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$^{87}Sr/^{86}Sr$ in Archeological and Paleobiological Research: A Perspective

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The stable isotope ratio $^{87}Sr/^{86}Sr$ has been shown to have extraordinary potential for documenting the movement and life-histories of humans and other animals, both in history and prehistory. Thirty years of expanding applications has taken the method from a niche (if not fringe) approach to a normal part of archeological and paleobiological enquiry; indeed a "Golden Age." The technique is inherently interdisciplinary, because in addition to those archeologists and paleobiologists wishing to apply it, most applications require informed input from ecologists, geochemists, and calcified tissue biologists. This perspective explores how such interdisciplinarity is both a strength and an impediment to further advancement.

Keywords: strontium isotopes, paleodiet, paleohabitat, paleoecology, life-history

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Thirty-five years ago, back in the paleolithic, archeologists and paleobiologists were just beginning to appreciate the potential of strontium isotope research for biological source-tracing, and the attendant implications for reconstructing landscape use and transhumance. A seminal article by Jonathon E. Ericson, who was then Professor of Environmental Health Science and Policy at UC Irvine, captured the attention of those few archeologists and physical anthropologists at the time who were interested in bone and fossil chemistry for any other purpose than radiocarbon dating (Ericson, 1985).

In those days, you could count on one hand the scientists whose primary interest was the past, and who were prepared to use biogeochemical phenomena to study it, and there were significant impediments for all of us. Those of us trained in Anthropology Departments already did not fit in any convenient departmental pigeon hole: we were using the material conventionally studied by physical anthropologists (skeletons) to address questions conventionally asked by archeologists (behavior): we were neither fish nor fowl.

An even bigger problem was the inherently interdisciplinary nature of isotope research in bioarcheology. Very few individuals could confidently – and competently – apply environmental chemical phenomena and methods to biological tissues that have undergone geochemical alteration, for the purpose of reconstructing ancient animal and human behavior! At the time, everyone involved in this kind of thing was undertrained in at least one aspect of what was necessary to navigate that vast terrain of diverse disciplines. And it always seemed like an amusing, albeit frustrating irony that, in drawing from the diverse disciplines of biogeochemistry, calcified tissue biology, paleobiology, and archeology, our work was thought of as "specialized."

By 1989, these issues were becoming better understood, when my colleagues at the University of Cape Town and I wrote "*Chemistry and Paleodietary Research: No More Easy Answers*" (Sillen et al., 1989). Strontium isotopes were just beginning to draw our attention and were included almost as an afterthought (the article focused on $\delta^{13}C$, $\delta^{15}N$, and Sr/Ca); and yet the conclusions were applicable to all of the techniques, and bear repeating:

> *"With few exceptions, basic research that has addressed the techniques themselves (rather than explicit applications) has consisted of manipulating the available archeological and modern faunal and floral specimens ... While necessary, this research strategy no longer suffices. Most of the stumbling blocks ... call for a more aggressively experimental approach ... Expanding the experimental basis of the research presents a formidable barrier mainly because the necessary intermediate research fits no convenient academic pigeon hole".*

The point has been taken up and re-emphasized in an important review article by Makarewicz and Sealy (2015) (see also Britton, 2017). As these authors emphasize, the need for foundational and proof-of-concept studies has become somewhat more urgent as the applications of isotopes to archeology and paleobiology (including strontium isotope analysis) have exploded. Strontium isotope analysis has been applied to ancient materials on every inhabited continent, from mammals and mollusks (Vanhaeren et al., 2004); and for just about every age from the Pleistocene (Hoppe et al., 1999; Britton et al., 2011; Copeland et al., 2011; Sillen and Balter, 2018), to changes in human and animal lifeways with the onset of agriculture (Bentley et al., 2005; Bentley, 2013), to the forced relocations of both Indonesian and African slaves (Schroeder et al., 2009; Bastos et al., 2016; Kootker et al., 2016).

For paleoanthropologists (a term I am using to include both archeologists and physical anthropologists), studies centered on isotopic techniques represented a methodological departure from approaches that depended on skeletal morphology or from indirect inference drawn from contextual contemporaneous archeological residues. For paleontologists, it represented a shift away from attempts aimed purely at characterizing or describing fossil bones (exemplified in Wyckoff's, 1972 volume The Biochemistry of Animal Fossils), and toward focused applications of chemical phenomena to archeological problems.

