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Matrilocalty in the Middle Period in San Francisco Bay? New Evidence from Strontium Isotopes at CA-SCL-287

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We explore strontium (Sr) isotope analysis as a means to reconstruct ancient migration patterns of individuals at SCL-287, a Middle Period site in southern San Francisco Bay. Comparison of Sr isotopes from first molars to that of bone suggests that males frequently immigrated to the site, while all females were born at or near the site. This pattern is consistent with a preference for matrilineal post-marital residence patterns. At the same time, analysis of third molars indicates that individuals frequently shifted residence during early teenage years, even those who were born and lived as adults at SCL-287. While adult residence shifts are commonly reported in the ethnography of Central California, matrilineality is not. In this respect, isotopic analyses allow us to generate new hypotheses about ancient migration patterns in prehistory independent of those reported in the ethnographic literature.

RECONSTRUCTING THE MOVEMENTS OF PEOPLE, or mobility, in ancient hunting and gathering societies has a long tradition in archaeological research in the Americas. Archaeologists are particularly interested in these issues because theory suggests that, while there is variation in the details, how mobility is organized has certain predictable effects on, and/or is predictably affected by, a range of other aspects in human societies, such as population density, the organization of material

technologies, health, and subsistence patterns (Kelly 1992). For example, societies that practice seasonal transhumance tend to minimize the weight and diversity of their toolkit, resulting in light-weight multi-purpose tools. Likewise, problems with waste disposal in residentially sedentary societies tend to increase disease vectors, resulting in decreased health, and territorial expansions are often associated with increased levels of interpersonal violence. Thus, by reconstructing how

people moved in the past, we can gain insight into a range of other behaviors and issues as well.

Archaeological studies of human mobility tend to focus on two “ends” of a continuum. On the one end are studies of how humans make short-term movements over a territory or landscape to exploit resources. Such strategies are typically dichotomized as residential and logistical mobility in the archaeological literature, and they occur in the space of days to months. Variation in how people organize logistical and residential mobility has resulted in a range of useful models that many California and Great Basin archaeologists will be familiar with, such as foragers vs. collectors (Binford 1980), and travelers vs. processors (Bettinger 1999). On the other end of the continuum are long-term movements of groups of people, often distinctive linguistic or ethnic groups. This type of mobility is typically thought of as part of territorial expansion or “migration” in the archaeological literature. Again, California and Great Basin archaeologists will be familiar with models such as the Numic Spread or Patwin Intrusion (Lamb 1958; Whistler 1977) that exemplify such mobility. Of course, ideas from these ends are not mutually exclusive and can be combined, as in Bettinger and Baumhoff’s (1982) examination of short-term land-use strategies to help explain the long-term pattern of how Numic speakers outcompeted pre-Numic people in the Great Basin.

Not surprisingly, archaeologists have developed a number of methods to reconstruct ancient mobility practices at both ends of the continuum. Typical approaches for reconstructing short-term mobility include the study of flaked stone (Bamforth 1991; Beck et al. 2002; Cowan 1999; Eerkens et al. 2008; Kelly 1988), domestic structures (Binford 1990), site organization (Hitchcock 1987; Kent 1991), seasonality indicators (Monks 1981), and storage features (Soffer 1989). At the other end, careful analysis of linguistic patterns (Lamb 1958; Whistler 1977), artifact or rock art style (Hull 2004; Moratto 1984), and more recently ancient DNA (Eshleman and Smith 2007; Johnson and Lorenz 2006; Johnson et al. 2012; Monroe et al. 2013), have been used to either generate new hypotheses or test existing ones regarding long-term migrations and expansions of groups of people. One drawback of these approaches is that they tend to emphasize the behaviors of certain segments of societies (e.g., men in the case of flaked stone) or

average mobility practices across all members of society (e.g., site structure). Kelly (1992:57) long ago stated that “it is important that we understand the differences in individual mobility patterns within a society,” yet acknowledged that there were few techniques to do so in 1992.

Less common in California archaeology is the exploration of more medium-term movements of humans. In particular, we refer to shifts in village residence that occur at the scale of years or decades, including (especially) post-marital residence shifts. While ethnographic information indicates such movements are common, until recently archaeologists have tended to ignore such movements because there were few methods to address and reconstruct such mobility. Advances in archaeometry have changed the situation, and isotopic signatures preserved in individual burials now offer such an approach (Beard and Johnson 2000; Bentley et al. 2003; Buzon and Bowen 2010; Price et al. 2002). Because biological, physical, and chemical processes often fractionate or change the isotopes of elements, the ratios of stable isotopes can be distinctive for certain geological formations or geographic regions. If these distinctive isotope signatures, or tracers, become embedded in biological tissues and are preserved over archaeological time scales, those remains can trace an individual back to regions or landforms. Further, by analyzing tissues that form during different temporal windows in an individual’s life—for example, first and third molars, and bone—we can trace their position on the landscape at different points in time, in addition to the place where an individual was ultimately buried. An advantage of this approach is that we can trace mobility for different segments of society (e.g., women vs. men, tall vs. short, etc.).

This study employs a developing methodology in archaeometry focused on strontium (Sr) isotope ratios as a way to estimate migration over the course of one individual’s life. Comparison of Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) from teeth which form early in life and do not remodel, and bone, which is constantly remodeling throughout life, can provide information about where someone lived during their first few years, versus where they lived during the last 10–20 years of life. Additional analyses on teeth that form later in life, such as third molars, can give further geographic estimates during

other temporal windows (ca. 10–14 years of age for a third molar). This approach works best for identifying cases where individuals tend to stay in a limited area (i.e., are spatially bound) for long periods of time (i.e., years), but then move to other geologically distinctive areas after these periods. In this sense, semi-sedentary groups with exogamous marriage are ideal for applying this technique.

Such information allows for detailed and specific analysis of migration for individuals at different points in their lives, not at the scale of months, nor of generations, but at a medium temporal scale of years to decades. When many individuals within a population are analyzed, such studies can provide insight into social organization and group composition (Bentley et al. 2003; Ezzo et al. 1997; Price et al. 1994; Prohaska et al. 2002). In particular, in small-scale societies where the number of eligible marriage partners within a community is typically low, marriage is one of the major reasons why individuals move residences. Such analyses, then, could indicate whether a society had a preference for patrilocality (if females were mostly moving locations between birth and adulthood to live with their spouse), matrilocality (if males were mostly moving location), or other post-marital residence patterns, such as ambilocal (married couples can choose to live at either the male's or female's locality), neolocal (married couples choose a new location), or avunculocal (the couple lives with the male's mother's brother). Cross-cultural studies of contemporary hunter-gatherers show that, where a clear preference is stated, 66% prefer patrilocality, 19% matrilocality, 12% ambilocality, and 4% avunculocality (Kelly 1995:271).

