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Applying isotope analyses of cremated human bones in archaeological research – a review

Abstract

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Numerous experiments have recently been conducted on burnt bones in order to develop methods of isotope analysis which would be useful in archaeological research. Since the results of these studies are not yet widely known, this review presents their potential applications in investigations of human remains from cremation burials. Radiocarbon dating of burnt osteological materials is discussed, including problems related to the "old wood effect". Also considered is the analysis of light stable isotopes, i.e. $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$, which is unsuitable for palaeodietary determinations, but useful as a source of information about certain parameters of funeral pyres. Tracing geographical origins and human mobility is possible by means of the analysis of strontium isotope ratio $^{87}Sr/^{86}Sr$. Since an understanding of high-temperature-induced transformations of bone structure and chemical composition is important for these considerations, a detailed account of the processes is given as an introduction.

Key words: isotopes, cremated human bones, radiocarbon dating, funerary practices, migration

1. Introduction

The application of isotope analyses in archaeological research is a landmark achievement of the cooperation between the humanities and the natural sciences. This remark is easily justified by pointing out the significance of $\delta^{14}C$ radiocarbon determinations, which have remained the first-choice method of absolute dating for over 70 years. Furthermore, the analyses of $\delta^{13}C$ and $\delta^{15}N$ isotopes are currently widely used in studies of dietary preferences of past populations. Another success was the development of protocols for measuring the ratio of strontium isotopes ^{87}Sr and ^{86}Sr, which allows the detection of geographical origins and for the possible migrations of selected individuals to be traced. The ability to provide answers to such basic questions as to when, who, what, wherefrom and where-to, was the primary drive which led to isotope analyses becoming a valued investigative tool in archaeology, and one which has also aroused interest among the Polish scientific community (e.g. Belka *et al.* 2018; Szczepanek *et al.* 2018; Wadyl (ed.) 2019; Linderholm *et al.* 2020).

The headway of isotope analyses of unburnt human skeletal remains attracted the attention of scholars concerned with those periods, when cremation was the common funerary rite. The first and foremost question was the following: are these analyses equally valuable in the study of osteological material from cremation burials? It is known that the process of burning causes fragmentation, warping and the shrinkage of bones, all of which reduces the pool of data about the deceased. However, it was noted that the high degree of fragmentation of burnt remains may not necessarily result from cremation itself, but instead be the effect of mortuary rituals, post-depositional processes and the exploration of urn vessels (Harvig *et al.* 2012; Harvig 2015, 44, fig. 3.1). In general, it was observed that cremated

remains may provide more information than poorly-preserved skeletal material from inhumation graves (Williams 2015, 259–261; cf. Thompson 2015a, 1–3). Recent decades have also brought progress in research on possible burning-related alterations of the chemical composition of bones (Snoeck 2014, 11–26). As a result, burnt osteological material became a valuable source of physico-chemical knowledge to be used in archaeology and forensic science (Harbeck *et al.* 2011; Schmidt and Symes (eds.) 2015; Ubelaker 2009; 2015; Mamede 2018). The current state-of-the-art allows the above-mentioned question to be answered and this constitutes the main objective of this paper.

2. Heat-induced transformations of the chemical composition of bone tissue

To assess the possible applications of isotope analyses to burnt osteological material, it is important to understand the transformations of bone structure and chemical composition that result from exposure to high temperatures.

Bone is made up of three basic components: 1) water, 2) the organic phase, mainly collagen (ca 90%) as well as proteoglycans, non-collagen proteins, phosphoproteins and lipids, and 3) the inorganic matrix called bone apatite or bioapatite (LeGeros 1991; Lee and Einhorn 2001). Due to the destructive impact of the temperature of the funerary pyre, only the inorganic phase, which constitutes ca 60% of bone mass, is useful in most studies of burnt remains.

Bioapatite is a crystal form of calcium hydroxyphosphate, which strongly reassembles the naturally occurring mineral hydroxyapatite ($Ca_5(PO_4)_3(Cl/F/OH)_2$). However, in contrast to the latter, it is more susceptible to non-stoichiometric transformations of chemical compounds, which enables the incorporation of ions present in the blood into the structure of bioapatite (Figure 1). Essential in this respect are the carbonate ions (CO_3^{2-}), which substitute nearly all of the hydroxyl groups (OH^-) and part of the phosphates (PO_4^{3-}) – called A-type carbonates (exchangeable with OH^-) and B-type carbonates (exchangeable with PO_4^{3-}) respectively (LeGeros 1969; 1991; Astala *et al.* 2005; Wopenka and Pasteris 2005; Snoeck 2014, 12; Madupalli *et al.* 2017). This process of substitution is highly relevant to the structure of the inorganic matrix of bone. The ions (A- and B-type carbonates) are not of the same shape and size, leading to deformations of bioapatite crystallinity during the exchange. For this reason, bioapatite is built up of smaller crystals than hydroxyapatite (it is less crystallized), which in turn leads to its enhanced susceptibility to various chemical processes, including diagenetic ones (Wopenka and Pasteris 2005; Snoeck 2014, 12; Snoeck *et al.* 2014a; Mamede *et al.* 2018).