In the early days, those who came together from different scientific backgrounds to undertake this new type of research understandably made many mistakes and had a habit of talking right past each other. The anthropologists, always seeking new tools and anticipating an avalanche of new insight, sometimes applied new techniques somewhat indiscriminately, and there were more than a few unfortunate rabbit-holes. There were endless squabbles with geochemists who approached fossils as if they were rocks. Geochemists had a point to make about diagenesis, but rarely articulated a useful archeological question.

There were no texts or guideposts. The closest thing to a text was Wyckoff's, 1972 book, written before anybody ever contemplated looking for any kind of isotope in a fossil.

After an initial burst of enthusiasm, it was clear there was a further problem – that there was not always a good fit between the proposed technique and a paleontological or archeological problem researchers sought to address. When the questions posed by one discipline are addressed with techniques and methodologies grafted from another, there are bound to be difficulties. There are the rare instances when the information provided by an analytical technique seamlessly addresses a narrative archeological or paleontological theme – the application of $\delta^{13}C$ to early maize cultivation comes to mind (Vogel and van der Merwe, 1977) – but, but such instances are the exception rather than the rule, and the danger comes when, in the pursuit of easy answers, techniques are force-fitted onto issues to which they are really not suited. Beyond strontium isotopes, the issues and opportunities around grafting new scientific techniques onto classical archeological problems have been reviewed by Killick (2015).

The classic example in archeology was the early adoption of radiocarbon dating. When the technique was first developed in the early 1950s, there was an explosive initial period of obvious applications and easy pickings, where rough approximations of age were sufficient. Subsequently, complications in the application of radiocarbon became apparent – such as the De Vries and Suess effects, the resolution of which, while no less heroic, was somewhat less glorious. Hard, highly technical work was required, both to explore the more subtle ramifications of the new development, and also to clean-up after some of the uncritical assumptions, excess, and errors of the earlier period (Damon and Peristykh, 2000).

With very few exceptions, the background data necessary to fully explore strontium isotope analysis to archeological and fossil materials are not available from the hard sciences. The gaps are not unpredictable, however, and derive from the different priorities which set the stage for the background research in the first place. This can be illustrated with the literature on elemental strontium, which was the focus of my research in the 1980s (Sillen and Kavanagh, 1982). Until then, virtually all literature on biological strontium focused on understanding and mitigating the health consequences of atmospheric fallout (especially ^{89}Sr and ^{90}Sr) from above-ground nuclear testing.

Figure 1 is the amount of ^{90}Sr and ^{89}Sr fallout which found its way into milk marketed in New York City during the early 1960s, which became a major public health concern. **Figure 2** taken from the bibliography of that review article, shows the frequency of articles on strontium in the biochemical literature from the 1950s to the 1970s. The dotted line in both graphs depicts the summer of 1963, when John F Kennedy and Nikita Kruschev signed the above-ground nuclear test-ban treaty. **Figure 1** shows that radiogenic Sr in milk increased dramatically as both countries accelerated atomic testing in anticipation of the treaty. The short-lived isotope ^{89}Sr is highest immediately before the treaty. Research into radiogenic Sr in food webs was similarly high during this period, and after a rush to get into print, published biochemical research on Sr declined.

The graphs illustrate that strontium research, like any other research, was conducted for a reason, in this case concern over the ubiquity of a radioactive isotope in food. What emerges as a

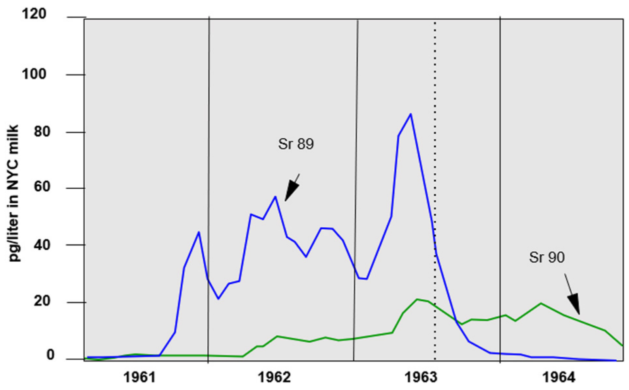

FIGURE 1 | Radioisotopes marketed in milk in New York City, 1960–1965.

