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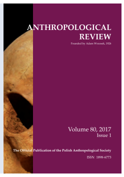

Oxygen stable isotopes variation in water precipitation in Poland – anthropological applications

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ABSTRACT: The main objective of oxygen isotope analysis is to determine the probable place of origin of an individual or the reconstruction of migration paths. The research are methodologically based on referencing oxygen isotope ratios of apatite phosphates ($\delta^{18}O_p$) to the range of environmental background $\delta^{18}O$, most frequently determined on the basis of precipitation.

The present work is a response to the need for providing background for oxygen isotope studies on skeletons excavated in Poland. Currently there no monitoring of the isotope composition of precipitation water in Poland is conducted. For this reason, based on the data generated in the Online Isotopes In Precipitation Calculator (OIPC), a database was developed, containing $\delta^{18}O$ levels in precipitation for locations in which exploration work was carried out in the archaeological fields from Poland. In total, 279 locations were analysed. The result of the data analysis was a complete isotope composition map for Poland with four zones distinguished by $\delta^{18}O_w$ values.

The observable differences in oxygen isotope composition of precipitation in Poland are sufficient to trace migrations of individuals and populations, although accurate only at the level of macroregions.

KEY WORDS: oxygen isotopes, precipitation, isotope gradient, environmental background, Poland

Introduction

Chemical methods involving the use of stable oxygen isotopes are used by anthropologists primarily to study the origin and migrations of individuals, as well as to reconstruct the weaning process.

Archaeological analyses involving dating and characterising artefacts discovered in a single tomb pit or in the vicinity of human remains constitute an important, albeit insufficient part of research work aimed at determining the origin of a specific individual or their approximate place of residence. Note that the term "origin" may be understood as a location or as an ethnic group. Isotope tests have become standard in the recent years, enhancing our knowledge on populations

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excavated at many archaeological sites and allowing us to confront information on their origin in territorial and ethnic context (Stuart-Williams 1996; White et al. 1998; White et al. 2004; Gregoricka and Sheridan 2017).

Origin and migration studies are based on the relationship between the isotope composition of tissues and the local environment inhabited by a given organism. Among elements the isotope composition of which may broaden our knowledge of the origin, migration, mobility dynamics or the history of settlement of a particular location by our ancestors, oxygen carries the most information. When studying human remains, researchers increasingly often seek information on mutual relations between individuals, both between groups and in the interaction between an individual and the group (Sjögren et al. 2009; Price et al. 2010; Wright et al. 2010). Decisions on changing one's abode or following specific migration groups by humans over the centuries were usually dictated by the need to prevent an epidemic, a conflict with a hostile community, an attempt to find new sources of food and water (seasonal/temporary migrations), to create new economic strategy, or caused by urban development issues. Human migrations involve resettlements of individuals, small groups or entire communities. The application of stable oxygen isotope analysis, even with small fragments of the compact substance of the bone at our disposal, enables us to identify individuals originating in a place different than the location in which their remains were buried after their death (Dupras and Schwarcz 2001; Budd et al. 2004; White et al. 2004; Evans et al. 2006; Prowse et al. 2007; Turner et al. 2009; Wright 2012; Szostek et al. 2014; Lisowska-Gaczorek et al. 2016).

Thanks to the information on the isotope composition of oxygen in local environmental water at a specific archaeological site, and with the use of specially designed regression formulas (Daux et al. 2008), we may calculate $\delta^{18}O_p$ reference range for the human population which potentially inhabited the area. Comparing oxygen isotope composition values for human skeletons to reference background enables us to identify individuals of non-local origin.

Concentration of stable oxygen isotopes in body water depends mostly on the isotope composition of drinking water, which, in a lesser extent on water contained in food and atmospheric oxygen, constitutes a source of oxygen that becomes ultimately incorporated into tissues (Bryant and Froelich 1995; Daux et al. 2008). The isotope composition of oxygen in bone phosphates ($\delta^{18}O_p$) becomes fixed as the balance between water ingested and excreted from the organism (Bryant and Froelich 1995; Kohn 1996). Permanent oxygen isotopes become incorporated into the bone mineral. They are primarily located in phosphate and carbonate groups of hydroxyapatite. Bone phosphates are analysed in terms of the isotope composition of oxygen due to greater stability of bonds between atoms in a phosphate group, and thus the greater resistance to diagenetic factors which threaten the biogenic chemical structure of the bone tissue.