High temperatures strongly alter both bone structure and their chemical composition. At first, the chain of transformation involves dehydration and the destruction of the organic phase, including the disintegration of collagen fibres. At the same time, the inorganic matrix undergoes a progressive loss of
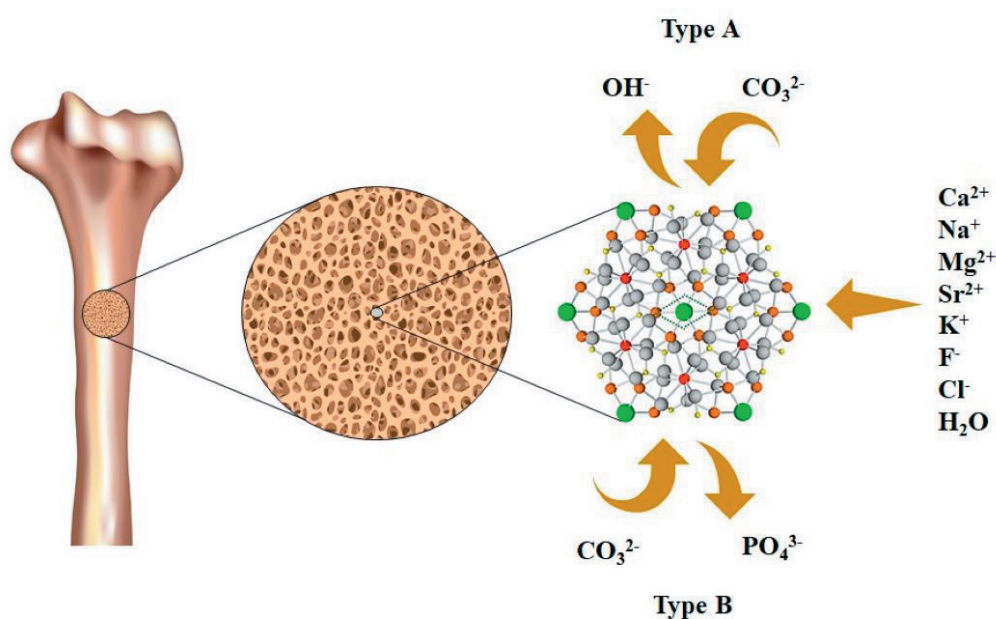

Fig. 1. The transformation of chemical compounds in bone apatite (after Mamede *et al.* 2017, modified by B. Wolska)

carbonates (CO_3^{2-}), a rise of hydroxyl groups (OH^-), and even the formation of new mineral forms, i.e. NaCaPO4, NaCl and KCl (Van Strydonck *et al.* 2005; Zazzo *et al.* 2009; Snoeck 2014, 39–94; Snoeck *et al.* 2014a; Mamede *et al.* 2018, Fig. 2). However, above all, these processes are accompanied by a gradual increase of bone apatite crystallinity, resulting in a high resilience to chemical weathering (Stiner *et al.* 1995; Lebon *et al.* 2010; Quarta *et al.* 2013; Thompson 2013; 2015; Snoeck 2014, 16, 89, 123; Snoeck *et al.* 2014a; Mamede *et al.* 2018). This property makes it similar to two-hydroxyapatite – the main component of the enamel of teeth which are considered the most robust elements of the human skeleton (LeGeros 1991; Hoppe *et al.* 2003; Chai *et al.* 2009; Muller *et al.* 2019). Consequently, burnt bone is highly resistant to post-depositional chemical transformations, which is significant from the perspective of physico-chemical and osteological analyses. It should be noted that this only pertains to fully calcined bones, that have been exposed to temperatures higher than 600°C (Snoeck *et al.* 2014a).

Isotopes (gr. "equal place") are variants of chemical elements that have the same atomic number but a different mass number (Jones and Atkins 2016, 11). Based on their stability, they are divided into stable, e.g. ^{13}C, ^{15}N, ^{18}O, ^{86}Sr, ^{87}Sr and radioactive, such as ^{14}C. In the life cycle of humans and animals, isotopes accumulate in the organic phase and inorganic matrix of bones. For instance, ^{14}C infiltrates organisms during the digestion of $^{14}CO_2$, which is an element of the food consumed (Jones and Atkins 2016, 1034). Similarly acquired are strontium isotopes ^{87}Sr and ^{86}Sr, present in ingested water and plant/animal tissues, in amounts dependant on the local geological background (Beard and Johnson 2000; Bentley 2006; Slovak and Paytan 2012; Snoeck *et al.* 2015).

The above-mentioned heat-induced alterations of bone tissue bear heavily on studies of its isotopic composition. Poor preservation of extractable collagen (with a nitrogen value lower than 0,8%; see Brock *et al.* 2010) precludes the possibility of analysing this particular fraction, as is usually done in the case of unburnt bones (e.g. skeletal burials). Bone apatite is subjected to significant deformations as a result of the gradual loss of carbonates and increased number of hydroxyl groups, what corresponds with the loss and increase (respectively) of certain chemical elements (isotopes). These undergo further transformations, such as exchange and/or incorporation/fractioning during the process of cremation or subsequent residence of the remains in the soil (see below). All in all, it seems justi-fied to say that burning causes irreversible changes in the original isotopic composition of bone. Nevertheless, even in this form, it is still a source of data that is extremely valuable in archaeological research.

3. Isotope analyses in studies on burnt human bones

3.1. Radiocarbon dating

Radiocarbon dating of burnt osteological remains was first conducted at the end of the 20th century. During the procedure, comparable ^{14}C dates were obtained for burnt bone and charcoal derived from the same context, opening up the possibility to determine the age of archaeological materials in which no organic matter was present (Lanting and Brindley 1998). This revolutionary discovery spurred further research (Lanting and Brindley 2000; Lanting *et al.* 2001; Van Strydonck *et al.* 2005; Naysmith *et al.* 2007), yet this did not fully consider the potential differences between the age of bones and the fuel used for their cremation. As it transpired, this has major relevance for radiocarbon dating: the process leading to the "old wood effect" takes place when a bone is burnt in the presence of much older wood – the latter "conveying" a portion of its age, resulting in the artificial oldening of osteological material (Olsen *et al.* 2008; 2013; Hüls *et al.* 2010; Zazzo *et al.* 2012; Snoeck *et al.* 2014b). This phenomenon is best illustrated by the results of an experiment in which a contemporaneous pig trotter was burnt using ca 480-year-old wood, and its remains obtained a date of 326 ± 22 BP (Snoeck *et al.* 2014b). A similar but opposite effect was observed in a test where "old" archaeological bone and modern-day wood were subjected to burning (Zazzo *et al.* 2012). These studies have shown that ^{14}C dates do not necessarily indicate the actual age of burnt remains, but the age of the fuel used.