CA-SCL-287 / CA-SMA-263

CA-SCL-287 and CA-SMA-263, or the *Yuki Kutsuimi Šaatoš Inūx*^w [Sand Hill Road] Sites, are adjacent prehistoric sites located in the southwestern area of San Francisco Bay (Fig.1). These two sites were excavated by Ohlone Families Consulting Services, the cultural resource arm of the Muwekma Ohlone Tribe, under contract with Stanford University, as part of the widening of Sandhill Road (Leventhal et al. 2010). Because the majority of the remains in this study (13 of 14 individuals) are associated with SCL-287, we refer to the two sites

collectively by this trinomial only. Indeed, Leventhal et al. (2010) conclude the two trinomials constitute different horizontal sections of the same archaeological site. The remains of at least 27 individuals were exhumed between 1987 and 2004 as part of construction activities on the Stanford University campus. In consultation with the Most Likely Descendant (MLD), Rosemary Cambra, Chairwoman of the Muwekma Ohlone Tribe of the San Francisco Bay Area, a sample of bone and teeth from 14 individuals was selected and analyzed for strontium isotopes, with the goal of reconstructing individual-level mobility patterns.

CA-SCL-287 is situated on the flood plain of San Francisquito Creek at approximately 40m. elevation (asl). When occupied, the site would have been some 5 km. southwest of the tidal flats of San Francisco Bay, and 20 km. east of the Pacific Ocean. The area immediately surrounding the site provided access to oak grasslands and small freshwater marshes. Vertebrate faunal remains recovered from the site include a large proportion of ungulates (deer, tule elk, pronghorn), representing over 50% of identified elements. Lagomorphs and rodents represent nearly 40%, while small numbers of canids, marine mammals, and a range of avifauna make up the remainder of the vertebrate assemblage. Shellfish remains are also common at the site, dominated by oyster (*Ostrea* sp.), horn snail (*Cerithidea californica*), and mussel (*Mytilus* sp.). Though no paleobotanical studies were undertaken on flotation samples, a range of groundstone implements, including mortars and pestles, suggests that plant foods were also an important component of the diet (Leventhal et al. 2010).

Twenty radiocarbon dates on charcoal from features and stratigraphic layers indicate that the majority of the site was deposited over a 1,200-year period, between 500 B.C. and A.D. 700 (n=12 dates; Fig. 2), with a small number (n=3) dating earlier and later (n=5). This is generally referred to as the Middle Period in Central California, though some refer to the earlier part of this window, between 500 and 200 B.C., as the Early-Middle Transition (Groza et al. 2011). An additional 14 radiocarbon dates on human bone collagen indicate that the majority of the burials date to a more narrow age range between A.D. 1 and 700 (12 of 14 dates; Buonasera 2013; Leventhal et al. 2010). Though Figure 2 shows all the dates, only eight of the radiocarbon-dated burials

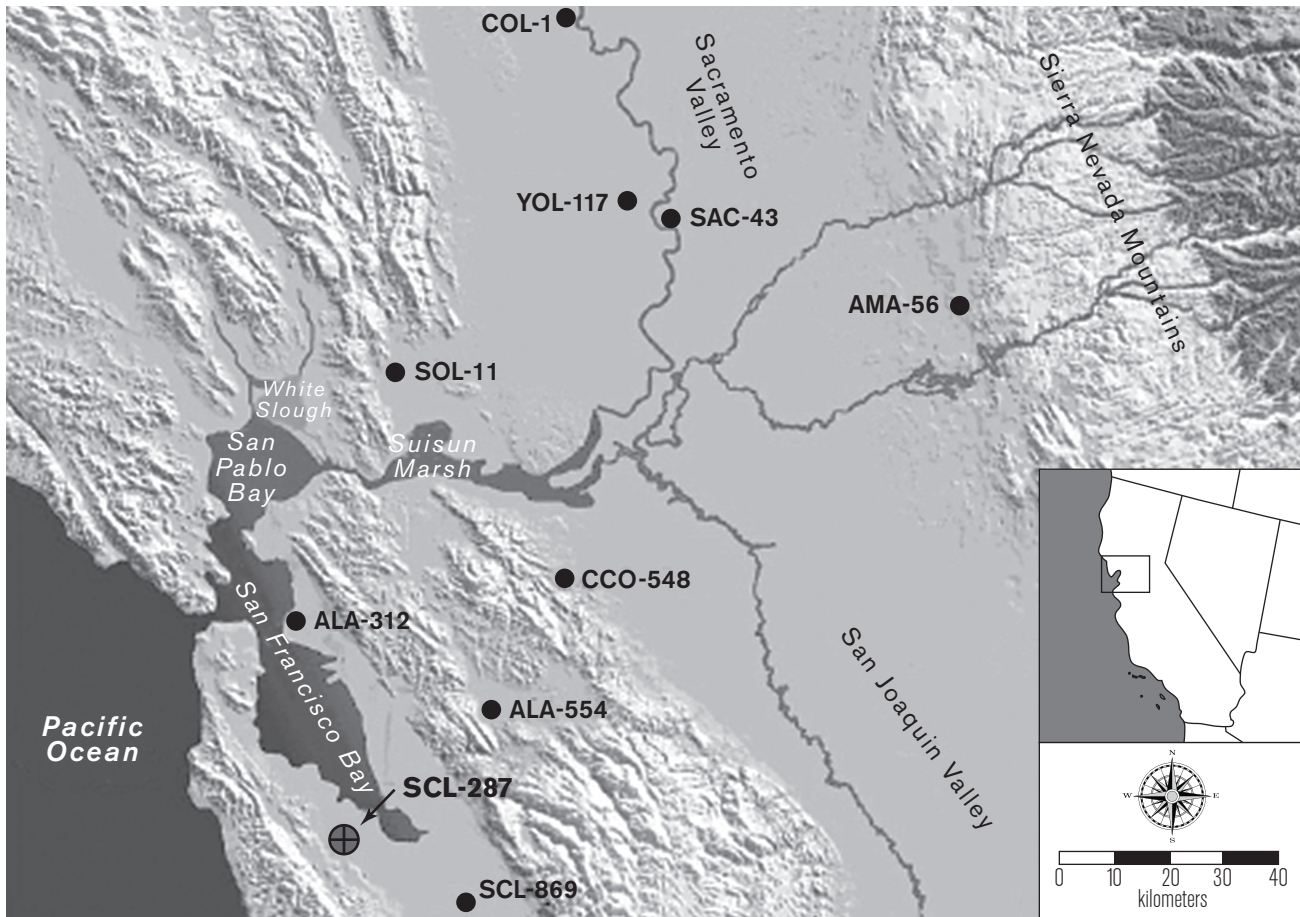


Figure 1. Map of Central California showing location of SCL-287 (in lower left) and other sites discussed in the text.

were included in the current analysis (see below), and in particular, we have excluded from our isotopic analysis the two oldest burials that pre-date 1,500 B.C. in order to focus our analysis on the Middle Period. The radiocarbon findings are bolstered by a small set of obsidian hydration readings and temporally diagnostic saddle F-series Olivella shell beads, supporting a predominantly Middle Period occupation (see Bennyhoff and Hughes 1987; Groza et al. 2011).

