Residential Mobility in the Prehistoric Southwest United States: A Preliminary Study using Strontium Isotope Analysis

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Strontium isotope ratios and strontium concentrations in bone and tooth enamel are used to investigate patterns of residential mobility and migration in the late prehistoric (14th century) period in the mountain province of east-central Arizona. This area is of interest because of significant questions concerning the movement of people into and within the region and because of the number of late prehistoric sites with well-studied burial populations. Grasshopper Pueblo is the main focus of analysis, with additional information from the site of Walnut Creek.

A pilot strontium isotope study of bone and tooth enamel of first molars from the Grasshopper and Walnut Creek regions has demonstrated intriguing variability in strontium isotope compositions of human samples and indicates a significant probability of the success of the investigations proposed here. This initial work indicates that there are measurable and meaningful differences between bones and tooth enamel from the same individuals, among individuals from the same site, and between communities in the study area.

Keywords: STRONTIUM ISOTOPE ANALYSIS, PREHISTORIC MIGRATION, AMERICAN SOUTHWEST, GRASSHOPPER PUEBLO, WALNUT CREEK.

Introduction

In this paper we report on the results of a preliminary study of migration and residential mobility in the late prehistoric Southwest United States using strontium isotope ratios and strontium concentrations in human femurs and the enamel of the first molar. Strontium (Sr) is an alkaline earth element that has no demonstrable essential biochemical or physiological function; its chemical behaviour is similar to that of calcium, although Sr has a larger ionic radius. Strontium commonly substitutes for calcium, including fixation in the crystalline lattice of hydroxyapatite in bone and teeth (Likins et al., 1960; Schroeder, Nason & Tipton, 1972; Rosenthal, Chochran & Eves, 1981; Nelson et al., 1986). Bone undergoes a complete replacement cycle of its inorganic phase every 7–10 years, which suggests that bone strontium content and isotopic composition reflects approximately the last 10 years of the life of the individual (Lowenstam &
Weiner, 1989). The enamel in teeth, which forms during childhood, has no organic structures penetrating it; as such it is considered dead tissue which does not recrystallize after formation (Steele & Bramblett, 1988). Differences in strontium isotope ratios of the bones and tooth enamel of an individual have great potential for reflecting the residential history of a population.

Initial research on fossil and modern animals (Ericson, 1985, 1989; Sealy, 1989) has demonstrated the potential for using strontium isotope ratios for studying questions of migration and inter-regional movement. Sealy's (1989) study of inland versus marine diets in South Africa represents the most detailed application to date. In her analysis she was able to distinguish groups of people on the basis of type of diet and thus could infer patterns of movements of the different groups. More recently, Sealy et al. (1991) have demonstrated an effective protocol for evaluating the effects of diagenesis (post-mortem contamination) of bone in strontium isotope ratios, which is discussed in greater detail below. The sensitivity of strontium isotope ratios to distinct geological regions has proved effective in identifying areas in South Africa from which elephant ivory was poached (van der Merwe et al., 1990; Vogel, Eglington & Auret, 1990).

The focus of the present study is Grasshopper Pueblo, a 14th century 500-room masonry pueblo located on a Palaeozoic limestone terrain in the White Mountains of east-central Arizona. Additional data are considered from the earlier pithouse site of Walnut Creek, located less than 20 km west of Grasshopper on a terrain of Pre-Cambrian diabase. Strontium elemental concentrations in bone and tooth enamel should be a measure of the trophic position of the individual, whereas strontium isotope ratios in human bone and tooth enamel are a reflection of the geology of the area where that individual lived. Central Arizona is exceptionally well suited for these investigations because geological units are diverse and well studied and their strontium isotope compositions, which vary markedly between physiographic provinces, are known in detail (Figure 1).
Migration and Residential Mobility in the Prehistoric Southwest

Human demography of the late prehistoric American Southwest can be described to a large extent by movements of people across the landscape. Indeed, Paul S. Martin (1970: 198) has referred to population movements as “one of the oldest concerns of Southwestern archaeologists”. Despite numerous archaeological investigations and discussion of population movements in the greater Southwest (e.g. Fewkes, 1900; Reed, 1950; Gladwin, 1957; DiPeso, 1958; Haury, 1958; Davis, 1964; Jeff, 1964; Dean, 1969, 1970; Schwartz, 1970; Franklin & Masse, 1976; Stebbins, 1977; Upham, 1982; Plog, 1983; Blake, Le Blanc & Minnis, 1986; Lindsay, 1987; Euler, 1988; Reid & Tuggle, 1988; Cordell & Gunterman, 1989; Reid, 1989), recent attempts to focus specifically on inter-regional resettlements of people are relatively few (cf. Blake, Le Blanc & Minnis, 1986; Lindsay, 1987; Euler, 1988). The formidable body of evidence dealing with population movements in the Southwest reaffirms the need to recognize the significance of human mobility.