The above-mentioned findings reflect certain chemical processes that take place in bone during its exposure to high temperatures, e.g. of a fireplace or funeral pyre. Specifically, of crucial importance is the origin of the carbon isotopes present in the carbonate fraction of burnt bone apatite, since surely some of them are not part of the original composition (hence the "old wood effect"). Four mutually non-exclusive possibilities were proposed: 1) contamination of the carbonate fraction of bone apatite by atmospheric carbon, 2) exchange of carbon between the carbonate fraction of bone apatite and the gas released by the cremation fuel, 3) incorporation of organic carbon

released during the combustion of organic matter, i.e. skin, muscle, fat, 4) incorporation of organic carbon released during the combustion of collagen as well as other proteins and lipids, and 5) heat-induced fractioning of the carbonate fraction of bone apatite (Figure 2) (Zazzo *et al.* 2009; Snoeck *et al.* 2014b).
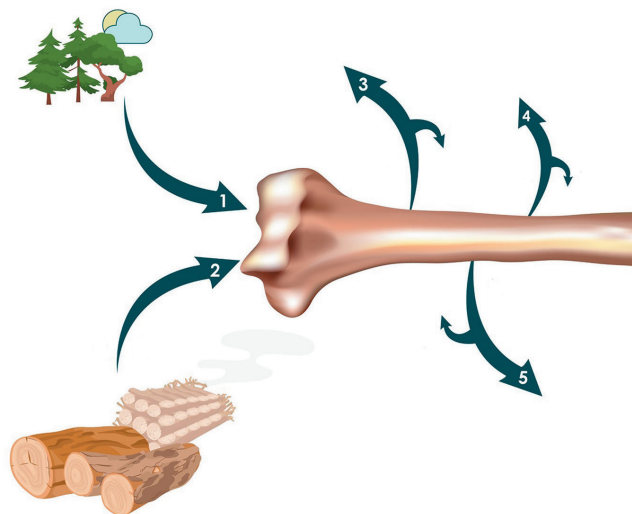

Fig. 2. Sources of CO_2 that probably affect the isotopic composition of the carbonate fraction of bone apatite during heating/burning: 1) the atmosphere, 2) the burnt fuel, 3) the burnt organic matter, i.e. skin, muscle, fat, marrow 4) the burnt collagen, 5) the burnt carbonate fraction of bone apatite. The arrows indicate the possible directions of carbonate and/or CO_2 flow, and the conditions in which the fractioning of carbon occurs (after Snoeck 2014, 97, fig. 5.1., modified by K. Kij)

In reality, only four possibilities are relevant (2–5), the first one being less feasible due to the low CO_2 content (0,04%) in the atmosphere. The third and fourth were confirmed only for the exchange of carbon between bone apatite and collagen. Soft tissues (skin, muscles, fat) undergo relatively rapid combustion (see Fairgrieve 2008, 44–45, tab. 3.3, 3.4.) and for this reason they do not have a substantial influence on the final chemical composition of the carbonate fraction of burnt bone apatite (Snoeck *et al.* 2014b). At the same time, since collagen is close to apatite and subjected to gradual degradation up to 600°C, it has more potential for mutual chemical interaction (Hüls *et al.* 2010; Van Strydonck *et al.* 2010; Zazzo *et al.* 2012; Snoeck *et al.* 2014b; 2016a). It is not responsible, however, for the incorrect radiocarbon dating of burnt bones, because both these fractions (collagen and apatite) share a similar (although not identical) ^{14}C age (Snoeck 2014, 121; Snoeck *et al.* 2014b). Experiments have also confirmed the fractioning of carbon isotopes, occurring between bone apatite and CO_2 released by burning organic mat-

ter and combustion gases (Zazzo *et al.* 2009; Hüls *et al.* 2010; Van Strydonck *et al.* 2010; Harbeck *et al.* 2011; Snoeck *et al.* 2014b; 2016a). Nevertheless, the isotopic composition of carbon in burnt bone is mostly influenced by the process of the exchange with the burning environment, i.e. an exchange with carbon emitted by the fuel (Table 1). It is precisely this phenomenon which is mainly responsible for the "old wood effect" (Olsen *et al.* 2008; 2013; Hüls *et al.* 2010; Zazzo *et al.* 2012; Snoeck *et al.* 2014b; 2016a).

Table 1. Research results indicating an increased exchange of carbon between the burnt fuel and the carbonate fraction of bone apatite, what is the main reason of the "old-wood" effect.

Authors	Research material	Carbon exchange with old fuel
Hüls *et al.* 2010	Modern bovine bone	36% – 86%
Zazzo *et al.* 2012	Archaeological human and animal bones	48% – 91%
Snoeck *et al.* 2014	Modern animal bones	39% – 95%

Summarizing, the carbon present in the carbonate fraction of burnt bone apatite has three possible sources: endogenic apatite carbon, endogenic carbon present in collagen, and fuel-derived carbon. In light of this knowledge, is it practical to date burnt remains using radiocarbon? Despite certain limitations, in most cases the method delivers relevant information. However, the following circumstances should be considered:

1) The remains of the deceased might have been cremated some-time after their death, using young wood as fuel. The result of the ^{14}C analysis will indicate the approximate date of the burning, not the actual moment of the individual's death.

