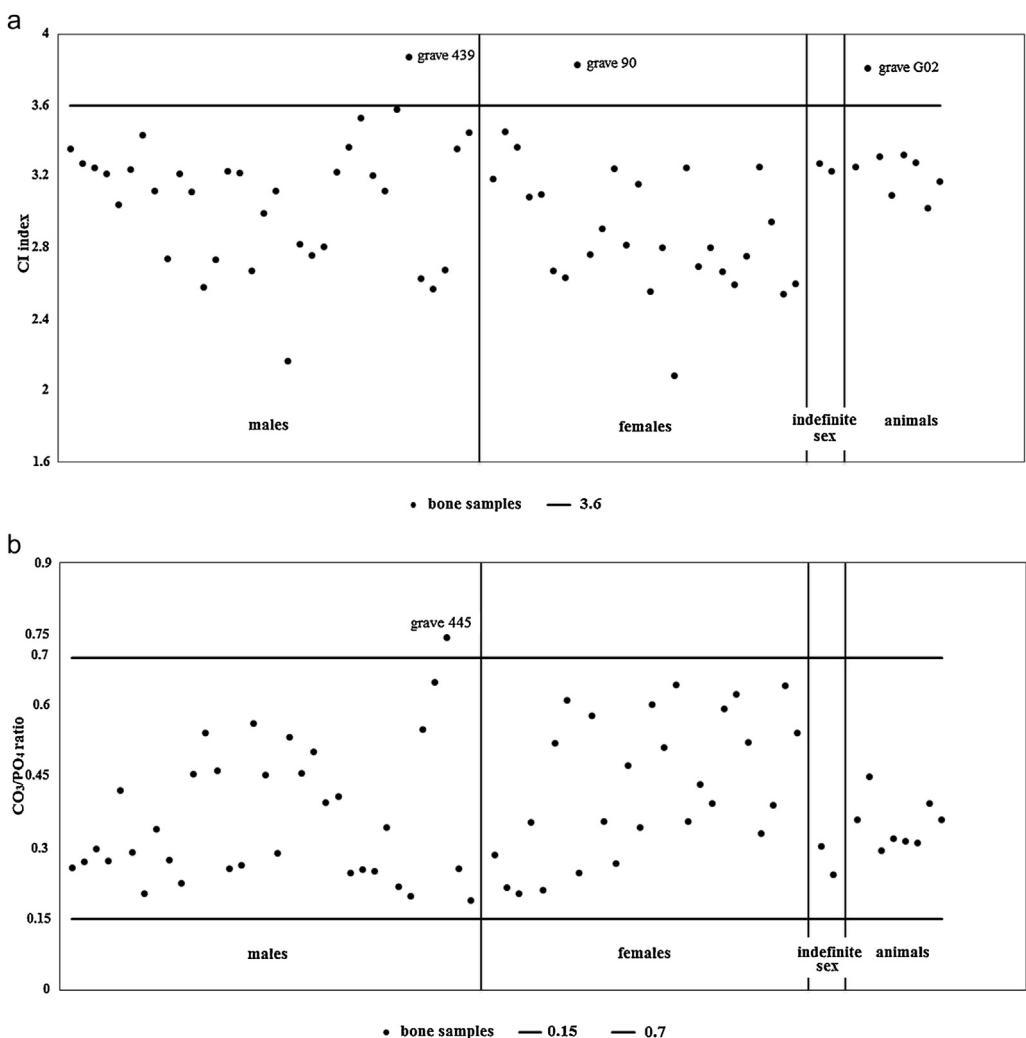


Fig. 2. (a) Crystallinity index (CI) obtained by FTIR for human and animal bone samples from Gródek on the Bug River. (b) Carbonate/phosphate ratio (CO_3/PO_4) for human and animal bone samples from Gródek on the Bug River.

Table 2Correlation between FTIR crystallinity index, CO_3/PO_4 ratio and $\delta^{18}\text{O}_{\text{p}}$ isotope values.