In research practice, the isotope composition of bone phosphates ($\delta^{18}O_p$) of individuals excavated at a given site is juxtaposed with reference values of $\delta^{18}O_p$, which may be provided in the form of:

1. $\delta^{18}O$ ranges for bone and/or teeth of animals which were present at the ar-

chaeological site and were representative of the local ecosystem during the life span of the analysed population;

2. $\delta^{18}O_w$ ranges of local environmental water the values of which are regulated by the effect of local physical, climate and geographic factors.

In view of the possibilities offered by isotope analyses, there are more and more studies in which researchers attempt to determine the isotope composition of surface water collected from various sites over a given area. In this way isotope maps of Italy (Longinelli and Selmo 2003), the British Isles (Darling, Bath and Talbot 2003), Germany (Bentley and Knipper 2005) and Finland (Kortelainen and Karhu 2004) were created. In many cases researchers also avail themselves of data from the IAEA/GNIP database (Bowen, Wassenaar and Hobson 2005) or estimate the isotope composition of environmental water using the OIPC calculator (Daux et al. 2008). This strategy of the oxygen isotope investigation of the environmental background were performed mainly in the regions where are not carried out of the oxygen concentration tests in the environmental water. It could be noted that there were only a few selective analyzes of water from the narrow micro-region of Poland, and the studies concerned only mineral, geothermal and therapeutic water (Ciężkowski et al.1992; Baran and Hałas 2010, Ciężkowski et al. 2010). Therefore, to determine the variation of the water oxygen concentration in Poland, in this study we used the mathematical model OIPC. In the current literature there are no a lot of data on the differences in the water oxygen concentrations between the prehistoric postglacial periods and modern times in Central Europe (Zuber et al. 1997) and they were not significant. Summarised, the OIPC model seemed to be a reliable method in the study of the prehistoric environmental background (Lisowska-Gaczorek et al. 2016). However, it can be observed a significant lack of data coming out of the environmental water and derived from the monitoring precipitation water.

No oxygen isotope map has to date been drawn up for Poland, the main reason being that there are no extensive isotope test of precipitation or surface water in this country. Literature sources lack specific environmental background ranges which would be used for studying human remains through the use of oxygen isotopes. An oxygen isotope map of Poland is therefore a desirable source of data which would facilitate the interpretation of isotope level ranges obtained in analyses of human remains and solve the fundamental problem in such studies.

Origin and migration studies using stable oxygen isotopes are currently often used both for new and old discoveries – in the case of the latter in the form of reinterpretation (White et al. 1998; White et al. 2000; White et al. 2004; Evans et al. 2006; Shaw et al. 2010; Roberts et al. 2013; Szostek et al. 2014; Lisowska-Gaczorek et al. 2016; Schuh and Makarewicz 2016).

Archaeological excavations took place every year on many sites in Poland (Poradnik, 1981; Kozak, 1998). It is difficult to interpret single samples collected from explored bone and odontological material without environmental background. The need for creating an isotope map of the whole country is therefore a response to the basic problem which hinders drawing conclusions on the origin and movements of past human populations.

Scientists applying isotope analyses in order to study the history and life strategies of past human populations make use of tests of precipitation water from multiple places around the world (Bowen and Revenaugh 2003). Established in 1961, the network of International Atomic Energy Agency and World Meteorological Agency stations analysing monthly isotope levels in precipitation has for years carried out the programme of quantitative monitoring of isotopes in precipitation, which is used, among other things, in climate, forensic, biogeographic, ecological or anthropological studies (Bowen et al. 2005). Knowledge of the isotope composition of environmental water is vital not only for studies on contemporary environment, but also in research on animal species and mankind in the past.