2) The remains of the deceased might have been cremated using also old wood as fuel. The result of the ^{14}C analysis will indicate the approximated age of the wood, not the actual moment of the individual's death.

Both these conditions may be difficult to assess for cremated materials from archaeological contexts, with the consequence that the radiocarbon dating of singular samples will deliver unambiguous data. The interpretative field can be narrowed by obtaining a series of dates for several graves, or in the case of

bi-ritual cemeteries, by additionally comparing values acquired for skeletal and cremation burials. Such radiocarbon research has recently been caried out on numerous (1428) samples from cremation and inhumation burials discovered at archaeological sites in Belgium. The results have shown cultural changes in funerary practices from the Mesolithic period to the Middle Ages (Capuzzo *et al.* 2020).

3.2. Light stable isotopes ¹³C, ¹⁵N and ¹⁸O

Isotopes of light elements present both in the organic phase and inorganic matrix of bone, such as carbon, nitrogen and oxygen, have been used in bioarchaeological studies to reconstruct the dietary preferences of past communities. Their successful applications to unburnt skeletal remains led to an interest in using a similar analysis for cremated osteological material. Unfortunately, however, this was found to be unsuitable for such determinations (DeNiro *et al.* 1985). The advantages of investigating stable isotopes in burnt bone only became clear in the last decade, although they turned out to be unrelated to palaeodietary research (Snoeck *et al.* 2014b; 2016a).

Isotope signatures of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{18}O$ preserve their original values only up to 200°C (DeNiro *et al.* 1985; Harbeck *et al.* 2011; Schurr *et al.* 2015). Changes occurring above this threshold were identified experimentally, with varying degrees of influence on the final isotopic composition. The most recent results indicate a rapid loss of light isotopes in collagen and apatite, except for structural carbon $\delta^{13}C$, the level of which decreases to 700–800°C but starts to increase with a further rise of temperature (Harbeck *et al.* 2011; Snoeck *et al.* 2016a). This general reduction is directly related to the heat-induced alteration of bone composition and structure, above all the combustion of the organic phase and loss of carbonates (CO_3^{2-}) from the inorganic matrix, accompanied by the processes of exchange, fractioning and incorporation of carbon from different sources (see 3.1., Fig. 2). The current state of research shows that palaeodietary analyses in burnt bone are not possible (DeNiro *et al.* 1985; Lanting *et al.* 2001; Van Strydonck *et al.* 2005; Olsen *et al.* 2008; 2013; Zazzo *et al.* 2009; 2013; Harbeck *et al.* 2011; Snoeck *et al.* 2014b; 2016a; cf. Schurr *et al.* 2015).

It has recently been pointed out that stable light isotopes may be used in studies oriented at reconstructing the cremation ritual, serving as proxies of the conditions in the funeral pyre during the burning of the deceased (Snoeck *et al.* 2016a).

This method was developed in the course of experiments concentrated on the isotopic variance of $\Delta^{13}C$ and $\Delta^{18}O$ ($\Delta= \delta$ of the sample – δ unburnt apatite), instead of their absolute values (Snoeck *et al.* 2016a). To confirm that the conditions of cremation have a meaningful bearing on this variance, a test was arranged that simulated possible different circumstances of the ritual – burning of a sample on firewood (with fuel), also with the addition of C_3 and C_4 plants (or their products, such as maize). Burning in laboratory conditions (without fuel) served as reference (Snoeck *et al.* 2016a). It was observed that bones cremated on firewood have less carbon $\delta^{13}C$ and oxygen $\delta^{18}O$, and that the values of oxygen $\delta^{18}O$ are lower when the exchange of carbon $\delta^{13}C$ between the bone and the fuel intensifies. Moreover, bones containing cyanamide – an organic compound identified by FTIR and expressed in relation to the amount of phosphorus in the sample (CN/P) – usually have higher values of carbon $\delta^{13}C$ with a slight difference in oxygen $\delta^{18}O$ presence. The addition of C_4 plants during the cremation also has an impact on the isotopic composition of samples, resulting in considerably enhanced levels of $\delta^{13}C$ and $\delta^{18}O$ (Snoeck *et al.* 2016a). All these observations are related to complex processes of exchange, fractioning and incorporation of the described elements, which to a varied extent (still unassessed) shape the final isotopic composition of burnt bone apatite. Tracing this composition in individual samples allows recognizing remains cremated under different conditions. Three possibilities were outlined:
1) identification of remains burnt in the presence of firewood and those cremated without its use (probably a rare occurrence in archaeological materials).
2) identification of remains burnt using C_3 firewood and C_4 plant fuel.
3) identification of remains burnt on larger or smaller funeral pyres, in different places (pyres located in landscape positions with higher or lower oxygen availability) and the positioning of the body during the cremation (on/in the pyre).

Considering these remarks, a comparison of the results of $\delta^{13}C$ and $\delta^{18}O$ isotope analysis of remains from a single cemetery allows the pinpointing of those individuals who were cremated in different circumstances than others (i.e. their isotopic values do not correlate with the cemetery "baseline"). Further investigations may address the possible reasons for such exceptional treatment, which can be a consequence of customs specific for a given community, or a sign suggesting that the deceased in question was cremated in a location different than the place of burial. In the lat-

ter case, an analysis of strontium isotope ^{87}Sr and ^{86}Sr ratio is a supplementary investigative method.