	CI – CO_3/PO_4	CI – $\delta^{18}\text{O}$	$\text{CO}_3/\text{PO}_4 – \delta^{18}\text{O}$
r	–0.88*	–0.16	0.19
r^2	77.79	2.66	3.65

* Statistically significant correlation.

e.g. due to cremation (Stuart-Williams et al., 1996). Such changes are reflected in a higher crystallinity index (CI). Analysis of human bones revealed two samples with a CI of above 3.6, which indicates the occurrence of slight diagenetic alterations mainly to the organic fraction of bones (Berna et al., 2004; Lebon et al., 2010). These samples were collected from an adult female (grave no. 90; CI = 3.83) and a mature male (grave no. 439; CI = 3.88) (Fig. 2a). According to generally accepted principles, the samples were eliminated from further analytical procedures.

One bone sample, taken from a juvenile male (grave no 445; $\text{CO}_3/\text{PO}_4 = 0.74$), was also excluded from isotope analysis, as its CO_3/PO_4 ratio was outside the acceptable range of 0.15–0.7 (Nagy et al., 2008; Yoder and Bartelink, 2010) (Fig. 2b). The other osteological samples exhibited ratios below 0.7, which indicates contamination of the investigated material by some exogenous carbonates (Szostek et al., 2011). No irregularities suggesting the presence of other possible contaminants, such as brushite or francolite, were observed in the analyzed FTIR band (Elorza et al., 1999; Lee-Thorp, 2002; McArthur et al., 1980).

In studies of human material, it is important to characterize the environment in which the individual lived to determine points of reference for stable oxygen isotope analysis. Animals, treated as environmental background, provide a good reference framework only if their bone tissue is unaffected by diagenetic changes. In the examined bone sample marked G02 and taken from a domesticated pig, the CI was equal to 3.81 (Fig. 2a). Macroscopic assessment of this skeletal sample revealed the presence of small opaque spots, which in conjunction with CI and CO_3/PO_4 data may suggest it had been burnt. Thus, the sample was eliminated from further analysis.

The absence of postmortem changes in the crystalline structure of bones and teeth can be further supported by a negative correlation between the CI index and the CO_3/PO_4 ratio as well as a lack of correlation between the isotope composition of apatites and CI or CO_3/PO_4 (White et al., 1998). The latter is the case in the presented study (Table 2 and Fig. 3a–c), which corroborates the absence of diagenetic changes in the investigated material. It must be noted that during a statistical analysis one sample on scatter plot was identified as an influential point. This sample comes from an animal bone (G03) and, despite being well preserved, shows a relatively low oxygen isotope ratio as compared with bone samples from other animals and humans from the studied site. The sample was excluded from further study.

To conclude, analysis of the osteological material in terms of diagenetic changes eliminated samples which could distort the interpretation of results as a result of possible recrystallization and alterations in the relative abundance of stable oxygen isotopes.

Oxygen isotopes and mobility

For historical and prehistoric human populations, broadly defined environmental water constituted the main source of drinking water. The population from Gródek probably used water from the Bug River and the nearby streams or lakes. Several studies have revealed a positive correlation between the oxygen isotope composition of environmental (drinking) water and that of phosphate groups isolated from bone and tooth apatite (Longinelli, 1984; Luz et al., 1984; Luz and Kolodny, 1989). At the same time, archaeological data prove that in the region of interest both solid and liquid food (including water) was heat-treated (Kirsanow and Tuross, 2011; McGlynn, 2007) in the process of preparation of stocks, infusions, soups, etc. It is also known that boiled water is characterized by a higher proportion of stable oxygen isotopes than running water due to evaporation-related oxygen isotope fractionation (Bowen et al., 2009; White et al., 2004). Experimental studies have shown that the heat-treatment of water and solutions, such as boiling for short or long periods of time, may increase water $\delta^{18}\text{O}$ by up

