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What is left behind: Advancing interpretation of pastoral land-use in Harappan Gujarat using herbivore dung to examine biosphere strontium isotope ($^{87}Sr/^{86}Sr$) variation

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ABSTRACT

The analysis of strontium isotopes in archaeologically preserved biological tissues is most productive when these can be compared to naturally occurring variation in strontium isotope ratios across the physical landscape. Such work is in its infancy in South Asia. Here, we report on the first attempt to monitor $^{87}Sr/^{86}Sr$ variation across the Indian state of Gujarat using herbivore dung. As it incorporates plant material from throughout an individual animal's grazing range, herbivore dung averages local isotopic variation in palatable vegetation and is therefore an ideal material for use in studies involving domestic livestock. In our analysis of 125 dung samples from 38 sampling locations across the study area, $^{87}Sr/^{86}Sr$ values and geographic variation are commensurate with expectations based on regional geology. The values that we report are significantly different from those reported for both ecosystem elements and archaeological humans and livestock that have been published for other regions of the Indus Civilization (2600–1900 BC). No individual humans or livestock in these studies appear to have their origins in Gujarat. The present study further allows for more detailed interpretations of our previously published study of strontium isotope ratios in faunal remains from the walled Indus manufacturing center of Bagasra in Gujarat (Chase et al., 2014b). Specifically, it is now clear that while most livestock show very little movement within the period of enamel formation, their places of origin were scattered throughout central Saurashtra, adjacent to the site, suggesting that a portion of the livestock consumed at Bagasra were initially raised in the many small unexcavated villages in the area. There is little evidence for the procurement of livestock from further afield within the region and none for livestock originating outside the region. These results demonstrate that monitoring geographic $^{87}Sr/^{86}Sr$ variation using herbivore dung has the potential to significantly advance archaeological interpretation of livestock mobility in the past and is applicable anywhere that modern livestock graze on natural vegetation.

1. Introduction

The analysis of strontium isotopes preserved in biological tissues has become an indispensable tool for archaeologists investigating the migration of humans and the movement of animals in the past (Bentley, 2006). This approach is most fruitful when strontium isotope ratios observed in archaeological materials are compared to naturally occurring variation in strontium isotope ratios across the physical landscape (Ericson, 1989). Such work is in its infancy in South Asia. Recent research has raised questions, however, regarding both appropriate samples and methods to capture this variation (Burton and Hahn, 2016; Grimstead et al., 2014; Hartman and Richards, 2014; Maurer et al., 2012). One recurring issue in these studies is the availability across the landscape of samples that represent the biosphere isotope variation for specific archaeological questions. Here, we report on the first attempt to monitor variation in $^{87}Sr/^{86}Sr$ in modern

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ecosystem elements across the Indian state of Gujarat. Specifically, we have undertaken what we believe to be the first attempt anywhere to do this by sampling herbivore dung. As it incorporates plant material from throughout an individual animal's grazing range, dung averages local isotopic variation, allowing for the examination of strontium isotope variation at a larger, regional scale. Following a discussion of the principles of strontium isotope analyses and the application of these techniques for reconstructing pastoral land-use practices, we discuss the geology of Gujarat and establish expectations for $^{87}Sr/^{86}Sr$ variation in this geologically diverse region. We then describe the results of our analysis of 125 samples from 38 sampling locations across the study area, comparing them to expectations grounded in regional geology. These results are discussed in relation to strontium isotope data published as part of studies of human migration in other regions of the Indus Civilization (2600–1900 BC) and especially our earlier study of strontium isotope ratios in faunal remains from the Indus settlement of Bagasra in Gujarat (Chase et al., 2014b).[1] In this study, our initial interpretations of livestock mobility were limited by a lack of knowledge regarding regional strontium isotope variation in the region. Here, we show that monitoring strontium isotope variation in livestock dung has generated significantly stronger and more refined interpretations of these data than was possible earlier, demonstrating the value of this technique and its potential to be applied in other regions of South Asia and beyond.

