A Multi-Substrate Strontium Isotope Baseline for the Promontory Caves, Utah: Implications for Studies of Ancient Bison Migration

THESIS

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THESIS ABSTRACT

The purpose of this thesis is to provide a framework for evaluating bison mobility in the eastern Great Basin during the thirteenth-century using strontium (Sr) isotope analysis. The Promontory Caves, Utah (42BO1 and 42BO2) were occupied for a relatively short period (A.D.1250-1290) but have a rich record of incredibly well-preserved organic remains including a high abundance of bison remains indicating that bison were a key prey species. Previous research indicates a decline in the local bison population which may have triggered a push for ancient people to navigate the landscape to shift their home (or seasonally-used territory). One possible site that the Promontory people visited is West Fork Rock Creek (WFRC) (10-Oa-275), Idaho. There is evidence that WFRC was visited by Promontory people as they were hunting bison in the late thirteenth-century.

Sr variability is complex and values can differ between different substrates in a single area. It is important to select suitable substrates for a baseline to facilitate a strong interpretation of provenience. Because of the incredible preservation of the organic material at the Promontory Caves, they provide an exceptional opportunity to explore Sr variability among multiple substrates. This thesis employs a multi-substrate baseline analysis for the Promontory Caves to explore the variability of Sr isotope values in multiple substrates including herbivore dung which is a relatively novel substrate in Sr isotope studies. Comparison of the Promontory Sr baseline with Sr isotope values of two teeth samples recovered from WFRC provides an indication that addressing bison migration between the Promontory area and WFRC in future mobility studies is promising. The concluding baseline for Promontory provides a framework for reconstructions of bison mobility. The baseline will be used in future studies to reveal whether bison at Promontory and WFRC had overlapping ranges or whether the sites were occupied by herds with distinct ranges

THESIS INTRODUCTION

First excavated by Julian Steward in 1937, the Promontory Caves have captured the attention of archaeologists with their abundance of well-preserved items and the stories they tell. Promontory Caves 1 (42BO1) and 2 (42BO2) have incredible preservation of organic remains, including bone tools, gaming pieces, arrow shafts, basketry, cordage, and moccasins (Ives, 2020). The over 300 moccasins excavated from the Promontory Caves were interpreted by Steward (1937) as incongruous for the late thirteenth-century Great Basin, but rather are fitting with more northern Subarctic Dene styles. This suggested that Promontory people were a Dene group transitioning to a southwestern way of life, and possibly ancestors of modern southwestern Apachean groups (Ives, 2014; 2020; Ives et al., 2014; Ives and Janetski, 2022; Steward 1937).

Multiple lines of evidence, including genetic and linguistic, indicate that the initial Dene journey to the south took place 1000-1100 years ago (Ives, 2022). The push to migrate was possibly initiated by the White River Ash east lobe eruption that occurred A.D. 852-853 where a founding population of northern Athapaskans left the north and gradually journeyed to the northern Plains and beyond (Ives, 2022, Kristensen et al., 2020). This transition would have been eased by the sophistication of northern Athapaskan hunting strategies and abilities of large game such as caribou, sheep, and wood bison (Ives, 2022).

Among the organic remains at the Promontory Caves are copious quantities of bison hide, bones, and fur, demonstrating that bison were a significant resource for the Promontory people. Because some bison remains found in the caves, such as skulls and hooves, are difficult to transport, it is likely that the Promontory people hunted bison nearby (i.e., see Figure 5.13 a,e in Ives, 2022). Based on archaeological and paleontological records, Grayson (2006) concludes that the Great Basin supported a flourishing of bison populations between 1600 and 600 BP. Due to the number of bison remains in the Promontory Caves, it is suggested that bison were abundant in the area around the caves. However, the caves were abandoned after a relatively short occupation of ~40 years (A.D. 1250-1290) (based on Bayesian modeling of AMS radiocarbon dates), thus leading researchers to question the reasons for the departure of Promontory people from the caves (Ives, 2014). A possible explanation for the departure is that the bison population in the region became significantly less abundant (Lupo and Schmitt, 1997), thus causing a 'push-factor' for the Promontory people to leave the caves. Because bison were a significant resource at Promontory, understanding bison mobility will allow researchers to make inferences about the relationship between Promontory people and bison. With their knowledge of the landscape, Promontory occupants would have been well-prepared to migrate in pursuit of bison, or for other reasons (Metcalfe et al., 2021).

Bowyer and Metcalfe (2023) examined pollen from Promontory-phase bison dung and obtained carbon isotope data from Promontory-phase bison tissues to examine the paleoenvironment of Promontory and explore whether there is evidence of a severe drought that would have caused the bison to leave the region around Promontory. The analyses indicate no strong evidence for severe drought in northeastern Utah during the occupation of Promontory Caves. This is consistent with other studies in the region (southeastern Idaho: Lundeen and Brunelle, 2016 and central Utah: Fisher and Valentine, 2013) that suggest relatively wet environmental conditions during and after this occupation. It remains possible that bison left as soon as dry conditions occurred, leaving no physical evidence of drought in any of the bison remains in the caves. The decline of bison local to Promontory, or shifts in their range, may have influenced the Promontory Cave inhabitants to migrate elsewhere around this time.

The purpose of this thesis is to provide a framework for evaluating Promontory bison mobility using Sr isotope analysis. Sr isotope studies provide direct evidence of mobility. Sr isotope reconstructions are based on the principle that eroding underlying geological material makes its way into the soil and is taken up into vegetation which is then consumed by animals, where Sr replaces calcium (Ca) in the skeletal bioapatite (Bentley, 2006). Because different regions can have different geological substrates with different Sr isotope values, the Sr isotope signatures within bones can be used to identify the geographic areas in which an animal obtains its food.

Recently, the use of a Sr isotope baseline has become common in Sr mobility studies. A Sr baseline provides a range of ‘local’ Sr isotope values to be used as a reference for assigning provenience to materials or tissues of interest. To date, no Sr isotope baseline exists for this region of study. This thesis pilots the use of Sr isotope analysis in the eastern Great Basin by establishing a Sr isotope baseline for the Promontory Caves. This will aid future researchers in making interpretations about ancient bison mobility patterns, which may, in turn, provide insight into the Promontory people's hunting strategies and perhaps give insight into why the Promontory people left the caves in the late thirteenth century.

There is no single way of creating a Sr baseline because different substrates are more or less applicable to different types of studies. Because of the incredible preservation of the organic material at the Promontory Caves, they provide an exceptional opportunity to explore Sr variability among multiple substrates. One such substrate is ancient bison dung. A recent study suggested that herbivore dung is the ideal substrate for a Sr baseline, but the use of dung in Sr isotope studies has only been minimally explored and only modern dung has been analyzed (Chase et al., 2018).

This thesis is motivated by the broad goal of determining the migrational range of bison, for which a local baseline is a crucial first step. This thesis follows an integrated-article style. This style presents the main chapters of this thesis as independent articles, thus resulting in some repetition of information. This thesis is divided into two main chapters: the first chapter reviews Sr baseline methods and discusses substrate variability; the second chapter is a geochemical study of Sr isotope values from multiple substrates (archaeological terrestrial animal teeth and dung and modern plant material) to establish a 'local' Sr isotope baseline for the Promontory Caves. The second chapter aims to answer the following specific research questions: (1) Do the Sr isotope values of Utah flora and Promontory fauna differ from Sr isotope values in other parts of Utah? (2) Which substrates best represent a 'local baseline' for Promontory? (3) Is dung a useful baseline substrate for Sr isotope studies? (4) Do the Sr isotope values of West Fork Rock Creek fauna differ from Sr isotope values in other parts of Idaho? (5) Do the Sr isotope values of Promontory fauna differ from those of WFRC?

CHAPTER ONE: Review of Strontium Isotope Baselines for Provenience Studies

Introduction

Strontium (Sr) isotopic studies have revolutionized archaeology in the last few decades as they allow researchers to reconstruct the mobility of past humans and animals. Simpson and colleagues (2021) have noted that the number of published Sr isotope studies has had a sharp increase in the last 20 years within six major-impact anthropological journals. The use of Sr isotopes for mobility is unique to other methods as it can provide direct evidence of residency. Sr isotope analyses can inform researchers about ancient human and animal practices. It has become increasingly common to use a Sr isotope baseline which is a defined range of isotopic Sr values that characterize a region. This chapter reviews the various substrates that can be used to create Sr baselines and why some are more or less relevant for particular research questions than others. Selecting the appropriate substrate for a study area and research question is a critical step in creating an effective baseline.

Background

Sr has four naturally occurring isotopes: three non-radiogenic isotopes, including ^{84}Sr, ^{86}Sr, and ^{88}Sr, and one radiogenic isotope ^{87}Sr that is formed through the β-decay of rubidium-87 (^{87}Rb) (Faure, 1997; Faure, 1998). Sr isotope values are typically expressed as the ratio between ^{87}Sr to ^{86}Sr ($^{87}Sr/^{86}Sr$). The $^{87}Sr/^{86}Sr$ value varies across geologies of different ages as it reflects the passage of geological time and is partially dependent on the Rb concentration of the parent bedrock (Bentley, 2006; Graustein, 1989). Very old rocks (> 100 million years ago) have more time for ^{87}Rb to decay into ^{87}Sr, thus, tend to have higher $^{87}Sr/^{86}Sr$ ratios (above 0.710), while younger rocks (< 1-10 million years ago) generally have lower $^{87}Sr/^{86}Sr$ values (Bentley, 2006).

The $^{87}Sr/^{86}Sr$ value of rocks do not change significantly over timescales of archaeological interest because ^{87}Rb has a very long half-life: 4.88 x 10^{10} years (Bentley, 2006; Holt et al., 2021).

Sr isotopic studies of mobility are based on the fact that Sr isotope signatures in animals are derived from their diets, with plants ultimately obtaining Sr from weathered geological materials. The basic principle of Sr isotope reconstructions is that grazing animals consume eroded bedrock Sr that has been taken up by vegetation from the soil. Sr^{2+} replaces calcium (Ca^{2+}) in the skeletal bioapatite of the consuming individuals (Figure 1.1) (Bentley, 2006). There is relatively little fractionation (i.e. change in the ratio of ^{87}Sr to ^{86}Sr) between trophic levels due to the large atomic mass of the Sr isotope; this means that animals have Sr isotope values that are nearly the same as those of the foods they consume (Bentley, 2006; Graustein, 1989).

Sr isotope values vary among different geological substrates, thus, the Sr isotope signatures within the skeleton can be used to identify the geographic area where an animal lived. Sr isotope studies of migration commonly infer geographical movements based on variations at the fourth (Bataille et al., 2020) or fifth decimal place (e.g., Bentley, 2006, Price et al., 2002). However, geologic Sr isotope values are not necessarily equivalent to biologically-available, or 'bioavailable' Sr isotope values, because Sr variability is complex and the bedrock weathering rates can differ. Using only bedrock Sr values is therefore not sufficient to analyze animal mobility. Non-geologic sources (e.g., sea-spray, anthropogenic products, atmospheric dust) of Sr also influence Sr isotope values (Figure 1.1).

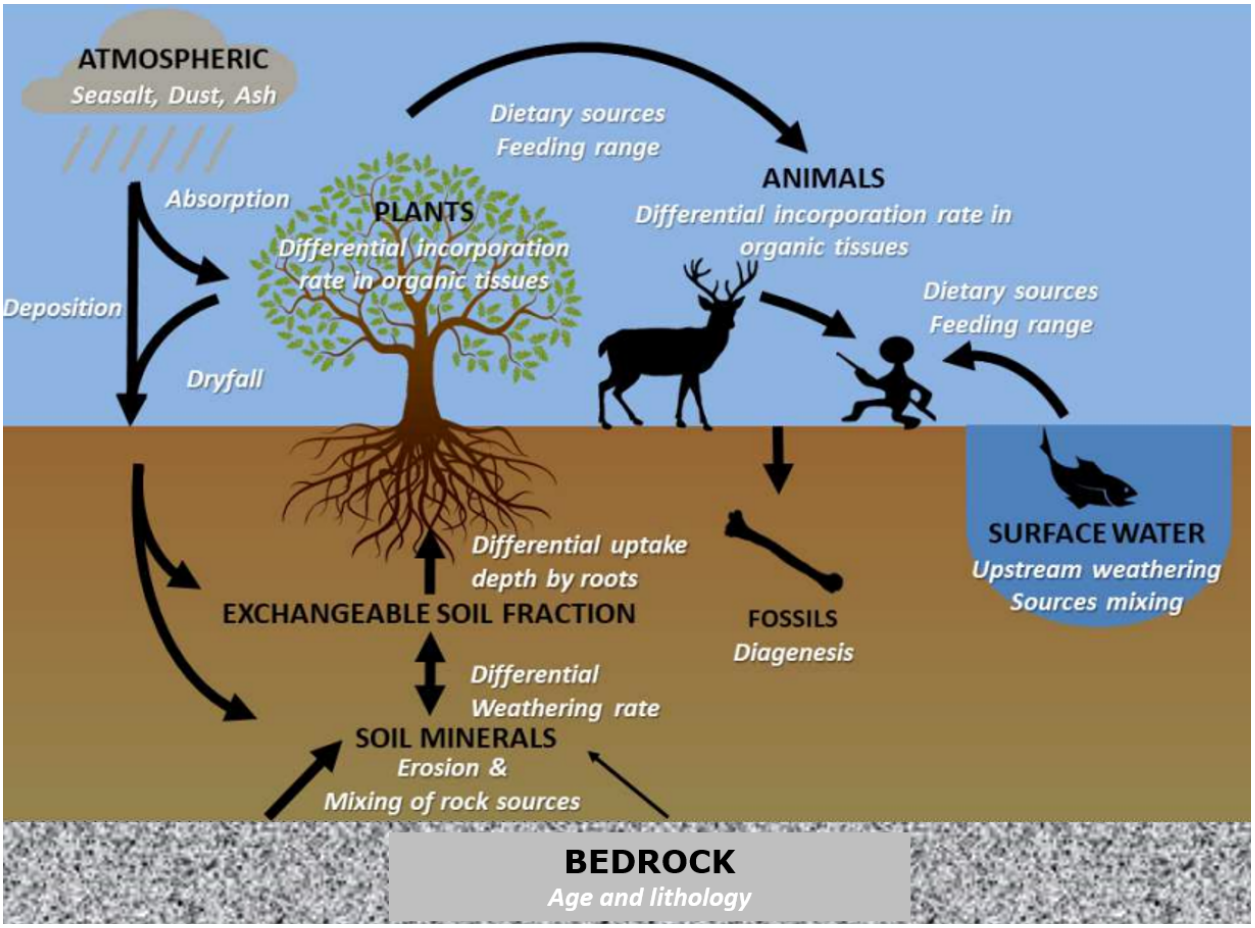

Figure 1.1. A simplified version of the strontium cycle whereby Sr from the bedrock is introduced to the ecosystem and individuals in a number of processes. Words in black are Sr reservoirs and words in white are the processes where Sr isotope ratios may be modified. Adapted from Figure 1 in Bataille et al., 2020.

Environmental and Other Factors Affecting Sr Isotope Values

Non-local Sr has the potential to be carried by water (i.e., streams, rivers, lakes) and/or wind through sediments or aerosols. Connecting water systems transport sediments that could be deposited on the banks or shores of distant locations. Thus, sampling soil or rock near waterways will likely provide a Sr isotope value that does not represent the immediate local environment. Sr isotope values may also change over time, thus modern water samples may have a different Sr isotope value than ancient waters, thus would not be suitable in an archaeological study. As well, water systems can transport meltwater from the tops of mountains which are also likely to have varying Sr values.

The sea-spray effect is another environmental phenomenon that, depending on the locality, can influence Sr isotope values. The sea-spray effect occurs when ocean-derived Sr is incorporated into the terrestrial soils via ocean spray or rainwater, which causes the Sr isotope values on land to be dominated by ocean Sr (Alonzi et al., 2020; Bentley, 2006). Present-day ocean water has a relatively homogeneous Sr isotope value of 0.7092 (Alonzi et al., 2020; Bentley, 2006; Elderfield, 1986; McArthur et al., 2001; Veizer, 1989). Whipkey and colleagues (2000) found that sea-spray supplies up to 83% of Sr in soils within 50 m of the coast in South Point, Hawaii. The sea-spray effect has also shown variable influence on Sr isotope values in coastal locations such as Portugal (James et al., 2022), Ireland (Alonzi et al., 2020; Ryan, 2017; Snoeck et al., 2020), and in coastal samples (within 100 km) of Europe (Hoogewerff et al., 2019). For example, plants growing within 50 m of the coast of Ireland have an average Sr isotope value of 0.7094 which is comparable to the value of seawater, while more distant plants growing on the same geological rock type have a Sr isotope value of 0.7089 (Ryan, 2017; Snoeck et al., 2020). However, Alonzi and colleagues (2020:7) caution that the sea-spray effect “should not be conceptualized as uniform blanketing of seawater on coastal lands” but rather “a process that introduces variability” into Sr isotope values from coastal locations.

Similarly, wind-carried (aeolian) dust can be transported across landscapes, potentially introducing sediments with different (non-local) Sr isotope values (Capo et al., 1998; Hartman and Richards, 2013; Reynolds et al., 2012). This Sr can be incorporated into the soil and taken up by plants, which then influences their isotopic values.