3.3. Strontium isotope ratio ^{87}Sr/^{86}Sr

Geographical origins and the mobility of people have been intensely studied topics in archaeology. Informative in this matter is an analysis of strontium isotopes ratios ^{87}Sr/^{86}Sr – an element assimilated by the human organism during the ingestion of food and water, which becomes incorporated in the structure of bones in a manner similar to calcium. Among the isotopes discussed in this paper, strontium is the only one resistant to high temperatures, a fact known from the early 1990's (Grupe and Hummel 1991). In the last decade, the method was applied to remains from cremation graves, confirming its usefulness as a tool in research on ancient migrations (Snoeck 2014, 125–137; Harvig *et al.*, 2014; Snoeck *et al.*, 2015; 2016b; 2018; Graham *et al.* 2019).

As an element heavier than 50u, strontium is not subjected to the same chemical processes as the above-mentioned light isotopes during burning. Experiments have indicated that the ^{87}Sr/^{86}Sr value in samples does not change, even after heating in temperatures exceeding 1000°C (Grupe and Hummel 1991; Beard and Johnson, 2000; Harbeck *et al.* 2011; Snoeck *et al.* 2015). This is related to a relatively high melting point of strontium carbonate (ca 1500°C), i.e. considerably above the temperatures potentially reached in funeral pyres (McKinley 1994; Ubelaker 2015; Snoeck 2014, 126; Snoeck *et al.* 2015). Moreover, there is no noticeable process of fractionation between ^{87}Sr and ^{86}Sr during bone combustion (as was it observed in the case of carbon isotopes), because the difference between their atomic masses is low (Harbeck *et al.* 2011; Snoeck 2014, 126; Snoeck *et al.* 2015).

Of crucial importance in strontium isotope analysis is the type of material selected for the study. In the case of inhumation burials, the enamel of teeth is usually sampled due to its specific properties: 1) the lack of metabolic activity, which ensures a fixed isotopic composition during the whole human life, 2) a high resilience to post-depositional alteration (see 3.1.), and 3) temporal differences in the formation of individual tooth crowns, allowing the assessment of the individuals' place of residence in particular periods of their lives, between the early childhood and adolescence, depending on the type of tooth studied. Due to the rare occurrence of tooth enamel in cremated materials, a substitute needed to be found. This role was taken by the otic capsule located in the petrous part of

the temporal bone which is composed of very dense bone tissue that is resilient to chemical processes (Jeffery and Spoor 2004; Jørkov *et al.* 2009; Harvig *et al.* 2014). Its morphology remains unchanged even under high temperatures and for this reason it is often discovered among burnt human remains. Experimental research confirmed the credibility of this material in studies on the geographical origins of cremated individuals (Harvig *et al.* 2014). However, it is important to note that analyses of the petrous portion of the temporal bone reveal information about the place of residence in very early childhood, as this bone forms at a prenatal age and does not change after the second year of life (Jeffery and Spoor 2004; Jørkov *et al.* 2009).

To ascertain the whereabouts of individuals in later stages of their lives, additional samples have to be taken from other parts of the human skeleton (e.g. the long bones or cranium), which had been rebuilt during the whole life due to progressing ossification. This process involves the embedding in bone of new bioapatite crystals, including strontium isotope values characteristic for the local geological background. However, ossification is a non-uniform process and proceeds differently in particular types and structures of bones. It is also determined by the metabolic level of the individual. For these reasons, the analysis of the strontium isotope composition in such samples is less straightforward as it cannot be related to a specific age of humans, (contrary to the case of the petrous part of the temporal bone or the enamel of teeth, whose period of formation in the human organism is well-researched), but only to a time interval of 10–20 years before their death (Jørkov *et al.* 2009; Szostek *et al.* 2015; Snoeck *et al.* 2015). Moreover, the possible intensive mobility of individuals or several year-long residence in new places have to be considered, which significantly influences the strontium isotope composition in the skeletal tissue, further complicating proper interpretation (Slovak and Paytan 2012, 748–749). Consequently, it is advised to conduct the analysis using samples taken from different elements of the cremated remains.

Another matter to be considered when studying strontium isotopes in the context of human mobility is the potential susceptibility of burnt bones to absorption/incorporation of exogenic strontium during their long residence in soil. This issue, important from the viewpoint of archaeology, was investigated in a series of experiments which have shown successive enrichment in Sr of a calcined cow tibia left for 12 months in a strontium-rich (^{87}Sr) solution (Snoeck *et al.* 2015). The subsequent application of acetic acid and an ul-

trasonic bath helped to remove the contamination, including the exogenic strontium isotopes; in effect, a sample with an original [87]Sr and [86]Sr composition was obtained (Snoeck *et al.* 2015). During the same research, an identical procedure (artificial enrichment in Sr and sample pre-treatment) was administered to the enamel of a horse tooth, which at the end of the experiment still exhibited a higher value of exogenic strontium compared to the burnt cow bone. Most likely, this results from the incorporation of the isotope into the crystallite structure of teeth, instead of its absorption onto the surface, as in the case of burnt cow bone. The experiment shows the high resilience of the latter to the diagenesis caused by the high crystallinity of the cremated bone (Snoeck *et al.* 2015). This points towards an equal (or even slightly higher) credibility of cremated osteological material in strontium isotope analysis, compared to teeth enamel.

In sum, the physico-chemical processes that occur during cremation do not affect the original composition of strontium isotopes in bone, and the possible alterations resulting from protracted burial in soil may be mitigated by diligent laboratory treatment. In this light, burnt osteological remains are reliable material in studies on geographical origins and mobility in communities that cremated their dead.

4. Conclusions

Cremation burials are thought to have been practiced in Polish lands as early as the Mesolithic (Gil-Drozd 2011). This funerary custom proliferated in later times and burnt human bones are frequently discovered during archaeological fieldwork as a result. The paper reviews the possibilities of conducting isotope analyses on such material and shows that the research perspectives that they entail are centred around several issues.

