



Silver Linings at the Dawn of a “Golden Age”

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Nearly four decades after the first applications of strontium isotope analyses in archaeology and paleoecology research, it could be said that we are entering a “Golden Age”. Here, we reflect on major past developments and current strengths in strontium isotope research, as well as speculate on future directions. We review (1) the currently limited number of (but much needed) controlled feeding experiments, (2) recent advances in isoscape mapping and spatial assignment, and (3) the strength of multi-proxy approaches (including both the integration of strontium isotopes with other isotope systems and complementary techniques such as ancient DNA analyses). We also explore the integration of strontium isotope research with other types of paleoecological or archaeology data, as well as with evidence and interpretative frameworks from other fields (such as conservation ecology, conservation paleobiology or history). This blending is critical as we seek to advance the field beyond simply distinguishing local or relatively sedentary individuals from those that were non-local or highly mobile. We finish with a call for future research centered on balancing methodological developments and novel applications with critical self-reflection, deeper theoretical considerations and cross-disciplinarity.

Keywords: mobility, provenance, migrations, landscape use, ⁸⁷Sr/⁸⁶Sr

INTRODUCTION

Almost 40 years have passed since the earliest uses of strontium isotopes (⁸⁷Sr/⁸⁶Sr) for evaluating provenance and mobility in paleoanthropology (Sillen and Kavanagh, 1982; Ericson, 1985). Today, strontium isotope investigations are increasingly common in studies of past human mobility and in applications to zooarchaeological remains. Analyses of other biogenic materials (such as wood, keratin and shell) are now also on the rise in archaeology. These trends are mirrored in the field of paleoecology. From large-scale studies of population movement histories of different species, to tracking the individual life-histories of single animals, strontium isotope research is proving a valuable means of reconstructing the spatial behaviors of humans and other species, as well as the geographical tracking of cultural objects in the past (see recent reviews in Crowley et al., 2017; Bataille et al., 2020; Britton, 2020). In archaeology in particular, the study of movement beyond the “fact of mobility” (Aldred, 2021: preface) is also vital to shaping our understanding of the past,

illuminating relationships between people and place, moving bodies, and material culture (Aldred, 2021). In the past, as in contemporary society, place is potent.

HISTORY OF RESEARCH AND CURRENT STATUS

As with other “new” tools for studying ancient remains, strontium isotope research saw a blossoming of early applications built on fundamental research, later to be tempered with more sobering explorations of the complexities and pitfalls of sample selection, data generation, environmental variability, diagenetic influences, and data treatment and analysis. For example, early archaeological research commonly utilized bone (Ericson, 1985; Price et al., 1994), but tooth enamel is now far more commonly (but not always) the favored analyte in studies of past human or faunal movement due to the issue of diagenesis—the consequence of more than 30 years of experimental research and lively debate (e.g., Nelson et al., 1986; Price et al., 1992; Budd et al., 2000; Montgomery, 2002; Hoppe et al., 2003). Despite these attentions, strontium isotope analysis has been relatively underutilized in both archaeology and paleoecology (as well as ecology) compared to other isotope systems (e.g., carbon, nitrogen, oxygen, hydrogen). This has largely been due to analytical costs and the need for robust empirical reference datasets. However, recent technical advances have lowered costs, accelerated sample throughput, and minimized destructive sampling. Other advances, such as predictively modeled spatially explicit isotope maps (isoscapes), are also contributing to rapidly moving the field forward. These improvements, coupled with a growing awareness of sampling issues, diagenesis and other limitations, are allowing for more widespread and nuanced application of strontium isotope analysis in archaeological and paleoecological enquiries. After nearly four decades of investigation, experimentation and application in archaeology, and more recently in paleoecology, strontium isotope research can perhaps finally be said to be entering a golden age.