Because of the frequent use of IAEA data, they are widely interpreted in combination with climate and geographic factors that determine or modify the isotope composition of the area. IAEA data are considered when interpreting even small areas such as river valleys, small mountain ranges, island or coastal areas. Locations which are not monitored for isotope composition may also be included in research thanks to the functionality offered by the Online Calculator of Precipitation, which applies its algorithm to IAEA data to determine the isotope composition of the environment in regions far away from IAEA measurement stations or locations which are no longer monitored. In Poland there is only one station situated in Kraków- Wola Justowska, which has been measured the isotope composition of precipitation. Still, the use of the OIPC enables us to estimate $\delta^{18}O_w$ ratio for all locations selected for the present study (Darling 2004).

Animal remains may provide reliable isotope background on condition that several requirements are met. Firstly, one must be sure that the animals lived in the same period as the human population of interest. Secondly, the animal whose bones are being analysed should not belong to a species that migrates over long distances. Consequently, low-mobility, domesticated species such as pigs, cows or sheep are preferred. Thirdly, note that animal bone fragments used as potential background in isotope studies of parts of human skeletons should not come from items such as bone decorations or small artefacts found at burial sites if they are suspected to have served as e.g. gifts. Such bone pieces may have come from distant areas and should be treated as items which could reveal the potential of relations between populations or the course of trade routes rather than being a reflection of the local environmental background. Another limitation of the use of animal material may simply be the absence thereof (Kendall et al. 2013).

Factors affecting the isotope composition of precipitation water

The isotope composition of environmental water in a specific geographic micro- or macroregion is the resultant of multiple geographic and climatic factors. There are a number of "effects" whose influence on $\delta^{18}O_w$ is observable with varying intensity across different latitudes and marine, continental or insular areas (Różański et al. 1993). This study focuses mostly on the isotope composition of continental Europe. The reason for the selection of such scope is Poland's location in the moderate climate zone with considerable continental effect, although the presence of coastal areas and mountain ranges was also considered later on.

The oxygen isotope composition of precipitation water varies depending on the location on the Earth's surface (Bowen and Revenough 2003). By monitoring the variability of the isotope composition of environmental water, many relationships were recorded. Dansgaard (1964) and Różański (1993) were first to link $\delta^{18}O_w$ values retrieved from IAEA & WMO database with climate and geography. The researchers also noticed that the distribution of oxygen isotope composition reflects local topography. Water which saturates atmospheric air is supplied in oceanic regions at low latitudes. The original isotope composition is gradually modified by the so-called "isotope effects", first in the borderline diffusion layer between the surface of a large aquatic basin and the lower section of the atmosphere, and then deep within the mainland (Boyle 1997; Bowen and Revenough 2003). Locations at high altitudes above sea level are characterised by lower $\delta^{18}O_w$ values; it is the so-called "altitude effect". Oxygen isotope composition values decrease with growing distance from the shore of a large basin to the inland area, which is called the "continental effect" the influence of which is very clear in continental Europe. On the European continent mean monthly and annual $\delta^{18}O_w$ values decrease with growing distance from the Atlantic Ocean. The drop in isotope values is about 8‰ per every 4,500 kilometers (Różański et al. 1993). A typical characteristic of medium and high latitudes in this respect is the unequal abundance of ^{18}O isotope in winter (lower value) and summer (higher value) – the so-called "seasonal effect". The "latitude effect" determines the presence of precipitation containing heavier isotopes in the equatorial zone; the closer to the poles, the lighter the oxygen isotopes. This relationship partly overlaps with the "continental effect" principle which states that the precipitation water of a warm climate is richer in ^{18}O isotopes in comparison with that of a cold climate. Air humidity too has a significant effect on the local isotope ratio. In low humidity conditions, relative quantity of ^{18}O isotopes in water is higher because ^{16}O as lighter isotopes are lost in the process of evaporation (Bowen and Revenough 2003).