Anthropogenic activities such as agricultural fertilization and industrial chemical production use and release substances that also have the potential to influence the Sr signature of the material. Britton and colleagues (2020) describe how modern environmental and anthropogenic practices may influence the isotopic values of plants. Products such as fertilizers from modern agricultural practices can significantly change the results of $^{87}Sr/^{86}Sr$ values in water and plants (e.g., Böhlke and Horan, 2000; Christian et al., 2011; Maurer et al., 2012, Tichomirowa et al., 2010). Böhlke and Horan (2000) found that in parts of Locust Grove, Maryland, USA between 1994 and 1997, the use of fertilizers with a Sr isotope value of ~0.715 raised the Sr isotope values of groundwaters from ~0.708 to 0.713-0.715. In another study, Maurer and colleagues (2012) found decreasing $^{87}Sr/^{86}Sr$ values within oak tree cores since the 1920's. They suggested that this trend mirrors the increasing use of industrial practices including local coal mining activities, liming, and/or soil acidification, which became significant processes over the last century in the region.

Since modern agricultural and industrial practices can have effects on the Sr isotope values of modern substrates, including water and plant materials, it is important that modern substrates for archaeological Sr baseline studies should only be recovered from areas that do not use modern fertilizers or pesticides and are not affected by run-off contamination or non-local water. However, anthropogenically affected values may be preferable for modern studies. In short, careful consideration of these factors is imperative when planning a Sr baseline for both archaeological and modern provenience studies.

Approaches to Strontium Isotope Mobility Studies

Mobility studies have gained a significant place in paleontology and archaeology. Interpretations of Sr isotope data can contribute to insights that otherwise may not be possible by examining archaeological materials. Among other applications, Sr isotopes have been used to explore ancient trade and food procurement strategies (e.g., Haverkort et al., 2008; Thornton, 2011), determine the location of origin of sacrificial victims (e.g., White et al., 2007), the mobility patterns of ancient groups (e.g., Grupe et al., 1997; Wright, 2005), and the migration of large mammals such as bison and mammoths (e.g., Esker et al., 2019; Glassburn et al., 2018; Wooler et al., 2021). The following section will review a few studies in more detail to show how Sr isotope analysis can be applied to different research questions.

Inter-Individual Mobility Studies

One use of Sr isotope analyses can be to identify non-local individuals within a population (e.g., Ezzo et al., 1997; Slovak et al., 2009; Wright, 2005) The results can be used to define the proportion of 'immigrants' in a population. Direct evidence of migration can inform us about the settlements of groups and interactions among them. This can be done by referencing the population's Sr isotope data with itself rather than using an established Sr isotope range.

Originally proposed by Wright (2005), this method removes individuals with outlying Sr isotope values so that the remaining sample approximates a normal distribution. Wright obtained Sr isotope values from 83 tooth enamel samples of individuals buried at Tikal, Guatemala to identify 'migrants' to the ancient Maya city. Wright discusses that a normal distribution of Sr isotope data may be expected if "there is good reason to believe that the majority of the population were born locally, that all individuals consumed foods grown on the same soils" (561). Wright defined a 'local' range for Tikal as 0.70766-0.70850 with a mean of 0.70812. Next, a "trimmed" range was defined first by excluding eight individuals whose Sr isotope values, when graphed by eye, were "clearly" non-local presenting values <0.7075 and >0.7085. Wright then excluded three more individuals (presenting values of 0.7075) to remove the skew in the "trimmed" dataset to obtain a normal distribution of values, thus defining this as the "local" range of values. Wright's approach suggests that ~10% of the sample population is non-local. However, this is just an inference based on the sampled population, and thus may not be entirely accurate. This approach was criticized by Grimstead (2017) who discusses that as sample size increases, it may become increasingly difficult to identify where the data should be trimmed.

Sr isotopes can also be used to assess the hunting or food procurement strategies of ancient groups, which in turn also provide insight into the social structures. For example, Haverkort and colleagues (2008) used Sr isotope values from human bone and tooth samples of Middle Holocene Glazkovo foragers in the Baikal region of Siberia to test which of two models of food procurement was more supported. The competing hypotheses would each produce a distinct pattern of intra- and inter-variability. Sr isotope results revealed four distinct patterns of intra-individual variability into which each individual was categorized. The results show that there is wide variability in the Sr isotope values between individuals and varying degrees of variability in the Sr isotope values within individuals, thus suggesting that a logistical procurement model, whereby a group is tasked with traveling on behalf of the population, is more likely to have been adopted. These Sr isotope studies provide insight into the organization and social structures of the group.

Intra-Individual Mobility Studies

Another approach to Sr mobility studies is to evaluate the mobility of an individual throughout their life by comparing Sr isotope signatures between the individual's skeletal elements (or portions of elements) (e.g., Ericson, 1985; Frei et al., 2015; Grupe et al., 1997; Haverkort et al., 2008; Hoogewerff and Papesch 2001; Müller et al., 2003; Price et al., 1994; Price et al., 2000). This approach is based on the turnaround times of bone and/or the sequential deposition of enamel throughout life. This method of sampling provides a general idea of whether or not an individual migrated and a relative idea of when these moves took place which allows researchers to make inferences about an individual's life history.

Bone

Although bone is highly susceptible to diagenetic alteration, if the diagenetic contaminants can be removed, the Sr isotope values that are incorporated into bone during an animal's lifetime could reflect animal mobility and be used for paleomigration studies or for Sr baselines. The incorporation of Sr into the bone is reliant on bone turnover rates, which vary between skeletal elements (Schweissing and Grupe, 2003 in Bentley, 2006). After an individual moves from place A to place B, there is a gradual change in their Sr isotopic signature until the whole bone has remodeled and there is little to no Sr isotope signal from place A. The rate of turnover varies between skeletal elements; cortical bones such as the diaphysis of the femur and tibia remodel over decades, while elements with higher proportions of trabecular bone, such as the ribs, can remodel over a few years (Price et al., 2002). Different elements that represent varying deposition times can be analyzed for Sr isotope signatures and then compared to one another.

Different skeletal elements or body tissues can be used to indicate locality at various times in an individual's life because they form at different times. The resulting Sr values can be compared in each of the materials to determine general moves and the relative time of said moves (e.g., childhood, early 20's, near-death). For example, the use of bone turnover rates paired with Sr isotopic values to identify mobility was applied to the 'Alpine Iceman' (aka' Ötzi the Iceman') by Müller and colleagues (2003). Müller and colleagues argue that the difference between Sr values in childhood (as represented by the enamel) and those at adult age (as represented by bone and intestinal contents) indicates mobility throughout life.

Teeth

Sampling a single skeletal element with a known sequence of deposition (i.e., a tooth, tusk) using micro-sampling techniques can also reveal mobility over time. Because tooth enamel is deposited in incremental layers and does not remodel as bone does, different enamel layers can be targeted for analysis to obtain a sequential 'timeline' of Sr isotope values (e.g., Britton et al., 2011; Esker et al., 2019; Glassburn et al., 2018; Widga et al., 2010). For some species, the enamel is accreted at known growth rates, thus, the approximate duration of individual enamel can be calculated. For example, Glassburn and colleagues (2018) determined seasonal mobility patterns of two modern bison from interior Alaska using sequential analysis to obtain a series of Sr isotope values from the second (M_2) and third molars (M_3). Using previously published bison enamel growth rates, the samples were expected to capture 9-10 months of growth from the M_2 of the first bison, 11-12 months from the M_3 of the first bison, and 14 months of growth from the M_3 of the second bison. By comparing the Sr and O isotope results from the same sequentially sampled enamel, it is possible to correlate physical movement patterns (Sr isotope values) with season changes (peak and troughs of sinusoidal O isotope values) (Glassburn et al., 2018). Doing this shows that the bison occupied seasonal habitats which correlate with the birthing season of bison. The results not only have important implications for understanding modern bison behavioral ecology but may also be useful for reconstructing prehistoric bison mobility patterns (Glassburn et al., 2018).

Using this method for obtaining Sr isotope values, researchers are also able to make inferences about the life histories of extinct animals. For example, Wooler and colleagues (2021) used sequential Sr isotope values from a 1.7-meter tusk of an Arctic woolly mammoth that lived 17,100 years ago to reconstruct its geographic range and patterns of movement. The results provide insight into habitats used during different life stages and suggest that the animal's range had constricted near the end of its life. Wooler and colleagues suggest that, due to environmental changes during the transition from the Ice Age to the Holocene, mammoths became geographically constrained which potentially contributed to their extinction. Studies such as these can provide insight into the life patterns of animals that cannot be observed today (i.e., extinct species).

Specific Locations of Residency

The use of Sr isotope baselines allows researchers to potentially identify specific regions of residency, rather than simply determining that there were changes in residence throughout an individual's life. A Sr isotope baseline is compared with the Sr isotope values of individual(s) in a mobility study, to determine if they 'match', and if, therefore, the animal lived in a particular location. Sr baselines allow the determination of locality to be narrowed down to one or multiple areas, depending on the variability of Sr isotope values in a location (e.g., Esker et al., 2019; Frei and Price, 2012; Glassburn et al., 2018; Price et al. 2002). To construct a Sr isotope baseline, a researcher collects material(s) to obtain a 'local' Sr isotope signature for the areas of interest. Different types of materials may be more or less applicable to a study depending on the research subject and objectives.

For example, Esker and colleagues (2019) compared a Sr isotope baseline to Sr isotope values obtained by serial-sampling enamel from four mammoths recovered from the Late Pleistocene fossil site at Waco Mammoth National Monument (WMNM), a location that was hypothesized to preserve remains from a catastrophic mass death of a mammoth (M. columbi) herd. For their Sr isotope baseline, they collected 38 vegetation and 37 sediment samples over 12 lithologies within a 300 km radius of their sample site. Esker and colleagues selected grasses for the baseline, as the mammoths were grazers and the primary source of Sr in terrestrial herbivore teeth is ingested vegetation. The serial samples of enamel Sr isotope values were compared to Sr isotope values from baseline data composed of regional vegetation and sediment to suggest possible locations where the mammoths grazed. The baseline Sr data was organized into a colour-coded map of Sr isotope values called an 'isoscape' using Google Earth Pro. The isoscape was generated based on an age-lithology model which assumed that rocks of the same geologic age and rock type have the same Sr isotope signatures. Esker and colleagues concluded that three of the mammoths could have been members of a single social unit since their Sr isotope values are relatively consistent with one another and are congruous with grazing on plant material that grew ≤70 km SE of the WMNM. The fourth mammoth was assumed to be part of a different social unit due to its higher Sr isotope values (different at the second or third decimal place). This individual spent some time feeding on vegetation growing ~180 km to the SSW of the WMNM. The application of the isoscape allowed Esker and colleagues to identify two distinct geographic ranges, contributing to interpretations of temporal and geographic habitat use. This also informs researchers about population dynamics and social units of extinct species.

However, the use of baselines is not as simple as it may appear since Sr isotope values can overlap in multiple areas of a region. Snoeck and colleagues (2018) were interested in the origins of human remains found at Stonehenge. Previous archeological evidence suggested that these individuals could have been local, or could have come from up to 200 km away in west Wales, where Stonehenge's bluestones are known to have been sourced from. They obtained Sr isotope values from fragments of cremated human occipital bone from Stonehenge, which represent about a decade of Sr intake prior to death. To compare with the human remains, an online isoscape (see next section for details on isoscapes) was updated to include Sr isotope values of modern plants from west Wales. Sr isotope values for 'local' individuals were defined as <0.7090. Individuals whose Sr isotope values are > 0.7110 are reflective of older lithologies such as those found in parts of southwest England and Wales, but also further in Scotland, Ireland, and continental Europe, however, the latter was suggested to be less probable. Individuals whose Sr isotope value is between 0.7091 and 0.7118 were proposed to reflect a mixture of sources. This suggests that these people were mobile, possibly between the sites of interest, within the last decade of life. However, if individuals moved to either location prior to their last living decade, their Sr isotope value would eventually become 'local'. Thus, it is difficult to identify complex patterns of mobility using the average Sr isotope value of a single element of interest. Snoeck and colleagues also used Sr concentrations and carbon isotope values ($\delta^{13}C$) to support their identification of 'locals' and 'non-locals', whereby the 'locals' tend to have higher $\delta^{13}C$ values, although there was some overlap. This example shows how Sr isotope analysis should be used in conjunction with other lines of evidence (i.e., archaeological, analytical) to support conclusions about locations of origins for individuals since Sr isotopes alone cannot identify a specific location, especially when there are areas with overlapping Sr isotope values.

Isoscapes

It is becoming increasingly common for those using a Sr isotope baseline to create an 'isoscape' using a computer program. Isoscapes are maps with colour-coded gradients of isotopic compositions across a given area (Figure 1.2). Isoscapes often derive their models based on the geologic compositions of local bedrock, in combination with a reference set of Sr isotope values for the different bedrock types.

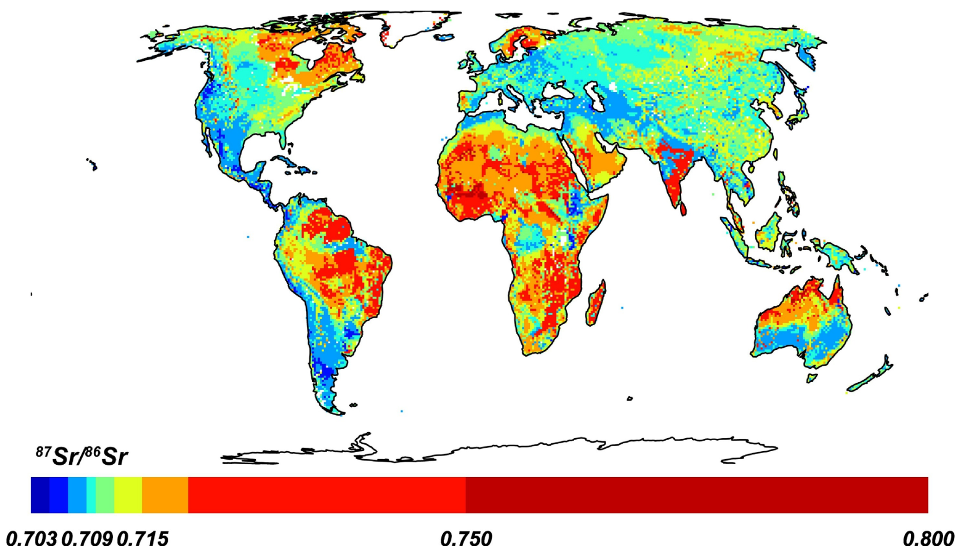

Figure 1.2. Global isoscape of predicted Sr isotope values. Adapted from Figure 9 in Bataille et al., 2020.

Domain mapping or the 'nominal approach' takes advantage of the relationship of Sr isotope values in relation to different lithologies based on their age and mineral compositions, and assumes that bedrock geology is the dominant control on bioavailable Sr isotope compositions (Bataille et al., 2018; Evans et al., 2010; Holt et al., 2021). Thus, proxy materials (i.e., baseline samples) are analyzed to determine the Sr isotope signature of an area, sometimes using the full range (i.e., Lambert 2019) or using a trimmed dataset and/or statistical analyses (i.e., mean, median, interquartile range, standard deviation) (i.e., Evans et al., 2010; Kootker et al., 2016). The Sr isotope value for the sample(s) of interest is/are then compared to the values that define a given area.

An alternative approach to isoscape mapping is using contour mapping or the 'Bayesian continuous approach' which applies geostatistics to extrapolate a continuous gradient of isotopic compositions across an area based on measured Sr isotope values (Bataille et al., 2018; Holt et al., 2021). Methods include various types of kriging (e.g., Adams et al., 2019, Willmes et al., 2018) or Inverse Distance Weighting in ArchGIS (e.g., Emery et al., 2018; Fenner and Frost, 2009). Hoogewerff and colleagues (2019:1040 in Holt et al., 2021) criticized kriging as it provides uncertainty by extrapolating the known data beyond its original limits. The scale of the study must be given some thought as this method relies on measured results that are extrapolated to other areas. Thus, more samples are necessary for a large landscape with diverse lithologies, compared with a smaller area with less diverse lithologies. Using a continental isoscape may not provide the degree of spatial resolution necessary when attempting to study the mobility of an animal known to stay within a smaller local area. As well, creating an isoscape with an unnecessary degree of detail may prove too time-consuming and/or expensive when attempting to study the mobility of an animal known to travel great distances. Depending on the scale required, obtaining sufficient data can be expensive.

Global and national Sr isoscapes (e.g., Bataille et al., 2020; Chesson et al., 2012; James et al., 2022; Lugli et al., 2022; Snoeck et al., 2020; West et al., 2009) have been published, but there have been few more detailed Sr isoscapes published of smaller areas (see Janzen et al., 2020; Lazzerini et al., 2021; Tucker et al., 2020 for exceptions). Research about animal migration patterns or suspected areas of travel should be done prior to planning a baseline sampling strategy.

Substrates for Strontium Baselines

The choice of appropriate materials to establish a Sr baseline is critical because different materials in the same location can have different Sr isotope values. For example, plant materials are representative of bioavailable dietary Sr (for the animals that consume those plants) whereas soil samples are representative of geologic Sr. Animal tissues represent an average of the local Sr isotope values of the foods consumed during the formation time of the particular tissue that is analyzed. Different materials can be more or less applicable to different studies (i.e., archaeological, forensic, agricultural). For example, archaeological skeletal remains are representative of ancient biologically available Sr, whereas, for modern samples, contamination may be a concern (e.g., due to the use of non-local modern fertilizers in agricultural areas).

Grimstead and colleagues (2017:185) called for a ‘comprehensive’ baseline for archaeological provenience studies, whereby multiple substrates are analyzed (e.g., rocks, soil, water, fauna, and vegetation) to capture the “total $^{87}Sr/^{86}Sr$ variability within the region”. This idea is echoed by Scaffidi and Knudson (2020:15) who emphasize the need for baseline models of the entire food chain (water, plant, fauna). However, in archaeology, sampling such a range of local archaeological materials is not always feasible due to the limited availability of faunal remains. Sampling modern materials may be complicated by possible influences on the Sr isotope values of modern practices such as fertilizers (Böhlke and Horan, 2000; Christian et al., 2011). For these reasons, a standardization of baseline methodology for archaeological studies is probably not practical. Instead, a case-by-case method should be considered, and careful planning of a baseline(s) prior to collecting samples is the most efficient way of preparing a provenience study using Sr isotope analysis.