UNDERSTANDING *IN VIVO* “INPUTS” AND TISSUE “OUTPUTS”

As demonstrated in the various works in this research topic, and by many recent papers in the field, there are developing trends and recent directions in strontium isotope research in archaeology and paleoecology. There is an emerging emphasis on experimental work, which has been missing from strontium isotope research for some time. For example, the recent publication of controlled feeding studies (Lewis et al., 2017; Anders et al., 2019; Weber et al., 2020, this research topic), provides important datasets on intra-group variability and the influences of factors such as dietary composition and nutritional content, drinking water, and dust on mammalian mineralized tissues from controlled settings. While other isotope systems, such as carbon and nitrogen, benefited from controlled feeding investigations as early as the 1970s (e.g., DeNiro and Epstein,

1978, 1981), such studies are only a very recent addition to strontium isotope research. These studies are, however, very welcome as they urge us to consider further caveats in archaeological and paleoecological applications, and also, conversely, can permit more confidence in data interpretations. On a related note, while the issue of diagenesis received some early attention (e.g., Nelson et al., 1986; Price et al., 1992; Budd et al., 2000; Montgomery, 2002; Hoppe et al., 2003), there has been relatively little interest in this topic for the past two decades. One exception is experimental research on calcined (burnt) bone (e.g., Snoeck et al., 2015), which is significant in that it permits mobility studies on cremated human remains, such as those from Stonehenge (Snoeck et al., 2018). Experiments on dental tissues using chemical tracers (combined with multi-element mapping) also mark an important methodological advance in understanding and quantifying diagenetic stability and change (Weber et al., 2021). Specimen alteration continues to be relevant to both archaeology and paleoecology, and additional research into how strontium isotope signatures in living tissues may be modified (or preserved) after death and in the burial environment is needed, especially as we seek to extend applications further into deep-time (e.g., Wallace et al., 2019; Terrill et al., 2020). These methodological considerations concerning the vital links between behavior in life, the isotope chemistry of tissues *in vivo*, and that of tissues recovered long after death are vital as we all seek to better understand and apply these approaches with confidence.

RECENT ADVANCES IN ISOSCAPE MAPPING AND SPATIAL ASSIGNMENT

One rapidly growing area of strontium isotope research, especially over the last 5 years, has been the advancement and use of computational approaches both to develop and refine strontium isoscapes (e.g., Bataille et al., 2018, 2020; Funck et al., 2021; Holt et al., 2021). The methodological considerations of isoscape mapping, especially in terms of appropriate data and sample selection, have been the subject of a number of recent papers. Spatial assignment tools targeted at identifying the origins of archaeological people, animals, and goods (e.g., the Biosphere Isotope Domains tool for the United Kingdom, see Evans et al., 2018) highlight the ways in which isoscape mapping is intersecting with the desire for empirical and probabilistic assignments of geographical origin in archaeological case studies. However, significant challenges remain in relating tissues values to (predicted) landscape variability in order to infer movements. In many deep-time paleontological applications, for example, establishing high-resolution isoscapes of contemporary strontium isotope ratios may be deeply challenging due to subsequent erosion, changes in sea-level and patterns of atmospheric strontium deposition, and even mountain building and other changes in strontium sources. Yet, even in such cases, assuming diagenetic alteration is controlled for, variability in strontium isotope ratios may still provide meaningful insight into seasonal movement histories, niche differentiation, and other aspects of paleoecology (e.g., Wallace et al., 2019; Terrill et al., 2020).

Moving forward, it is also clear that strontium isotope research is critically lacking controlled studies that link isoscapes with empirical isotope data to reconstruct individual movements. Although unsuccessful for strontium isotopes, Hu et al. (2020) provide an example in this special issue of such a “controlled movement” study. There is a serious need for designing such controlled movement studies linking isoscapes and isotope values from an individual with known travel history. These records of movement from free ranging organisms could come from the application of GPS, radio collars, satellite tracking, and drones which are also rapidly advancing technologies. For example, expected $^{87}\text{Sr}/^{86}\text{Sr}$ of GPS-collared animals could be reconstructed and compared to isotope profiles recorded in the same individuals’ teeth, tusks, antlers, or possibly hair (e.g., Lazzerini et al., 2021). Integration of these approaches with movement models, such as those borrowed from spatial ecology, is perhaps the next natural step in reconstructing the movement of people and animals in the past (e.g., see discussion in Britton, 2017, and the PleistoHERD project webpage¹).