POST-MARITAL RESIDENCE EXPECTATIONS

The ethnographic record in California shows a strong bias towards patrilocal post-marital residence (Jorgensen 1980; Kroeber 1925; Wallace 1978). The dominance of this pattern varies by region, however. For example, in an analysis of the ethnographic data, Bettinger (n.d.) finds that patri/virilocal residence is the dominant post-marital residence for 75% of groups where such information

is available. Tribal groups of the Sacramento and San Joaquin valleys show this pattern strongly, with 84% and 73% stating patrilocal preference, respectively. Bettinger (n.d.) attributes much of this patrilocal preference to the need to keep related males together for village defense. On the other hand, just one of seven (14%) tribal groups in the North Coast Ranges stated a patrilocal preference, with matriloc and ambiloc post-marital residence being more common. More directly related to SCL-287, Milliken (2007) found evidence for ambiloc post-marital residence patterns in the San Francisco Peninsula based on examination of mission records.

The ethnographic record also indicates that post-marital residence patterns were more complicated than a simple classification into patrilocal or matriloc. For example, among the Patwin of the Sacramento Valley, a newly married man would typically live with his wife's family (i.e., matriloc) until he could build enough capital to establish his own household (McKern 1922).

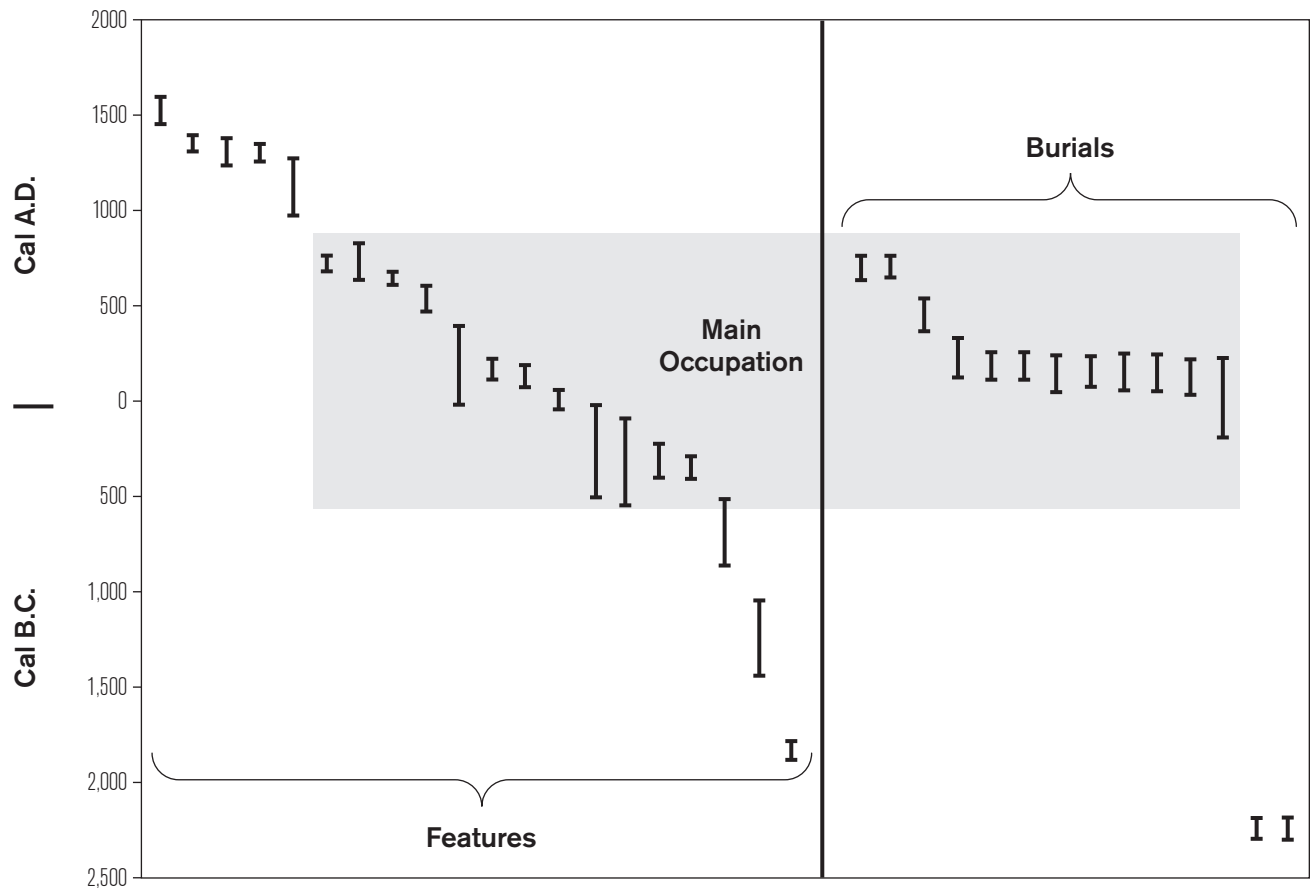


Figure 2. Radiocarbon dates on features and burials from CA-SCL-287, showing that the burials date primarily to the early first millennium A.D., or Middle Period.

At that point, the couple, and any children, would often move to live with the husband’s family and/or in his village (i.e., patrilocal). Indeed, some 54% of California groups with a preference for patrilocality stated that couples initially lived matrilocally or uxorilocally upon marriage (Bettinger, n.d.). Likewise, among the Pomo of the North Coast Ranges, there was general preference for matrilocality, but only after a first child was born (Loeb 1926:279).

Although there may have been preferences among certain groups for a certain mode of post-marital residence, most ethnographic data indicate that decisions were often made on a case-by-case basis. Thus, couples could choose where to live depending on circumstances, personalities, and their individual preferences. Furthermore, married couples would often make one or more residence shifts in the course of their lives; perhaps, for example, spending several years with the wife’s family before moving to the location of the husband’s family or vice versa.

In sum, if the California ethnographic record is used to provide a model for expected prehistoric patterns, we should generally see a preference for patrilocality in the archaeological record, but with evidence for significant fluidity in residence choices. Of course, many have argued that the ethnographic record should not be used in such a fashion (Wobst 1978). Our goal here is not to project patterns on prehistory, but to provide an hypothesis that can be tested with new archaeological data.