Population movements reflect a complex pattern of both inter- and intra-regional mobility. For example, Fewkes’ (1900) study of clan structure and ritual at Hopi pueblos represents one of the first attempts to relate modern pueblos in the Hopi region to their prehistoric counterparts. His results indicate that certain Hopi towns were peopled largely by immigrants from the Tanoan region, and that migrations probably played a significant role in settlement systems that extended back into the prehistoric period. From these data, Fewkes warned against assuming that prehistoric sites in the Hopi region were occupied exclusively by direct ancestors of the Hopi.

Haury (1958) presents the strongest case yet for residential mobility in the prehistoric Southwest, suggesting that immigrants from the Kayenta-Hopi region migrated to Point of Pines in the late 13th century AD. Several lines of evidence, including architecture (a 70-room block built during the 1280s containing a D-shaped kiva), ceramics, imported maize and wood, and ceremonial paraphernalia led to this interpretation. Conflict with local inhabitants is inferred from evidence of conflagration which swept through the entire roomblock. However, Reed (1958: 7) notes that the Point of Pines evidence is an unusual case, and that “many proposed hypotheses of migration . . . have been based on pottery types alone, or on no actual evidence whatever.” Plog et al. (1989) claim that the Kayenta migration into Point of Pines and the San Pedro Valley (DiPeso, 1958) is the only well-documented migration in the prehistoric Southwest. Bennett’s (1973) skeletal analysis of the Point of Pines fails to support the evidence for migration, but it may be that, due to the long tradition of mobility in the Southwest, the populations of the Colorado Plateau and Transition Zone during the pueblan period are not phenotypically distinct. There is possibly Anasazi occupation at Grasshopper Pueblo as well, but the evidence is more equivocal (cf. Reid, 1989: 87–88).

Social/ethnic diversity within the aggregated pueblos of the 14th century AD Southwest has long been recognized and considered critical for an understanding of late prehistoric adaptations (e.g. Haury, 1958; Scarborough & Shimada, 1974; Longacre, 1976; Schiffer, 1976; Graves, Longacre & Holbrook, 1982; Reid & Whittlesey, 1982; Upham, 1982; Cordell, Upham & Brock, 1987; Lindsay, 1987; Reid, 1989; Reid et al., 1989; Kintigh, 1990). Social/ethnic diversity at large pueblos is thought to arise from intra- and inter-regional mobility; investigations of this issue have focused primarily on identification of local versus non-local traits or on intra-site variation in ceramic design (e.g. DiPeso, 1958; Haury, 1958; Hill, 1970; Longacre, 1970; Franklin & Masse, 1976). The evidence is equivocal and interpretations tenuous because of the uncertain association between artefacts and their makers. Nevertheless, recognition of distinctive patterning of artefact traits has allowed archaeologists to examine questions such as the nature of pueblo social organization, residence and marriage patterns, and conflict between groups (Haury, 1958; Hill, 1970; Longacre, 1970; Upham, 1982; Plog, 1983; Reid, 1989).

For example, Longacre’s (1964a, 1970) inference of a matrilocale residence pattern at the Carter Ranch site was formulated primarily on the basis of intra-site distribution of ceramic designs (as well as on the assumption, based on analogy to modern pueblos, that pots were manufactured by women).

A more compelling case for social/ethnic diversity is presented by Dean (1969, 1970). Using tree-ring data, he focused attention on the occupational histories of Kiet Siel and Betatankin in Tsegi Canyon, and found marked differences in the building sequences between the two cliff-dwellings. Kiet Siel is characterized by a notable lack of planning; several discrete building episodes occurred, and the heterogeneity of architectural forms and techniques suggest settlement of the sites by different social groups.

Evidence of Diverse Social Groups at Grasshopper Pueblo

Grasshopper Pueblo (Figure 2) is a particularly important case study of immigration because of the intensive study that has focused on the pueblo’s growth and development. Aggregation at Grasshopper, in the late 13th century, suggests coexistence of three social groups during the founding of the site. The earliest construction phase at each of the three, spatially discrete, major roomblocks dates to the late 13th century, coinciding with the Great Drought (Longacre, 1976; Dean & Robinson, 1982). By this time the Chevelon region, northwest of Grasshopper, was undergoing
depopulation and it is likely that some of its population moved into the Grasshopper Region (Euler, 1988). Other depopulated regions whence people may have relocated in the mountain province include Hopi Buttes and the Upper Little Colorado River (Longacre, 1964b; Euler, 1988).