IMPORTANCE OF MULTI-PROXY APPROACHES

Integrating strontium isotope data within multi-proxy frameworks will be another important future research direction. A logical first step would be to better combine strontium isotopes with other isotope systems. The benefit of multi-isotope research is not new, but researchers are only beginning to combine multiple isotopes in isoscape mapping and spatial assignments (see Bataille et al., 2021 for an example and discussion). Depending on what underpins spatial variability in other isotope systems (e.g., geology, anthropogenic emissions, and coastal proximity for sulfur, or climate and topography for oxygen or hydrogen), multi-isotope approaches can reinforce (or alternatively, challenge) inferences made from strontium isotopes alone (e.g., Leach et al., 2009; Crowley et al., in press; Czère et al., in press; Neil et al., 2020; Colleter et al., 2021; Funck et al., 2021; Reich et al., 2021; Wooller et al., 2021). Trace element studies, such as those using lead, can also provide more nuanced insights (e.g., Shaw et al., 2016; Moore et al., 2020; Walser et al., 2020). Ultimately, with analytical advances in “non-traditional” isotopes (e.g., zinc, copper) and the development of new isotope tools, multi-isotope studies will become increasingly common and powerful (Jaouen and Pons, 2017).

An additional key step in both archaeology and paleoecology will be the continued integration of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis with other cross-disciplinary tools. For example, strontium isotope studies focused on human or animal remains will greatly benefit from further integration with ancient DNA (aDNA) analysis. In paleoecology, aDNA often provides a “broad brush” biogeographic context that can form the basis for testable hypotheses of faunal and human movement using

strontium isotopes (e.g., Funck et al., 2020; Vershinina et al., 2021). Genetic data can also provide important information about individual samples, such as sex, which may be highly relevant to movement studies (e.g., Wooller et al., 2021). In archaeology, isotope and aDNA analyses can be combined to approach ancestry in a more holistic sense, particularly when material cultural, funereal, or other archaeological evidence is taken into account. Of course, strontium isotope and aDNA analyses provide evidence of movement histories on very different scales. However, integrated approaches provide the best opportunities to explore the life histories of individuals or groups of individuals beyond simply reconstructing patterns of movement, landscape use, or geographical location of an individual during childhood and allow us to infer “origin” on multiple levels. Significantly, such studies also lead us to question preconceived notions of whom might be considered “non-local” on the basis of either geographical provenance or biogeographical ancestry in the past, and to examine our own biases. The recent isotopic, genetic and forensic evidence for ethnic diversity in both Roman and Tudor Britain (Leach et al., 2009, 2015; Martiniano et al., 2016; Scorrer et al., 2021), and the negative reception of these findings by some (largely anti-immigration) factions of the British media and public, highlights the value of such studies in illuminating past societies, and also the part such research can play in helping to dispel dangerous myths of racial or cultural homogeneity in past populations. The field must, however, also acknowledge, anticipate, and challenge narratives that attempt to draw on isotopic studies that may show a lack of past population mobility, for example, to support nationalist agendas, as recently called for with ancient DNA studies (e.g., Hakenbeck, 2019).

TOWARD AN INTEGRATED, CROSS-DISCIPLINARY FUTURE

Strontium isotope studies in archaeology and paleoecology not only benefit from fuller integration with other techniques, but also with other disciplines. For example, historically-focused research is one area to which ecologists, historians, archaeologists and isotope scientists can all contribute. Themes in historical archaeology, such as agricultural intensification, urbanism, and industrialization, are just now beginning to receive attention by isotope bioarchaeologists as researchers seek to better understand changes in animal and human diet that characterized these major transitions (see discussion in Britton and Guiry, 2020). Not only are strontium isotope studies in archaeology now increasingly focusing on historic periods, researchers are also increasingly employing truly interdisciplinary approaches (see Colleter et al., 2021 for an example). Future work in historical isotope archaeology must continue to go beyond just referring to historical sources or documents and remain on this trajectory of cross-disciplinary collaboration, where studies are co-designed, and interpretations made within frameworks meaningful for all fields involved. This should include evaluating and embracing diverse (and sometimes

¹<https://www.leverhulme.ac.uk/research-project-grants/pleistoherd-integrative-approaches-late-pleistocene-herbivore-ecology>

contradictory) evidence types, as opposed to simply pitting isotopic evidence (“hard science”) against current historical discourse (Britton and Guiry, 2020).

