ARCHAEOLOGICAL FUTURES

Research

A stable relationship: isotopes and bioarchaeology are in it for the long haul

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Elemental beginnings

Given their ubiquity in dietary reconstruction, it is fitting that the story of isotopes began with a conversation over dinner. Although coined in scientific literature by Frederick Soddy (1913), the word 'isotope' was first conceived by Margaret Todd, a medical doctor (also known as the novelist 'Graham Travers', and an all-round gender-stereotype-smasher of their age). In 1912, Soddy and Todd were attending a supper in Glasgow. When talk turned to work, Soddy described the then nameless concept of elements of different masses that occupy the same place in the periodic table. Todd suggested the term 'isotope', from the Greek *isos* ('same') + *topos* ('place'), and the name stuck (Nicol 1957; Nagel 1982).

Two decades after Soddy's death, the first stable isotope studies in archaeology were published. Emerging from advances in radiocarbon dating, plant sciences and ecosystem research (e.g. DeNiro & Epstein 1978a; Vogel 1978), initial applications focused on the uptake of maize agriculture in North America, with prehistoric human bones serving as 'markers' for maize consumption (Vogel & van der Merwe 1977; van der Merwe & Vogel 1978). These seminal studies demonstrated the ground-breaking potential of this new technique in estimating past dietary patterns.

The use of nitrogen isotopes in exploring trophic level relationships in terrestrial and marine ecosystems followed soon after (DeNiro & Epstein 1981; Minagawa & Wada 1984; Schoeninger & DeNiro 1984), and archaeological investigations of marine resource exploitation using carbon and nitrogen isotope data were published (e.g. Schoeninger *et al.* 1983). Research on oxygen isotope ratios of meteoric water (Craig 1961; Dansgaard 1964) allowed relationships between drinking water, body water and mammalian mineralised tissues to be investigated as a means of reconstructing climate (Longinelli 1984; Luz *et al.* 1984). In 1985, the first study relating skeletal strontium isotope ratios to geologically sourced strontium to establish lifetime mobility in archaeological individuals was published (Ericson 1985).

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ANTIQUITY 91 358 (2017): 853–864 doi:10.15184/aqy.2017.98

Fractionating into a field

Research into the relationship between isotopic inputs and bodily isotope values has been central to the development of isotope bioarchaeology. This has involved probing the complexities of environmental, physiological and metabolic variation in modern plants and animals (e.g. Ambrose 1991; Kohn 1996; Burton *et al.* 1999; Heaton 1999). Controlled feeding experiments provided vital perspectives on the systematics, caveats and capabilities of isotopic approaches (e.g. DeNiro & Epstein 1978b; Tieszen *et al.* 1983; Ambrose & Norr 1993; Ambrose 2000; Howland *et al.* 2003; Sponheimer *et al.* 2003). Of equal importance were studies of the ways isotope ratios can be altered after burial (e.g. DeNiro 1985; Nelson *et al.* 1986; Tuross *et al.* 1988; Hedges *et al.* 1995; Collins *et al.* 2002).

Quality criteria for bone collagen have increased confidence in the data produced (Ambrose 1990; van Klinken 1999; Nehlich & Richards 2009). While similar easily applicable criteria are not available for the assessment of biomineral isotope data, there are emerging consensuses: e.g. that tooth enamel best preserves *in vivo* signatures, and that preparation protocols can alter isotope measurements substantially, particularly in bone (e.g. Koch *et al.* 1997; Hoppe *et al.* 2003; Grimes & Pellegrini 2013).

By highlighting the caveats and limitations of isotope approaches in bioarchaeology, these studies have together led to greater certainty that isotope measurements determined from archaeological remains are representative of *in vivo* values and have widened their applications. With the parallel developments in mass spectrometry (and its increased cost-effectiveness and availability), the 1990s and 2000s saw a huge increase in the output of isotopic data for archaeological case studies (Makarewicz & Sealy 2015: 147).

With the non-specialist in mind, this commentary aims to provide a discursive overview of the history of isotope bioarchaeology, explore some highlights and challenges, and speculate a little on the position of isotope analysis in bioarchaeology now and into the future. Given the burgeoning size of the field, and in light of the author's own experiences, case studies explored here are largely focused on (relatively) recent time periods, and on Western Europe, although themes are hopefully universal. With a view to brevity, the reader, and the confines of word count, a limited number of references are given in the main text, and a more extensive (but not exhaustive) list of recommended further reading is provided as online supplementary material for some of the topics explored here. In the companion bibliography I also refer the reader to excellent specialist reviews for detailed information on the background, theory and methods, current status and future directions of isotope bioarchaeology.