2. Strontium isotopes and pastoral land-use in Harappan Gujarat

Analyses of strontium isotopes preserved in biological tissues have become an indispensable tool for archaeologists to reconstruct human and animal mobility in the past (Bentley, 2006). Occurring naturally in four isotopic forms, strontium in the environment derives from strontium in bedrock, the $^{87}Sr/^{86}Sr$ ratio of which varies according to its age and composition. Variation in $^{87}Sr/^{86}Sr$ across the landscape thus primarily reflects variation in the geological foundation, although subsequent earth processes also contributes to variation in $^{87}Sr/^{86}Sr$ ratios as discussed in more detail below. As strontium behaves in a similar fashion to calcium, a portion of this strontium cycles through the food web and is incorporated into biological tissues, where they are preserved archaeologically in the bones and teeth of humans and animals. Because strontium does not appreciably fractionate as it cycles through environmental systems (Flockhart et al., 2015), the ratio $^{87}Sr/^{86}Sr$ in biological tissues reflects the $^{87}Sr/^{86}Sr$ of biologically available strontium in the environment from which an organism lived at the time that those tissues formed. Unlike bone, which is continuously reformed throughout adulthood, and, being porous, is especially subject to diagenesis, absorbing strontium from the matrix in which it was buried, mammalian tooth enamel does not continue to grow after it has formed and is exceptionally resistant to diagenesis (Trickett et al., 2003). $^{87}Sr/^{86}Sr$ isotope ratios in human and animal tooth enamel thus reflect that of the biologically available strontium in the geographic location of the individual's dietary input, and particularly, major sources of dietary calcium (Burton and Wright, 1995). When compared to the local $^{87}Sr/^{86}Sr$ value of the find location—and other locations with known $^{87}Sr/^{86}Sr$ values—analyses of strontium isotopes are a powerful tool for the identification of initial provenance and subsequent movement of humans and animals across the landscape.

Widely applied in studies of past human movement and migration (Szostek et al., 2015), analyses of Sr isotopes in faunal tissues are increasingly integrated into zooarchaeological studies to investigate a wide variety of issues related to the animal mobility (Makarewicz, 2016). Studies of strontium isotopes in the teeth of domestic animals have been particularly fruitful in reconstructing past human-animal relationships in the past (Arnold et al., 2016, 2013; Bentley and Knipper, 2005; Grimstead et al., 2014; Gron et al., 2016; Knudson et al., 2012; Minniti et al., 2013; Shaw et al., 2009; Sjögren and Price, 2013; Somerville et al., 2016; Stephan et al., 2012; Sugiyama et al., 2015; Towers et al., 2010; Viner et al., 2010). The molar teeth of ruminants, which include domestic livestock such as cattle, goats, and sheep, as well as wild animals such as reindeer are a particularly rich source of information regarding animal mobility because they form from cusp to cervix over the course of the first one to two years of life (Hillson, 2005). Analysis of multiple samples along this growth axis thus provides an intra-annual picture of isotope ratios during the period of enamel formation (Balasse, 2002; Montgomery et al., 2010; Passey and Cerling, 2002; Zazzo et al., 2006), which can be correlated with geographic areas to reconstruct movement of animals across the landscape during this time (Arnold et al., 2016, 2013; Bentley and Knipper, 2005; Pellegrini et al., 2008; Price et al., 2015; Schweissing and Grupe, 2003; Sjögren and Price, 2013; Stephan et al., 2012; Towers et al., 2010; Viner et al., 2010). As domestic livestock are managed by people, tracing the movement of animals across the landscape—or in complementary fashion, the geographic origin of fodder—provides valuable insights into past pastoral land-use practices as well as patterns of trade and exchange of livestock.

In an earlier report we applied this technique to a representative sample of mostly domestic livestock from Bagasra, a small settlement of the Indus Civilization (2600–1900 BC) located in the modern Indian state of Gujarat (Chase et al., 2014b). Although small (~2 ha), the residents of Bagasra lived within a massive walled structure and were intensely involved in the manufacture and trade of highly valued Indus craft goods (Bhan et al., 2004, 2005; Chase et al., 2014a; Sonawane et al., 2003). Undertaken as a pilot study to determine the feasibility of applying isotopic analyses for the reconstruction of pastoral land-use practices in the region, we analyzed three samples, taken sequentially from root to crown along the growth axis, from 20 cattle/buffalo and 19 goat/sheep molars. Single samples from four pig molars, which do not form sequentially as ruminants' teeth do, were also included in a first attempt to determine the local $^{87}Sr/^{86}Sr$ value of biologically available strontium at the site. In our analyses, we examined intra-annual variation within individual teeth to determine the extent to which animals underwent seasonal migrations. We also interpreted variation between individuals to assess the *relative* geographic range across which different taxa were raised. Our interpretations were hindered in their specificity, however, by lack of knowledge regarding $^{87}Sr/^{86}Sr$ variation in the region beyond the site itself. Here, we present the first results from a systematic program to monitor $^{87}Sr/^{86}Sr$ ratios in biologically available strontium across Gujarat. Below, we revisit our earlier data and interpretations considering these new findings and show that they are significantly enhanced. First, however, we develop some basic expectations for $^{87}Sr/^{86}Sr$ variation based on the geological parameters of the region.

[1] The archaeological site referred to here as Bagasra, the name of the nearest modern village, is also known as Gola Dhoro, the local name of the mound. Initially referred to in the literature as Bagasra (Sonawane et al., 2003), it has been referred to in subsequent publications as Gola Dhoro (Bhan et al., 2004, 2005; Chase, 2010). Here, we maintain convention and refer to it as Bagasra.