Significant distinctions between the major roomblocks at Grasshopper include architectural style (Scarborough & Shimada, 1974), frequency and occurrence of ceramic wares (Mayro, Whittlesey & Reid, 1976; Reid & Whittlesey, 1982), household configuration (Ciolek-Torello & Reid, 1974), cranial deformation [the majority exhibiting occipital deformation (Birkby, 1973, 1982)], differential occurrence of skeletal pathologies (Berry, 1985a,b), rate of growth (Graves, Longacre & Holbrook, 1982; Reid & Shimada, 1982), and treatment of the dead (Whittlesey, 1978). Regarding this last factor, for example, a possible Salado presence at the site is indicated by the association of Pinedale style Pinto-Gila polychromes with Great Kiva (Plaza III) burials (Mayro, Whittlesey & Reid, 1976). Graves, Longacre & Holbrook (1982) state that simultaneous construction of the major three roomblocks within 100 m of one another is a substantial departure from the earlier pattern of small, dispersed pueblos in the region, suggesting social diversity among the founding groups. Speculation regarding the practice of group inter-marriage has also been considered (Reid & Whittlesey, 1982).

Birkby (1973, 1982) examined discrete attributes of crania from Grasshopper, Turkey Creek, Point of Pines and Kinishba, and on the basis of these morphological traits suggests that the inhabitants of the sites represent a single biological population. Birkby was also able to delineate two distinct social/ethnic cemetery areas at Grasshopper and argued for male exogamy in the marriage pattern. He suggests that women from Roomblock 1 at Grasshopper were marrying men from either Roomblock 2 or 3 and relocating into those roomblocks, although he acknowledges his evidence is equivocal at best. He also considered biological distance between the populations of the four pueblos. Turkey Creek and Point of Pines were most closely related, and Point of Pines and Grasshopper were slightly more closely related than Turkey Creek and Grasshopper. Kinishba was the most distantly related to all three (Figure 3).

Shipman (1982), utilizing the same skeletal series, examined discrete and metric traits of the axial and appendicular skeletons and found discordant results when comparing the axial and appendicular skeleton. Discrete and metric traits of the axial skeleton argue for a single biological population, while the discrete and metric traits of the appendicular skeleton suggest that several distinct populations coexisted during the late prehistoric period in east-central Arizona. Shipman notes that values for appendicular skeletal traits are less consistent than those of the axial skeleton. A comparison of the skeletons from the east and west units at Grasshopper revealed that males exhibited a significant Pearson's Lambda Criterion ($P=0.025$) while females did not ($P=0.60$). This is a measure whereby the probabilities from tests of significance for any number of discrete traits are combined and tested for significance, and the results tend to support Birkby's hypothesis. Since postcranial metric traits of males from the east and west units are extremely similar, however, Shipman states that it cannot be concluded that these are distinct biological populations. On the whole, he argues for considerable morphological homogeneity in the late prehistoric populations of east-central Arizona. This does not, however, preclude the possibility of aggregation by distinctive social groups emigrating from geologically distinct regions (see below).

In summary, there are a number of suggestions of population movement and residential shifts in the archaeological record but evidence remains ambiguous. The archaeological record has been well studied but it has been generally impossible to differentiate the movement of people from the movement of ideas and
artefacts. As noted above, Reed (1958) suggests that many inferred cases of migration in the Southwest probably indicate movement of goods across regions. The biological evidence is useful for distinguishing potentially different groups within and between pueblos but has not been able to determine the range of variability for a biologically distinct population. Thus a different line of evidence from skeletal remains is needed to resolve questions concerning population movement and residential mobility in the prehistoric Southwest.

Methods of Investigation

Strontium contents and isotope ratios in rock, groundwater, soil, plants and animals vary depending on local geology (Dasch, 1969; Hurst & Davis, 1981; Faure, 1986). Although strontium concentrations in plant and animal tissue vary with trophic position, the isotopic composition of strontium is not changed (fractionated) by biological processes, due to the very small relative mass differences of the strontium isotopes (m=84, 86, 87, and 88). The lack of mass fractionation of strontium in processes that are ephemeral relative to the age of the Earth is well established by more than three decades of research on the strontium isotope compositions of natural and synthetic materials (e.g. Faure, 1986). The strontium isotope composition of bones and teeth, therefore, will match those of the diets of the individuals, which in turn will reflect the strontium isotope compositions of the local geology. This stands in marked contrast to isotopic studies of light elements such as hydrogen, carbon, nitrogen and oxygen, which are significantly fractionated during many natural reactions as a function of temperature and biological factors, due to the large relative mass differences of the isotopes of light elements (e.g. Faure, 1986).