The first is the determination of the absolute chronology of sepulchral sites by means of the radiocarbon dating of burnt bones. It must be remembered, however, that the obtained $\delta^{14}C$ dates will not reflect the actual radiocarbon age of the remains, but of the wood used for the cremation. Consequently, the analysed samples may be oldened if they were burned in the presence of old wood (the "old wood effect"). Such circumstances may have been common in the past, as shown by anthracological studies of charcoal from cremation graves discovered in present-day Poland (Moskal-del Hoyo 2012).

The second is the interpretation of the funerary rite, albeit focused on the cremation procedure itself,

instead of the manner in which the burnt remains were deposited in graves. By comparing the values of $\delta^{13}C$ and $\delta^{18}O$ it is possible to assess whether the corpse was burned in the presence of fuel (usually wood; probably a universal occurrence in archaeological materials) or without it. Also feasible are estimates regarding the size of the funeral pyre and its location in the landscape with higher or lower oxygen availability, as well as the positioning of the body in/on the pyre. Tracing the values of these isotopes in a series of samples from a single cemetery allows us to recognize those individuals who were cremated in different conditions. This opens further avenues of inference.

Another issue is the identification of the geographical origins of people interred in cremation graves by an analysis of the strontium $^{87}Sr/^{86}Sr$ ratio, which in certain circumstances is simultaneously linked with attempts to describe the migrations they made during their lifetime. These matters are raised in discussions regarding long-range trade, mobility of labourers/specialists or even of whole communities, and for this reason information about the birthplace of individuals seems to have significance in many areas of research on the past.

On the other hand, isotope analysis of cremated bone is not a suitable method in palaeodietary studies. This is caused by the lack of collagen and the high temperature-induced changes in bone apatite which result in an irreversible alteration of $\delta^{13}C$ and $\delta^{15}N$ values. Other procedures should be sought to investigate the issue of alimentation.

Acknowledgements

References

Astala R. and Stott M. J. 2005. First principles investigation of mineral component of bone: CO_3 Substitutions in Hydroxyapatite. *Chemistry of Materials* 17(16), 4125–4133.

Beard B. L. and Johnson C. M. 2000. Strontium Isotope Composition of Skeletal Material Can Determine the Birth Place and Geographic Mobility of Humans and Animals. *Journal of Forensic Science* 45(5), 1049–1061.

Belka Z., Dopieralska J., Szczepanek A. and Jarosz P. 2018. Human mobility in the final eneolithic population

of Święte, Jarosław district, south-eastern Poland: evidence from strontium isotope data. In A. Kośko, A. Szczepanek and P. Włodarczak (eds.), *Reception of pontic culture traditions among the final eneolithic communities in the Subcarpathian Region, 3rd Millennium BC, Baltic-Pontic Studies 23.* Poznań: Adam Mickiewicz University. Institute of Eastern Studies, 246–258.

Bentley R. A. 2006. Strontium isotopes from the earth to the archaeological skeleton: A Review. *Journal of Archaeological Method and Theory* 13, 135–187.

Brock F., Higham T. and Bronk Ramsey C. 2010. Pre-screening techniques for identification of samples suitable for radiocarbon dating of poorly preserved bones. *Journal of Archaeological Science* 37(4), 855–865.

Capuzzo G., Snoeck Ch., Boudin M.*et al.* 2020. Cremation vs. inhumation: modeling cultural changes in funerary practices from the Mesolithic to the Middle Ages in Belgium using Kernel Density Analyses on ¹⁴C data. *Radiocarbon* 00(0), 1–24.

Chai H., Lee J. J., Constantino P. J., Lucas P. W. and Lawn B. R. 2009. Remarkable resilience of teeth. *Proceeding of the National Academy of Sciences USA* 106(18), 7289–7293.

DeNiro M. J., Schoeninger M. J. and Hastorf C. 1985. Effect of Heating on the Stable Carbon and Nitrogen Isotope Ratios of Bone Collagen. *Journal of Archaeological Science 12*, 1–7.

Fairgrieve S. 2008. *Forensic cremation: recovery and analysis.* Boca Raton, Londyn, New York: CRC Press.

Gil-Drozd A. 2010. Początki ciałopalenia na obszarze Europy. *Analecta Archaeologica Ressoviensia* 5, 9–94.

Gonçalves D., Campanacho V., Thompson T. and Mataloto R. 2015. The bioarchaeological analysis of cremation at the Iron Age necropolis of Tera (Portugal). In T. Thompson (ed.), *The Archaeology of Cremation.* Oxford, Philadelphia: Oxbow Books, 63–96.

Graham D. D., Bethard J. D. 2019. Reconstructing the origins of the Perrins Ledge cremains using strontium isotope analysis. *Journal of Archaeological Science. Reports* 24, 350–362.

Grupe G. and Hummel S. 1991. Trace element studies on experimentally cremated bone, I. Alteration of the chemical composition at high temperatures. *Journal of Archaeological Science* 18(2), 177–186.

Harbeck M., Schleuder R., Schneider J., Wiechmann I., Schmahl W. W. and Grupe G. 2011. Research potential and limitations of trace analyses of cremated remains. *Forensic Science International* 204(1-3), 191–200.

Harvig L. 2015. Past cremation practise from a bioarchaeological perspective: How new methods and techniques revealed conceptual changes in cremation practises during the late Bronze Age and early Iron Age in Den-

mark. In T. Thompson (ed.), *The Archaeology of Cremation. Burned human remains in funerary studies.* Oxford, Philadelphia: Oxbow Books, 43–62.