Major contributions

Stable isotope approaches have made central contributions to several archaeological debates, and have opened new lines of enquiry. For example, isotope evidence for the diets and movements of our earliest ancestors has had profound implications for our understanding of human ecology and evolution (Lee-Thorp *et al.* 2010; Copeland *et al.* 2011; Schoeninger 2014).

Isotope analysis has also proved to be a valuable tool for investigating major archaeological transitions, such as the shift from Mesolithic hunter-gatherer-fisher communities to Neolithic farmers. Initial bone collagen studies suggested the abandonment of marine foods at the onset of the British Neolithic (Richards *et al.* 2003). This sparked debate, as researchers sought to reconcile isotope data with other evidence (Milner *et al.* 2004; Richards & Schulting 2006). Dental micro-sampling approaches have somewhat resolved this, confirming not only the dietary *predominance* of terrestrial foods, but also the intermittent, regional consumption of marine resources (Montgomery *et al.* 2013). Beyond the issue of fish, the first studies were significant in contributing to a rethinking of the *mode* of change during the Mesolithic to Neolithic transition in Britain, prompting new analyses that now overwhelmingly support an 'abruptist' model (Rowley-Conwy 2011). Isotope approaches have, however, demonstrated that the dynamics of 'Neolithisation' were non-homogeneous world-wide. Strontium and oxygen isotopes, for example, indicate a more prolonged transition in Thailand, with changes in residency patterns as matrilocality gained predominance alongside agriculture (Bentley *et al.* 2005). In contrast, analyses in Central Europe have concluded that patrilocality very likely prevailed (Haak *et al.* 2008; Bentley 2013).

These studies illustrate perhaps the most valuable contribution that isotope bioarchaeology makes to archaeology: the illumination of past intra-society variation. By providing evidence for individual life-histories, isotope studies reveal differences between individuals and within societies, such as dietary variation by age group (Pearson *et al.* 2015) or faith (Alexander *et al.* 2015). Multi-isotope approaches are particularly effective for characterising inter-personal variations linked to socio-cultural identities (Knudson & Stojanowski 2008); for example, the combination of isotope analyses used to identify fish consumption among the high-status immigrant Bishops of Whithorn (Müldner *et al.* 2009).

Expanding the spectrum

Isotope bioarchaeology is not confined to human mobility and diet; other aspects of nutrition, malnutrition and similar physiological conditions have been investigated. Isotope datasets evidencing the age at onset and subsequent completion of weaning (evidenced by a drop in trophic level; Fogel *et al.* 1989) have been published from British sites across multiple periods, from the Iron Age to the eighteenth/nineteenth centuries AD (e.g. Jay *et al.* 2008; Nitsch *et al.* 2011). Despite being from geographically and socially disparate populations, the volume of isotope data allows broad trends to emerge. Within a diachronic framework, the implications of the post-medieval reduction in breastfeeding duration in Britain highlight the potential relationship between breastfeeding, population increase and urbanism (Haydock *et al.* 2013).

Isotope studies of infant feeding practices are significant in that they illuminate an aspect of the past that is otherwise 'invisible', and create a narrative built around the experiences of women and children. These studies also mark an emerging area of bioarchaeology to which isotopes will contribute heavily in the future; namely, the interaction between socio-cultural change and diet, mobility and other life-history events. Culture-mediated biological

https://doi.org/10.15184/aqy.2017.98 Published online by Cambridge University Press

and ecological change in humans has become highly topical in bioarchaeology in recent years. For example, research on the evolution of the human microbiome (Warinner *et al.* 2015) can be viewed as a response to the shift in archaeological theoretical frameworks to include those from evolutionary ecology, such as gene-culture co-evolution and niche construction theory (Laland & O'Brien 2010; Laland *et al.* 2010; Makarewicz 2016: 200). Urbanism and industrialisation are likely to be focal points of future bioarchaeological research within these new frameworks. The near unique potential of isotope analyses to access the cultural, biological and environmental (White & Longstaffe 2016), and to broaden our understanding of past activities and culturally mediated ecological changes, places these approaches at the centre of future bioarchaeological research.