Strontium isotope ratios vary with the age and type of rock and are used by geologists and geochemists to determine the age or source of rock formations (Faure, 1986; Faure & Powell, 1972). $^{87}$Sr is formed over time by radioactive decay of rubidium ($^{87}$Rb, $1/2 \approx 4.5 \times 10^{10}$ years), and comprises approximately 7.04% of total strontium (Faure & Powell, 1972). The other isotopes of strontium are nonradioactive, and include $^{84}$Sr ($\sim 0.56\%$), $^{86}$Sr ($\sim 9.87\%$) and $^{88}$Sr ($\sim 82.53\%$). Because natural materials have variable strontium contents, strontium isotope compositions are expressed as isotope ratios to normalize variations in absolute $^{87}$Sr abundances that are due solely to variations in strontium contents and not the relative abundances of the isotopes. Variations in strontium isotope compositions in natural materials are generally expressed as $^{87}$Sr/$^{86}$Sr ratios because the abundance of $^{86}$Sr is similar to that of $^{87}$Sr.

$^{87}$Sr/$^{86}$Sr ratios in natural materials vary directly as a function of the $^{87}$Rb/$^{86}$Sr ratio of a source and its age, through the equation:

$$\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = \frac{^{87}\text{Sr}}{^{86}\text{Sr}}_{\text{initial}} \left(1 + \frac{^{87}\text{Rb}}{^{86}\text{Sr}} \right) (e^{-\lambda t} - 1)$$

where $^{87}$Sr/$^{86}$Sr$_{\text{initial}}$ is the isotope ratio that a bedrock sample had when it formed; $\lambda$ is the decay constant, and $t$ is time (in years). Because this equation can be well approximated as:

$$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}_{\text{today}} = \frac{^{87}\text{Sr}}{^{86}\text{Sr}}_{\text{initial}} + \frac{^{87}\text{Rb}}{^{86}\text{Sr}} \lambda t$$

($\lambda < 1$), $^{87}$Sr/$^{86}$Sr$_{\text{today}}$ ratios in areas of closely related geology vary systematically and predictably with 1/Sr, and this covariance is confirmed by our own analyses of local bedrock and soil in the study area.

Geologic units that are very old (>100 million years) and had very high Rb/Sr ratios will have the highest $^{87}$Sr/$^{86}$Sr ratios today or in the recent past (<1 million years). Rocks that contain high Rb/Sr ratios include clay-rich rocks such as slate, or igneous rocks that have high silica contents such as granite (see review in Faure, 1986). Shales and granites of Mesozoic (>65 million years) to Precambrian age are common in the American Southwest, and these have $^{87}$Sr/$^{86}$Sr ratios greater than 0.730 (e.g. Farmer & DePaolo, 1984). In contrast, rocks that are geologically young (<1-10 million years) and that have low Rb/Sr ratios, such as many of the late-Cenozoic volcanic fields in the American Southwest, generally have $^{87}$Sr/$^{86}$Sr ratios less than 0.706 (e.g. Stuckless & O'Neil, 1983; Alibert, Michard & Albareda, 1986; Kempton et al., 1991). Rocks that have very low Rb/Sr ratios, such as basalt, can have $^{87}$Sr/$^{86}$Sr ratios less than 0.704 (e.g. Alibert, Michard & Albareda, 1986). These variations may seem small, but they are exceptionally large from a geologic standpoint, and far in excess of analytical error (c. ± 0.00003 for $^{87}$Sr/$^{86}$Sr).

A major concern in the analysis of biological materials is the recovery of biogenic rather than post-depositional (diagenetic) compositions for both isotopic and elemental analysis. During the past two years we have developed methods for estimating the degree of diagenetic contamination and for chemically cleaning bone and teeth to recover the biogenic signature. We monitor values of a suite of elements including calcium, phosphorus, iron, aluminium and manganese to determine if known biological values are recovered. For example, biological bone should have a Ca/P ratio of 2.1-2.2; excess calcium carbonate contamination, the principal source of diagenetic strontium, raises this ratio. Iron, aluminium and manganese are not normally present in any appreciable amounts in pristine bone. Elevated amounts of these elements indicate that the bone is contaminated with soil-derived minerals. We also compare strontium contents in archaeological faunal material to modern faunal samples of the same species from the same region as a further check to see if we are recovering biological concentrations.
Sillen (1986, 1989, 1990) was successful in removing post-depositional contaminants by washing bone in buffered, dilute acetic acid. This is intended to remove relatively soluble carbonate contamination that can contain significant strontium as well as calcium. In contrast to Sillen's method using solubility profiles, our procedure involves the overnight soaking of bone samples in 1N acetic acid and analysis of the residue rather than the solution (Ezzo, 1991; Price et al., 1992). We have found that after mechanically removing outer material through abrasive cleaning, dilute acetic acid will dissolve not only the soluble carbonates, but also that portion of the bone mineral that is most likely to be contaminated by interactions with diagenetic fluids.