Harvig L., Frei K., Price T. and Lynnerup N. 2014. Strontium isotope signals in cremated petrous portions as indicator for childhood origin. *PLoS ONE* 9(7): *e101603.*

Harvig L., Lunnerup N. and Amsgaard Ebsen J. 2012. Computed Tomography and Computed Radiography of Late Bronze Age cremation urns from Denmark: An interdisciplinary attempt to develop methods applied in bioarchaeological cremation research. *Archaeometry* 54(2), 369–387.

Hoppe K., Koch P. and Furutani T. 2003. Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. *International Journal of Osteoarchaeology* 13, 20–28.

Hüls C. M., ErlenkeuserH., NadeauM. J., GrootesP. M. and AndersenN. 2010. Experimental study on the origin of cremated bone apatite carbon. *Radiocarbon* 52(2-3), 587–599.

Jeffery N. and Spoor F. 2004. Prenatal growth and development of the modern human labyrinth. *Journal of Anatomy* 204(2), 71–92.

Jones L. and Atkins P. 2016. *Chemia ogólna. Cząsteczki, materia, reakcje.* Warszawa: PWN.

Jørkov M. L., Heinemeier J. and Lynnerup N. 2009. The petrous bone – A new sampling site for identifying early dietary patterns in stable isotopic studies. *American Journal of Physical Anthropology* 138(2), 199–209.

Lanting J. N. and Brindley A. L. 1998. Dating Cremated Bone: The Dawn of a New Era. *The Journal of Irish Archaeology* 9, 1–7.

Lanting J. N. and Brindley A. L. 2000. An exciting new development: calcined bones can be ¹⁴C-dated. *The European Archaeologist* 13, 7–8.

Lanting J. N., Aerts-Bijma A. T. and van der Plicht J. 2001. Dating of cremated bones. *Radiocarbon* 43(2A), 249–254.

Lebon M., Reiche I., Bahain J. J., Chadefaux C., Moigne A. M., Fröhlich F., Sémah F., Schwarcz H. P. and Falguères C. 2010. New parameters for the characterization of diagenetic alterations and heat-induced changes of fossil bone mineral using Fourier Transform Infrared Spectrometry. *Journal of Archaeological Science* 37(9), 2265–2276.

Lee C. L. and Einhorn T. A. 2001. The bone organ system – form and function. In R. Marcus, D. Feldman and J. Kelsey (eds.), *Osteoporosis.* Standford, California: Academic Press, 3–20.

LeGeros R. Z., Trautz O. R., Klein E. and LeGeros J. P. 1969. Two types of carbonate substitution in the apatite structure. *Cellular and Molecular Life Science* 25(1), 5–7.

LeGeros, R. Z. 1991. *Calcium phosphates in oral biology and medicine.* Basel, New York: Karger.

Linderholm A., Kılınç M. G., Szczepanek A., Włodarczak P., Jarosz P., Belka Z., Dopieralska J., Werens K., Górski J., Mazurek M., Hozer M., Rybicka M., Ostrowski M., Bagińska J., Koman W., Rodrígez-Verela R., Storå J., Götherström A. and Krzewińska M. 2020. Corded Ware cultural complexity uncovered using genomic and isotopic analysis from south-eastern Poland. *Scientific Reports* 10: 6885(2020).

Mamede A., Goncalves D., Marques M. P.and Batista de Carvalho L. 2018. Burned bones tell their own stories: A review of methodological approaches to assesss heat-induced diagenesis. *Applied Spectroscopy Reviews* 53(8), 603–635.

Madupalli H., Pavan B. and Tecklenburg M.M. 2017. Carbonate substitution in the mineral component of bone: discriminating the structural changes, simultaneously imposed by carbonate in A and B sites of apatite. *Journal of Solid State Chemistry* 255, 27–35.

McKinley J. I. 1994. The Anglo-Saxon cemetery at Spong Hill, North Elmham. Part VIII: The cremations. *East Anglian Archaeology 69.*Moskal-del Hoyo M. 2012. The use of wood in funerary pyres: random gathering or special selection of species? Case study of three necropolises from Poland. *Journal of Archaeological Science* 39(11), 3386–3395.

Munro L. E., Longstaffe F.J. and White C. D. 2008. Effect of heating on the carbon and oxygen-isotope compositions of structural carbonate in bioapatite from modern deer bone. *Paleogeography, Paleoclimatology, Paleoecology* 266(3-4), 142–150.

Müller W., Nava A., Evans D., Rossi P., Alt K. and Bondioli L. 2019. Enamel mineralization and compositional time-resolution in human teeth evaluated via histologically-defined LA-ICPMS profiles. *Geochimica et Cosmochimica Acta* 255, 105–126.

Naysmith P., Scott E. M., Cook G. T., Heinemeier J., van der Plicht J., Van Strydonck M., Bronk Ramsey C., Grootes P.M. and Freemann S. 2007. A cremated bone intercomparison study. *Radiocarbon* 49(2), 403–408.

Olsen J., Heinemeier J., Bennike P., Krause C., Hornstrup K. M. and Thrane H. 2008. Characterisation and blind testing of radiocarbon dating of cremated bone. *Journal of Archaeological Science* 35(3), 791–800.

Olsen J., Heinemeier J., Bennike P., Krause C., Hornstrup K. M. and ThraneH. 2013. "Old wood" effect in radiocarbon dating of prehistoric cremated bones? *Journal of Archaeological Science* 40(1), 30–34.

Quarta G., Calcagnile L., D'Elia M., Maruccio L., Gaballo V. and Carmia A. 2013. A combined PIXE-PIGE approach for the assessment of the diagenetic state of cremated bones submitted to AMS radiocarbon dating.

Nuclear Instruments and Methods in Physics Research B 294, 221–225.