If isotope bioarchaeology is to rise to these and other challenges, new or refined analytical approaches must be a priority. While bulk bone collagen studies are the current mainstay of palaeodietary reconstruction, carbon isotope analysis of single amino acids can provide more nuanced insights into protein sources, particularly in complex foodwebs (Fogel & Tuross 2003; Corr *et al.* 2005; McCullagh *et al.* 2005; Webb *et al.* 2015). Single amino acid nitrogen isotope analysis, along with the compound-specific carbon isotope analysis of lipids and bone mineral, also have the potential to provide more nuanced insights into diet (Jim *et al.* 2004; Styring *et al.* 2010; Colonese *et al.* 2015). 'Non-traditional' elements, such as calcium (Reynard *et al.* 2013) and zinc (Jaouen *et al.* 2016), will prove increasingly useful in palaeodietary studies, particularly where organics are not preserved (Jaouen & Pons 2016). Underused since initial research, lead isotope applications will also become more widely used, corroborating strontium isotope evidence for human and animal mobility (e.g. Shaw *et al.* 2016). Other isotopes, such as neodymium (Tütken *et al.* 2011), may also prove to be useful provenance proxies. Finally, recent advances in micro-sampling approaches to human dentition (Beaumont & Montgomery 2015; Willmes *et al.* 2016) will make their application more routine, thereby enhancing temporal resolution in isotope studies by providing time-series dietary or mobility data for archaeological individuals.

Compound-specific approaches and new sampling strategies will help in taking stable isotope analyses 'beyond diet', and will aid in the identification of nutritional stress and disease (Reitsema 2013). Similarly, as our understanding of the impact of culinary preparation on the isotope ratios of food and drink improves, other applications will arise. Boiling and fermentation, for example, can alter the oxygen isotope values of drinking water and therefore potentially alter human tissues when consumed (Brettell *et al.* 2012). While this poses problems for mobility studies, it could throw light on past drinking habits (Lamb *et al.* 2014). If experimental studies can improve our understanding of the isotope systematics of post-procurement foodways, then the use of established or 'non-traditional' isotope approaches in investigating cooking, or other preparation/culinary practices, may move to the fore.

Four legs good

Isotope zooarchaeology has recently proved valuable in disentangling complex aspects of human-animal subsistence, and economic and socio-cultural relationships (Makarewicz 2016). Often using intra-tooth sampling (which provides time-series isotope records;

https://doi.org/10.15184/aqy.2017.98 Published online by Cambridge University Press

Balasse 2003; Zazzo *et al.* 2006), aspects of animal husbandry such as foddering and birth seasonality have been investigated, illuminating the experiences of animals and the decisions of herders (Balasse *et al.* 2006; Towers *et al.* 2014). Strontium isotope studies on archaeological fauna have explored aspects of past human lifeways such as trade and transhumance (Bentley & Knipper 2005; Thornton 2011). The need to provide food for omnivorous domesticates brings additional considerations to human foodways, and isotope studies have explored these in a range of contexts (e.g. McManus-Fry *et al.* 2016).

Remains of wild animals from Pleistocene sites have also been analysed to explore ancient foodwebs and environmental change (Bocherens 2003; Richards & Hedges 2003; Stevens *et al.* 2008; Feranec *et al.* 2010). While this kind of isotope palaeoecology is well-established, its potential for archaeological studies is only now being realised. Archaeological faunal remains are significant in that they are often the product of human activity, and can provide insights into that activity. Herbivore intra-tooth oxygen isotope data can, for example, provide evidence of seasonal temperature variations and, when applied to anthropogenically derived assemblages, generate terrestrial palaeoclimate proxy data near-synchronous to human site-use (e.g. Bernard *et al.* 2009). Strontium isotope evidence for migratory behaviours of important prey species, such as reindeer, can provide useful insights into human behaviours and decisions, such as landscape-use and hunting strategies (Britton *et al.* 2011; Price *et al.* 2017).

Connected lines of enquiry in isotope ecology and archaeology are now set to emerge; for example, in investigating the relationship between past climatic change, faunal migrations and human societies. Cross-disciplinary research projects will require specialists from both fields, and the combination of methodological and theoretical frameworks. Site-formation processes, and site-specific physical and chemical taphonomy, must all be understood in order to assess the potential and limitations of any particular assemblage or research question. New approaches to sampling must be sought, since the large sample sizes and controls typical in isotope ecology are difficult for archaeological materials to meet. To utilise isotope evidence for climatic change or faunal mobility (and through this, human behaviours and experiences), novel methods of analysing isotope data are also required. Among these, GIS tools and computational models that are commonly used in spatial ecology could allow landscape-level approaches to isotope data. This could take intra-tooth strontium data beyond the identification of migratory or non-migratory individuals, to the modelling of seasonal movements across 'iscoscapes'. First, however, it will be essential to develop these tools within a proof-of-concept framework using modern materials.

An unnatural abundance

A growing strength of isotope bioarchaeology is the sheer quantity of data generated from 'routine' applications. The publication of full isotope datasets, along with %C, %N, C:N or strontium concentration data, is increasingly common and ensures that other scientists can properly access the data. Although practices in data reporting still require improvement (Szpak *et al.* 2017), it is now possible to conduct original research using datasets combined from previously published studies. Such syntheses reveal diachronic and population-level trends, and allow enhanced critique of the capabilities of the techniques to, for example, identify immigrants from oxygen isotopes (Lightfoot & O'Connell 2016). New methods of analysing large datasets, such as Bayesian mixing models or GIS tools, will prove increasingly valuable (e.g. Fernandes *et al.* 2014; Willmes *et al.* 2014).