Although it is certainly not possible in all cases to recover uncontaminated bone or biological compositions, our experiments were successful in recovering biological Ca/P ratios in many hundreds of archaeological samples (Price et al., 1992). Human bone from Grasshopper also yields Ca/P ratios that are appropriate for biological compositions after acid treatment (Figure 4) (Ezzo, 1991). Moreover, Sealy (1990) recently tested the acid-wash procedure of Sillen on the isotopic compositions of strontium in bone and was successful in recovering the known, biological compositions from bone which was initially contaminated with diagenetic strontium that had a different isotopic ratio. Dental enamel, which we will examine as a potential indicator of non-local residence during adolescence, is much denser and less susceptible to diagenetic contamination than bone (Molleson, 1988; Vernois, Unb Bao & Deschamps, 1988).

In summary we believe we can eliminate the possibility that non-biological Sr, which could be introduced through deposition of diagenetic (new) minerals or isotopic exchange during water/mineral interaction, is not present in the samples reported here. As outlined above, deposition of new diagenetic minerals would almost certainly involve primary carbonate, which is completely removed by our acid-washing procedures. For the second possibility, isotopic exchange with bone or tooth enamel apatite, considerations of diagenetic exchange between apatite and groundwater suggest that all of the isotopic ratios reported here reflect biological compositions.

Strontium was analysed using a thermal ionization multiple collector mass spectrometer, and $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios were corrected for mass fractionation in the instrument using an exponential mass fractionation law and $^{87}\text{Sr} / ^{86}\text{Sr} = 0.1194$; these are standard practices in all radiogenic isotope laboratories. Fifty-two analyses of NBS-987 Sr standard produced an $^{87}\text{Sr} / ^{86}\text{Sr}$ of $0.710273 \pm 0.000011$ (2 s.e.). $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios were also measured for Sr concentration determinations by isotope dilution. Rubidium interference was monitored at mass 85, and was always negligible. No correction of the measured $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio is required for in situ $^{87}\text{Rb}$ decay since bone or tooth enamel formation because the very small decay constant results in undetectable $^{87}\text{Sr}$ generation over time periods <10$^6$ years for these samples.

Acid-washed bone and tooth enamel samples were dissolved in HNO$_3$, followed by separation using cation exchange chromatography with HCl as the mobile phase. Complete separation of Rb and Sr was attained, which is critical due to the potential isobaric interference of $^{87}\text{Rb}$ on $^{87}\text{Sr}$ and the relatively high ionization efficiency of Rb in the mass spectrometer. Total procedural blanks were <10 ng for Sr, which is entirely
negligible relative to the amount of strontium analysed ($10^2$–$10^3$ ng).

Strontium isotope ratios are generally discussed here using the $\varepsilon_{Sr}$ notation of DePaolo & Wasserburg (1976, 1977) for ease in discriminating small differences in isotopic composition. $\varepsilon_{Sr}$ for young samples is defined as

$$\varepsilon_{Sr} = \left[\frac{87_{Sr}^{\text{Sample}}}{87_{Sr}^{\text{Bulk Earth}}} - 1\right] \times 10^4$$

where $87_{Sr}^{\text{Bulk Earth}}$ is estimated as 0.7045 (DePaolo & Wasserburg, 1976, 1977). Typical analytical precision is ±0.5 $\varepsilon_{Sr}$ units.

Results of the Pilot Study

Grasshopper Pueblo and Walnut Creek were selected for this pilot study because they are located in a region of diverse geology that should have a range of present-day $87_{Sr}^{86}$Sr ratios which may be used to fingerprint sources of diet and migration. Grasshopper Pueblo is located on a plateau of Upper Palaeozoic limestone which has relative high Sr concentrations and low $87_{Sr}^{86}$Sr ratios (Table 1). Walnut Creek is located on Precambrian intrusive rocks which should have relatively high present-day $87_{Sr}^{86}$Sr ratios, and this has been confirmed by one soil analysis (Table 1). High-Rb Precambrian intrusive rocks lie to the west and southwest, and these have exceptionally high $87_{Sr}^{86}$Sr ratios. These variations allow for the testing of the migration models proposed for Grasshopper (discussed above), in addition to those proposed for Walnut Creek, such as a Hohokam migration from the southwest (Harris, 1974).