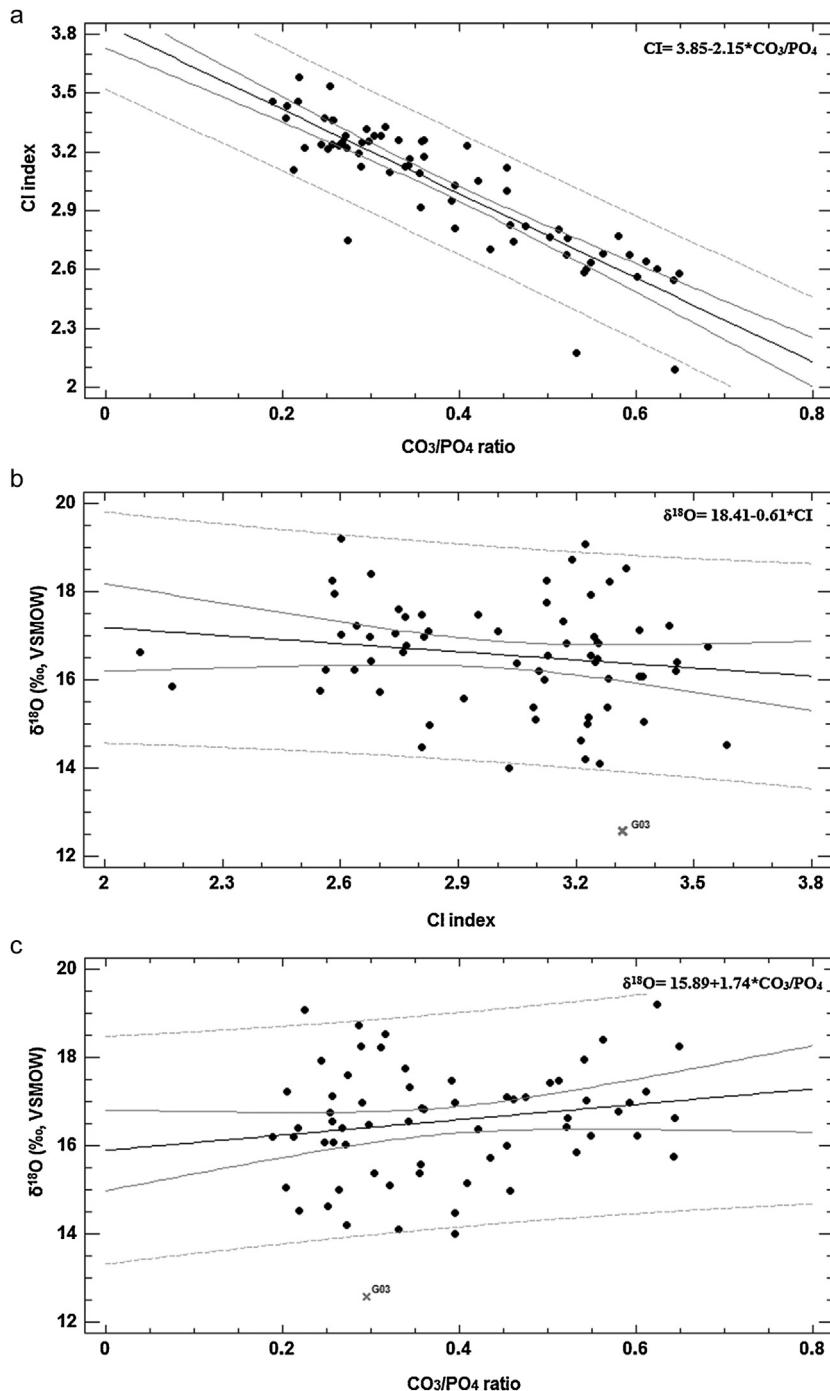


Fig. 3. (a) Cl versus CO_3/PO_4 . (b) Cl versus $\delta^{18}\text{O}_p$. (c) CO_3/PO_4 versus $\delta^{18}\text{O}_p$.

to a few parts per thousand and it may affect the results for enamel phosphate $\delta^{18}\text{O}$ determination (Brettell et al., 2012).