Plant Materials

Plant materials are very useful substrates for Sr isotope baselines. Plant materials represent the bioavailable Sr in the region. By collecting multiple plant specimens, one can form a comprehensive baseline of the bioavailable Sr in a region. This type of baseline is useful for establishing Sr isotope values to later apply to a broad range of provenience studies. Because Sr is more abundant in plants than animal tissues, and because plants are the base source of Sr for animals (i.e., through diet), plant materials are often considered highly informative when constructing a bioavailable Sr baseline (Coelho et al., 2017; Ladegaard-Pedersen et al., 2020; Ryan et al., 2018). Plant material collected from a modern site is reliably local and often readily available and relatively easy to collect and transport. These are important qualities for archaeological provenience studies if there are limited archaeological faunal remains to collect.

Root depth can be a source of variation in the Sr isotope compositions of plants. Differences in Sr isotope values can be found with changes in the rooting depth of different species, as the plant will reflect the values of the layer of soil it grows in, which may themselves have different Sr isotope values. The Sr isotope values in different soil layers may vary due to multiple factors influencing soil components such as soil movement and geological processes at deep root depths or surficial deposits at the topsoil (Åberg et al., 1990; Britton et al., 2020; Mauer et al., 2012; Nakano et al., 2001; Poszea et al., 2002; Poszwa et al., 2004, Snoeck et al., 2020). For example, Snoeck and colleagues (2020) explored the differences between plants at different rooting depths (trees, shrubs, grasses) at 62 locations in Ireland. While some locations showed minimal variation (0.0001) between the plant types, other locations showed differences in the Sr isotope values up to 0.0052. Therefore, plants growing next to each other but at different rooting depths have the potential to have differences in their Sr signature. Despite this, few archaeological studies consider root depth when creating a Sr isotope baseline.

Many studies use plant materials for Sr baselines without also considering the diets of the study animals (e.g., Adams et al., 2019; Copeland et al., 2016; Evans et al., 2012; Glassburn et al., 2018; Ladegaard-Pedersen et al., 2020; James et al., 2022; Snoeck et al., 2020). Britton and colleagues (2020:11) state that:

> …grazing animals, for example, would be expected to represent grass and therefore topsoil values, and perhaps be more directly relatable to isoscapes generated using such proxy data. The same may be true of human groups eating grain-based agricultural diets, and human tissues could reasonably be expected to show lower intra-group variability were those individuals subsisting on locally-grown grains. However, hunter-gatherer groups reliant on a wider range of plant food sources including berries, fruits or tubers, as well as greens (as well as animal foods, in varying quantities) could be incorporating Sr from a variety of different sources and catchments, even locally.

Therefore, when studying the mobility of a specific herbivore species, selecting diet-specific plants allows researchers to obtain relevant dietary bioavailable Sr isotope values. However, when studying an animal with a more variable diet (i.e., omnivore, carnivore), selecting only diet-specific plants may negatively influence the possibility of an accurate interpretation of mobility. Animals with more complex diets obtain Sr from a number of sources. Omnivore and carnivore diets may include multiple species of animals that have various diet strategies. In these cases (i.e., for studies of omnivores and carnivores), selecting multiple species of plants with varying rooting depths (i.e., grasses, shrubs, trees) would allow a better idea of bioavailable variability in an area. For an archaeological study, care must be taken not to sample any plant from a location whose Sr isotope values may have been heavily altered (i.e., anthropogenic influence such as modern fertilizers), nor from a location near a water source which likely includes non-local Sr collected upstream. Although most Sr intake will be sourced from plants which are Sr-rich while meat is Sr-poor (Lambert and Weydert-Homeyer, 1993; Montgomery, 2010), omnivore and carnivore diets may also include species that traverse a wide range of geological boundaries. Therefore, the addition of animal skeletal materials to a baseline will provide an averaged bioavailable Sr isotope value for a region.

Skeletal Materials

Animal remains represent bioavailable Sr compositions, as Sr^{2+} replaces Ca^{2+} in the skeleton with little fractionation from the environment to incorporation into body tissues through ingestion (Graustein, 1989). The animal material most commonly used in Sr isotope baselines for archaeological studies is tooth enamel. Tooth enamel is generally preferred because it is more resistant to diagenetic effects than bone or dentine, due to its higher inorganic content and lower porosity (e.g., Bocherens et al., 1994; Budd et al., 2000; Chiaradia et al., 2003; Hoppe et al., 2003; Horn et al., 1994; Kohn et al., 1999; Lee-Thorp et al., 2003; Parker and Toots, 1970). While some earlier researchers argued that bone can be analyzed after pre-treatment (e.g., Frei and Price, 2012; Nelson et al., 1986; Sillen, 1986), most recent publications avoid bone since it is difficult, if not impossible, to assess the original Sr content of the bone (e.g., Budd et al., 2000). However, recent studies advocate for the use of calcined (burnt) bone which has been demonstrated to reliably preserve the original Sr isotope value (Snoeck et al., 2015; 2016; 2018). Calcined bone demonstrates at least as much resistance to diagenetic alteration as tooth enamel due to the high crystallinity of the inorganic fraction which is the only part of the bone that survives the high temperatures of cremation (Snoeck et al., 2015).

There are advantages and disadvantages to using modern versus archaeological faunal remains in a Sr baseline. Modern remains can be relatively easy to collect if one coordinates with local government agencies (i.e., roadkill collection, wildlife organizations) or people in the community (i.e., hunters). However, the defleshing process can be rather time-consuming and difficult. As well, modern animal Sr isotope compositions may not be equivalent to archaeological values, because environmental changes or other factors can alter bioavailable Sr compositions. For example, erosion, climate, and agricultural activities may have changed the bioavailable Sr in the soils over time, thus archaeological animals may have been consuming plants with Sr isotope values that are different from modern plants.

Grimstead and colleagues (2017) recommend that in archaeological studies, ancient fauna should be included but should not be the only source for the baseline, since one cannot be certain that the fauna were local to the site. They argue that the Sr isotope values of archaeological fauna should always be compared to other substrates being sampled as well as previously published geologic Sr values for the area.

Size and Migratory Range of Fauna

Animals provide a "regional average" of bioavailable Sr since they acquire Sr from multiple local sources (Price et al., 2004:124 in Hedman et al., 2009). Small mammals consume vegetation and water within their relatively small home range and thus are likely to represent local bioavailable Sr compositions. If a study is limited to a relatively small geographic scale, small mammals are likely to better represent the detailed changes in the Sr values in the area. For example, rabbits are not likely to travel long distances, thus, they could be used in a baseline study of two or more sites that are relatively close to each other.

Although small mammals often have small home ranges, this does not mean they are non-mobile and strictly stay within their region. Small animals are only assumed to have a 'local' home base, however, they have the potential to represent Sr from farther distances. As well, there is no guarantee that archaeological faunal remains were killed nearby; it is possible that they were transported to the site. For example, Grimstead and colleagues (2016) found that the Sr isotope results of archaeological small game from Pueblo Bonito point to several potential source areas greater than 40 km away, thus suggesting that even small mammals at Pueblo Bonito were transported to the site (i.e., by humans). Contextual analysis is required to evaluate if it is likely that an ancient group transported animal remains to the study site.

Though small mammals are generally accepted to be better samples to establish local Sr baselines than large mammals, the objective of the study should be considered when selecting baseline substrates. Medium-bodied animals (e.g., deer) who have relatively larger home ranges reflect averaged Sr values from across a region. Thus, medium-bodied animals may provide more appropriate baselines for a study of mobile individuals who traverse large geographic ranges (e.g., mobile hunter-gatherer humans or omnivores/carnivores with large migratory ranges).

Tissue Formation Times

The relevance of formation times of animal tissues should be considered when planning a Sr isotope study since the variable rates of formation and turnover can reflect different periods of Sr intake. Large mobile animals are expected to have variability in their Sr isotope values (i.e., between an individual's bones and teeth) because they are more mobile and often have relatively long lifespans, and therefore, their teeth and bone isotopic compositions will represent longer periods of time. Whole tooth analysis of enamel will provide Sr isotope values during the time of formation (for most species' teeth, during the juvenile phase of development). Targeting specific elements with known formation times (i.e., enamel layers) can provide insight into short-term variations of Sr isotope intake.

In small animals, the difference in formation times between bones and teeth may be irrelevant because small mammals have a relatively small home range that they stay in within their relatively short lifetime. Thus, small animals are expected to have more consistent Sr isotope values between an individual's bones and teeth. This means that selecting any element from a small animal should theoretically represent the local bioavailable Sr value.

Diet

The diet of the animal of interest can affect which species of faunal material one may consider collecting for a Sr baseline. Because Sr isotope values are reflective of the dietary intake of Sr, for mobility studies of carnivores/omnivores it is necessary to sample dietary fauna for bioavailable Sr isotope values. Alternatively, for mobility studies of herbivores, sampling small mammals is unnecessary to represent the herbivores' diet but may be useful to establish a representative 'local' bioavailable baseline. As stated, the Sr isotope values of herbivores are similar to those of dietary plants, so animals with similar diets should theoretically have similar Sr isotope values. As discussed above, root depth can cause variances in the Sr isotope values of plants meaning that animals may be consuming plants that grow next to each other but have different Sr ratios (Grimstead et al., 2017:186). Thus, when selecting fauna for a baseline in a herbivore study, animals with identical or similar diets to the herbivore whose mobility patterns are being reconstructed should be preferred.

Animal Dung

The use of dung as a Sr baseline substrate is relatively novel for mobility studies (Chase et al., 2018). Chase and colleagues (2018:5) state that the dung of terrestrial herbivores (i.e., cattle, buffalo, sheep, and goats) is an "ideal proxy for $^{87}Sr/^{86}Sr$ ratios" as dung is "composed of relatively homogenous plant matter consumed by an individual animal over [a recent period of time]". Herbivore dung contains plants that were probably relatively local to the site of deposition, as dung is generally unlikely to have been transported long distances. The use of dung from the animal being studied ensures that the substrate is relevant to the diet of the animal. However, in modern situations, an animal's sustenance may be derived from far-away areas (i.e., commercial feed supplied to farm animals). If dung from the study's focus species is not available, dung from animals with a similar diet may also provide a reliable baseline. Dung represents a relatively recent intake of dietary Sr compared to commonly analyzed substrates such as bone and teeth which represent average Sr isotope values over a longer period of time. Thus, dung could be a useful proxy for biologically available Sr values.

Chase and colleagues (2018) used modern herbivore dung (cattle/buffalo, goat/sheep, nilgai) to explore Sr isotope variation across the Indian state of Gujarat for the interpretation of archaeological procurement of livestock. Thirty-four of the 38 sampling locations showed variation in Sr isotope values below 0.0005. There was no clear taxonomic bias in the Sr isotope values of the species sampled, indicating that variation in the diet of the herbivores sampled studied did not affect the Sr isotope values in a systematic way (Chase et al., 2018:6). Comparing their Sr isotope results to previously published geologic Sr isotope values, Chase and colleagues' values conform to the general trends observed with the geological values (Chase et al., 2018:6-7). Chase and colleagues (2018) also found that three snail shells had Sr isotope values within 0.0001 of the means for dung values from the same locations. Snails incorporate Sr into their shells and have very small home ranges, thus are likely to reflect a 'local' Sr isotope value (Chase et al., 2018). However, snail shells may have systematically lower Sr isotope values than plants (at the third or fourth decimal place) (Britton et al., 2020). Unfortunately, Chase and colleagues did not investigate the comparability of bioavailable Sr between dung and plants. This comparison would have strengthened the interpretation that dung Sr isotope values reliably reflect local plant Sr isotope values. To our knowledge, this is the only previous study to have used dung as a substrate in Sr baselines for mobility.

Conclusions

The application of Sr isotope reconstructions of mobility patterns in the fields of archaeology and paleontology has allowed major interpretations of ancient life such as migration, trade, hunting strategies, and animal behavior. The increasingly common application of a Sr isotope baseline in Sr isotope mobility studies allows the determination of probable locations of residency, rather than simply evaluating whether or not an individual was mobile. This approach requires researchers to obtain a range of Sr isotope values from substrates that should provide a local Sr isotope signature.

Since Sr isotope values of consumers are derived from dietary Sr, substrates that comprise the subject's diet should ideally be sampled. For herbivores, samples of dietary plants are preferable, however, plants with similar rooting depth to those in the diet may be sampled as well. When this is not possible (or as an additional line of evidence), faunal remains, preferably enamel, of smaller animals with similar diets but more limited mobility can be used in the creation of a Sr baseline. For studies of carnivores and/or omnivores, dietary faunal remains can be used in addition to plants as baseline substrates since these types of diets include Sr intake from multiple sources. For substrates that average an animal's Sr intake over a longer period of time (e.g., bulk enamel or bone), selectively micro-sampling the specimen may be advantageous as this method can provide a 'timeline' of mobility to reconstruct the individual(s) migratory behavior.

For archaeological Sr-based provenience studies, obtaining well-preserved archaeological substrates (e.g., enamel) should be preferred for use in a baseline to avoid possible modern contamination. However, when this is not possible, modern samples (e.g., small fauna or local plant material) may be used to create a modern Sr baseline. In these situations, the investigation into the modern anthropogenic influence of Sr values should be carried out. This can include whether or not modern agricultural additives or industrial runoff is present locally or near a site.

The variability of Sr isotope values between substrates is complex and can differ between different substrates in a single area. There is no single method for creating a Sr baseline, including substrate choices, and distance apart. Thus, all choices should be optimized for the particular research that is being undertaken.

CHAPTER TWO: Multi-Substrate Sr Isotope Baselines for the Promontory Caves, Utah, and West Fork Rock Creek, Idaho

Introduction

Geochemical reconstructions of past mobility allow interpretations about ancient populations that may otherwise be impossible. Strontium (Sr) isotopic studies in particular have revolutionized archaeology in the last few decades as they provide direct evidence for the reconstruction of the mobility of past humans and animals.

Sr isotopic studies of mobility are based on the fact that Sr isotope signatures in animals are derived from the diet, with plants ultimately obtaining Sr from weathered geological materials. Sr^{2+} substitutes for Ca^{2+} in the animal's skeletal bioapatite through ingestion (Bentley, 2006). Due to their large atomic mass, Sr isotopes undergo negligible fractionation from the environment to metabolism and tissue synthesis (Graustein, 1989 in Scaffidi and Knudson, 2020). Because different regions have different geologies, the Sr signatures within archaeological remains reflect the geochemical makeup of the animal's grazing surface and thus can be used to identify the geographic area in which an animal has previously lived.

However, using only bedrock Sr values is not sufficient to analyze animal mobility as Sr variability is complex and the bedrock weathering rates can differ. Geologic Sr is not equivalent to biologically available, or 'bioavailable', Sr. In addition to geologic Sr, animals intake Sr from water which includes Sr from various non-local origins, as well as other potential sources including sea-spray, aeolian dust, and anthropogenic inputs such as fertilizers (Böhlke and Horan, 2000; Britton et al., 2020; Capo et al., 1998; Christian et al., 2011; Hartman and Richards, 2013; Hoogewerff et al., 2019; James et al., 2022; Maurer et al., 2012; Ryan, 2017; Reynolds et al., 2012; Snoeck et al.,2020; Whipkey et al., 2000).

A Sr baseline is a set of isotopic values for a particular region that establishes the 'expected' Sr-isotope range for local animals. Sr baselines allow the determination of whether or not an animal was local to an area, and/or the identification of other possible locations where an individual consumed local Sr (i.e., food or water). There is no single approach to creating a Sr baseline. Grimstead and colleagues (2017) called for standardization of Sr baselines by sampling a range of substrates including rocks, soils, water, vegetation, and modern fauna.

However, there are multiple reasons why the standardization of a Sr baseline is not practical. The use of archaeological substrates recovered from a site does not guarantee that they were killed nearby and not transported to the site (either by people or by animals). As well, archaeological faunal remains are sometimes not readily abundant for analysis and may not be well-preserved thus influencing the Sr isotope result. Even so, the use of modern substrates may not be necessarily reliable due to possible influences on the Sr isotope values of modern materials (i.e., modern fertilizers on plants) (Böhlke and Horan, 2000; Britton et al., 2020; Christian et al., 2011; Maurer et al., 2012).

Nevertheless, relevant Sr baselines are crucial for interpreting the mobility of ancient animals. Substrate variability is complex and different materials can be applicable to different studies (i.e., archaeological, forensic, and agricultural). Each substrate has strengths and weaknesses for use in a baseline, as described in Chapter 1 of this thesis. In cases of exceptional organic preservation, such as that at the Promontory Caves, Utah, there is a rare opportunity to study the variability of Sr isotope values in a wide range of archaeological substrates.

The broad motivation for this thesis is to determine the migrational range of Promontory bison. For example, did the migratory range of Promontory Caves bison overlap with that of Promontory-era bison recovered from the West Fork Rock Creek (WFRC) (10-Oa-275), Idaho site, ca. 100 km to the north? Bison were a key prey species for the Promontory people, thus, they would have been highly knowledgeable about bison mobility. Bison landscape use would have been strongly linked to human landscape use. Therefore, this research has the potential to provide insight into ancient bison hunting strategies used by the Promontory people as they navigated a turbulent landscape in the late thirteenth century.