Although currently underused in historical and contemporary ecology, strontium isotopes are now beginning to be increasingly employed (for example, to explore the historical movements of North American caribou; Gignoux et al., 2019; Miller et al., 2021, this research topic). Against a backdrop of dramatically changing patterns of seasonal movements and migration for a variety of populations and species (Berger, 2004; Tucker et al., 2018), there is a clear need to more fully understand the ecological impacts on landscape use and movement associated with climate change, human encroachment, and other modern ecological stressors. Subfossil, archaeological, and fossil collections provide unique opportunities to fill in temporal gaps in available ecological data. These are critical resources for reconstructing animal behaviors and their variability prior to human disturbances, as well as building more holistic strategies for successfully managing populations into the future (i.e., Conservation Paleobiology: Dietl and Flessa, 2011; Behrensmeyer and Miller, 2012; Dietl et al., 2015; Barnosky et al., 2017). Such research would be further strengthened by incorporating some of the other factors mentioned above (e.g., multi-isotope approaches, DNA, ecological niche models, etc.), and other useful spatial data to refine historical movement reconstructions.

Finally, it must be noted that applications of strontium isotopes in both archaeology and paleoecology will continue to benefit from advances in other fields. For example, numerous advances have been, and are continuing to be made in the field of fisheries science, both in terms of isoscape development and technical improvements, such as laser ablation of small samples like otoliths (fish ear bones). Fish otoliths are a particularly attractive target for studying the lifetime movement patterns of anadromous and other highly mobile fish due to the high temporal resolution they preserve. Interpreting $^{87}\text{Sr}/^{86}\text{Sr}$ records preserved in otoliths has also necessitated the development of sophisticated modeling approaches to relate fish $^{87}\text{Sr}/^{86}\text{Sr}$ to the $^{87}\text{Sr}/^{86}\text{Sr}$ in their environment (e.g., Brennan et al., 2015, 2019; Brennan and Schindler, 2017). Laser ablation technology is continuing to advance and is now becoming more readily available to investigators. The same approaches can be used to analyze larger specimens, including teeth or tusks, provided potential interferences from other elements are taken into account and strontium concentrations are adequately high (Irrgeher et al., 2016; Wooller et al., 2021). Both archaeology and paleoecology will also benefit from (but also have great potential to contribute to) developments in forensic science and food source authentication, as these fields, too, seek to better understand strontium isotope systematics for geographic tracing and provenance studies (e.g., Almeida and Vasconcelos, 2001; Coelho et al., 2017; Techer et al., 2017; Bartelink and Chesson, 2019). Identifying cross-disciplinary challenges and common goals, as well as exchanging of ideas, data and best practices will maximize the value of strontium isotope analysis to researchers in a wide number of allied fields.

CONCLUDING THOUGHTS

As explored above, it can perhaps now be said that we are at the dawn of a golden age of strontium isotope research in both archaeology and paleoecology—and yet much work lays ahead. Current research is addressing significant practical and methodological concerns, alongside novel applications. Scrutiny in research design, experimental studies (*sensu stricto*) and analytical innovation must continue along with research that addresses fundamental queries for isotope research in all fields, including tissue formation processes and diagenesis. Now is perhaps also the time for revisiting some theoretical concerns, leaning on the epistemologies of fields such as ecology but also on the frameworks of humanities research. While documenting and characterizing the “fact of mobility” may be a primary goal in most archaeological and paleoecological strontium isotope research, the use of $^{87}\text{Sr}/^{86}\text{Sr}$ data—particularly in the study of past human societies—necessitates such introspection. These silver linings will increase the confidence in our data and interpretations but will also serve to influence the theoretical frameworks within which we interpret these data and may even serve to change the questions we ask of the past.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

KB and BEC planned out the manuscript. KB wrote the complete initial draft with input from BEC, CPB, JHM, and MJW who all made written contributions, comments, and edits. KB had oversight of integration of changes and edits. All authors contributed to the article and approved the submitted version.

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