User-contributed datasets, such as 'GenBank' for DNA, present a promising new method of collating large quantities of bioarchaeological isotope data ready to be 'excavated' later. A recent call for a similar 'IsoBank' from the ecological community (Pauli *et al.* 2015) was met with enthusiasm from isotope archaeologists (Pilaar Birch & Graham 2015). The framework, management and costs of such a database, among other issues, still need to be addressed by the broader community (Pauli *et al.* 2015). Once these hurdles are overcome, however, 'IsoBank' will represent not only a sound curatorial move for a field with burgeoning data, but (and more significantly) will yield fantastic new opportunities to generate new knowledge.

Concluding thoughts and moving forward

In the era of 'big data', isotope analyses provide a valuable, accessible and relatively inexpensive means of exploring past human lifeways and experiences. From population-level insights to individual 'biographies' (Eriksson & Lidén 2013), isotopic studies help to answer archaeological enquiries at a range of scales. Isotope data allow the experiences of individual people, and intra-societal differences, to be traced. Applied *en masse* and in the context of societal or cultural transitions, isotope data can illuminate the modes and temporalities of change, and its consequences.

As archaeological research begins to focus on the relationship between human life-histories, physiology and socio-cultural change, isotope approaches are well positioned to drive these emerging research directions. They are a tool for accessing the past by encompassing both the cultural and the ecological (Bogaard & Outram 2013). Methodological and analytical developments must continue, however, for more nuanced interpretations to become possible, and to distinguish between dietary, physiological or other influences. Multi-isotope approaches, compound-specific analyses, and intra-tissue/multi-tissue comparisons must become more routine. A better understanding of how culinary preparation or other culturally mediated behaviours can influence isotope values in food or water is also required. Fundamental experimental investigations and proof-of-concept research must continue *alongside* archaeological applications for both the adoption of new analytical approaches and the more confident (and creative) use of existing ones (Pollard 2011). It is essential that funders and grant reviewers recognise these priorities.

Another priority must be the continued integration of isotopic datasets into broader archaeological frameworks. This should embrace the complementarity of diverse lines of enquiry, while exploiting the contradictions of parallel datasets, to explore new research directions. For example, isotopic records of human diets could be contrasted with excavated evidence of food remains to raise questions about cultural construction of space, waste and diet. Isotope studies do not, and should not, exist in isolation, but should be components of well-integrated studies using diverse theoretical and methodological approaches; for example, in the combination of isotope and genetic data for studying Romano-British 'origins' (Martiniano *et al.* 2016). The integration of isotope data with other lines of

https://doi.org/10.15184/aqy.2017.98 Published online by Cambridge University Press

evidence is key. Archaeologists can contribute to this by integrating broad datasets from a range of specialisms (including isotopes) in their research designs, with all data properly collected, analysed and contextualised.

Isotope zooarchaeology will continue to grow as a sub-field, facilitating the understanding of past human societies and natural environments. This is illustrative of the continued growth of inter-disciplinary research in academia, and isotope archaeologists are now actively contributing to other fields. To meet the challenge of emerging fields (such as faunal spatial palaeoecology), cross-disciplinary methodologies and epistemologies will need to be reconciled. Issues of research design and sample size are sources of discrepancy, as are the methods of analysing, visualising and interacting with data and the theoretical frameworks used to interpret it. To move forward, an understanding of the archaeological record, taphonomy and diagenesis will need to be combined with ecologically derived theoretical and practical approaches.

Perhaps the most immediate concern for the discipline and its future, however, lies with the availability and usability of datasets. The creation of a universal isotope data repository will not only allay curatorial concerns, but will lead to new directions in research. The harnessing of large datasets is likely to stimulate entirely new lines of enquiry into temporal, spatial and cultural variation. As recently voiced in ecological literature, and echoed in the archaeological community, 'IsoBank' would be a very welcome addition. Forty years on from the first published applications, we can be confident that bioarchaeology and isotopes are in it for the long haul, so perhaps it is time to start saving.

Supplementary material

To view supplementary material for this article, please visit http://doi.org/10.15184/aqy.2017.98

Acknowledgements

I am grateful for the invitation to contribute this piece and for comments on earlier versions, especially from two anonymous reviewers. Thanks are also due to Gundula Müldner, Mike Richards, Michelle Alexander, Jennifer Jones, Joshua Wright and Orsolya Czére. Finally, I should like to acknowledge the isotope archaeology community in the UK and elsewhere, who make for lively conferences and an exciting and inclusive field.

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