OIPC

The Online Isotopes in Precipitation Calculator (OIPC) is a tool for computing long-term mean oxygen and hydrogen isotope levels in precipitation water by geostatic modeling. Since 1961 the International Atomic Energy Agency (IAEA) and World Meteorological Organisation (WMO) have gathered and published isotope data for precipitation collected in over 800 meteorological stations around the world. Currently, isotope composition records over a period of minimum one year come from approx. 350 stations (Bowen and Revenaugh 2003). Since 2000 there have been several methods for interpolating $\delta^{18}O$ in precipitation, which contributed to the emergence of new isotope maps (Birks et al. 2002 cited in Bowen and Revenaugh 2003:9–2). Bowen and Wilkinson (2002), thanks to their proprietary algorithm improved by Bowen and Revenaugh (2003) and Bowen et al. (2005), designed an interpolation scheme, which was a combination of an empirical model of isotope levels distribution related to latitude and altitude above sea level (including temperature) and a spatial interpolation model (Bowen and Revenaugh 2003). The algorithm estimates oxygen isotope composition values in precipitation in a location of interest (selectable worldwide) with a confidence interval of 95%.

The main objective of the present work was to determine the diversity of oxygen isotope levels in precipitation water in Poland. The analysis of data of the isotope ratios in precipitation obtained from the global database OIPC was applied in order to divide Poland into territories of unique oxygen isotope content, taking into account the gradient of the parameter. Tracing the isotope composition of precipitation, especially in locations where archaeological excavations were performed, will reveal the potential in the interpretation of the results of isotope tests and help retrace probable trek routes of analysed communities. A closer look at the isotope data in East-Central Europe will facilitate studying the directions of potential migrations, also in a broader context than today's territory of Poland.

Materials and methods

Oxygen isotope composition data for sites in Poland in which excavations had been conducted were estimated by means of the Online Isotopes in Precipitation Calculator, OIPC (http://waterisotopes.org, accessed in June 2016). The 279 archaeological sites considered in our investigations is based on studies by Poradnik (1981) and Kozak (1998) (Fig. 1). The base of locations was supplemented by archaeological sites explored in recent years. Also there were included locations that were interesting in terms of geographic and climatic conditions eg. Tatra Mountains, and 13 locations from countries bordering Poland. For each of the locations referred to above, geographic coordinates and altitude above sea level were collected using the Geocontext profiler tool (http://geocontext.org). Then, by means of the OIPC, mean annual isotope values were obtained for each location. The values were superimposed on a map presenting mean annual air temperatures in Poland. Areas with few or no sites such as the regions of Podhale or Sudety were also analysed in terms of isotope ratios in order to supplement the network of locations for which data were available. This study contains geographic names of macroregions as used by Kondracki (2002).

Results

On the basis of the values generated by means of the OIPC, an oxygen isotope value database was created for 279 investigated locations in which excavation work had been carried out from almost 60 years. Due to the high number of sites and their relatively even distribution (Fig. 2) we arrived at a complete image of the isotope composition of the territory of Poland. The highest δ^{18}Ow value is –8.9‰ and was recorded in towns which are currently situated in the vicinity of Zielona Góra in Lubuskie voivodeship, in Dolnośląskie voivodeship (e.g. Wrocław), Opolskie voivodeship (e.g. Opole), Małopolskie voivodeship (e.g. Krakow). The lowest recorded value is –10.2‰ near Suwałki.

Considering factors which affect the isotope composition of environmental water and territorial variation of $\delta^{18}O_w$ values in Poland, the country was divided into four regions according to the isotope composition of precipitation.

The macroregions of Poland which fall within the defined "isotope regions" are listed below.