STRONTIUM ISOTOPE ANALYSIS AND MIGRATION

The ratio of ⁸⁷Sr to ⁸⁶Sr varies as a function of age in geologic formations (Capo et al. 1998; Faure 1986). While both isotopes of Sr are stable, ⁸⁷Rb (an isotope of rubidium) is radioactive (unstable), with a half-life of 4.88 billion years, and decays into radiogenic (and stable) ⁸⁷Sr. As a result, the ⁸⁷Sr/⁸⁶Sr ratio increases over time in rocks

and minerals containing significant amounts of Rb, and thus continental formations vary widely in their $^{87}\text{Sr}/^{86}\text{Sr}$ signatures. For example, $^{87}\text{Sr}/^{86}\text{Sr}$ varies between 0.702 and 0.704 in newly formed rock derived from the earth's mantle at mid-oceanic spreading centers, to over 0.725 in Precambrian formations that are over 3 billion years old (Faure and Hurley 1963). The present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in oceanic waters is remarkably constant at 0.7092, though this value too has changed over geological time (Veizer 1989). By contrast, our instrumental precision for $^{87}\text{Sr}/^{86}\text{Sr}$ in bone and enamel is typically less than ± 0.00002 .

Strontium has chemical properties similar to calcium, so that it is easily substituted for calcium in organic molecules (Bronner et al. 1963). It is incorporated into the human body through food consumed by the individual. Strontium is found in significant amounts in human hydroxyapatite [$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$], the inorganic mineral component of bone and teeth, as substitutions for Ca.

Plants take up Sr available in the soil of their immediate surroundings, and thus humans receive their Sr from those plants and the animals feeding on those plants. Fractionation within the human body is negligible for $^{87}\text{Sr}/^{86}\text{Sr}$ because the relative difference in mass between the two isotopes is minimal. Thus, for Sr there is very little enrichment of one isotope over another at different trophic levels, compared to, for example, enrichment in carbon and nitrogen stable isotope ratios (DeNiro and Epstein 1981). The $^{87}\text{Sr}/^{86}\text{Sr}$ present in tissues in the body generally reflects the strontium that is biologically available in the diet from the local environment (Price et al. 2002).

Examining $^{87}\text{Sr}/^{86}\text{Sr}$ in different human tissues provides a means of determining changes in residence during an individual's lifetime (see Bentley et al. 2002; Bentley et al. 2003; Ezzo et al. 1997; Price et al. 1994; Prohaska et al. 2002). Teeth in the human body are formed relatively early in life and do not change their chemical composition once they are formed. Some teeth, such as first molars and incisors, begin forming quite early, at around birth, and are finished growing in early childhood (e.g., by age 9). Others, such as third molars, form later in life (ca. ages 9–22). In this respect, $^{87}\text{Sr}/^{86}\text{Sr}$ values obtained from enamel in teeth reflect the strontium available when an individual was young

and their teeth were developing (Hillson 2005). On the other hand, bone is continuously remodeled throughout life, and the majority of Sr in bone reflects the last ten to twenty years of an individual's life.

These properties of Sr and its relationship to the human body provide the opportunity to study changes in the geographic source of food resources consumed over time by one individual. Simple economics dictate that the majority of food in societies lacking mechanized transport (i.e., easily exploitable sources of stored energy, such as oil) must be gained from the immediate environment. Transporting foods over long distances significantly reduces caloric and nutritional yield, and if such transport must be sustained over long periods of time, humans typically move themselves to such food patches (i.e., are residentially mobile) rather than the reverse (Jones and Madsen 1989). Of course, the size of a foraging territory may vary among groups of people, and some "special" foods may be transported over long distances (Hildebrandt et al. 2009). However, for sedentary and semi-sedentary groups heavily reliant on bulky plant foods, such foraging territories are typically constricted (Kelly 1995). In general, foraging for most foods occurs within a 10–15 km. radius of the base camp, except for foods with exceptionally high return rates. This figure will be even lower in tightly packed human landscapes with well-defined and defended territories. Indeed, as Heizer (1978:648) stated, most Native Californians lived "from birth to death within an area bounded by a horizon lying not more than 10 or 15 miles from one's village." We believe this figure represents the extent of a typical "local" foraging range.

The $^{87}\text{Sr}/^{86}\text{Sr}$ values from bone and enamel samples in humans can be compared to values expected from a given geographic region. A common method to do this involves measuring $^{87}\text{Sr}/^{86}\text{Sr}$ in the tissues of mammals with limited mobility, such as small rodents. These animals will have obtained the majority of their food from the immediate surroundings, establishing an expected "local" value. These values can then be compared to isotopes in humans. It is expected that the majority of human bone samples will reflect this same "local" signature, since individuals in small-scale societies are often buried near their place of recent residence. Values from teeth can then be used to establish those that are "locals," or people who were born and raised

near this same location, and “non-locals,” people who immigrated to the site at some point in their lives.

Because villages tend to be small in many small-scale societies, and potential marriage partners limited within the village, it is often necessary for individuals to marry exogamously to avoid inbreeding. In other words, marriage is a major reason why people in such societies migrate and change residence. If individuals are tied to particular permanent villages for extended periods of time (i.e., practice some degree of residential sedentism), aggregating individual local versus non-local isotope data at a population level may allow archaeologists to identify certain aspects of ancient post-marital residence patterns. For example, we may provide evidence that supports matrilocality if males comprise the majority of non-locals, patrilocality if females comprise the majority of non-locals, neolocality if even numbers of males and females are among the non-locals, or other marriage strategies.

METHODS

With permission from the Muwekma Ohlone Tribal Council and Rosemary Cambra, MLD for this cultural resource mitigation project, small bone and tooth samples from fourteen adults from CA-SCL-287 were removed for Sr isotope analysis. The study included six females, seven males, and one adult of indeterminate sex (see Leventhal et al. 2010 for additional details about the site and the individual burials included in this study). For each individual we sampled an early-growing tooth, typically a first molar, a third molar (when present), and a small piece of bone, in nearly all cases a rib fragment. Aging and sexing methods and details are reported in Leventhal et al. (2010).

Because a complete $^{87}\text{Sr}/^{86}\text{Sr}$ base map does not yet exist for California, we also analyzed $^{87}\text{Sr}/^{86}\text{Sr}$ from small mammal bones collected from midden at the site and thought to be prehistoric in age. All are from species that do not migrate over long distances, two from small unidentified rodents and two from squirrels. These faunal $^{87}\text{Sr}/^{86}\text{Sr}$ values help establish what a human forager with a small mammal-like diet would look like isotopically if they were consuming foods only from the immediate environment. Of course, humans typically forage over a larger area than small mammals and will include some foods that are migratory themselves (e.g., ungulates,

anadromous fish); thus, we do not expect human values to duplicate the fauna. Instead, the small mammal data help us to develop a context for interpreting the human tooth data, establishing a hypothetical “local” signature. Along with the human bone data themselves, this isotopic signature provides a baseline for identifying non-local tooth Sr isotope values in the human population, which in turn can provide information about migration patterns, including post-marital residence shifts.