This chapter creates a comprehensive baseline for Promontory and compares the utility of different baseline substrates (i.e., archaeological dung, small mammal remains, and modern plant material). This chapter builds a framework for reconstructing Promontory bison migration by addressing the specific following research questions: (1) Do the Sr isotope values of Utah flora and Promontory fauna differ from Sr isotope values in other parts of Utah? (2) Which substrates best represent a 'local baseline' for Promontory? (3) Is dung a useful baseline substrate for Sr isotope studies? (4) Do the Sr isotope values of West Fork Rock Creek fauna differ from Sr isotope values in other parts of Idaho? (5) Do the Sr isotope values of Promontory fauna differ from those of WFRC?

Sites

The Promontory Caves

The area around the Promontory Caves, henceforth known as 'Promontory Point', is the primary focus of this study. The Promontory Caves are located in northern Utah, on the northern shore of Great Salt Lake (Figure 2.2). Promontory Point is the area where Promontory Caves 1 and 2 are located. The Promontory Caves were excavated in 1930-1931 by Julian Steward (1937), then again by Ives, Janetski, and colleagues in 2011 and 2014 (Billinger and Ives 2015; Ives, 2014; 2020; Ives, et al. 2014).

Promontory Caves 1 (42BO1) and 2 (42BO2) have provided insights into cultural transitions that occurred as ancient people moved from northern to southern territories. It has been theorized that Subarctic Dene groups migrated southwards and that the Promontory assemblage is an example of one such group (Ives et al., 2014; Ives, 2020; Metcalfe et al., 2021; Steward, 1937) (Figure 2.1). Moccasins, which typically reflect the cultural identities of the wearer, and other artifacts/belongings found at Promontory have Subarctic Dene affinities and are atypical of footwear from local Great Basin groups. Other characteristics of the Promontory assemblage, including the focus on bison hunting, resemble Northern Plains culture. Genetic and linguistic (Figure 2.1) evidence suggests that the initial migration of a founding northern Athapaskan population occurred 1000-1100 years ago. The ‘push’ to move was possibly initiated by the White River Ash eruption in A.D. 852-853 (Ives, 2022; Kristensen et al., 2020). It has been suggested that Promontory people could have been ancestors of modern Southwestern Apachean groups who are currently located in southwest America (Ives, 2020; Metcalfe et al., 2021) (Figure 2.1).

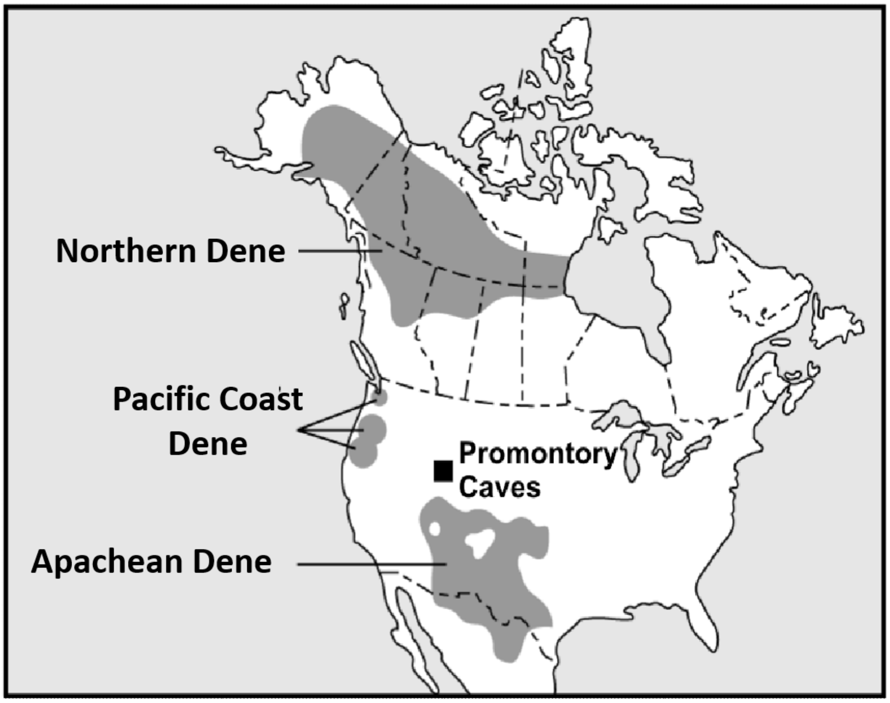

Figure. 2.1. Distribution of Dene language families in North America. The black star marks the location of the Promontory Caves. Adapted from Figure 1 in Metcalfe et al., 2021.

The Promontory Cave occupants were a relatively small group of ~35 people with exceptional big-game hunting skills (Hallson, 2017; Lakevold, 2017). Due to incredible organic preservation, the Promontory assemblage consists of a massive abundance of bison hide, bones, and fur, thus demonstrating that bison were a key prey species that were likely readily available and intensively hunted (Stewart, 1937; Metcalfe et al., 2021). Occupants likely hunted close to the caves as large bison remains found in the caves would have been difficult to transport; however, they likely also traveled beyond the caves as part of their seasonally mobile lifeway.

Despite the seeming abundance of bison near Promontory as evidenced by the massive assemblage, the caves were only occupied for a relatively short period, spanning 1-2 human generations between A.D. 1250 and 1290 (according to Bayesian modeling 95% probability estimates) (Ives et al., 2014). At this time, the local climate was similar to what it is today and likely supported the growth of nutritious grasses to feed a sizable population of bison (Bowyer and Metcalfe, 2022). Based on the abundance of bison remains preserved at archaeological sites in the broader region, previous research suggested that bison became less abundant after A.D. 1300 (Lupo and Schmitt, 1997). Therefore, a decline in local bison, possibly due to a shift in their geographical range, may have influenced the Promontory Cave inhabitants to migrate elsewhere around this time.

Steward (1937) first suggested that the Promontory people were Dene ancestors who engaged with neighboring Fremont groups. Multi-disciplinary research in the last decade has supported this hypothesis (Ives and Janetski, 2022). Promontory Cave 1 basketry, pottery, and rock art suggest interaction with local Fremont people (Ives, 2020). Further, obsidian sourcing analyses suggest that Promontory cave occupants ranged into southern Idaho and beyond (Ives, 2020). One possible site they visited is West Fork Rock Creek, Idaho. This site is geographically close to Promontory and contains similarities in material culture, suggesting they may have been used by the same or closely related groups (Arkush, 2014; 2022). At West Fork Rock Creek, there is evidence of intense bison hunting and Promontory-style pottery around the same time as the Promontory Caves were occupied (Arkush 2014; 2022).

West Fork Rock Creek

West Fork Rock Creek (WFRC) (10-Oa-275) is an archaeological site located ~100 km north of Promontory Point on the Curlew National Grasslands in southern Idaho. The site was repeatedly occupied as a short-term camp from A.D. 750-1800 (Arkush, 2014). Bison remains are present throughout all 11 living floors, suggesting that bison hunting and processing was a main activity at WFRC, even though any given occupation of WFRC was comparatively less intense than Promontory. This site was chosen for this research as it may have been a site that was visited by Promontory people as they were hunting bison in the late thirteenth century (Janetski, 2022). Arkush (2014; 2022) proposes that WFRC is easily accessible from Promontory Caves and that WFRC could have been a short-term, seasonal camp for the Promontory people, whereas the caves may have been a residential base.

At WFRC, following the 'Fremont Period' (A.D. 400-1300), the beginning of the 'Late Prehistoric Period' (A.D. 1300-1800) is characterized by a rapid change in material culture (ceramics and projectile point styles) from that of Northern Fremont to that of Promontory (Arkush, 2014). The rise of the later period is contemporaneous with the end of the occupation at the Promontory Caves, which suggests that Promontory people may have used WFRC to a greater extent after they abandoned the Promontory Caves.

Geology of the Sites

The Promontory Caves and WFRC are located in areas of different bedrock substrates, which suggests that the local Sr isotope ratios at the two sites will be different (Figure 2.2). WFRC is surrounded by igneous and sedimentary bedrock (US Geological Survey Database). There is also a large igneous province north of WFRC: the Snake River Plain, which extends the length of Idaho. In contrast, the Promontory Caves are situated on largely sedimentary substrates (US Geological Survey Database).

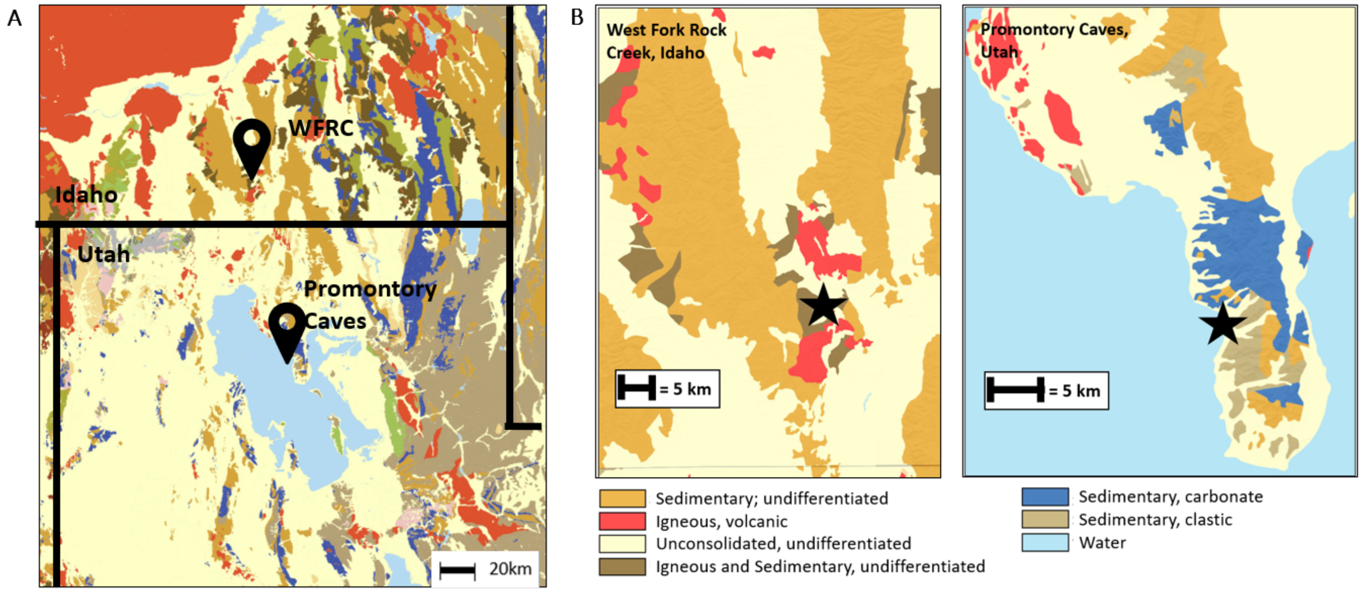

Figure 2.2. Geologic map of the study area. Adapted from US Geological Survey Database (https://mrdata.usgs.gov/geology/state). (a) Southern Idaho and northern Utah. (b) The area around WFRC (star). (c) The area around the Promontory Caves (star).

No previous studies of Sr isotopes at the Promontory Caves or WFRC had been conducted prior to this project. Previous studies of Sr isotope values in Utah include bedrock minerals from a late-Cenozoic olivine basalt ~18 km away from the Promontory Caves (Leeman, 1970), water from Great Salt Lake (Jones and Faire, 1972), and archaeological fauna from Fremont sites along the southern Wasatch Front and central-southern and Utah, southeast of the Promontory Caves (Lambert 2019 a,b) (Figure 2.10). A previous study of Sr isotope values in southern Idaho included bedrock minerals from Cenozoic igneous rock across the Snake River Plain which at its closest point is ~40 km away from WFRC (Leeman and Manton, 1971).

Substrates for a Strontium Baseline

To obtain a robust Sr isotope baseline it can be useful to select multiple types of substrates. Plants can provide a reliably local signature and are relatively easy to collect. Small mammal remains are useful for establishing local bioavailable Sr isotope compositions as they have a relatively restricted 'home range'. Small mammal remains are particularly useful baseline substrates if they have similar diets to the taxon whose migration is to be studied. For this thesis, lagomorphs, in particular, were targeted for analysis because they have a similar diet to bison (MacCracken and Hansen, 1984; Van Vuren, 1984). Herbivore Sr isotope values are variable depending on the root depth of the plants they consume, among other things. Thus, sampling individuals with similar diets ensures that there is limited variability of Sr isotope values concerning root depth.

Teeth, specifically enamel, are generally preferred over dentine or bone for geochemical analysis because previous studies have shown that tooth enamel is more resistant to diagenetic effects than dentine (e.g., Bocherens et al., 1994; Budd et al., 2000; Chiaradia et al., 2003; Hoppe et al., 2003; Horn et al., 2994; Lee-Thorp et al., 2003; Parker and Toots, 1970). Though archaeological remains could have been transported into the caves from another location, transportation of small mammal remains from distant locations would probably have been rare (if it occurred at all), since large game was highly accessible and small animals were relatively abundant throughout Utah and Idaho.

Dung is a relatively novel substrate for Sr isotope analysis. To our knowledge only modern dung has been used as a substrate in Sr baselines for mobility (Chase et al., 2018). Archaeological dung, when preserved, may have the potential to strengthen the reliability of Sr isotope baselines since it contains plants that were likely consumed relatively close to the site of deposition and therefore should reliably represent the local biologically available Sr value. Chase and colleagues (2018) used herbivore dung (cattle/buffalo, goat/sheep, nilgai) to explore Sr isotope variation across the Indian state of Gujarat for the interpretation of archaeological procurement of livestock. Chase and colleagues' results indicate that herbivore dung Sr isotope values conform to the general trends observed with the geological values. This thesis will further explore the application of dung in Sr isotope baselines as I will compare dung Sr isotope values to those of multiple other substrates.

Bison are ruminants, meaning they ingest and re-chew their regurgitated partially digested food (called "cud") to aid digestion and for optimal nutrient intake. This process homogenizes the plant materials which are then further homogenized by digestion processes throughout the body up to deposition. Bison graze multiple times throughout the day, so their dung may be composed of plant matter from multiple areas within the past 24-72 hours (Rutley and Hudson, 2000; Schaefer et al., 1978). Modern wood bison herds have a general tendency to stay within 50-80 km of the center of activity (Gates et al., 2010; Metcalfe et al., 2021). However, Metcalfe and colleagues (2021) discuss several unusually long journeys made by individual modern bison in Wood Buffalo National Park: the first was ~320 km in six months, the second was ~480 km in four months, and finally ~1550 km in 21 months. Despite being unusually long migrations, these indicate mean travel distances of only ~2 to 4 km per day. Nevertheless, Carbyn (1997) documented a herd of bison that traveled 82 km in 24 hours to flee a preying wolf pack. Therefore, bison dung potentially represents an average Sr isotope value of multiple grazing areas throughout the 24-72 hours prior to deposition. Dung could include plants from locations with highly variable Sr isotope signatures.

In comparison to tissues that form over longer periods of time, such as bones and teeth, dung will theoretically represent a more recent period of food consumption (i.e., for bison, 1-3 days prior to deposition). The bones and teeth represent an average of biologically available Sr over time (i.e., teeth have a record of Sr deposited over life). It seems likely that well-preserved archaeological bison dung could be an ideal substrate for comparison to Promontory bison tissues that form over longer periods of time (i.e., bones and teeth).

Materials and Methods

Sample Selection

Various types of samples were obtained from within the Promontory Caves, the surrounding area, and WFRC. In the subsequent text, 'Promontory Caves' refers to samples recovered only from inside the Promontory Caves 1 and 2. 'Promontory Point' refers to faunal samples recovered from Promontory Caves 1 and 2 and plant samples from the following locations: ‘Chournos Springs/Granitic Wash’, ‘Promontory Cave 3’, and ‘Promontory Landforms 1’ and ‘2’. Promontory Point plant sampling locations exist within 5 km of the caves.

Promontory Region (Modern)

Modern samples from the Promontory region include plants (n=13) and modern dung samples (n=2) (Table 2.2) (Figure 2.4). Modern plant samples were collected between 2013 and 2014 from nine locations in Utah (Figure 2.3). Plants were collected with the intent of using them in a baseline for a Sr isotope study of cane dice sourcing and botanical studies, not to assess bison migration. The inclusion of these samples in this thesis was opportunistic. Four genera of plants were collected (*Phragmites, Chrysothamnus., Juniperus, and Sarcobatus*). At seven sites, a single plant was sampled. While these genera of plants were not what bison are, their results provide an idea of the modern bioavailable Sr in the region. At one site (Promontory Landform

2), two plants were sampled and at another site (Chournos Springs/Granitic Wash), four plants were sampled. Specific sampling coordinates of most plant samples are located in the Appendix.