As part of our initial study, we have analysed Sr concentrations and isotope ratios of 20 bones and teeth (enamel only), including eight bone-tooth enamel pairs (six from Grasshopper, two from Walnut Creek—see
Table 2. Water/Mineral ratios calculated for diagenetic exchange

<table>
<thead>
<tr>
<th>System</th>
<th>High-Sr Bone†</th>
<th>Low-Sr Bone‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Water/Mineral)_dilute</td>
<td>(Water/Mineral)_conce</td>
</tr>
<tr>
<td>Closed-system exchange</td>
<td>5145</td>
<td>515</td>
</tr>
<tr>
<td>over total (^{87}\text{Sr}/^{86}\text{Sr}) range of bones</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open-system exchange</td>
<td>4560</td>
<td>455</td>
</tr>
<tr>
<td>over total (^{87}\text{Sr}/^{86}\text{Sr}) range of bones and enamel</td>
<td>200,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Closed-system exchange</td>
<td>46,960</td>
<td>4695</td>
</tr>
<tr>
<td>over total (^{87}\text{Sr}/^{86}\text{Sr}) range of bones and enamel</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

†e.g. Burial 197; ‡e.g. Burial 545. Open-system exchange modelled as one-pass process (McCulloch et al., 1981). Starting \(^{87}\text{Sr}/^{86}\text{Sr}\) of groundwater assumed to be 0.715 (e.g. Vosberg soil composition). Starting \(^{87}\text{Sr}/^{86}\text{Sr}\) of bone assumed to be 0.7091 (e.g. Burial 292). Dilute water is average of shallow groundwaters, 0.06 ppm Sr (Livingstone, 1963; White, Hem & Waring, 1965). Concentrated water is 10 times concentration of dilute groundwaters, although this too is concentrated for waters above the water table in low-Sr soil (see Vosberg soil analysis, Table 1). Integrated water/mineral ratios for burial sites during the last 700 years likely be <30.

Table 1). We interpret the measured Sr concentrations and isotope ratios as reflecting biogenic compositions and do not see any evidence for significant diagenetic alteration. The most common form of diagenetic alteration in the samples would consist of secondary calcite that was precipitated from groundwaters; this was minor in the selected samples, as indicated by minimal change in Ca concentrations of ashed samples before and after acid leaching (Ezzo, 1991). Given the evidence that all secondary carbonate is removed during acid washing, the only other source of possible diagenetic alteration is Sr exchange with Sr-bearing groundwaters. This seems extremely unlikely given the fact that \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of the bone and tooth enamel samples are markedly lower than that measured for the soil in which they are buried, and considering the water/mineral ratios that would be required for significant Sr exchange. For example, using the exchange equations of McCulloch et al. (1981) and Nabelek (1987), water/mineral ratios of ~1000 to 200,000 are calculated as required to produce the range of \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios measured in the bones and tooth enamel samples using typical Sr concentrations and \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios for dilute groundwaters that would be associated with low-Sr soils in the region at or above the water table (Table 2). Even if Sr concentrations of shallow groundwaters were assumed to be 10 times that measured for such groundwaters, the water/mineral ratios far exceed those calculated for the region. Integrating current rainfall rates for the region during the past 700 years (Dean & Robinson, 1982), in addition to accounting for infiltration rates and areas, total water/mineral ratios at the burial sites are expected to be less than 30, assuming continuous exchange since burial.

**Sr concentration—\(^{87}\text{Sr}/^{86}\text{Sr}\) Ratio co-variations**

Sr concentrations in calcified tissues have been used for more than twenty years as indicators of past diets (e.g. Toots & Voorhies, 1965; Sillen & Kavanagh, 1982; Price, Schoeninger & Armelagos, 1985). Because Sr is an alkaline earth and substitutes for Ca, high Sr concentrations have been generally associated with a high-Ca diet, such as that obtained from a diet rich in plant food sources such as nuts and seeds. Low Sr concentrations are likely to reflect a greater emphasis on meat intake or other food sources low in Ca; the most conspicuous example of the latter in the prehistoric Southwest is maize (e.g. Price, Schoeninger & Armelagos, 1985; Buikstra et al., 1989; Ezzo, 1991). However, large variations in Sr concentrations of bone or tooth enamel may also be due to variations in bedrock or soil concentrations. For example, the Sr concentrations of the four bedrock and soil samples analysed in this study, which probably encompass the range of Sr concentrations in the study area, vary from over 600 ppm to less than 20 ppm (Table 1), indicating that geoecologic variation in Sr concentrations must first be accounted for before diets can be inferred.

The fact that \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios are not fractionated during incorporation of Sr into the food chain, coupled with the systematic co-variance of Sr concentrations and \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios for bedrock in regions that contain old (>several hundred million years) rock, provides a means for normalizing Sr concentrations of bone and tooth enamel samples based on their \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios. Although the bedrock in the Grasshopper and Walnut Creek regions is not all of the same age and therefore will not lie along the same ppm Sr—\(^{87}\text{Sr}/^{86}\text{Sr}\) curve, the basement data can be reasonably fit to a theoretical
Figure 5. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($\varepsilon_{\text{Sr}}$) and Sr concentrations of bones and tooth enamel, for (a) Grasshopper Pueblo and (b) Walnut Creek.

curve based on the $^{87}\text{Rb}-^{87}\text{Sr}$ decay equation (above) that can be used as a basis for comparison of the bone and tooth enamel data (Figure 5). Some of the samples have Sr concentrations, relative to their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, that fall near the basement curve, while others are displaced to Sr concentrations that lie significantly above the basement curve (Figure 5).