While enamel appears to be relatively conservative, bone can sometimes undergo diagenetic change (Budd et al. 2000), though recent studies suggest some parts of bone are also more resistant (Scharlotta et al. 2013). To minimize the potential effects of diagenesis, we mechanically removed the outer layers of bone and tooth samples more susceptible to diagenetic change. As well, we subjected the remaining bone to chemical cleaning. As such, our study focuses on interior sections of well-preserved cortical bone, and enamel, minimizing the potential effects of diagenetic changes to isotopic values (Knudsen et al. 2005). Our analyses at other sites in Central California show that bone Sr isotopes of burials identified as non-locals based on other criteria (e.g., burial style) have not converged on the local value, despite being buried for hundreds to thousands of years (Eerkens et al. 2014a; Eerkens et al. 2014b). This suggests that human bone from Central California cleaned in this manner can retain the original Sr isotopic signature.

Sr from bone and tooth samples was separated and purified. This process removes all isotopes of rubidium (Rb), one of which (^{87}Rb) can interfere with the measurement of ^{87}Sr . Bone and enamel (~0.05 grams of powder each) were treated with 2 milliliters (mL) of 15% hydrogen peroxide (H_2O_2), sonicated for 5 min, and then soaked for 24 hours to remove organic material. Samples were then rinsed in distilled water, dried down and treated with 2 mL of 0.1 N acetic acid and soaked for 24 hours to remove secondary non-biogenic carbonates. They were then rinsed two times with distilled water, dried down and dissolved with 4 mL of 2.5 N hydrochloric acid (HCl). All samples were dissolved completely (i.e., no residual solids remained) by placing them on a hotplate for 24 hours while soaking in HCl. Samples were dried down to evaporate HCl and brought up in 800 microliters (μL) of 8 N nitric acid (HNO_3) and centrifuged. The supernatant was

loaded onto teflon columns containing Eichrom® Sr Spec resin. Rubidium (Rb), barium (Ba), lead (Pb), and most other elements were eluted in 2 mL 3 N HNO₃. Sr was collected in 2.8 mL of 0.5 N HNO₃, dried down and reloaded onto the columns a second time (in 8 N HNO₃) to ensure complete purification of Sr from Rb. All acids used were distilled to ensure their purity and titrated to ensure the correct concentrations.

Sr isotope ratios were determined by Nu Plasma HR MC-ICP-MS at the U.C. Davis Interdisciplinary Center for Plasma Mass Spectrometry. Sample solutions were introduced through a DSN 100 desolvating nebulizer and isotope analyses were mass-fractionation corrected internally to the ‘true’ ⁸⁶Sr/⁸⁷Sr ratio of 0.1194. ⁸⁵Rb and ions with mass 84 (including ⁸⁴Kr and ⁸⁴Sr) were monitored to correct for ⁸⁷Rb interfering with ⁸⁷Sr and ⁸⁶Kr with ⁸⁶Sr, respectively. ⁸⁵Rb was only present at a few mV or less due to the double-pass of Sr through the columns. ⁸⁴Kr and thus ⁸⁶Kr interference on ⁸⁶Sr was corrected by iterations using the assumption that ⁸⁴Sr/⁸⁶Sr=0.00675476.

The analytical protocol involves 3-4 samples bracketed by the Sr standard SRM987 allowing for normalization of sample ⁸⁷Sr/⁸⁶Sr isotope measurements to an accepted value of 0.710249 for SRM987. Sample uncertainties for SRM987 were ~0.000020, determined by measuring 2 standard deviations on repeated measures of ocean coral that was run with the CA-SCL-287 samples (0.70794 ± 0.000022; n=3).

RESULTS

Table 1 summarizes results from our analyses, and from previous radiocarbon dating (see Buronaser 2013; Leventhal et al. 2010). Note that the table only reports dates for burials included in the isotope analysis, not all of the dated burials discussed above. It is also worth noting that the burials included in our analysis are unlikely to be exactly contemporaneous. In that respect, like nearly all research at archaeological sites (excepting sites such as Pompeii), our analysis of the “society” at CA-SCL-287, and mobility patterns of individuals

Table 1

BURIAL AND FAUNAL DEMOGRAPHIC AND STRONTIUM ISOTOPE DATA

Burial #	Sex	Age	⁸⁷ Sr/ ⁸⁶ Sr Enamel M1/Inc.	⁸⁷ Sr/ ⁸⁶ Sr Enamel M3	⁸⁷ Sr/ ⁸⁶ Sr Bone	Early Childhood Years (M1/Inc.)	Early Teenage Years (M3)	¹⁴ C Date
04-09	Female	30+	0.70817	0.70820	0.70814	Local	Local	
04-12	Female	45-49	0.70807		0.70803	Local		1,301 ± 34
04-13	Female	40-49	0.70803	0.70793	0.70810	Local	Local	1,841 ± 46
04-15	Female	33-46	0.70808		0.70817	Local		1,814 ± 36
04-17/18	Female	40-50	0.70815	0.70745	0.70805	Local	Non-Local*	1,787 ± 36
04-21	Female	45-59	0.70800		0.70814	Local		
01-02	Male	25-35	0.70797	0.70823	0.70809	Local	Non-Local	1,850 ± 43
00-2	Male	45+	0.70803		0.70800	Local		
00-3	Male	18-25	0.70838	0.70837	0.70810	Non-Local	Non-Local	
04-07	Male	25+	0.70763	0.70782	0.70792	Non-Local	Local	1,987 ± 42
04-08	Male	26-39	0.70718	0.70790	0.70802	Non-Local	Local	1,822 ± 35
04-10	Male	30+	0.70818	0.70834	0.70800	Local	Non-Local*	
04-06	Male	18+	0.70838	0.70830	0.70808	Non-Local	Non-Local	1,611 ± 42
00-3A	Indeterm.	35+			0.70806			
Squirrel					0.70727	Intrusive		
Rodent					0.70795	Local		
Rodent					0.70794	Local		
Squirrel					0.70793	Local		

Notes: *Data from Burial 4-17/18 indicate she lived her early years (0-3) at or near SCL-287, moved away for an extended period sometime between the ages of 9 and 15 when the third molar crown was forming, and returned in adulthood. A similar pattern also holds for 04-10, a male. Instrumental precision for all ⁸⁷Sr/⁸⁶Sr values = ~0.00002 (2 standard deviations). Dates are uncalibrated.