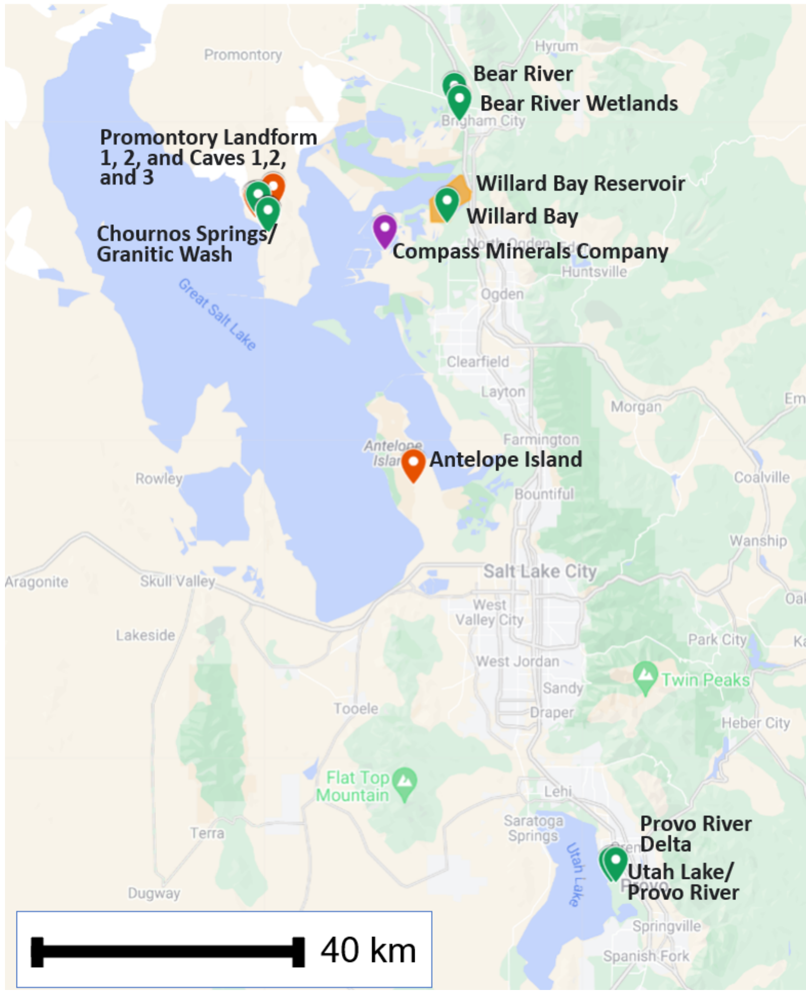

Figure 2.3. Map of sample locations in Utah. Green points represent plant sampling locations. Red points represent faunal sampling sites. The purple point denotes the location of a mineral company (Compass Minerals) whose production could influence the Sr isotope values of plants from nearby sampling locations (i.e., Willard Bay). The orange area denotes Willard Bay Reservoir, a recreation area where activities could also be affecting the Sr isotope value of the Willard Bay plant sample.

A sample of modern cattle dung was collected from the game trail near the Promontory Caves in November 2011. A sample of modern sheep dung (n=1) was collected from the back of the caves during field season between 2011-2014. A sample of modern bison dung was also collected from Antelope Island in May 2017. Antelope Island is a 24 km stretch of land northwest of Salt Lake City that extends into Great Salt Lake. The island is home to free-ranging large mammals including bison, mule deer, pronghorn, and bighorn sheep. None of the modern dung samples were collected immediately after excretion by the animal. The specific sampling coordinates of the Antelope Island dung sample are located in the Appendix.

Promontory Region (Archaeological)

Archaeological samples from the Promontory Caves include small mammal teeth (n=7), small mammal dung (n=5), mule deer (*Odocoileus hemionus*) teeth (n=2), and bison dung (n=5) (Figure 2.4) (Table 2.2). Archaeological samples were collected from the Promontory Caves 1 and 2 during excavations between 2011-2014.

WFRC Samples (Archaeological)

For West Fork Rock Creek (WFRC), Idaho, Sr isotope values were obtained from an archaeological rodent tooth (n=1) and an archaeological bison tooth (n=1). The WFRC rodent tooth was recovered between floors 1 and 2 which dates to A.D., 1650-1890 while the bison tooth was recovered between floors 3 and 4 which dates to A.D. 1320-1650, based on radiocarbon dates of burnt wood and charcoal, and bison bone, respectively (Arkush 2014, Table 2). At the time of the thesis research, these were the only tooth enamel samples available from WFRC for Sr isotope analysis, although additional teeth may be accessible for future research.

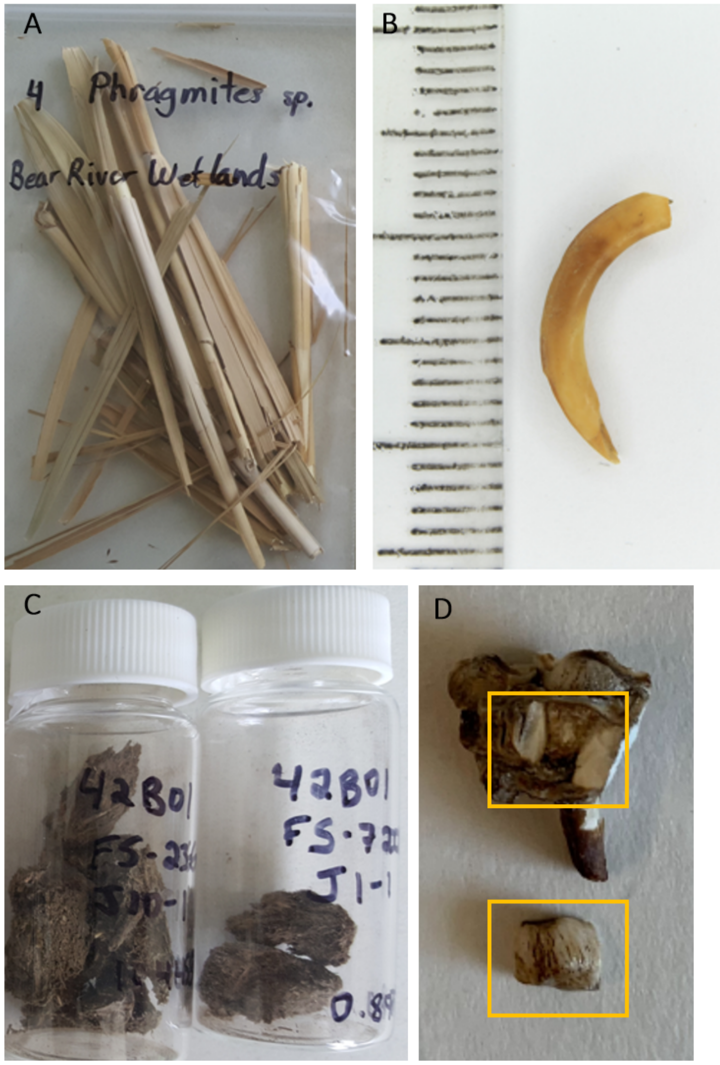

Figure 2.4. Examples of substrates prior to subsampling and analysis. (a) *Phragmites* sample 'Bag 4' from Bear River Wetlands. (b) *Sylvilagus* incisor from FS-601. (c) Bison dung samples FS-236 and FS-720. (d) Mule deer tooth FS-679.14 from Promontory. Bottom orange rectangle indicates the piece of sample used for analysis. Top orange rectangle indicates the part of the molar where the piece fell off.

Analytical Methods

All sample preparation and trace element and Sr isotope analyses were completed at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) in the Department of Earth, Ocean and Atmospheric Sciences at the University of British Columbia.

Sample Preparation

Some previous Sr isotope studies of modern plants have not pretreated or washed the samples (Evans et al., 2009; Ryan et al., 2018; Snoeck et al., 2020), whereas others rinsed their plant samples with (MilliQ) water to remove potential dust contaminants (i.e., Adams et al., 2019; Britton et al., 2020; Ladegaard-Pedersen et al., 2020; Maurer et al., 2012). Therefore, in this study, plant samples were not washed prior to freeze-drying and analysis.

All plant and dung samples were freeze-dried prior to analysis. Pieces were broken off of the plant samples from at least 3 reeds or branches to homogenize potential variations of Sr isotope compositions within each plant. *Sarcobatus* and *Chrysothamnus* plant samples proved difficult to mill, so small pieces (~3-10 mm long) were broken off from the stems of multiple branches instead of milling. Sampling different portions of the dung was deemed unnecessary because dung is already a homogenized sample of dietary plants. Freeze-dried *Phragmites* and *Juniperus* plant samples and dung specimens were milled in a Laval Lab Pulverisette 6 with small aggregate beads. Both plants and dung were milled at 380 rotational speed for 3-20 minutes each. The aggregate bowl and beads were cleaned with isopropyl alcohol (IPA) between each sample.

For the mule deer and bison tooth enamel samples, a small piece (~ 1 x 2 cm) was broken off at the crown and used for analysis. A Dremel rotary tool was used to attempt to grind off the dentine of these specimens. However, due to the morphology of mule deer tooth FS-679.14 (Figure 2.4), the piece of crown used for analysis had a cusp that may have contained dentine that was not completely removed prior to analysis.

For most small mammal teeth, pieces of tooth (primarily enamel) were snapped off by hand. The dentine was not milled off the small mammal teeth (as it was for the large mammals) since the weights of the small mammal teeth were close to the ideal minimum weight. As well, it was difficult to differentiate between enamel and dentine due to the small size of the teeth.

Sample Digestion

To begin, 50-100 mg of milled plant or dung sample was weighed into a microwave PFA tube and pre-digested in a mixture of 0.5 ml mQ water, 8 ml 15N HNO_3, 3 ml 6N HCl, and 0.5 ml 28N HF overnight in a fume hood. Pre-digested samples were then loaded onto the turret and microwave-digested. The CEM MARS 6 microwave digestion system was run for 30 minutes and then samples were allowed to cool overnight. The digests were left in a fumehood to degas, then samples were poured into Savillex bottles and rinsed with a small amount of mQ water. Samples sat on a 120°C hotblock overnight with the lids off and evaporated to dryness. Samples were then treated with a drop of 2N HNO_3 and dried down on a 100°C hotplate for 1-2 hours; this process was repeated three times.

Teeth were digested using a hotplate method modeled after that of Lazzerini and colleagues (2021). To each 50-100 mg tooth sample, 2.0 mL of concentrated HNO_3 was added, then each Savillex bottle was tightly sealed and left on a 120-130°C hotplate for 72 hours. After that, 0.5 mL of 30% Suprapur® H_2O_2 was added to remove any organics that may be in the sample, then resealed and placed on the hotplate overnight at 130°C. The samples were then evaporated until dry, treated three times with a drop of HNO_3, and dried down on a 100°C hotplate for 1-2 hours. Finally, the dry samples were dissolved in 2.0 mL of 2N HNO_3.

Trace Element Analysis by ICP-MS

For trace element analysis, 0.1 mL of plant, dung, or tooth digests were topped up to 10.0 mL with 2% HNO_3. Following established sample preparation and analytical procedures, Sr and other trace element concentrations for the digested plant, dung, and teeth samples were obtained using an Agilent 7700x quadrupole inductively coupled plasma mass spectrometer (ICP-MS). Element concentrations were calibrated using a five-point calibration curve (0 ppb, 1 ppb, 10 ppb, 50 ppb, 100 ppb) consisting of a calibration solution produced by Inorganic Ventures (IV-71A).

Strontium Isotope Analysis by TIMS

To isolate the Sr from the sample matrix, a Sr-specific Sr-resin (Eichrom, USA) was used in an extraction chromatographic procedure adapted from Deniel and Pin (2001). Pre-cleaned 2 mL BioRad PP microcolumns were filled with Sr-resin (~0.5 mL) which was then cleaned and conditioned twice with 18 MΩ water, 2.2 ml 0.05 N HNO_3, and 0.3 ml 2N HNO_3, successively. Aliquots samples from the TE analyses were centrifuged for 6 minutes at 14,5000 rpm and then 1.0mL of sample digest was loaded into its respective clean and conditioned microcolumn.

The resin matrix was then washed 4 times with 0.1mL 2N HNO_3, once with 1.0mL 7N HNO_3, and another 2 times with 0.1mL 2N HNO_3, all to purify the matrix from unwanted elements. The elutions from these steps were collected in a tray and rinsed down the sink. Then, the isolated Sr was eluted from the resin matrix with 2.0mL of 0.05N HNO_3 and collected into a new Savillex bottle. The collected sample was dried down on a 100°C hotblock for 2-3 hours, then treated with 0.3mL 14N HNO_3 to destroy potential resin residues. The microcolumns were kept from drying by placing the bottom tip in mQ water. The elution procedure was then repeated using the same microcolumns for a second time to ensure the isolation of the Sr and maximize the collection of Sr from the matrices.

Based on the trace element results, each sample was diluted to 300 ng of Sr /µL with 0.05 M HNO_3. Then 2.0 µL of sample solution was loaded onto a filament and 1.0 µL of Ta activator solution was added to the drop of sample. The filament was dried at ~0.7 amps and then flashed at ~2 amps on a Finnigan MAT. Filaments were loaded onto a wheel for thermal ionization mass spectrometry (TIMS) analysis on the Nu Instruments TIMS machine (NT002). All data were normalized to the accepted USGS SRM-987 $^{87}Sr/^{86}Sr$ ratio of 0.710248 (Weis et al., 2006). The average $^{87}Sr/^{86}Sr$ ratio in SRM-987 during the period of analysis was 0.710249 ± 0.000013 (2SE, n=15). $^{87}Sr/^{86}Sr$ ratios of individual sample analyses gave 2SE uncertainties of less than 0.000085, with the exception of one plant sample (Bag 7, *Phragmites* from the Bear River Wetlands) at 0.000149. Two samples were run in duplicate and one sample was run in quadruplicate. Sample replicates were averaged in subsequent analyses (Table 2.1).

The Sr isotope results from each site were compared to one another to discuss consistencies and inconsistencies between sample locations. Also, the Sr isotope results of each substrate were compared to one another to discuss the optimization of a Sr isotope baseline for the Promontory Point region.

A principal component analysis (PCA) of the trace elements values of substrates was completed in PAST (PAleontological STatistics) version 4.03. The correlation matrix and between-group settings were chosen to standardize the values and maximally separate the groups, respectively. The correlation matrix allows the values to be compared against each other without one variable overriding the other. The between-group setting uses both between- and within-group variances.

Table 2.1. Sr concentrations and isotope values of replicate samples of archaeological dung from the Promontory Caves and modern dung from Antelope Island.

Material	Sample	Type	Sr ppm	$^{87}Sr/^{86}Sr$	2SE	Average $^{87}Sr/^{86}Sr$
Dung	FS-236	Bison	107	0.712148	0.000009	0.712154
			103	0.712160	0.000009	
	FS-305	Lagomorph	115	0.711964	0.000018	0.711940
			119	0.711919	0.000010	
				0.711949	0.000010	
				0.711928	0.000014	
	AI-009	Bison	115	0.717446	0.000007	0.717302
			87	0.717302	0.000009	

Results

Sr Isotope Values and Sr Concentrations

All of the Sr isotope values and Sr concentrations generated in this study are reported in Table 2.2. The Sr isotope values (excluding the high plant sample described below in section *Unusually High Plant Sr Isotope Value*) ranged from 0.709958 to 0.717965. Comparisons based on substrate and location are presented in the following sections.

Table 2.2. Sr concentrations and isotope values of teeth, dung, and plant samples from Promontory, WFRC, Antelope Island, and other locations in Utah.

Material	Location	Site number	Sample	Type	Sr ppm	$^{87}Sr/^{86}Sr$	2SE
Teeth							
	Promontory Cave 2	42BO2	FS-601A	*Sylvilagus*	581	0.712069	0.000009
	Promontory Cave 2	42BO2	FS-601B	*Sylvilagus*	820	0.711820	0.000043
	Promontory Cave 2	42BO2	FS-601	*Sylvilagus*	556	0.711794	0.000010
	Promontory Cave 2	42BO2	FS-625	*Spermophilus*	729	0.711615	0.000010
	Promontory Cave 2	42BO2	FS-625	*Leporid*	814	0.711613	0.000009
	Promontory Cave 2	42BO2	FS-655	*Microtus*	317	0.712004	0.000017
	Promontory Cave 2	42BO2	FS-708	*Sylvilagus*	332	0.711669	0.000013
	Promontory Cave 1	42BO1	FS-575.267	*Odocoileus hemionus*	84*	0.711126	0.000012
	Promontory Cave 1	42BO1	FS-679.14	*Odocoileus hemionus*	2068	0.711204	0.000011
	WFRC	10-Oa-275	FS-29-111-12	*Bison bison*	341	0.710526	0.000010
	WFRC	10-Oa-275	FS-29-155-6	Rodentia	362*	0.711039	0.000018
Dung							
	Promontory Cave 2	42BO2	FS-305	Lagomorpha	117*	0.711940*	0.000013
	Promontory Cave 2	42BO2	FS-307	Lagomorpha	101	0.711948	0.000010
	Promontory Cave 2	42BO2	FS-360	Lagomorpha	111	0.711894	0.000009
	Promontory Cave 2	42BO2	FS-367	Lagomorpha	93	0.712063	0.000014
	Promontory Cave 2	42BO2	FS-374	Lagomorpha	97	0.711876	0.000010
	Promontory Cave 1	42BO1	FS-120	*Bison bison*	74	0.711689	0.000085
	Promontory Cave 1	42BO1	FS-193	*Bison bison*	87	0.712160	0.000009
	Promontory Cave 1	42BO1	FS-236	*Bison bison*	105*	0.712154*	0.000009
	Promontory Cave 2	42BO2	FS-660	*Bison bison*	75	0.713306	0.000016
	Promontory Cave 1	42BO1	FS-720	*Bison bison*	107	0.711923	0.000014
	Promontory Caves	-	Modern	*Ovis aries*	181	0.712420	0.000052
	Promontory Caves	-	Modern	*Bos taurus*	35	0.712251	0.000013
	Antelope Island		AI-009	*Bison bison*	101*	0.717374*	0.000008
Plants							
	Bear River	-	Bag 2	*Phragmites*	16	0.714948	0.000061
	Bear River Wetlands	-	Bag 4	*Phragmites*	32	0.717965	0.000013
	Chournos Springs/ Granitic Wash	-	Bag 7	*Phragmites*	21	0.713758	0.000149
	Chournos Springs/ Granitic Wash	-	Bag 9	*Sarcobatus*	61	0.712347	0.000009
	Chournos Springs/ Granitic Wash	-	Bag 10	*Sarcobatus*	45	0.711869	0.000010
	Chournos Springs/ Granitic Wash	-	Bag 11	*Sarcobatus*	93	0.712178	0.000009
	Promontory Landform 1	-	Bag 12	*Sarcobatus*	58	0.711988	0.000010
	Promontory Landform 2	-	Bag 14	*Juniperus*	81	0.711933	0.000011
	Promontory Landform 2	-	Bag 15	*Chrysothamnus*	152	0.711836	0.000009
	Promontory Cave 3	-	Bag 13	*Juniperus*	99	0.711590	0.000009
	Provo River Delta	-	Bag 3	*Phragmites*	59	0.709958	0.000013
	Utah Lake/Provo River	-	Bag 1	*Phragmites*	28	0.710035	0.000025
	Willard Bay	-	Bag 5	*Phragmites*	40	0. 764596+	0.000010

* Indicates average of repeat analysis

+ Indicates unusually high value not considered in interpretations within this chapter, as described in the text

A principal component analysis (PCA) of trace element concentrations of substrates obtained in this study from Utah was performed to observe similarities or differences in the composition of substrates (Figure 2.5). The PCA shows that modern plant material overlaps with modern and archaeological lagomorph and herbivore (bison, cattle, sheep) dung, indicating that the trace element concentrations of plant and dung substrates are very similar. The loadings plot shows that 76.6% of the variance in the trace element values is explained by principal component 1 (PC1). Phosphorus (P) and calcium (Ca) concentrations are responsible for most of the variation in PC1.