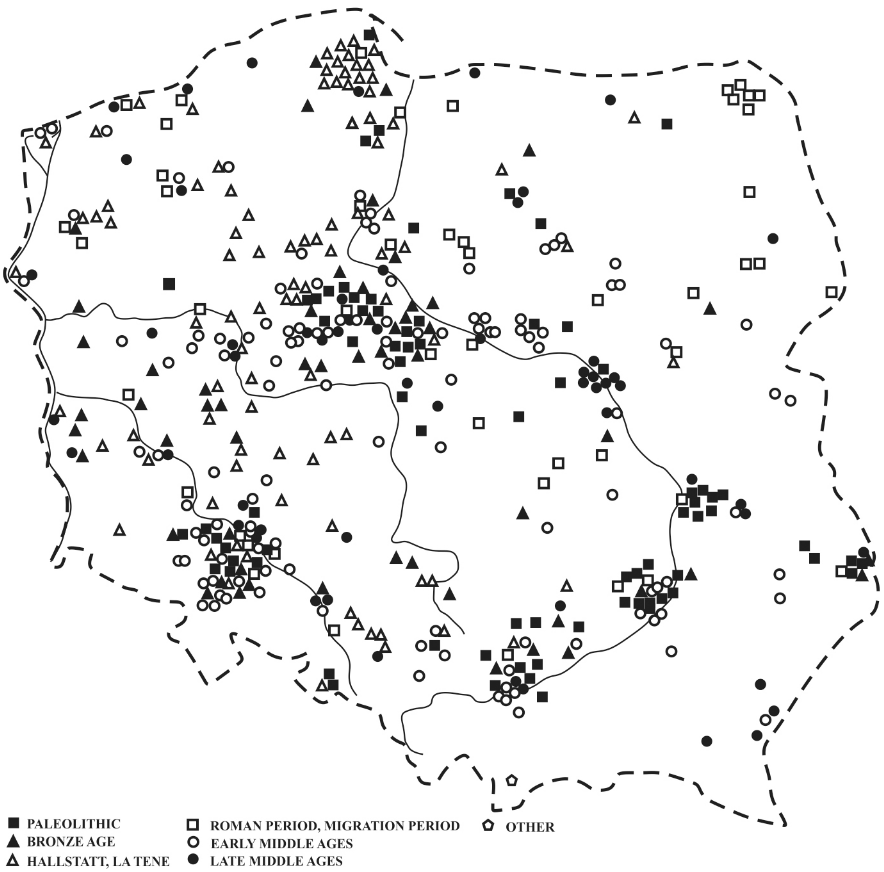

Fig 1. Archaeological sites in Poland selected from study by Poradnik (1981) supplemented with new fields. For each location was generated oxygen isotope ratio in precipitation.

I: Lithuanian Lakeland (Pojezierze Litewskie), the northern part of North Podlachian Lowland (Nizina Północnopodlaska), the western part of Masurian Lakeland (Pojezierze Mazurskie) and Old Prussian Lowland (Nizina Staropruska). Isotope levels from –9.8‰ to –10.2‰

II: Littoral Koszalin Region (Pobrzeże Koszalińskie), Littoral Gdańsk Region (Pobrzeże Gdańskie), East Pomeranian Lakeland (Pojezierze Wschodniopomorskie), the upper part of West Pomeranian Lakeland (Pojezierze Zachodniopomorskie), South Pomeranian Lakeland (Pojezierze Południowopomorskie) except for the areas belonging to Lubuskie voivodeship, Lower Vistula Valley (Dolina Dolnej Wisły), Iława Lakeland (Pojezierze Iławskie), western parts of Old Prussian Lowland (Nizina Staropruska) and Masurian Lakeland (Pojezierze Mazurskie) with Olsztyn and Szczytno poviat districts, Chełmno-Dobrzyń Lakeland (Pojezierze Chełmińsko-Dobrzyńskie), North Masovian Lowland (Nizina Północnomazowiecka), the northern part of South Podlachian Lowland (Nizina Południowopodlaska), a small part of Central Masovian Lowland (Nizina Środkowomazowiecka) (near Siedlce), the upper part of Western Polesie (Polesie Zachodnie), the northernmost part of Toruń-Eberswalde Glacial Valley (Pradolina Toruńsko-Eberswaldzka). Isotope levels ranging from –9.4‰ to –9.9‰.

In the 2nd "isotope region", two small areas which stand out due to higher $\delta^{18}O_w$ values are highlighted on the map (Fig. 2). It is the region of Chojnice (–9.7‰) and Dylewska Górka 307 m above sea level (–10.1‰).