We here define a parameter, $\Delta_{\text{Sr}}$, as the difference in the Sr concentrations of the bone or tooth enamel samples from that expected for the basement based on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the bone or enamel; these variations are presented in Figure 6. Given the scatter in ppm Sr–$^{87}\text{Sr}/^{86}\text{Sr}$ curves measured for bedrock samples of varying age in other regions, we estimate that the basement uncertainty in the $\Delta_{\text{Sr}}$ parameter is $\pm$ 100–200 ppm, which suggests that nearly all of the tooth enamel samples and two of the bone samples have the same basement-normalized Sr concentrations and therefore these individuals had the same Sr concentrations in the diets (Figure 6). Such a conclusion is not
clear if only the measured Sr concentrations of the bone and tooth enamel samples are considered (Table 1), as is done in most studies. The majority of the bone samples, however, have anomalously high $\Delta_{Sr}$ values ranging from +300–+900 ppm, suggesting that these individuals had a higher Sr diet late in life. The anomalously high $\Delta_{Sr}$ concentrations of the bones are well correlated with the differences in Sr concentrations for bone and tooth enamel for specific bone-tooth enamel pairs, lying along a 1:1 line that intersects the origin (Figure 7). The probable reason for this difference in $\Delta_{Sr}$ between the high Sr-bone samples and the tooth enamel samples lies in the fact that the enamel of the first molar is forming in the first two to three years.
of life (Massler, Schour & Poncher, 1941; Steele & Bramblett, 1988; Hillson, 1990), when an individual’s diet is most likely to be dominated by mother’s milk. Milk is the one food that is high in Ca but contains virtually no Sr (Twardock, 1963; Schroeder, Nason & Tipton, 1972). The differences in $\Delta_{\text{Sr}}$ between high-Sr and low-Sr bone samples reflects dietary differences in adulthood. High strontium values are associated with diets consisting largely of calcium-rich plants such as nuts, seeds, legumes, and (in the case of the Southwest) desert succulents such as prickly pear and cholla. Low-Sr diets are associated with high meat intakes or calcium-poor staples; in the prehistoric Southwest the most conspicuous example of the latter is maize, which has been demonstrated to be prominent in the Grasshopper diet (Ezzo, 1991; Reid, 1978).

**Sr isotope composition**

The most striking aspect of the Sr isotope data is the relative constancy of the bone isotope compositions as compared to those of the tooth enamel. This confirmed our initial expectations that the bone samples should reflect Sr isotope ratios of the local diet, whereas the isotopic compositions of the tooth enamel, given the possibility that migration occurred after early childhood, would be more variable. $\varepsilon_{\text{Sr}}$ values for bones from Grasshopper average +79.6 and have a restricted range ($\pm 3.0$ s.d.), whereas the two bones from Walnut Creek have slightly lower $\varepsilon_{\text{Sr}}$ values of +65.3 and +71.1 (Table 1). It is particularly significant that all of the bones have $\varepsilon_{\text{Sr}}$ values that are significantly less than that measured for the Vosberg soil ($\varepsilon_{\text{Sr}} = +152.3$), although the bones have Sr isotopic compositions that are closer to the Sr concentration-weighted average that is calculated for the bedrock/soil samples ($\varepsilon_{\text{Sr}} = +56$). This strongly suggests that the dietary Sr input was not restricted to agriculture that was established on the local soil, but that the diets included foodstuffs and/or animals that obtained their Sr on the high Sr-low$^{87/86}$Sr limestone and sandstone terrains nearby. That the isotopic compositions of the bones at Grasshopper and Walnut Creek remained relatively constant over the range of occupations of the sites (c. 125 years at Grasshopper, 200 for Walnut Creek) suggests that the isotopic compositions, if not necessarily the foodstuffs, of the local diet remained relatively constant through time. We are currently investigating Sr isotope variations in bone and teeth of modern small fauna from the study area to determine possible ranges in dietary Sr isotope compositions.