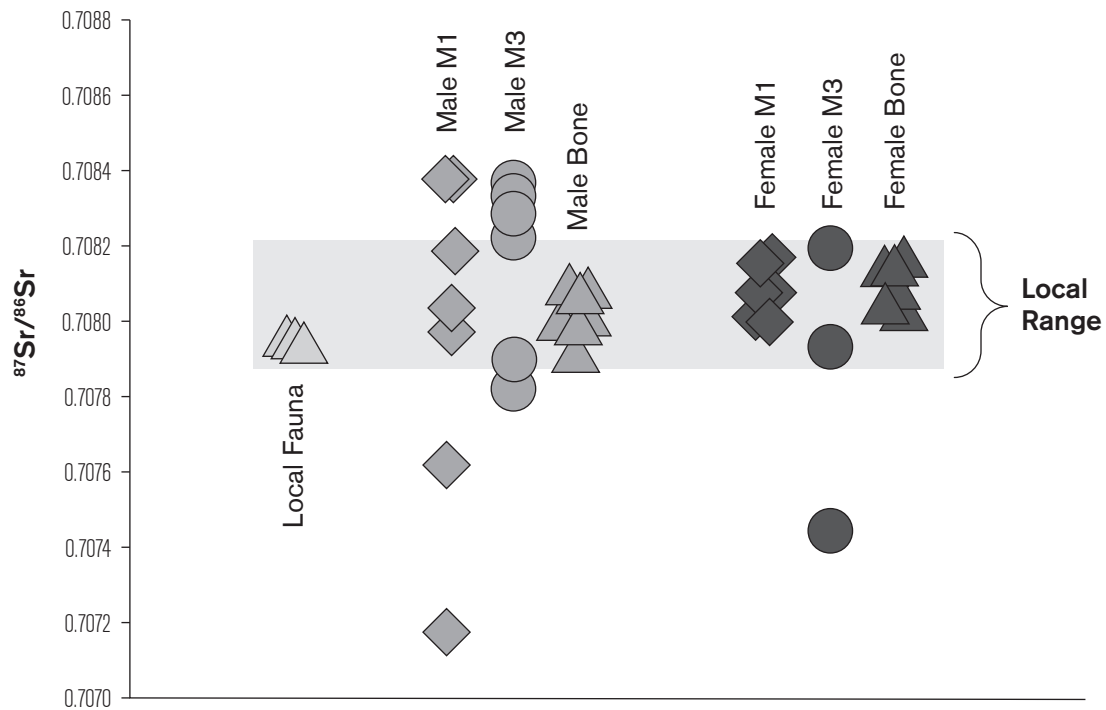


Figure 3. $^{87}\text{Sr}/^{86}\text{Sr}$ values for rodents, males, and females at SCL-287 for first molar, third molar, and bone.

therein, is really an aggregate of patterns averaged over hundreds of years for people buried at the site.

Four animal bones produced three nearly identical $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging between 0.70793 and 0.70795, and one very different value at 0.70727 (Table 1). The latter comes from a squirrel bone associated with a highly disturbed burial (04-11 at SCL-287; human bone from this burial was not included in this study). Excavation indicated that this burial was highly disturbed in recent times. It is possible, therefore, that this squirrel bone is not prehistoric in nature and is intrusive to the burial. We therefore reject the isotopic data from this bone sample for interpreting the ancient human samples.

In general, the human bone $^{87}\text{Sr}/^{86}\text{Sr}$ values are similar but slightly elevated compared to the three accepted prehistoric animal bones from the site (Fig. 3). Human bone values are highly clustered, ranging between 0.70792 and 0.70814, with an average of 0.70805 and a standard deviation of just 0.00007. This indicates that humans were consuming a slightly different range of foods than the local rodents we measured, causing their

$^{87}\text{Sr}/^{86}\text{Sr}$ to be slightly higher. At the same time, the low variation among the humans suggests they were very similar in where they obtained their foods as adults, and more importantly, suggests all 13 males and females, as well the one burial (04-06) of indeterminate sex, were living at or very near SCL-287 during the last 10–20 years of their life.

The slightly elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values relative to local fauna may be explained by an incorporation of small amounts of marine-derived foods into the human diet. $^{87}\text{Sr}/^{86}\text{Sr}$ in ocean water is fairly constant around the globe at 0.7092, values that are passed on to marine fauna, including shellfish, fish, and marine mammals. We believe that the incorporation of some marine-derived foods or salt, including salmon, in the diets of SCL-287 inhabitants may have raised $^{87}\text{Sr}/^{86}\text{Sr}$ values in the human population. Indeed, carbon isotope values from bone collagen and apatite in these same burials show that some marine food was important in local diets at SCL-287 (Bartelink 2010). Bartelink's analysis also showed significant overlap in the range of carbon (and nitrogen) isotope values for males and females at the site, suggesting similar diets for the sexes.

In this study, female bone $^{87}\text{Sr}/^{86}\text{Sr}$ values also largely overlap with those of the males. A T-test (two tailed, equal variance) comparing the mean $^{87}\text{Sr}/^{86}\text{Sr}$ of males and females failed to show a significant difference ($p=0.16$). Similarly, an F-test comparing variance among female and male bone $^{87}\text{Sr}/^{86}\text{Sr}$ values suggests the range of variation observed within males is similar to that observed in the females ($p=0.76$). As adults, then, males and females seem to have been consuming foods from roughly the same environments and there is little inter-individual (low standard deviation among both males and females) or inter-sex difference.

On the other hand, $^{87}\text{Sr}/^{86}\text{Sr}$ is much more variable in early growing teeth, particularly among males (Fig. 3). Here, the difference between males and females is pronounced, and a T-test (two tailed, unequal variance) comparing the mean early-growing-tooth $^{87}\text{Sr}/^{86}\text{Sr}$ for males against females is significant ($p=0.04$). As well, an F-test comparing variation is highly significant ($p=0.0008$), showing the males are much more variable than females. Four of the seven males have $^{87}\text{Sr}/^{86}\text{Sr}$ values in their permanent first molar that mark them as non-locals to the site. By contrast, all six females have M1 or incisor $^{87}\text{Sr}/^{86}\text{Sr}$ values within the established local range. This suggests they lived their early years, through at least age 3, at SCL-287, the same place they lived the last 10–20 years of their adult lives, and the same place they were ultimately buried. Indeed, a T-test comparing female bone with M1/incisor values does not suggest a different mean value ($p=0.59$; two tailed, unequal variance), suggesting that these females were born and lived as adults in the same location.

A two-tailed Fisher's exact test comparing sex (male/female) by residence status (local/immigrant) is not quite significant, with a p-value of 0.07. However, the same comparison produces a high Φ coefficient at -0.62 . This suggests that the probability that males and females were immigrating to SCL-287 at a similar rate is low. In particular, there are many more males identified as immigrants (57%), relative to females (0%).

Data from third molars provide additional information on the spatial location of nine individuals during their late childhood to early teenage years (four individuals, three female and one male, did not have M3 teeth with enamel that we could sample). As among first molars, variation in third molars for the males is

high, suggesting that at least four of the six males, and perhaps all six, did not live at or near SCL-287 while these teeth were forming. Of the four males identified as non-locals based on M1's, two (00-3 and 04-6) appear to have still been living in their natal village during M3 formation, one may have moved to SCL-287 while the M3 was forming (04-07; as indicated by an intermediate value between the M1 and bone), and one may have moved to SCL-287 just prior to formation of the M3 (04-08) causing nearly identical bone and M3 values. Interestingly, two of the males identified as locals based on their M1s (01-02 and 04-10) have M3 $^{87}\text{Sr}/^{86}\text{Sr}$ values that suggest they moved away from SCL-287 during the time the M3s were growing. This suggests they were born near the site, moved away during early teenage years, and ultimately returned to the village as adults. By contrast, two of the three females with M3s still appear to have been living at the site during their early teenage years, while one of the three (04-17/18) appears to have moved away from SCL-287 before returning in adulthood.