III: Littoral Szeczecin Region (Pobrzeże Szczecińskie), part of South Pomeranian Lakeland (Pojezierze Południowopomorskie), which administratively belongs to Lubuskie voivodeship, the northern part of Lubusz Lakeland (Pojezierze Lubuskie), Greater Poland Lakeland (Pojezierze Wielkopolskie), Toruń-Eberswalde Glacial Valley (Pradolina Toruńsko-Eberswaldzka) (except for the part referred to in Region II), South Greater Poland Lowland (Nizina Południowowielkopolska), Central Masovian Lowland (Nizina Środkowomazowiecka), South Mazovian Heights (Wzniesienia Południowomazowieckie), Leszno Lakeland (Pojezierze Leszczyńskie), Woźniki-Wieluń Upland (Wyżyna Wożnicko-Wieluńska), Przedbórz Upland (Wyżyna Przedborska), Kielce Upland (Wyżyna Kielecka), the northern part of Kraków–Częstochowa Upland (Wyżyna Krakowsko-Częstochowska), northeast part of Sandomierz

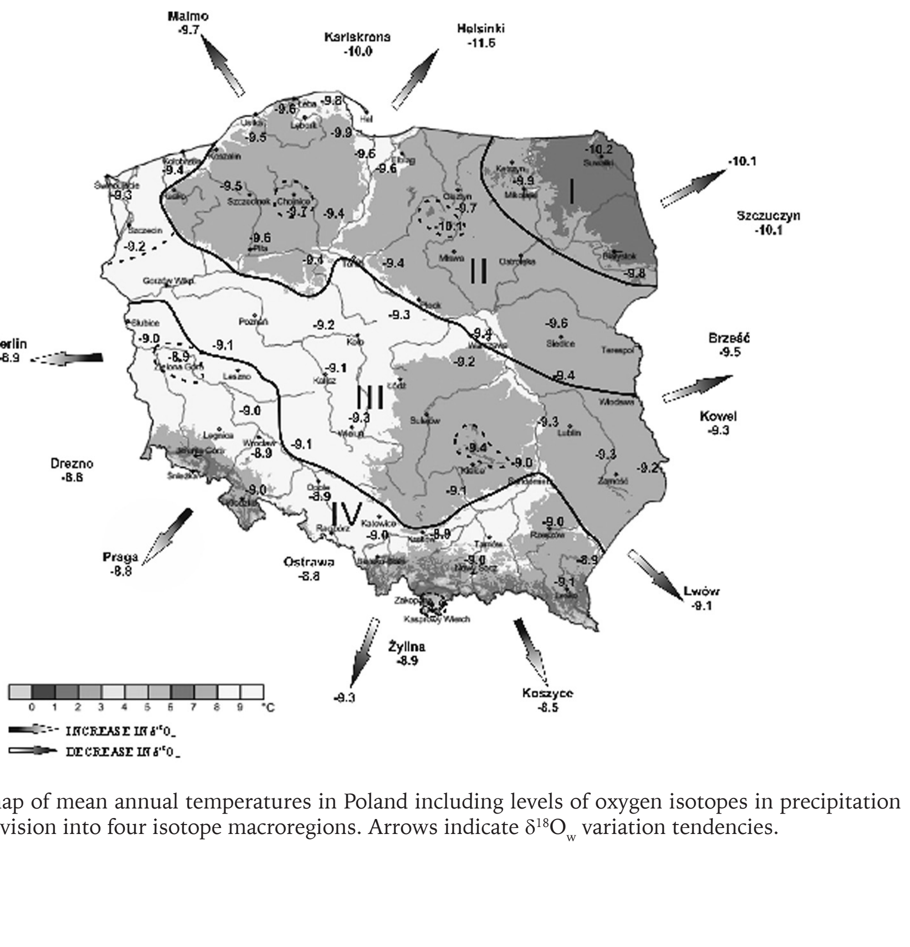

Fig. 2. A map of mean annual temperatures in Poland including levels of oxygen isotopes in precipitation with division into four isotope macroregions. Arrows indicate $\delta^{18}O_w$ variation tendencies.