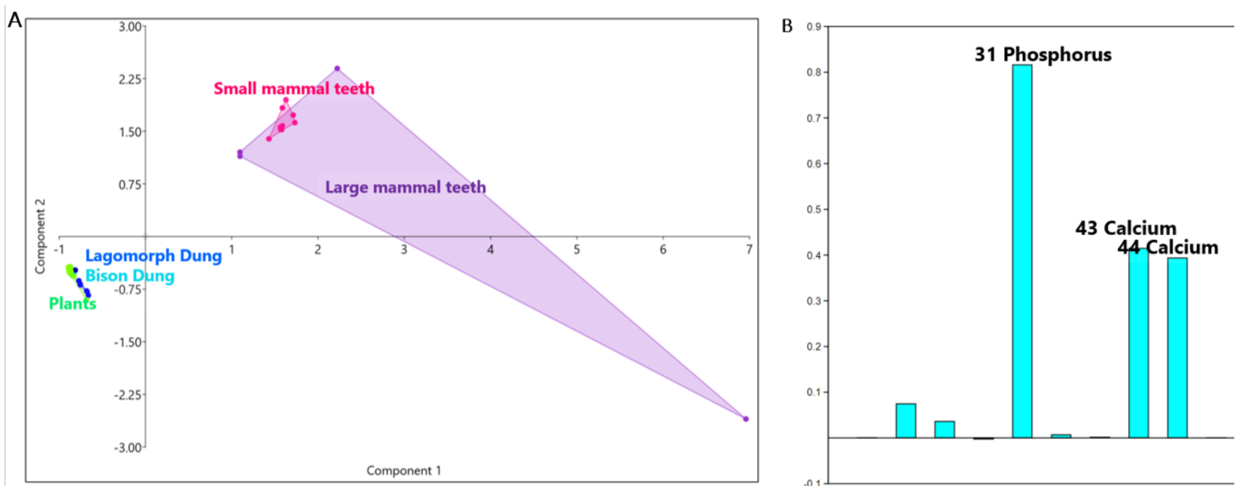

Figure 2.5. (a) Principal component analysis (PCA) of trace element concentrations in all substrates. Substrates are grouped and labeled. (b) Loadings plot of the PCA. Shows PC1 and PC2 have the greatest variance between phosphorus (P) and calcium (Ca).

Utah Samples

The Sr isotope values from Utah substrates analyzed in this thesis, including both modern and archaeological samples, ranged from 0.709958 to 0.717965, with a total range of 0.008007 and a mean of 0.712302 (excluding the outlying plant sample discussed below) (Figure 2.6; Table 2.2).

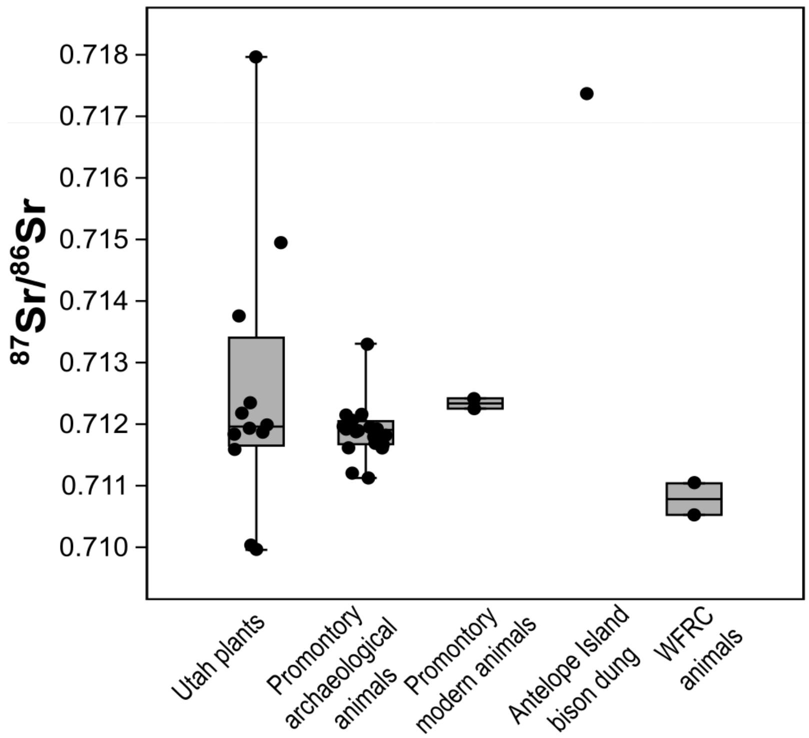

Figure 2.6. Comparison of Sr isotope values obtained from all Utah and Idaho samples included in this thesis separated by location, age, and substrate (excluding the very high plant value described in the text). Utah plants are modern. Archaeological Promontory animals include *Bison*, *Sylvilagus*, *Spermophilus*, *Microtus*, and *Leporid*, Modern Promontory animals include cattle and sheep. Antelope Island bison dung is modern. WFRC animals include archaeological bison and rodent.

Unusually High Plant Sr Isotope Value

A *Phragmites* sample from Willard Bay (Figure 2.3) had an extremely high Sr isotope value (0.764596) compared with the other plant samples from Utah analyzed in this thesis (0.709958 to 0.717965) (Figure 2.7a). There were no interruptions to the TIMS instrument during this run. Samples analyzed before and after this sample did not result in unusually high Sr isotope values, suggesting that carryover of Sr did not occur during analysis. The Sr concentration ([Sr]) for this plant sample (40 ppm) was comparable to those of the other plants (range=16 to 152 ppm, median= 58 ppm, mean= 60 ppm), which suggests that its high Sr isotope value is not due to an abnormal amount of Sr in the sample (e.g., from a Sr contaminant or from incomplete digestion).

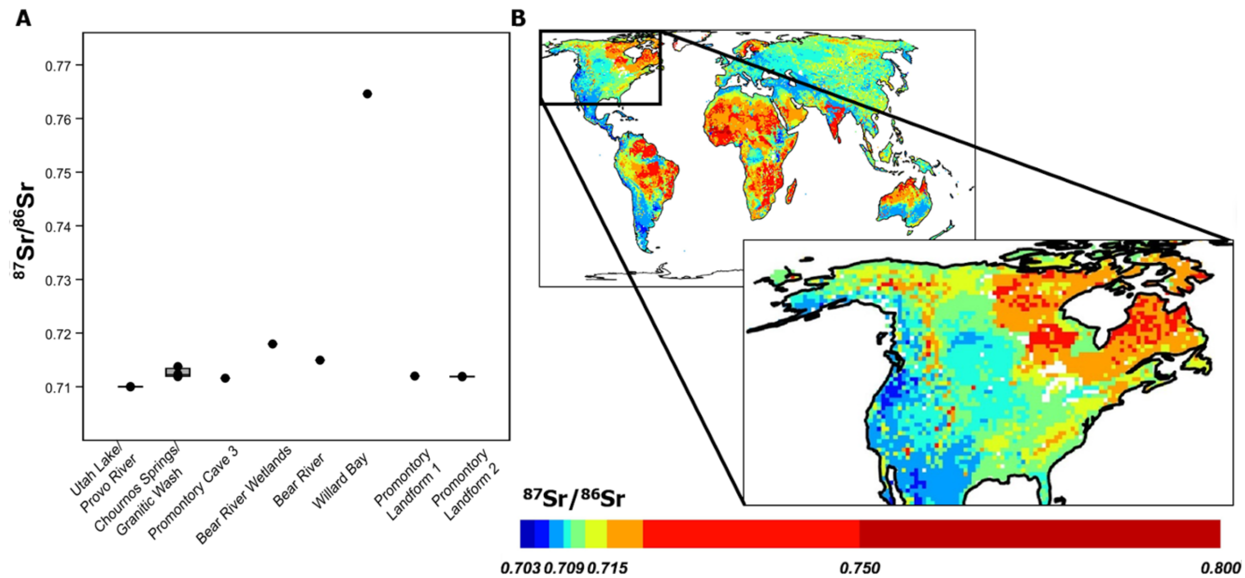

Figure 2.7. (a) Strontium isotope values of modern plants sampled from eight locations across Utah. (b) A predictive model of global $^{87}Sr/^{86}Sr$ values focusing on North America. Adapted from Figure 9 of Bataille and colleagues (2020).

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Not only was this sample's isotopic value comparatively high relative to all modern plants in this study, but it is also high on a global scale. Based on Bataille and colleagues' (2020) predictive model (Figure 2.7b), a Sr isotope value >0.76 is unlikely for the Great Basin region, though it may be observed in portions of the Rocky Mountains and the American Southwest. Although Bataille and colleagues' model does not account for small, local variations in Sr values, the high value for Willard Bay is highly unusual given its significant difference from other plant and substrate values in this study. Why might this sample have such a high $^{87}Sr/^{86}Sr$ value?

The sampling site for the plant with the extremely high $^{87}Sr/^{86}Sr$ value is less than 400 m away from Willard Bay Reservoir, a man-made freshwater reservoir in Great Salt Lake commonly used for recreation purposes including camping and boating (Figure 2.3). The sample was taken from a waterfowl management area where multiple from Willard Bay drain into. The sample could have been affected by non-local water. Since the multiple sources drain into the reservoir, the water in the bay likely includes Sr from upstream. Thus the surrounding sediments incorporate the non-local Sr which is taken up by the plants resulting in a non-local Sr isotope value for this sample. Alternatively, waterfowl (e.g., dung) or human activities (e.g., boating supplies/waste and pet dung) in the management area could have contributed to this high value.

The sampling site is also located ~12 km away from a mineral company's (Compass Minerals) evaporation ponds used to produce salt, sulfate of potash, and magnesium chloride (MgCl). Thus, it is also possible that this sample includes Sr from an industrial source. Böhlke and Horan, (2000) found that some agricultural additives used in parts of Locust Grove, Maryland, USA between 1994 and 1997 had Sr isotope values of 0.708 to 0.835, with potash (potassium chloride) having the highest value of 0.8352. A small amount of a contaminant with such a high Sr isotope value might produce an outlier such as the sample from Willard Bay.

Unfortunately, there was no other plant sample recovered from this area, nor was there another recovered from around this water reservoir to compare with this high value. Based on its highly unusual Sr isotope value and proximity to possible sources of contamination, the *Phragmites* sample from Willard Bay is excluded from further discussion in this chapter.

Utah Plants (Modern)

Excluding the unusually high outlier discussed above, Utah plant samples exhibited Sr isotope values ranging from 0.709958 to 0.717965, for a total variation of 0.008007, and a mean of 0.712534 (Table 2.2, Figure 2.8a). The largest range of values for any one plant location that had multiple specimen samples is Chournos Springs/Granitic Wash. *Phragmites* tend to have higher Sr isotope values than the other species (*Sarcobatus, Juniperus,* and *Chrysothamnus*).

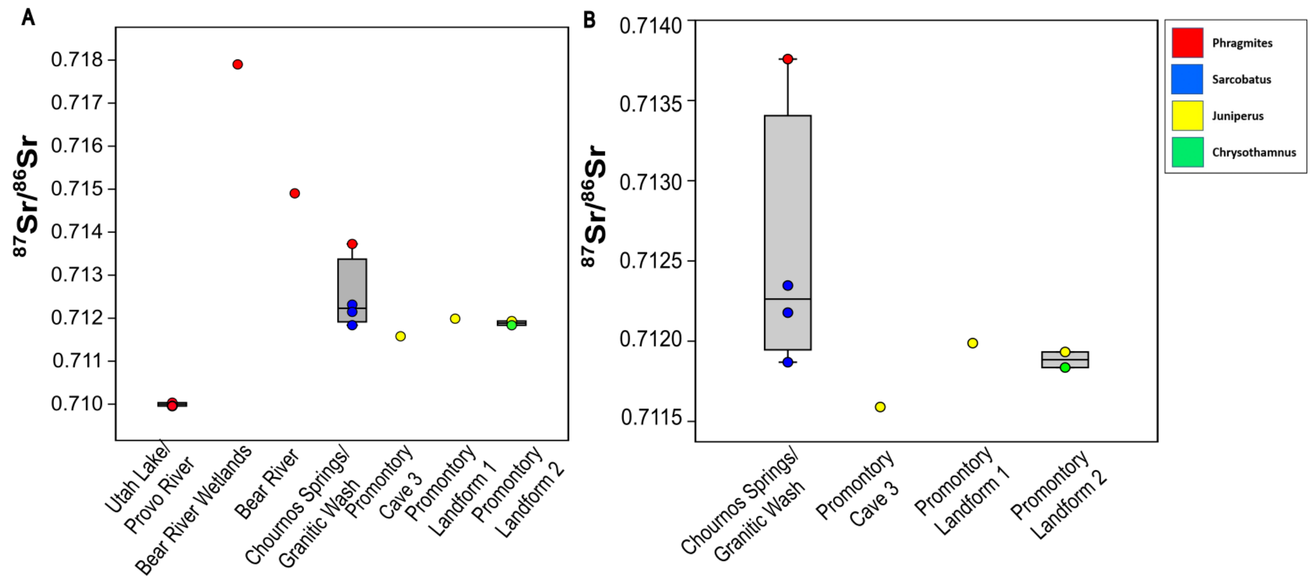

Figure 2.8. (a) Comparison of Sr isotope values obtained from modern plants from seven locations across Utah. Four species (*Phragmites sp., Sarcobatus, Juniperus,* and *Chrysothamnus*) were collected. (b) Comparison of Sr isotope values obtained from modern plants collected from four locations on Promontory Point to illustrate the variations of plants within Promontory Point.

Promontory Point Plants (Modern)

Compared to the range of all sampled plants, the range for those recovered from Promontory Point is narrower (Figure 2.8b). The range for plants recovered from Promontory Point is 0.711590 to 0.713758 with an average of 0.712187 and a total variation of 0.002168.

Four of the Promontory Point plant samples were taken from the Granitic Wash/Chournos Springs location. Interestingly, the single *Phragmites* sample from Chournos Springs/Granitic Wash (0.713758) has a comparatively higher Sr isotope value (at the third decimal place) while the *Sarcobatus* (n=3) shows relatively consistent values (0.711869, 0.712178, 0.712347, respectively) at this sampling site and are comparable to all of the Promontory Point plant samples (Figure 2.8b). That is, at Chournos Springs/Granitic Wash, the terrestrial plants

(*Sarcobatus, Juniperus, and Chrysothamnus*) show consistent values while the single semi-aquatic *Phragmites* specimen is higher.

Utah Faunal Substrates (Archaeological and Modern)

Archaeological faunal substrates (bison, rabbit, rodent, mule deer) recovered from the Promontory Caves show a range in Sr isotope values from 0.711126 to 0.713306, for a total variation of 0.002180 and an average of 0.711882 (Table 2.2) (Figure 2.6). Summary data for each substrate are located in Table 2.3.

Table 2.3. Summary table of Sr isotope values of substrates from Utah (excluding the outlying plant sample).

Location	Material	n=	Minimum	Maximum	Total range	Mean
Promontory Caves	Small mammal teeth	7	0.711613	0.712069	0.000456	0.711798
	Lagomorph dung	5	0.711876	0.712063	0.000187	0.711944
	Modern dung	2	0.712252	0.712420	0.000168	0.712336
	Bison dung	5	0.711689	0.713306	0.001616	0.712224
	Mule deer teeth	2	0.711126	0.711204	0.000078	0.711165
	All archaeological animals	19	0.711126	0.713306	0.002180	0.711882
Promontory Point	Flora	8	0.711590	0.713758	0.002168	0.712187
	Flora and archaeological fauna	27	0.711126	0.713758	0.002632	0.711972
Utah	Flora	13	0.709958	0.717965	0.008007	0.712534

Promontory small mammal (lagomorph dung and teeth from *Sylvilagus, Spermophilus, Microtus, and Leporid*) Sr isotope values show relatively small variation whereas large mammals (bison dung and mule deer teeth) from Promontory have a wider range (Table 2.3). Lagomorph dung from Promontory has a smaller range of values than bison dung from Promontory (Table 2.3). The Sr isotope values for modern cattle and sheep dung from the Promontory Caves fall within the range for floral and faunal samples recovered from Promontory Point (Figure 2.6, Table 2.3). The modern bison dung sample from Antelope Island was run in duplicate for an average Sr isotope result of 0.717374, which is high compared to other samples. Archaeological small mammal substrates (*Sylyilagus, Spermophilus, Microtus, Leporid,* unknown rodent) have higher Sr isotope values than archaeological mule deer teeth from Promontory Caves (Table 2.3).