Schmidt C. W. and Symes S. A. (eds.) 2015. *The analysis of burned human remains. Second Edition*: Elsevier.

Slovak N. M. and Paytan A. 2012. Applications of Sr Isotopes in Archaeology. In M. Baskaran (ed.), *Handbook of Environmental Isotope Geochemistry. Advances in Isotope Geochemistry*. Berlin, Heidelberg: Springer, 743–768.

Snoeck Ch. 2014. *A Burning Question: Structural and Isotopic Studies of Cremated Bone in Archaeological Contexts.*Unpublished PhD thesis: University of Oxford.

Snoeck Ch., Lee-Thorp J. A. and Schulting R. J. 2014a. From bone to ash: Compositional and structural changes in burned modern and archaeological bone. *Palaeogeography, Palaeoclimatology, Palaeoecology* 416, 55–68.

Snoeck Ch., Brock F. and Schulting R. J. 2014b. Carbon exchanges between bone apatite and fuels during cremation: impact on radiocarbon dates. *Radiocarbon* 56(2), 591–602.

Snoeck Ch., Lee-Thorp J. A., Schulting R., de Jong J., Debouge W. and Mattielli N. 2015. Calcined bone provides a reliable substrate for strontium isotope ratios as shown by an enrichment experiment. *Rapid Communication in Mass Spectrometry* 29(1), 107–114.

Snoeck Ch., Schulting R. J., Lee-Thorp J. A., Lebon M. and Zazzo A. 2016a. Impact of heating conditions on the carbon and oxygen isotope composition of calcined bone. *Journal of Archaeological Science* 65, 32–43.

Snoeck Ch., Pouncett J., Ramsey G., Meighan I. G., Mattielli N., Goderis S., Lee-Thorp J. A. and Schulting R. J. 2016b. Mobility during the Neolithic and Bronze Age in Northern Ireland explored using strontium isotope analysis of cremated human bone. *American Journal of Physical Anthropology* 160(3), 397–413.

Snoeck Ch., Pouncett J., Claeys P., Goderis S., Mattielli N., Parker Pearson M., Willis Ch., Zazzo A., Lee-Thorp J. and Schulting R. 2018. Strontium isotope analysis on cremated human remains from Stonehenge support links with west Wales. *Scientific Reports* 8: *10790*.

Stiner M., Kuhn S., Weiner S. and Bar-Yosef O. 1995. Differential burning, recrystallization and fragmentation of archaeological bone. *Journal of Archaeological Science* 22, 223–237.

Szczepanek A., Belka Z., Jarosz P., Pospieszny Ł., Dopieralska J., Frei K., Rauba-Bukowska A., Werens K., Górski J., Hozer M., Mazurek M. and Włodarczak P. 2018. Understanding Final Neolithic communities in southeastern Poland: New insights on diet and mobility from isotopic data. *PLoS ONE* 13(12): *e0207748*.

Szostek K., Mądrzyk K. and Cienkosz-Stepańczak B. 2015. Strontium isotopes as an indicator of human migra-

tion – easy questions, difficult answers. *Anthropological Review* 78(2), 133–156.

Thomspon T. J., Islam M. and Bonniere M. 2013. A new statistical approach for determining the crystallinity of heat-altered bone mineral from FTIR spectra. *Journal of Archaeological Science* 40(1), 416–422.

Thompson T. 2015a. Fire and the body: Fire and the people. In T. Thomspon (ed.), *The Archaeology of Cremation. Burned human remains in funerary studies*. Oxford, Philadelphia: Oxbow Books, 1–17.

Thompson T. 2015b. The analysis of heat-induced crystallinity change in bone. In C. W. Schmidt and S. A. Symes (eds.), *The analysis of burned human remains. Second Edition*. Oxford: Elsevier, 323–337.

Ubelaker D. H. 2009. The forensic evaluation of burned skeletal remains: a synthesis. *Forensic Science International* 183, 1–5.

Ubelaker D. 2015. Case applications of recent research on thermal effects on the skeleton. In T. Thompson (ed.), *The Archaeology of Cremation*. Oxford, Philadelphia: Oxbow Books, 213–226.

Van Strydonck M., Boudin M., Hoefkens M. and De Mulder G. 2005. ^{14}C-dating of cremated bones, why does it work? *Lunula* 13, 3–10.

Van Strydonck M., Boudin M. and De Mulder G. 2009. [14]C dating of cremated bone: the issue of sample contamination. *Radiocarbon* 51(2), 553–568.

Van Strydonck M., Boudin M. and De Mulder G. 2010. The carbon origin of structural carbonate in bone apatite of cremated bones. *Radiocarbon* 52(2), 578–586.

Wadyl S. (ed.) 2019. *Ciepłe. Elitarna nekropola wczesnośredniowieczna na Pomorzu Wschodnim*. Gdańsk: Muzeum Archeologiczne w Gdańsku.

Williams H. 2015. Towards an Archaeology of Cremation. In C. W. Schmidt and S. A. Symes (eds.), *The analysis of burned human remains. Second Edition*. Oxford: Elsevier, 259–295.

Wopenka B. and Pasteris J. D. 2005. A mineralogical perspective on the apatite in bone. *Materials Science and Engineering:* C 25(2), 131–143.

Zazzo A., Saliège J. F., Person A. and Boucher H. 2009. Radiocarbon dating of calcined bones: where does the carbon come from? *Radiocarbon* 51(2), 601–611.

Zazzo A., Saliège J. F., Lebon M., Lepetz S. and Moreau C. 2012. Radiocarbon dating of calcined bones: insights from combustion experiments under natural conditions. *Radiocarbon* 54 (3-4), 855–866.