It should be stressed that while in studies concerning the origin and historical migrations of human groups oxygen isotope analysis enables the identification of non-local individuals, it cannot ascertain whether individuals exhibiting an isotope ratio characteristic of the burial area are autochthonous or come from a different region with a similar isotope ratio (Roberts et al., 2013). Increased oxygen isotope concentrations may also result from natural physiological and ontogenetic processes or from food preparation, such as the boiling of water and foodstuffs (Brettell et al., 2012; Stepańczak et al., 2014). Increased $\delta^{18}\text{O}$ levels may also result from interindividual variation attributable to differences in the metabolic rate, physical activity, and age, or disorders such as the presence of urinary stones in the excretory system (Levinson et al., 1987). Regardless of the cause, the final effect is more likely to be an increased rather than decreased isotope ratio.

The results of oxygen isotope analysis for all examined individuals are presented in Table 1. The $\delta^{18}\text{O}$ values obtained for the skeletons found at the archaeological site in Gródek fall in the range of 14.10–19.20 per thousand (mean = 16.52, standard deviation = 1.15) while those for animal bones are 14.00–18.52 per thousand (mean = 16.58, standard deviation = 1.76).

Tests for normality and outlier identification were performed to analyze interindividual variation in oxygen isotope ratios. No outliers were observed in the samples, with the most extreme value noted for the skeleton from grave G02 (standard deviation = 3.07), which was excluded from further analysis because of a high CI (3.81). Since the p -value for Grubbs's test equals 0.104, that outlier is not significant at a 5% level, assuming that all other values follow a normal distribution. The lowest p -value amongst the performed tests (Chi-squared goodness-of-fit statistic, Shapiro-Wilk's W statistic, Z score for skewness, and Z score for kurtosis) equals 0.123. As the p -value for that test is greater than 0.10, the hypothesis that the oxygen isotope ratio in bones comes from a normal distribution cannot be rejected with 90% or greater confidence.

In order to reconstruct the migration processes of the investigated group of individuals, their $\delta^{18}\text{O}$ results were referred to the variability range for the control animal group (Fig. 4, continuous lines) and environmental water (Fig. 4, dashed lines). The $\delta^{18}\text{O}$ for water was determined based on data from

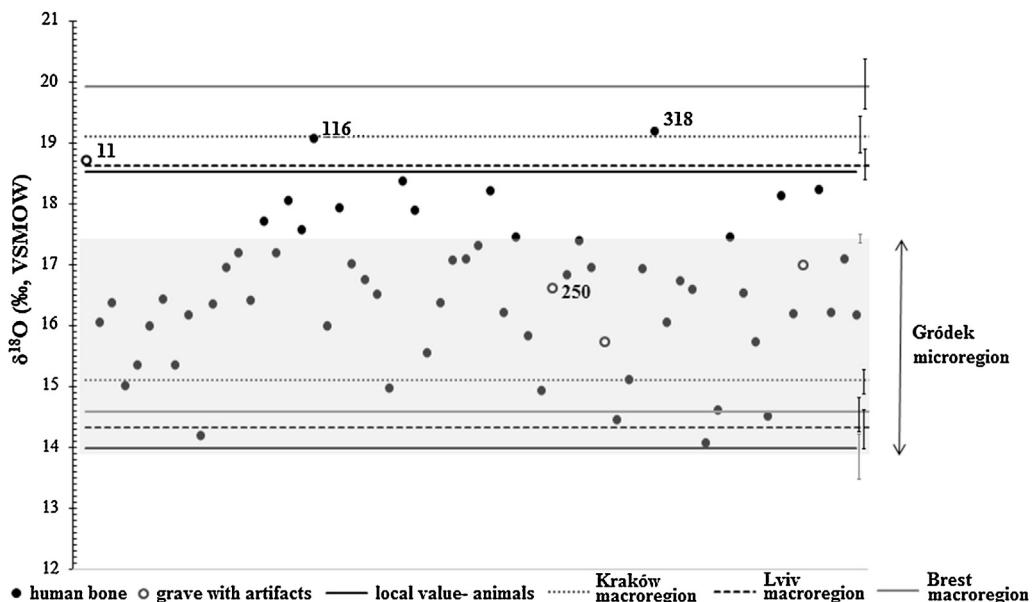


Fig. 4. $\delta^{18}\text{O}$ levels for all investigated individuals as compared to $\delta^{18}\text{O}$ for animal bone samples and local precipitation water for Kraków, Lviv, Brest (lines), and Gródek (grey background). Encircled points represent graves with burial goods.