Idaho Samples

The rodent tooth from WFRC had a Sr isotope value of 0.711039 and the bison tooth had a value of 0.710526. The difference between these values is 0.000513 (Figure 2.6).

Discussion

Preservation of Archaeological Materials

In general, the Promontory Caves have exceptional preservation of multiple materials from multiple species. All archaeological and modern samples used in this thesis appeared well-preserved to the naked eye (Figure 2.4). Previous studies have found excellent preservation of Promontory dung, hair, and bone based on %C and %N values (Metcalfe et al., 2021; Bowyer and Metcalfe, 2022) and DNA preservation (Shirazi et al. 2022). Good organic preservation is an indicator of overall preservation, but it does not guarantee that inorganic preservation is also good.

Teeth

The majority of teeth analyzed in this thesis had a [Sr] value in the range of 317-820 ppm. However, the mule deer teeth (FS-575.267 and FS-679.14) from Promontory have [Sr] outside of this range (84 and 2068 ppm, respectively) (Table 2.2). The very high [Sr] of mule deer FS-679.14 suggests that exogenous Sr may have been included in the digestion and analysis of this sample. For that sample, the piece of crown selected for analysis included an enamel fold that may have contained dentine that was not removed during sample preparation (Figure 2.4). This increases the likelihood of contamination since dentine is much more susceptible to diagenesis than enamel. It is notable, however, that the Sr isotope value of both mule deer teeth were similar (0.711204, 0.711126 respectively) (Table 2.2). The morphology of FS-575.267 likely includes only enamel, which is resistant to diagenesis. This suggests that the potential inclusion of exogenous Sr in FS-679.14 did not produce a major change in its Sr isotope value.

One might expect a narrow range of Sr isotope values for substrates that have been highly contaminated by soil Sr from the same location. The Sr isotope values of the small mammal teeth, which included both enamel and dentine, are higher and more variable when compared to the two mule deer teeth (0.711613-0.712069, 0.711126 and 0.711204, respectively) (Figure 2.11). If the mule deer teeth were contaminated, the small mammal teeth would also be expected to have contamination and thus expected to have similar values. This is not the case (small mammal teeth had Sr isotope values that were systematically higher than those of mule deer, Figure 2.11), suggesting that the values do not match the expectations for diagenetic alteration.

Dung

No quality control indicators exist for Sr isotope analysis of dung, and contamination with exogenous Sr is an important concern. The [Sr] of archaeological dung from Promontory (74-117 ppm) are consistent with the modern dung [Sr] from Antelope Island (101 ppm) and fit within the range of modern dung from Promontory (35-181 ppm) (Figure 2.9). These similarities in [Sr] suggest that relatively little Sr contamination of archaeological dung has occurred (Figure 2.9). Although the range of Sr isotope values of Promontory archaeological lagomorph dung is narrow, and thus could be a consequence of exchange with Sr in sediments, the range of Sr isotope values for archaeological bison dung is much wider (Figure 2.11). One caveat to this line of reasoning is that the modern dung samples from both locations were not collected immediately after excretion. Without [Sr] and Sr isotope values from freshly excreted dung from Promontory, there exists the possibility that exogenous Sr has contaminated both the modern and archaeological dung samples. Still, the consistency of [Sr] and Sr isotope values between modern dung and dung that were excreted centuries ago indicates that if exogenous Sr has contaminated the archaeological Promontory dung, a similar level of contamination in the modern dung samples occurred in a much shorter period of time. Future studies could analyze freshly excreted dung to compare the [Sr] and Sr isotope values with that of archaeological dung to further investigate if exogenous Sr contamination is likely.

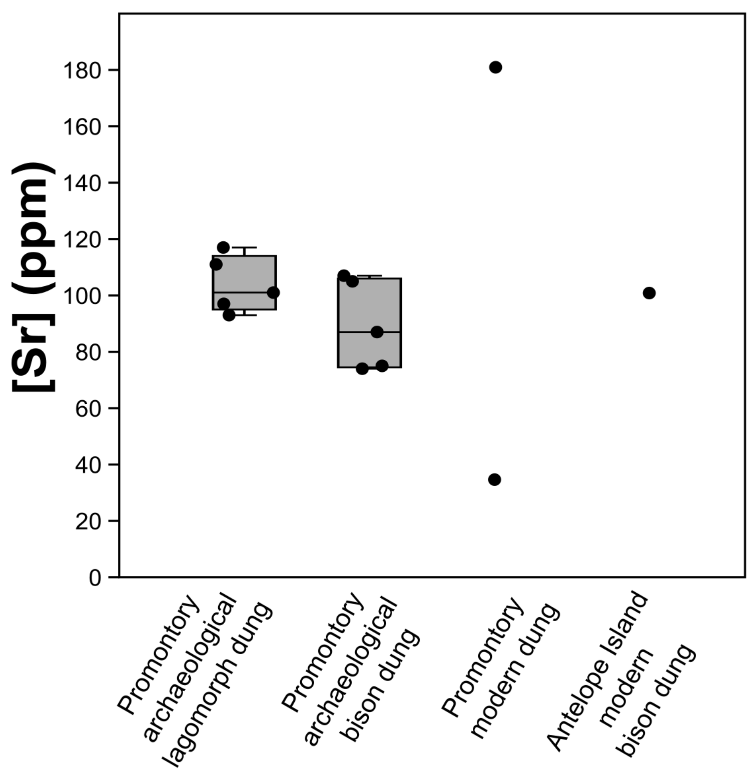

Figure 2.9. Strontium concentrations in archaeological and modern dung from Promontory Caves and Antelope Island.

Do the Sr isotope values of Utah flora and Promontory Point fauna differ from Sr isotope values in other parts of Utah?

Comparison With Previous Bedrock Sr Isotope Values

The Sr isotope values obtained for the Promontory Caves and surrounding areas in this study are higher than those previously obtained for other locations in Utah (Figure 2.10b). No Sr isotope values have been previously published for the Promontory Caves. However, Leeman (1970) obtained a Sr isotope result of 0.7104 from late-Cenozoic olivine basalt (igneous rock) that is approximately 18 km northeast of Promontory Caves 1 and 2 (Figure 2.10). The Sr isotope value for Leeman's basalt is lower at the third decimal place from all values obtained in this study for samples from Promontory Point. The lower Sr isotope value for the late-Cenozoic olivine basalt that Leeman analyzed is expected as this lithology is younger than the Middle-Cambrian sedimentary rock that the Promontory Caves are largely situated on (https://mrdata.usgs.gov/geology/ state/). This demonstrates that locations in close proximity do not necessarily have the same Sr isotope value. Bison who roamed the area around the Promontory Caves could have grazed over the younger igneous bedrock and thus have a lower Sr isotope signal than the substrates analyzed in this thesis. While the bison would have had to consistently graze over the igneous rock for the Sr isotope signal to be incorporated into the skeleton (i.e., bones and teeth), bison dung would reflect the igneous Sr isotope value if the bison had grazed over it within 24-72 hours prior to deposition. None of the bison dung samples analyzed in this thesis reflect such a low value.

Comparison With Archaeological Small Mammals at Fremont Sites in Utah

Lambert (2019a,b) obtained Sr isotope values from a total of 75 archaeological small mammals (lagomorph and rodent) incisors to determine a Sr baseline for nine archaeological Fremont sites in central and southern Utah (Figure 2.10). Archaeological small mammal substrates (teeth and dung) from Promontory have higher Sr isotope values than those of small mammal incisors found at these Fremont archaeological sites which are southeast of the Promontory Caves (0.711613 to 0.712069 versus 0.70724 to 0.71071, respectively) (Figure 2.10).

There is no clear north-south variation in Sr isotope values among the sites analyzed by Lambert (2019a,b). Rather, there is a significant overlap in Sr isotope values at archaeological Fremont sites in central and southern Utah (Figure 2.10). The Icicle Bench site has much lower values than all sites at the second or third decimal place, despite being in close proximity to Five Finger Ridge (<5 km). Lambert (2019a) explains that Icicle Bench and Five Finger Ridge are located within a canyon that cuts through both Miocene and Pliocene deposits. Varying geologies likely explain why there is variability between the sites. The Sr isotope ranges for the sites Paragonah and Parowan are highly variable at the second decimal place despite also being in close proximity to one another. Paragonah and Parowan are located on similar geologic settings, however, each site has different creek water sources passing through (Lambert, 2019a). Thus, incoming water sources are likely contributing non-local Sr to each site. While Sr isotope values from Paragonah and Parowan may not be reliable due to the possible influence of non-local Sr, the baselines for the other archaeological sites created by Lambert indicate that there is variability in Sr isotope values for multiple sites in Utah.

The differences in Sr isotope values between sites are important for reconstructing mobility patterns within Utah. The magnitude of difference in Sr isotope values is at the second or third decimal point between northern Promontory Caves and more southern sites studied by Lambert. Many Sr isotope studies of migration infer geographical movements based on variations at the fourth (Bataille et al., 2020) or fifth decimal place (e.g., Bentley, 2006, Price et al., 2002).

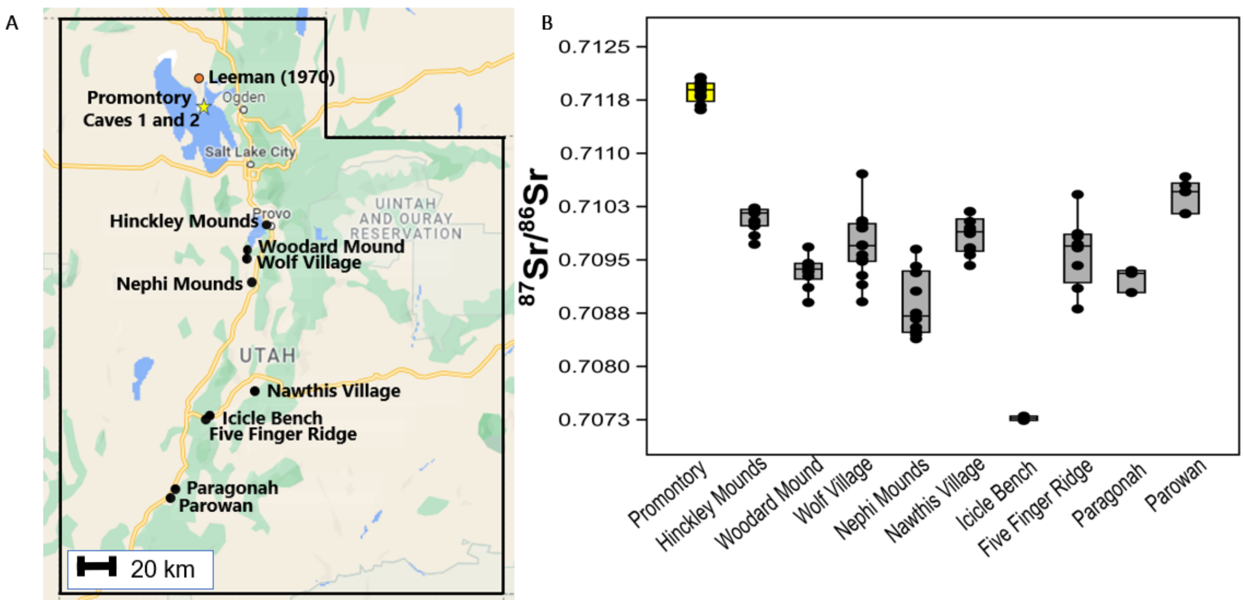

Figure 2.10. Sampling locations of previously published Sr isotope values in Utah. The orange circle represents late-Cenozoic olivine basalt analyzed by Leeman (1970). Black circles represent nine archaeological Fremont sites from which small mammal samples were analyzed by Lambert (2019a,b). (b) Comparison of Sr isotope values obtained from ancient small mammal substrates recovered from Promontory Point (this thesis) and nine Fremont sites across Utah (Lambert 2019 a,b) separated by site.

Comparison With Antelope Island

The Antelope Island modern bison dung value (0.717374) falls within the high end of the range for modern plants recovered from Utah (only one plant has a higher value) and is much higher than the values of Promontory animal substrates (by 0.004068 at the least and 0.006248 at the most) (Figure 2.6). However, the Sr isotope value of the Antelope Island sample is very similar to the average Sr isotope value of brine from Great Salt Lake (0.7174 ± 0.0004) (Jones and Faure, 1972). It has been shown that in coastal environments, the Sr isotope values of plants are very similar to that of the ocean and an analogous effect could be affecting plants growing around Great Salt Lake (Alonzi et al., 2020; Bentley, 2006; Elderfield, 1986; McArthur et al., 2001; Veizer, 1989). While the salinity of Great Salt Lake changes seasonally and annually, its salt concentrations are typically several times that of the ocean and some areas reach salt saturation (Davis et al., 2022). Due to the extreme saltiness of Great Salt Lake, it is a major contributor of Sr to local plants and animals. In 1966, the brines from the northern arm of the lake had [Sr]'s of 4-6 ppm (Whelan, 1973).While the input of Sr from the lake will not completely blanket the contribution of Sr from bedrock, it will introduce variability between geologic and bioavailable Sr.

Although both Promontory Caves and Antelope Island exist on landforms that extend into Great Salt Lake, only the Antelope Island Sr isotope values are consistent with those of Great Salt Lake, whereas animal samples from Promontory Point are different at the third decimal place. A possible explanation as to why the Promontory bison are not experiencing this effect may be that those bison were not frequently in as close proximity to Great Salt Lake. While Antelope Island bison are confined to a relatively small area around the lake, the Promontory bison would have been free-ranging. Rather than grazing directly along the shores of Great Salt Lake, as Antelope Island bison do, Promontory bison may have primarily grazed high on Promontory Point and in areas further from the lake, thus not intaking as much Sr from Great Salt Lake as Antelope Island bison do.

Which substrates best represent a 'local baseline' for Promontory?

Modern vs. Archaeological Samples

The Sr isotope values for the modern cattle and sheep dung from Promontory overlap with the higher values for archaeological animal substrates and modern plants from Promontory Point (Figure 2.6) (Table 2.3). While only two modern samples were analyzed and were not freshly excreted, the results indicate that the archaeological and modern Sr isotope values on Promontory Point are likely similar.

Plant Species Comparison

The only semi-aquatic plant sample (*Phragmites*) from Promontory Point is higher at the third decimal place than the terrestrial plants (*Sarcobatus, Juniperus, and Chrysothamnus*) which show consistency in their values (Figure 2.8b). Grimstead and colleagues (2017) point out that water can represent a mixing of Sr isotope values since tributary water bodies (i.e., creeks, rivers, mountains, and meltwater) can have different sources of Sr. Non-local Sr is likely fed into Great Salt Lake from other bodies of water (via rivers), and may be taken up by plants growing along the shoreline. As well, the salty lake spray has the potential to influence the isotopic values of plants growing near the shore (Alonzi et al., 2020; Evans et al., 2010; Snoeck et al., 2020; Whipkey et al., 2000), which could result in unique values near the lake. Perhaps this is also why two *Phragmites* plants sampled ~2.5 km apart (from Bear River and Bear River Wetlands), also show a difference at the second decimal place despite being geographically close. This can serve as a caution that aquatic and semi-aquatic substrates can have Sr isotope values derived from multiple sources.

Animal vs. Plant Substrates

Since the small mammals' Sr isotope range fits within the Promontory Point plant range, it is likely that the small mammals recovered from the caves were not obtained from distant localities but were local to the area around the Promontory Caves (Figure 2.11). This indicates that both plants and small mammal remains (teeth and dung) can be used to create a local bioavailable Sr isotope value for Promontory Point.

The fact that the Sr isotope range for Promontory plants is wider than the range for small mammals shows that small mammals do not represent the entire range of bioavailable Sr in the region. Instead, small mammal tissue represents an averaged value of the dietary plants.

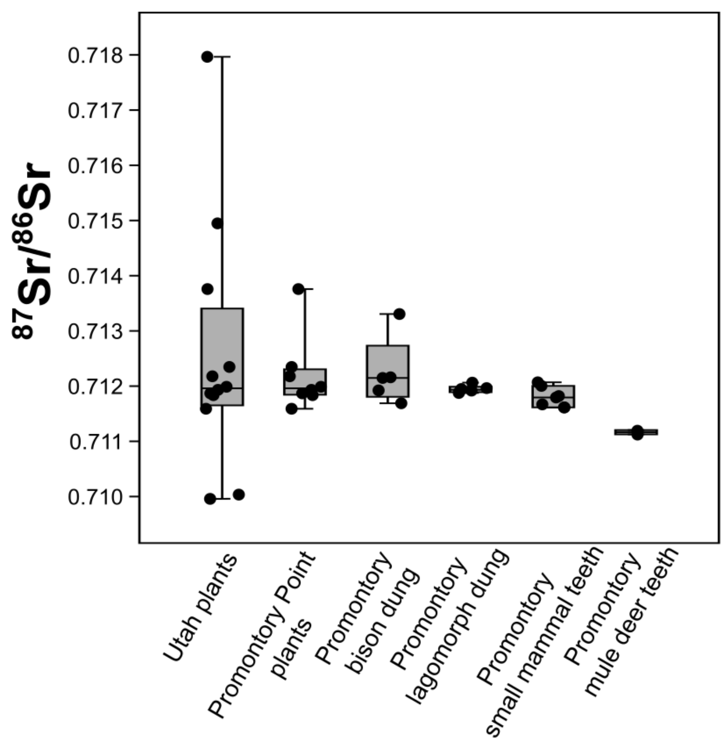

Figure 2.11. Comparison of Sr isotope values obtained from modern Utah plants and archaeological animal teeth and dung from Promontory separated by material and taxa. Promontory Point plant data points are repeated in Utah plants. Small mammals include *Sylvilagus*, *Spermophilus*, *Microtus*, and *Leporid*) recovered from Promontory Caves.