DISCUSSION

Comparing $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from bone to $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in early-growing teeth allows us to evaluate whether individuals were born and grew up near the site where they were buried, and to trace their movements over the course of their lives. The data reveal several interesting trends that provide information on individual mobility and social structure in the Middle Period of the southern San Francisco Bay region.

Post-Marital Residence

Figure 3 shows that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in male first molars (M1) are highly variable, displaying a range of variation significantly greater than those of both female M1/incisors, and male bone values. This suggests males were born in a wide range of locations outside of SCL-287. By contrast, male bone $^{87}\text{Sr}/^{86}\text{Sr}$ is highly clustered around the local value for the site, suggesting that all six males had been living at SCL-287 and eating local foods for the last 10–20 years of their lives. That is, they must have immigrated to the site sometime between age 3 and their early adult years. Relative to the males, variation in female M1/incisor and bone $^{87}\text{Sr}/^{86}\text{Sr}$ is low, and centers on the local SCL-287 value. This is consistent with the

interpretation that all six females were born at the site and lived there as adults as well.

This overall pattern is consistent with what would be expected under a post-marital residence system that favors matrilocality, and (importantly) is inconsistent with a patrilocal or virilocal system. A similar pattern has been found in a larger sample size in an Early Period cemetery, CCO-548, to the northeast of SCL-287 (Jorgenson 2012). In general, then, the findings from SCL-287 are unlike the dominant pattern reported in Central California ethnography, where patrilocality is most common. Why this might be so is considered in greater detail below.

As shown in the third molar data, however, the picture is not so black and white (i.e., matrilocal and patrilocal). Variation in male M3s falls between the highly variable male M1s and the standardized male bone. Data indicate that four of the six males were living outside SCL-287 for at least a majority of the time when their M3 crowns were forming. This includes one of the males who seems to have been born at SCL-287 (Burial 04-10), suggesting he moved away during early teenage years and then later came back. Further, many of the males identified as immigrants based on signatures in M1s show M3 values intermediate between the M1 and the local signature (Burials 04-06, 04-07, and 04-08). If these males moved to SCL-287 while their M3 crowns were still forming, strontium in the enamel would represent a mixture of that deposited prior to and after the move, hence would have an intermediate value between the M1 and local bone value. Of course, it is also possible that these males lived in an altogether different region, isotopically intermediate between their birthplace and SCL-287. Additional microsampling of growth layers within the M3 that grew at different times might resolve this issue, but must await future research. In any case, the overall pattern in M3s is consistent with the interpretation that many of the immigrant males moved to SCL-287 around the time the crowns of their M3s were completing or shortly thereafter; that is, roughly between the ages of 12–16. Such movements, then, are consistent with the time frame expected in a post-marital residence shift.

Although only three of the females included in the study had M3s, it is surprising that $^{87}\text{Sr}/^{86}\text{Sr}$ in the female M3s is also highly variable; in fact, more variable than either female M1/incisors or bone. This suggests that

females, too, were often shifting residences between the ages of 12–16; i.e., around the time they may have been married. For example, one of the females (burial 04-17/18) clearly moved away from her natal village prior to formation of her M3 crown, and returned again after the M3 crown had formed. Together, the M3 data from both sexes indicate that individuals were frequently shifting residence between the ages of 12–16, even those who eventually ended up back in their natal village as adults. This is consistent with descriptions from Central California ethnography, where bride service, the need to build up economic capital, and personal desires, among other factors, would influence a couple's decision to shift residence location after marriage.

Sources of Immigrants

By comparing the male M1 $^{87}\text{Sr}/^{86}\text{Sr}$ values to other studies, we can also estimate potential source populations for immigrants. Figure 4 shows $^{87}\text{Sr}/^{86}\text{Sr}$ values for human and rodent bone for a range of sites in Central California (see Fig. 1 for locations of sites; note that the X-axis in Fig. 4 is meaningless; it simply spreads out samples across the graph to facilitate intersite comparison; see Eerkens et al. 2014a). The Y-axis is reversed so that sites in the north are generally situated at the top of the figure and southerly sites at the bottom. As shown in Figure 4, the range of isotopic values within archaeological sites tends to be small, while the between-site differences are much greater. Also plotted in Figure 4 are the non-local M1 and M3 $^{87}\text{Sr}/^{86}\text{Sr}$ values from SCL-287.

Overall, the SCL-287 humans are most similar in their bone $^{87}\text{Sr}/^{86}\text{Sr}$ to two 4,000 B.P. burials we have analyzed from ALA-312, a site also located on San Francisco Bay. This suggests that foragers living near and on the southern part of San Francisco Bay may acquire a similar $^{87}\text{Sr}/^{86}\text{Sr}$ signature, or alternatively, that the two ALA-312 individuals had lived their recent adult years near SCL-287 and had migrated to ALA-312 just prior to death.

The four non-local M1 values from the SCL-287 males are shown as stars in Figure 4. As seen, two of the $^{87}\text{Sr}/^{86}\text{Sr}$ M1 values are smaller than the SCL-287 local range and two are larger. The smaller values, from burials 04-07 and 04-08, plot near the range of three other sites we have investigated, SCL-869, CCO-548, and ALA-554. These sites are nearby to the south and east of SCL-287. Burial 04-07 overlaps especially well