Table 3

Stable oxygen isotope compositions (‰ versus VSMOW) of precipitation water ($\delta^{18}\text{O}_w$) for the Gródek microregion and three neighbouring macroregions (data from IAEA and <http://www.waterisotopes.org>) and phosphate $\delta^{18}\text{O}$ of ($\delta^{18}\text{O}_p$) calculated based on Daux et al. (2008; Eq. (4) – values estimated for Gródek, Eq. (5) – water precipitation database). Error bars correspond to the uncertainty associated with conversion of equations.

Region	$\delta^{18}\text{O}_w$ minimal value	$\delta^{18}\text{O}_p$ minimal value	Lower error range	Upper error range	$\delta^{18}\text{O}_w$ maximal value	$\delta^{18}\text{O}_p$ maximal value	Lower error range	Upper error range
Kraków	-15.39	15.11	14.87	15.29	-6.81	19.11	18.83	19.45
Lviv	-14.93	14.32	13.97	14.60	-7.63	18.62	18.40	18.90
Brest	-14.50	14.58	14.26	14.82	-5.42	19.92	19.55	20.39
Gródek	-13.20	13.90	17.37	17.50	-7.10	17.43	13.49	14.23

three measurement stations covering the macroregions of south-eastern Polish borderland (Kraków), western Belarus (Brest) and western Ukraine (Lviv) (Table 3).

It is known that the local ratio of stable oxygen isotopes can be represented by non-migratory animals living or hibernating in immediate proximity to people (Grupe and Price, 1997). The tissues of animals coexisting in time and space with the studied population exhibit a characteristic isotope pattern determined by climatic, geological, and hydrological conditions. In the present study, the range of local oxygen isotope ratios was determined by the minimum and maximum $\delta^{18}\text{O}$ for animal remains from the Gródek site. The variability range of precipitation water $\delta^{18}\text{O}$ was then calculated based on the lowest and highest monthly figures for each of the three macroregions and the Gródek microregion. Within the studied macroregions, the variability of precipitation water $\delta^{18}\text{O}$ was high due to both varied climatic conditions (hot summers, cold winters) and terrain topography (uplands, lowlands). Taking into consideration the above factors, it may be expected that the isotope composition of environmental water from the Gródek area may be related to the variability of this parameter in the neighbouring regions. It should be remembered that neither in Poland nor elsewhere in East Europe river water $\delta^{18}\text{O}$ is monitored. Therefore, we used data obtained from three measurement stations, Kraków, Lviv and Brest, located within 300 km of Gródek, which supply data on precipitation water $\delta^{18}\text{O}$ to the International Atomic Energy Agency (IAEA). Based on the IAEA database, we computed the average oxygen isotope composition of precipitation water (Table 3).

In order to obtain more detailed data on environmental water $\delta^{18}\text{O}$ for the Gródek site, we used the Online Isotopes in Precipitation Calculator (OIPC), which applies the algorithm developed by Bowen and Wilkinson (2002) and subsequently improved by Bowen and Revenaugh (2003). Using the geographic coordinates of Gródek, average monthly $\delta^{18}\text{O}$ levels in precipitation water were computed. The lowest and highest values formed the basis for the determination of $\delta^{18}\text{O}$ variability in Gródek (Table 3).

Subsequently, the monthly minimum and maximum oxygen isotope ratios for precipitation water ($\delta^{18}\text{O}_w$) from Gródek (using Eq. (4), Daux et al., 2008) and from Kraków, Lviv, and Brest (using Eq. (5), Daux et al., 2008) were computationally converted into corresponding ratios for bone phosphates ($\delta^{18}\text{O}_p$). The $\delta^{18}\text{O}_w$ variability ranges for the analyzed regions are given in Table 3 and Fig. 4. In the case of the studied archaeological site, it should be noted that the wide $\delta^{18}\text{O}$ variability characteristic of Gródek corresponds to that of bone phosphates (13.9–17.43 per thousand) (Eq. (4), Daux et al., 2008). The data calculated for Gródek using the OIPC indicate that 48 out of 62 individuals fall within the $\delta^{18}\text{O}_w$ variability range, which accounts for 77% of the samples.