Basin (Kotlina Sandomierska) continuing to San-Dniester Plateau (Płaskowyż Sańsko-Dniestrzański), Lublin Upland (Wyżyna Lubelska), the southern part of Western Polesie (Polesie Zachodnie), Volhynian Polesie (Polesie Wołyńskie), Roztochia (Roztocze), Volhynian Upland (Wyżyna Wołyńska), Western Bug Basin (Kotlina Pobuża). The areas which fall outside the –9.3‰ to –9.1‰ range include Littoral Szeczecin Region (Pobrzeże Szczecińskie) and Świętokrzyskie Mountains (Góry Świętokrzyskie) (–9.4‰).

IV: the southern part of Lubusz Lakeland (Pojezierze Lubuskie), Warta-Oder Glacial Valley (Pradolina Warciańsko-Odrzańska- western part), Zielona Góra Heights (Wzniesienia Zielonogórskie), Lower Lusatian Depression (Obniżenie Dolnołużyckie), Lusatian Heights (Wzniesienia Łużyckie), Milicz-Głogów Depression (Obniżenie Milicko-Głogowskie), Silesian-Lusatian Lowland (Nizina Śląsko-Łużycka), Trzebnica Embankment (Wał Trzebnicki), West Sudetic Upland (Pogórze Zachodniosudeckie), Sudetes Foreland (Przedgórze Sudeckie), Western Sudetes (Sudety Zachodnie), Central Sudetes (Sudety Środkowe) and Eastern Sudetes (Sudety Wschodnie), Sandomierz Basin (Kotlina Sandomierska), San-Dniester Plateau (Płaskowyż Sańsko-Dniestrzański), the western part of Silesian Lowland (Nizina Śląska), Silesian Upland (Wyżyna Śląska), Oświęcim Basin (Kotlina Oświęcimska), the southern part of Kraków–Częstochowa Upland (Wyżyna Krakowsko-Częstochowska), Cracow Gate (Brama Krakowska), West Beskid Upland (Pogórze Zachodniobeskidzkie) and Central Beskidian Piedmont (Pogórze Środkowobeskidzkie), Western Beskid (Beskidy Zachodnie), Central Beskids (Beskidy Środkowe) and Wooded Beskids (Beskidy Lesiste), Podhale-Magura Area (Obniżenie Orawsko-Podhalańskie), Tatra Chain (Łańcuch Tatrzański). The isotope range for Region III includes values from –8.9‰ to –9.0‰ with two distinct areas: Zielona Góra Heights (Wzniesienia Zielonogórskie) and Tatra Chain (Łańcuch Tatrzański) –9.9‰.

Figure 2 also shows the increasing and decreasing tendencies for oxygen isotopes in regions bordering with Poland. A rise in the $\delta^{18}O_w$ value was reported in westward and southward direction, whereas further north and east from the Polish border lower values of the parameter in precipitation are observed.

As can be seen in Figure 2, data generated by means of the OIPC allowed us to define four regions with similar $\delta^{18}O_w$ values. The regions are characterised by a layered structure and oriented along the east/northwest line.

The presence of the lowest values of $\delta^{18}O_w$ in Region I may be due to low mean air temperatures during the year in the area between Suwałki, Kętrzyn and Białystok: Its mean temperature in January is the lowest in comparison to other locations in Northern and Central Poland. Such conditions may be additionally affected by a high mean total precipitation during the year. It is likely that isotope levels in the area are subject to the “altitude effect”. It is predominately a lowland region with many lakes and lake districts, yet there is no lack of uplands. In several locations altitude above sea level exceeds 300 m, which may be locally significant.

The isotope region labeled as Region II is a belt with mean annual air temperatures of 7 to 8°C. It covers seaside areas of noticeably lower $\delta^{18}O_w$ values than those situated south and east of the sea.

The climate of the region is influenced by the Baltic Sea, although the further south, the more the marine impact is limited. Characteristics of wind directions in Poland show that the coastal areas from Półwysep Helski to Świnoujście are characterised by high mean annual wind speed.

Oxygen isotope ratio values in precipitation in Regions I and II are clearly lower than those observed in Central and South Poland. When referring those values to $\delta^{18}O_w$ parameters generated for the Scandinavian region, one may notice that the inflow of the Arctic air from Scandinavia in winter is not without significance for the northern part of Poland. We may suppose that (heavy isotope-bearing) humidity contained in the Arctic air, in addition to low temperature, causes precipitation with high ^{18}O content, thereby neutralising/reducing the opposing effect of other factors such as the latitude effect or the continental effect.