A number of individuals have $\varepsilon_{\text{Sr}}$ values for enamel that lie within the range expected for the local diet, as inferred from the bone isotopic compositions (Figure 6). These include Burials 197 (female, age 16-17), 152 (male, age 15-17) and 543 (male, age 30-40) from Grasshopper and Burial 301 (adult male) from Walnut Creek (Figure 6). Two of the Grasshopper individuals were interred in the Great Kiva (Plaza III), which is associated with Roomblock 2, whereas Burial 543 is from an outlying roomblock. All of the Great Kiva burials at Grasshopper date to the early period of occupation (pre-1330), while the outlier burials are late (AD 1330-1400) (Dean & Robinson, 1982; Graves,
The Sr isotope compositions suggest that these individuals lived their entire lives at their respective sites.

In contrast, the $\varepsilon_{\text{Sr}}$ values from the tooth enamel of Grasshopper Burials 112 (female, age 35-45), 466 (female, age 14-16) and 545 (female, age 30+), and Walnut Creek Burials 291 (adult female), 292 (adult male), 294 (adult female) and 300 (adult male), have $\varepsilon_{\text{Sr}}$ values that are significantly higher (+87 to +142) than those of the local value (c. +70 to +80). It is therefore likely that these individuals were born elsewhere and moved to their respective sites later in life.

From the above data, the following inferences can be made, beginning with and emphasizing Grasshopper Pueblo.

Burial 112 is also a Great Kiva/Plaza III interment; this suggests that both local and nonlocal individuals were buried in this plaza, and furthermore supports earlier inferences of a complex pattern of aggregation in which individuals within a major room block comprise several distinct social groups of both local and non-local origin (Longacre, 1976; Reid, 1978; Graves, Longacre & Holbrook, 1982; Reid & Whittlesey, 1982; Graves, 1983). It is also possible that the two Great Kiva adolescents (Burials 152 and 197) are offspring of early immigrants to the site, having been born and reared at Grasshopper.

Sr isotope compositions of tooth enamel from Burials 466 and 545 are dramatically different than the inferred local compositions (466, $\varepsilon_{\text{Sr}}$ = +105-3; 545, $\varepsilon_{\text{Sr}}$ = +141-7). Burial 466 was interred beneath Room 164 in Roomblock 2 (Figure 2), which is part of a 21-room core construction unit at the site (Longacre, 1976; Reid & Shimada, 1982); this individual must therefore date to the beginnings of Grasshopper occupation. Burial 545 is an outlier burial (Roomblock 11), and dates to the later period of occupation. This suggests a pattern of continual migration into the Grasshopper region between the late 13th century and the beginning of the 15th century, and this has been inferred in a number of earlier studies (Longacre, 1976; Graves, 1983; Berry, 1985a; Reid, 1989). While the origins of these individuals that have anomalously high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios cannot be currently defined, the high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios could not have been derived from the volcanic terrains of the Kinshipa and Point of Pines regions to the southeast of Grasshopper (Heatherington, 1988; Kempton et al., 1991). It is also unlikely these individuals came from the limestone-dominated terrains of the Colorado Plateau or the volcanic regions of the Colorado Plateau such as Hopi Buttes, both of which have very low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Burke et al., 1982; Albert, Michard & Albarede, 1986).

Because there is no clear archaeological evidence for migration from the Hohokam area (i.e. regions dominated by older granitic rocks), origins in the Little Colorado region or farther north should be considered for individuals that have exceptionally high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (high $\varepsilon_{\text{Sr}}$ values).

The anomalously high $\varepsilon_{\text{Sr}}$ values for the tooth enamel of the four Walnut Creek individuals would seem to support Morris’ contention, based on the ceramic variation and the evidence of distinct building episodes at the 9th-century pithouse village, that the site was settled to a significant extent by immigrants from the Sonoran Desert who were culturally affiliated with the Hohokam (Morris, 1970). Such a pattern of human mobility is consistent with much of the history of human adaptation in the American Southwest (Schwartz, 1970).

Conclusions

The pilot study has provided exciting results in terms of the use of combined Sr concentration and Sr isotope ratio analysis of tooth enamel and bone for studying residential mobility in the past. Grasshopper Pueblo is an exceptional locality for such studies because: (1) the site excavations have produced a large, well-provenanced and well-studied burial assemblage; (2) previous studies, as well as the migration evidence from contemporaneous Point of Pines, suggest the settlement of the site by diverse social groups of both local and nonlocal origin; and (3) the geological distinctiveness of the physiologic province of the northeast quarter of Arizona provides marked variability in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between regions.

The data presented provide strong initial evidence for the settlement of both migrants and locals at both Walnut Creek and Grasshopper Pueblo, which is consistent with previous models. Our current research seeks to build on this data base, analysing additional bone-tooth enamel pairs from individuals from Grasshopper Pueblo in the hopes that, with an adequate sample size, we will be able to provide new insights into the nature of aggregation at Grasshopper Pueblo.

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References


Residential Mobility in the Prehistoric Southwest 329