The oxygen isotope range characteristic for the western macroregion (Kraków measurement station) involves a greater number of investigated individuals, for which the fraction is placed in the middle of the range, and in this case equals 85%.

The $\delta^{18}\text{O}$ variability range for the Lviv macroregion, located to the south of Gródek, includes a greater number of individuals, the fraction equals 92%. Environmental range of $^{18}\text{O}/^{16}\text{O}$ obtained for macroregion of Brest, which is located to the north of Gródek, includes the largest fraction of examined individuals (94%).

A comparison of human $\delta^{18}\text{O}_p$ with the Lviv environmental variability range reveals 2 samples (3%) below its lower limit, possibly indicating a non-local origin. However, the $\delta^{18}\text{O}_p$ values for those human samples fall within the local environmental range established by analysis of animal $\delta^{18}\text{O}_p$ and water $\delta^{18}\text{O}$ for the Gródek microregion. Therefore, the local origin of those individuals cannot be excluded.

The $\delta^{18}\text{O}_p$ values obtained for all individuals fall within the environmental oxygen isotope variability range established based on animal and precipitation water $\delta^{18}\text{O}$ levels. This indicates that the investigated group probably did not include any individuals of non-local origin, at least in terms of the macroregions considered (Fig. 4).

This cautious conclusion indirectly supports the fact that the investigated group was homogeneous in terms of oxygen isotope ratios, which formed a normal distribution without outliers.

Individuals with a $\delta^{18}\text{O}_p$ of over 17.43 per thousand, falling within the $\delta^{18}\text{O}$ variability range for the local environment, may have come from the area where they were buried or, in case of the three individuals with the highest $\delta^{18}\text{O}_p$ values, from an area to the north of Gródek within the variability range of the Brest region.

A comparison of $\delta^{18}\text{O}$ for human and animal bones reveals three individuals from Gródek with an elevated concentration of the heavy oxygen isotope; these are an adult female (grave 11), a mature male (grave 116), and an adult female (grave 318). To interpret these findings, we consulted archaeological data. Grave 11 contained three decorative copper elements of a diadem characteristic of the interfluve of the Seret and Dniester rivers and a fragment of a glass bracelet of East Slavonic nature (Kuśnierz, 2010, 2012). Given the fact that the environmental oxygen isotope ratio in the region of Seret and Dniester rivers (near the macroregion of Lviv) is lower than the values obtained for samples from grave 11, the likelihood that the individuals in question came from those areas is low. In the case of the two other individuals, archaeological indicators did not allow verification.

Furthermore, taking into account the fact that phosphate ^{18}O levels may have increased as a result of consumption of heat-treated water and food, intense exertion and sweating, a higher metabolic rate, or an advanced age (Bryant and Froelich, 1995), it can be assumed that the three individuals in question were local. Their $\delta^{18}\text{O}_p$ levels were within the range determined for the local environment by precipitation water analysis. However, those individuals may have spent the last years of their lives inhabiting other places, where their skeletons were found.

Based on grave goods analysis and anthropological findings of other authors, J. Kuśnierz proposed in his archaeological papers (Kuśnierz, 2010, 2012) that the Early Medieval population of Gródek on the Bug River exhibited East Slavonic characteristics except for two individuals, whose graves contained s-shaped temple rings characteristic of the West Slavs. However, the isotope examination of a bone sample from one of them (grave no. 250) showed a $\delta^{18}\text{O}$ level similar to other members of the population.

Endeavours to elucidate the origin of the individuals buried at the Gródek site are fraught with difficulty, and the presented study offers a contribution to a comprehensive understanding of the migrations of the people inhabiting this area at a time of dynamic biocultural changes.

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