Region III, crossing the country from the west to the east through its central part, is climatically influenced by maritime polar air (warm in summer, cold in winter) coming from the west, which is manifested in slightly higher $\delta^{18}O_w$ values (–9.1‰) in the west. Meanwhile, the eastern part is affected by masses of continental air causing low temperatures. Growing distance from the Atlantic Ocean also results in a lower oxygen isotope proportion (–9.3‰) in precipitation.

The highest $\delta^{18}O_w$ values are reported for Region IV. This means that precipitation water of locations included in Region IV contains a relatively high quantity of ^{16}O isotopes. The influence of the Atlantic Ocean and tropical air masses is undoubtedly at work here, bringing warm air with lighter isotopes, which, although mostly stopped by the high mountain ranges, still exerts noticeable impact on the climate and isotope composition of precipitation in South Poland.

Discussion

A discussion of oxygen isotope ratios in environmental water may entail a question whether values which characterise contemporary water may also be considered in studying pre-historic populations. To date there have been few recorded analyses of the isotope composition of surface or ground water in Poland. Still, studies by Zuber et al. (1997) on water samples collected from a shallow layer of a water system dated at the interglacial and interstadial period show that their isotope composition does not significantly differ from the composition of today's water. The difference was only reported for samples taken at greater depths. In the study, water from deeper layers of the system contained heavier isotopes than contemporary water, which – according to authors – could stem from the impact of a much warmer climate in the period to which the water samples from deeper strata were dated, i.e. the period preceding the Quaternary. We may therefore conclude that the water from surface layers of the lithosphere representative of the period preceding the Quaternary does not substantially differ from today's water in terms of isotope ratios.

The isotope composition of drinking water may depend on three factors: surface waters, ground waters and soil humidity (Darling 2004). The author also emphasized that the heaviest impact on the composition of surface and ground water was exerted by precipitation and suggested that the highest isotope variability characterises flowing watercourses (rivers), for which $\delta^{18}O$ is modified with every consecutive tributary from a new territory.

Environmental water isotope ratios are proved to be manifested in $\delta^{18}O_p$ values for the bone tissue. The conclusion which may be drawn from the present study is that individuals from historical or pre-historical populations from what today is the territory of Poland could differ in terms of oxygen isotope ratios in bone tissues, and the $\delta^{18}O_p$ value depends on the "isotope region" from which the specific individual originated. In Figure 2 we may find $\delta^{18}O_p$ values could be expected to be measured in tissues of individuals representing a given location in Poland.

Conclusions

The analysis of $\delta^{18}O$ data for precipitation in 279 locations where archaeological excavation works had been performed yielded a complete image of the isotope composition of the territory of Poland and allowed us to define four regions according to $\delta^{18}Ow$ levels. The regions are arranged in layers characterised by growing oxygen isotope level along the northeast/southwest axis. The highest values of isotope ratios were reported in the southeast belt with a tendency for the value to increase in the direction of Germany, Czech Republic and Slovakia; the lowest ones are characteristic of the region of Suwałki with a trend to decrease in the direction of the countries bordering Poland in the east. $\delta^{18}O_w$ value read-outs for individual regions to a large extent reflect the climatic and geographic conditions in respective locations in Poland. Recorded variations in oxygen isotope composition are sufficient to capture the differences in the origin of human groups from the area of Poland, albeit only accurate to the level of a macroregion.

Considering the fact that the data presented in this work are based on the results of isotope value modeling by the OIPC software, the is a need for isotope studies conducted on environmental water samples from various regions of Poland. When juxtaposed with results from the OIPC, such values would provide a precise image of oxygen isotope variation across Poland.

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Author contribution

All Authors equally contributed to this paper i.e. in study conception and design, data acquisition and interpretation, drafting the manuscript and critically revised it. All authors read and approved final version of the manuscript.

Conflict of interest

The Authors declare that there is no conflict of interests regarding publication of this paper.

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