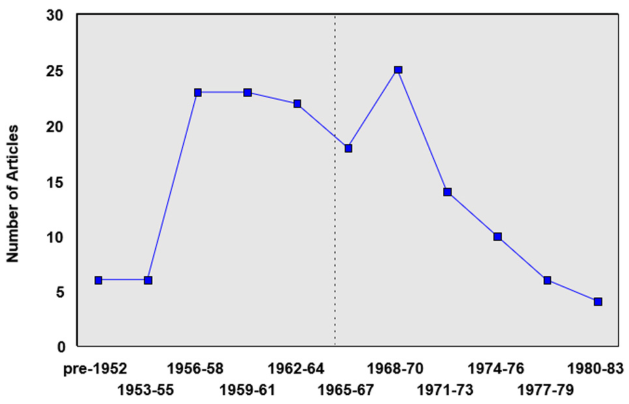

FIGURE 2 | Frequency of articles published on strontium in the biochemical literature, 1952–1983.

point of great importance is what the research was *not* aimed at: the development of dietary, mobility, and environmental markers for paleobiologists and archeologists. As a direct result, there were, at the time of the first applications of elemental strontium to archeology, significant gaps in background data necessary to apply these new methods appropriately.

To take just one example from my own experience, in the early days of $^{87}Sr/^{86}Sr$ research, well before ecologist J. B. West et al. (2010) coined the term "isoscape," a lot of people thought that all you had to do was look at a geological map to infer meaning to observed differences in $^{87}Sr/^{86}Sr$ isotopes in archeological materials. From my dissertation research on elemental strontium, I was aware that total and available soil Sr/Ca could differ enormously, so suggested an empirical approach at the Pleistocene site of Swartkrans, in the Sterkfontein Valley. The discoveries available in $^{87}Sr/^{86}Sr$ plants in this region bore little resemblance to that of whole rock substrates, and that $^{87}Sr/^{86}Sr$ varied more with hydrology (riparian vs. dry habitats) than geological maps may have been lucky accidents (Sillen et al., 1998), but illustrated rather profoundly the potential distance between existing theory and the real world which in many cases may not be serious, but in others might fatally undermine the unwary.

Over 20 years later, we may indeed think of strontium isotopic research as entering a "Golden Age" firstly because the number of actual and potential applications in archeology and paleobiology is ever increasing, but perhaps more importantly that there is a full appreciation of the basic research necessary to realize more fully the archeological and paleobiological potentials of these methods. The problem remains that by no stretch of the imagination could this basic research be considered to be archeology or paleobiology.

For my own home discipline, it is exciting to see the evolution of $^{87}Sr/^{86}Sr$ applications (along with light isotopes) from a somewhat exotic untested approach on the margins, to one fully embedded in the discipline. It is hard to imagine a single modern archeological monograph that does not include isotopic analysis as a key element of past behavioral reconstruction. Wow.

It is similarly satisfying to see a continued and growing emphasis on basic research, notably an emphasis on isoscape mapping, modeling, and *in vivo* feeding studies. It seems obvious, as well, that it has finally been established beyond any doubt that research depending on the wide diversity of knowledge outlined in the beginning of this short essay (and that featured in the field at its outset), is perhaps best conducted in interdisciplinary teams. In addition to archeologists, paleoecologists and geochemists, to fully explore the potential for elucidating life-histories (of both humans and other animals), my sense is there will need to be a far greater participation of calcified tissue biochemists and micromorphologists going forward.

To whom does the responsibility fall to provide such basic studies – mapping, modeling, feeding – and of course studies of tissue formation and diagenetic alteration? Very few scientists have both the proper training and motivation to undertake these: those with the greatest motivation are not necessarily the best qualified to do so, while those most familiar with the necessary methods have little motivation to make a contribution. As a result, it can often prove difficult to attract funding for such issues (as opposed to eye-catching applications).

Ultimately it must be those who have a stake in their application: while those outside our disciplines may have the instrumentation and essential expertise, few will have the inclination, funds – or most importantly – the sense of problem. Therefore, excursions into unfamiliar terrain will require the continued indulgence of established disciplines prepared to invest in their future, and the active participation of those best equipped to help us with the problems and questions we articulate. A powerful case exists to pursue the necessary basic research, and experience shows that well-conceived projects with the potential to materially advance eventual applications can attract funding, as they should.

This volume demonstrates that the questions addressed by strontium isotopic research are inherently cross-disciplinary, are essentially limitless, and may profoundly advance our understanding of both history and prehistory. Here, we have a special issue about strontium in which the nominally different fields of archeology and paleoecology are blurred almost to the point of fusion. From this it is apparent that the question-asking stage of strontium paleobiology has reached maturity; indeed the cusp of a golden age. The task now is to explicitly recognize that interdisciplinarity is both a strength and an impediment, and to address the impediment.

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

The author confirms being the sole contributor of this work and has approved it for publication.

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