The range of Sr isotope values for Promontory large mammals overlaps with that of small mammals; however, the small mammals from Promontory Caves have a narrower range (Figure 2.11). The greater variability in large animals probably reflects the consumption of plants with variable Sr isotope values over a wider geographical area.

The small mammal values include teeth from a variety of species as well as lagomorph dung. The range of values for lagomorph dung is narrow (0.711876-0.712063) and fits within the range of values for small mammal teeth (0.711613-0.712069) (Figure 2.11). This could be because a variety of species' teeth were sampled, not only lagomorph. Thus the teeth values represent a wider range of dietary strategies than the lagomorph dung.

Comparison of Animal Species

Sr isotope values of Promontory Caves archaeological small mammal teeth and dung and bison dung are relatively consistent with each other. However, the two Promontory mule deer have comparatively lower Sr isotope values (at the third or fourth decimal place) than the other Promontory animals (Figure 2.11). The difference between mule deer and small mammals could be because mule deer have a larger home range, and thus graze from a wider range of geologic surfaces compared to small mammals. The difference between mule deer and bison could be due to the different diets and habitats of the two species. In general, mule deer are mixed feeders whereas bison are grazers. Mower and Smith (1989) found that the winter diets of mule deer in northern Utah were 57% shrubs, 15% forbs, and 28% grass. Van Vuren (1984) studied the summer diets of bison (*Bison bison*) in the shrub-steppe Henry Mountains, Utah, and found that most of the diet (~99%) was grasses and sedges, of which ~66% of those was *Poa* spp. (meadow-grasses). If each species' preferred diet tended to grow in areas with different Sr isotope compositions, it could explain the different values. Alternatively, the mule deer could simply have had very different geographical ranges than the other taxa.

Is dung a useful baseline substrate for Sr isotope studies?

The Sr isotope values of the archaeological bison dung are consistent with the results of ancient small mammal teeth and dung as well as those of modern plants collected from Promontory Point (Figure 2.11), suggesting that herbivore dung reliably represents local Sr isotope values. Despite the selection of plants that were not necessarily part of bison diets, there was overlap between the Sr isotope values of these plants and bison dung. The PCA (Figure 2.5) provides further evidence that herbivore dung is representative of ingested plant material since the trace element makeup of dung (in PCA space) overlaps with that of plant material. The similarities in [Sr] values of archaeological dung from Promontory to modern dung collected from Antelope Island and Promontory do not support the contention that exogenous Sr is a major concern (Figure 2.9).

It is noteworthy that the Sr isotope value for bison dung sample FS-660 (0.713306) is higher by at least 0.001617 than the other four bison dung samples, which have a relatively small range (0.711689-0.712160). Since bison dung may consist of plant matter consumed in multiple areas within the 24-72 hours prior to deposition, this animal could have been ranging some distance from the Promontory Caves before its dung was deposited. Alternatively, individual FS-660 could have been grazing in a nearby area with a higher Sr value than the area utilized by most of the other bison.

Overall, this thesis suggests that archaeological bison dung reflects the local Sr isotope value of Promontory. This indicates that dung could be used as a single substrate in a Sr baseline for a specific species in future mobility studies. Dung would provide a Sr isotope range that is specific to the dietary habits of the species of interest. Dung belonging to the study's focal species (i.e., bison) is the ideal substrate to represent local dietary Sr compared to tissues that form over longer periods of time (i.e., enamel). However, care must be taken to exclude modern dung from animals that were supplemented with non-local feed, which might alter their Sr isotope values.

Determining the local Sr baseline for Promontory

To determine whether or not an individual or object was local to Promontory, a Sr baseline must be determined using substrates that are reliably local. This thesis suggests that the small mammal teeth and dung, and bison dung collected at Promontory Point all reliably reflect the local Sr isotope value for Promontory. This is because the range of Sr isotope values of these substrates consistently overlap with that of modern plants which are reliably local and reflect a wide range of bioavailable Sr in the area around the Promontory Caves. Thus, a robust baseline for Promontory Point that reflects this wide range of Sr bioavailability is defined as 0.711590 to 0.713758. This includes Sr isotope values from modern plants, archaeological bison dung, small mammal dung, and small mammal teeth. The creation of a robust baseline for Promontory lays the framework for future provenience studies from the Promontory assemblage.

A more targeted Sr baseline for *bison* mobility at the Promontory Caves should be defined as the range of Sr isotope values obtained from Promontory bison dung. The range for Sr isotope values of bison dung from the Promontory Caves is narrower than that of plants from

Promontory Point (Figure 2.11) which reflects how an individual may not consume all the plant species available in a region and thus not intake a full range of bioavailable Sr. As well, bison are not known to consume any plant species analyzed in this thesis while dung reliably represents dietary intake. Thus, for a baseline specific to the objective of reconstructing bison mobility, the addition of plant matter collected from Promontory Point in the baseline is unnecessary. Therefore, a baseline defined as 0.711689 to 0.713306, analyzed from archaeological bison dung collected from the Promontory Caves in this study defines a bison-specific Sr baseline for determining bison locality at Promontory.

Do the Sr isotope values of WFRC fauna differ from Sr isotope values in other parts of Idaho?

The Snake River Plain (SRP) is dominated by igneous basalts or more specifically, Pliocene-Holocene olivine tholeiites, which are characterized by a high degree of mineralogical and chemical similarity (Leeman and Manton 1971:423). Although some igneous regions exist near WFRC, the area is composed largely of sedimentary rock. Unfortunately, no previous Sr isotope values exist for the sedimentary rock in this area. Comparing Sr isotope values from the WFRC bison and rodent to the geologic Sr values of the Cenozoic igneous province that exists north of WFRC (0.7060-0.7080; Leeman and Manton, 1971), the archaeological animal values from this study are non-overlapping and substantially higher (0.710526, 0,711039). The lower Sr isotope values for the igneous rock at SRP are expected as this lithology is younger than the Permina-Pennsylvanian sedimentary rock at WFRC (https://mrdata.usgs.gov/geology/state/), hence, the ^{87}Rb has had more time to decay into ^{87}Sr, providing a higher ^{87}Sr/^{86}Sr value. More small mammal samples are necessary to strengthen the WFRC baseline and allow better interpretation of mobility at WFRC, but this study provides a starting point.

Do the Sr isotope values of Promontory fauna differ from those of WFRC?

The Sr isotope values in mammal substrates suggested to represent a 'local' Sr isotope value for the Promontory Caves (bison dung, lagomorph dung, and small mammal teeth) and WFRC have no overlap and reveal a difference between sites at the fourth decimal place, demonstrating very different Sr isotope values for these two locations (Figure 2.12). Although there are only 2 samples from WFRC, the fact that their Sr isotope values are both lower than any of the Promontory animal values suggests that the opportunity for bison mobility research in this area is promising.

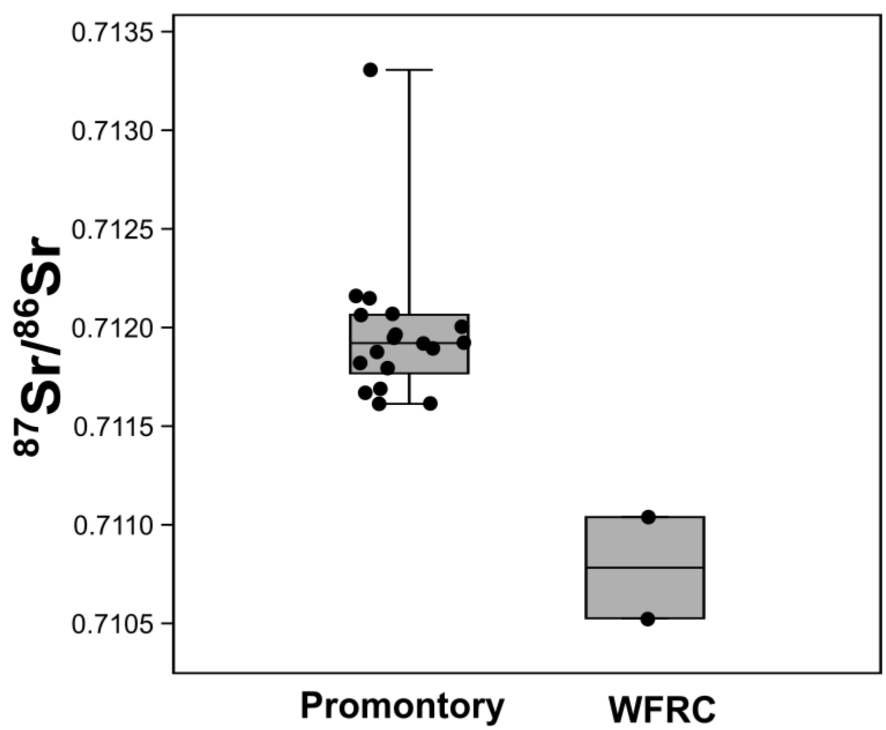

Figure 2.12. Comparison of Sr isotope values obtained from ancient fauna substrates recovered from Promontory Caves, Utah (bison dung, small mammal dung and teeth) and WFRC, Idaho (rodent and bison teeth), separated by site.

Conclusions

Using the full range of Sr isotope values analyzed from plants collected from Promontory Point and archaeological bison dung and small mammal teeth/dung collected from Promontory Caves defines a robust Sr isotope baseline for Promontory as 0.711590 to 0.713758. In addition, a preliminary Sr isotope baseline for WFRC, based on teeth from an archaeological rodent and a bison is defined as 0.711039 to 0.710526, respectively. Although additional WFRC samples should be analyzed, the two WFRC values obtained here are different from those of Promontory at the fourth decimal place. This is a large-magnitude difference and suggests that the opportunity for studying bison movements between Promontory and WFRC is promising.

The comparison of [Sr] between modern and archaeological dung from Promontory and Antelope Island supports the conclusion that there was relatively little exogenous Sr in the archaeological dung samples from Promontory. In terms of lagomorph dung, the narrow range of Sr isotope values could indicate contamination, or alternatively, they could have resulted from the smaller home range of lagomorphs relative to bison. Further study of diagenetic effects on Sr isotope compositions of dung should be completed in the future.

Sr isotope values from bison dung overlap with the values of reliably-local modern plants, and also overlap with the values from theoretically-local archaeological small mammal dung and teeth. This overlap reinforces the idea that the use of herbivore dung can strengthen the reliability of an Sr baseline.

Herbivore dung contains plants that were consumed relatively close to the site of deposition and reflects an integration of plants consumed over more than a day. Thus, archaeological bison dung recovered from the Promontory Caves is an ideal substrate for creating a Sr isotope baseline specific to the objective of determining *bison* locality at

Promontory Caves. For reconstructions of bison migration based on bones or teeth, which form over longer periods of time, the ideal baseline is defined as 0.711689 to 0.713306, obtained from archaeological bison dung collected from the Promontory Caves.

Not only does Promontory have a unique Sr isotope signature compared to WFRC, but previously-published Sr isotope values from Fremont sites located south of the Promontory Caves are also different at the second or third decimal place. These differences indicate that there is strong potential for using Sr isotopes to investigate human and animal mobility in Utah. Comparing the geographic ranges of archaeological bison from Promontory Caves and WFRC has the potential to provide insight into landscape use by ancient peoples. There is also potential for analyzing other animals' teeth from Promontory whose Sr isotope values might be used to investigate trade and human mobility. As well, future research could compare the sourcing of artifacts such as gaming pieces made from *Phragmites* plants (Yanicki and Ives, 2017; Yanicki, 2019).

The difference between the Sr isotope values of bison dung from Promontory and that of Antelope Island is interesting since it appears that the Antelope Island bison Sr isotope values are very similar to that of Great Salt Lake. A possible explanation is that the bison killed at Promontory did not frequent the shores of Great Salt Lake, but rather were more often local to the area around the Promontory Caves. Future studies may consider analyzing more Antelope Island specimens to further study this effect.

Future analytical needs for bison migration research in this region requires precision to the third decimal place. This indicates that we probably do not require the higher precision of TIMS, but rather could use a less expensive, less precise analytical technique called laser ablation-inductively coupled plasma-mass spectroscopy (LA-ICP-MS). LA-ICP-MS requires minimal sample preparation and can be accomplished with very small sample sizes. LA-ICP-MS also has higher resolution, meaning we can chronologically micro-sample multiple points on a single tooth or bone thin section to return a ‘timeline’ of Sr values.

THESIS CONCLUSIONS

Research Summary

This thesis reviewed common Sr isotope baseline substrates and then used this knowledge to pilot the creation of a robust Sr isotope baseline for the Promontory Caves, Utah, and a preliminary Sr isotope baseline for West Fork Rock Creek, Idaho. The exceptional preservation in the Promontory Caves also permitted the comparison of Sr isotope values between multiple substrates. Overall, these data provide important baselines for future studies of locality at the Promontory Caves.

This thesis defines a comprehensive Sr isotope baseline for the area around Promontory as the range of values between 0.711590-0.713758. This baseline was obtained from archaeological terrestrial small mammal teeth, archaeological lagomorph dung, archaeological bison dung, modern plant materials (*Phragmites sp., Chrysothamnus sp., Juniperus sp., and Sarcobatus sp.*). The range of Sr isotope values from Promontory bison dung alone is 0.711689 to 0.713306. Through this comparison, I was able to support the idea put forward by Chase and colleagues (2018) that herbivore dung (or alternatively the dung of the species whose migration you are interested in analyzing), is an excellent substrate for a Sr baseline. Dung reflects a relatively local and recent intake of dietary Sr. Thus, the archaeological bison dung recovered from the Promontory Caves is likely a useful substrate for comparison to Promontory bison tissues that form over longer periods of time (i.e., bones and teeth).

The Sr isotope baseline for Promontory was found to be higher than West Fork Rock Creek's at the fourth decimal place, and also higher at the second or third decimal place compared to previously published Sr isotope values for Fremont sites in Utah south of

Promontory along the Wasatch Front. This indicates that future provenience studies in this region can confidently employ Sr isotope analysis to provide direct evidence of mobility.

Future Directions

In the future, an experimental study should be conducted to better assess the preservation of dung Sr isotope compositions. This could include collecting dung samples from animals on Promontory Point and Antelope Island immediately after excretion to compare the [Sr] and Sr isotope values to that of dung analyzed in this thesis. This will further support the conclusion in this thesis that bison dung from Promontory Caves is an ideal substrate for an Sr isotope baseline.

This thesis initiated the application of geochemical studies to research ancient mobility at the Promontory Caves. Not only are the conclusions of this thesis relevant to bison mobility at Promontory, but there is also potential for comparing the geographic mobility and sourcing of artifacts and other remains recovered at Promontory. For example, the caves contain gaming pieces made from *Phragmites* plants and animal teeth whose Sr isotope values might be used to investigate trade and human mobility (Yanicki and Ives, 2017; Yanicki, 2019).

Since the Sr isotope values from Promontory and WFRC were different at the third decimal place, future studies of Promontory bison migration could use a less precise and less expensive analysis called laser ablation (LA-ICP-MS). LA-ICP-MS has higher resolution, meaning we can micro-sample multiple points of enamel and/or bone to gain a sequence of Sr isotope values, and thus a ‘timeline’ of mobility.

To achieve the ultimate goal of determining the migrational range of Promontory bison, future researchers should obtain Sr isotope values from archaeological bison tissue recovered from Promontory Caves to advance our knowledge of bison mobility in the Eastern Great Basin region. Specifically, future analyses should include micro-sampling of multiple points (via laser ablation) on bison bone, teeth, and hair. These tissues each develop by a chronological sequence of deposition. Using previously published deposition rates, specific areas on the tissues can be targeted for Sr isotope analysis to give a sequence of values, in turn, giving us a 'timeline' of mobility.

Sr isotope analyses should be able to reveal whether the bison at Promontory Caves and WFRC, Idaho had overlapping ranges or if the sites were occupied by herds with distinct ranges. Comparing the geographic range of ancient bison from Promontory and WFRC could provide insight into Promontory hunting strategies and why the occupation at Promontory ceased after A.D. 1290. This will aid in understanding the relationship between humans and bison as they navigated the changing landscape of the late thirteenth century.

Appendix

Table A.1. Dung and plant sampling location coordinates. Coordinates unavailable for plant samples 'Bag 12', 'Bag 13', 'Bag 14' from Promontory Landforms 1 and 2.

Material	Location	Sample ID	Type	Coordinates
Dung				
	Antelope Island	AI-009	*Bison bison*	40.90576, -112.17198
Plants				
	Bear River	Bag 2	*Phragmites*	41.529428, -112.081176
	Bear River Wetlands	Bag 4	*Phragmites*	41.508781, -112.070176
	Chournos Springs/ Granitic Wash	Bag 7	*Phragmites*	41.321367, -112.495133
	Chournos Springs/ Granitic Wash	Bag 9	*Sarcobatus*	41.322783, -112.494517
	Chournos Springs/ Granitic Wash	Bag 10	*Sarcobatus*	41.321317, -112.49315
	Chournos Springs/ Granitic Wash	Bag 11	*Sarcobatus*	41.322883, -112.49415
	Promontory Landform 1	Bag 12	*Sarcobatus*	N/A
	Promontory Landform 2	Bag 14	*Juniperus*	N/A
	Promontory Landform 2	Bag 15	*Chrysothamnus*	N/A
	Promontory Cave 3	Bag 13	*Juniperus*	41.35054, -112.5172
	Provo River Delta	Bag 3	*Phragmites*	40.238461, -111.726623
	Utah Lake/Provo River	Bag 1	*Phragmites*	40.236670, -111.735818
	Willard Bay	Bag 5	*Phragmites*	41.339276, -112.098106

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