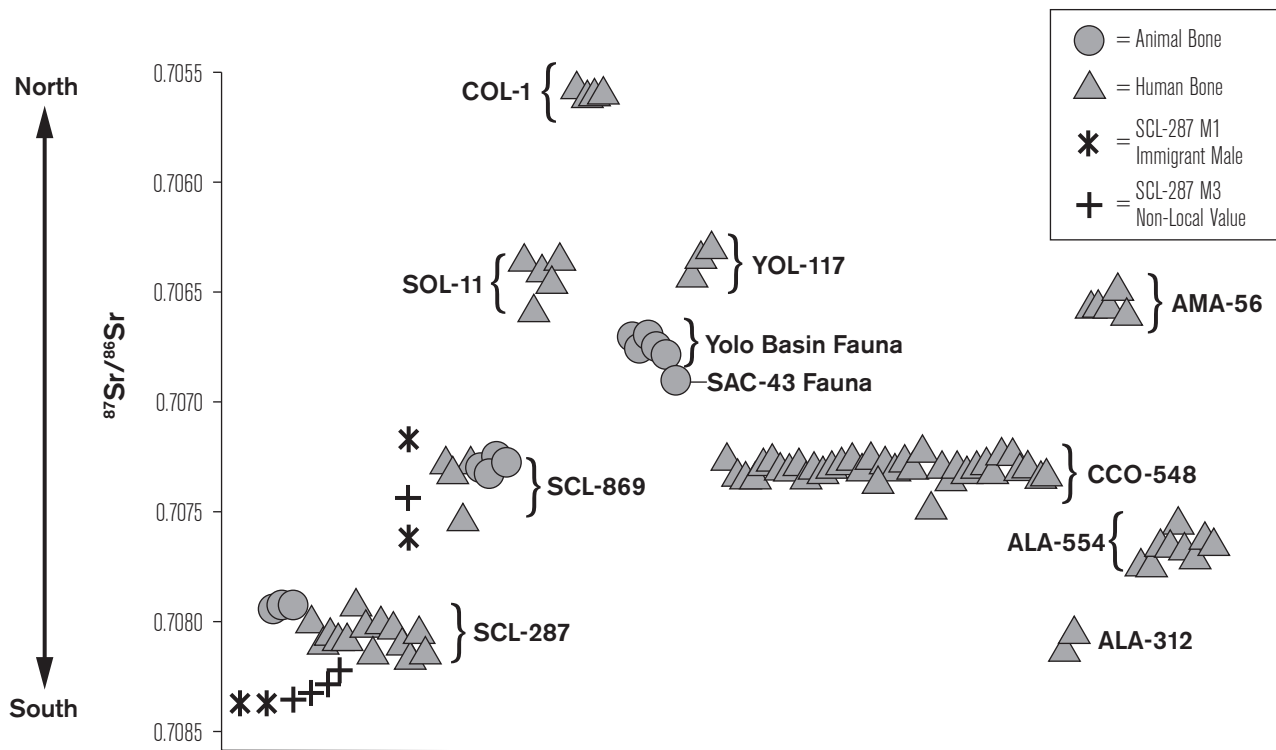


Figure 4. SCL-287 $^{87}\text{Sr}/^{86}\text{Sr}$ values against regional human and faunal bone samples. Human samples are triangles, faunal samples are circles. Non-local M1 and M3 values are also plotted.

with values recorded at ALA-554, and it is possible that burial 04-07 may have been born in the Amador/Livermore Valley, though unsampled areas to the west of SCL-287 are also possible. By contrast, burial 04-08 may have been born near SCL-869 (see Leventhal et al. 2009) or to the north along the San Francisco Peninsula where younger geological formations are present. The other two non-local M1 values (at the bottom left of Fig. 4), from burials 00-3 and 04-06, are distinctive and do not overlap any previously recorded $^{87}\text{Sr}/^{86}\text{Sr}$ values in Central California humans. The larger $^{87}\text{Sr}/^{86}\text{Sr}$ values for these two individuals indicate occupation on or near older geological formations. In general, older Mesozoic deposits are present to the southeast of SCL-287 in the Santa Clara Valley. It is possible these two individuals came from that region, but additional studies are necessary to test that hypothesis.

Figure 4 also plots the five non-local M3 values. One of these from burial 04-17/18 (a female) is similar to values recorded for SCL-869. As a teenager, then, this woman may have moved to the southeast, near that site. The remaining four non-local M3 values, all from males,

vary between the two larger M1 values and the local SCL-287 value. It is possible that these males lived in the same region, or even the same village, as teenagers, but migrated to SCL-287 at slightly different ages, while their M3 crowns were forming.

In sum, there seem to be at least two different regions from which migrants came to SCL-287. One may have been towards the northeast, in the Amador/Livermore Valley region, given similarities in Sr to ALA-554 locals. The other is isotopically unusual, but may have been to the southeast in the Santa Clara Valley, though additional sampling will be necessary to evaluate these hypotheses.

CONCLUSIONS

The isotopic approach described here is new to California archaeology (see also Eerkens et al. 2014a; Jorgenson et al. 2009; Jorgenson 2012), and there is still much baseline data we need to collect about underlying spatial variation in stable isotopes across the state. We can turn to other disciplines for some help here. Thus, Sr-isotopic studies have been used to trace salmon

back to particular Sierra Nevada natal streams (e.g., Barnett-Johnson et al. 2008; Ingram and Weber 1999), to determine paleo-salinity in San Francisco Bay (e.g., Ingram et al. 1996), and to calculate the ages of particular geological formations (Chen and Tilton 1991; DePaolo 1981; Ingram 1998; Kistler and Peterman 1973; Nelson 1995). But to estimate the Sr biologically available to humans it will be necessary to sample local and ancient rodents, or preferably, ancient humans. Thus, much of the legwork will have to be carried out by archaeologists. As shown here, this approach has much to offer California archaeology, opening new windows into ancient mobility patterns, societal organization, and marriage networks.

The sample size from SCL-287 is small. Nevertheless, the data suggest differences in variation in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between males and females. Males were much more variable than females in their early-growing teeth. This pattern is consistent with the interpretation that inhabitants at SCL-287 had a preference for matrilocality. This is an hypothesis that can be tested in future studies with larger sample sizes if additional excavations are conducted at the site. It should also be tested at other Middle Period sites in the region.

Matrilocality contrasts with what we know from the ethnographic record from central California, where patrilocality was clearly dominant. Of course, we should not expect the archaeological record to duplicate the ethnographic one. For example, Johnson (1988) has shown that while ethnographic studies among the Chumash suggest a preference for patrilocality, ethnohistoric mission records indicate that matrilocality was actually more common, accounting for roughly 70% of marriages. A major exception to this matrilocality pattern were polygamous chiefs, who practiced patrilocality. In short, a stated preference by consultants in the early twentieth century for one form of post-marital residence may not be an accurate model for patterns at contact, much less pre-contact, times.

The results from SCL-287 are, however, similar to results from Early Period burials dating between 4,000 and 3,000 B.P. at CCO-548 (Jorgenson 2012), where data are also most consistent with a preference for matrilocality. An interesting question for future research, then, is whether SCL-287 is unique in this respect in the Middle Period (and whether CCO-548 is unique for the Early Period). Assuming our interpretation is accurate,

we think this is unlikely, since marriage networks require coordination between villages, and villages practicing matrilocality in regions where patrilocality was dominant would find it difficult to obtain marriage partners.

If SCL-287 is not unique in being matrilocality, an interesting question is when and how quickly post-marital residence patterns changed to approximate the patterns recorded ethnographically, and indeed, whether the ethnographic pattern is a good model for any prehistoric or historic period. As mentioned, CCO-548 (which predates SCL-287) shows a similar pattern, suggesting matrilocality was the ancestral preference in Central California. Some have argued that post-marital residence patterns change in response to other conditions in societies. Bettinger (n.d.), in particular, has argued that growing inter-personal violence in the Late Holocene in California may have encouraged related males to stay together to defend villages. This, in turn, may have encouraged a shift from matrilocality to patrilocality preference. Others have shown that violence significantly increased during the Middle Period and into the Late Period in Central California (Allen 2012; Andrushko et al. 2005, 2010; Bartelink et al. 2013; Jones and Schwitalla 2008; Jurmain 2001; Jurmain and Bellifemine 1997; Jurmain et al. 2009; Schwitalla 2013). Sharp-force trauma, which includes projectile injuries, in particular, steadily increased over time in Central California, with the highest rates recorded in historic periods (Schwitalla et al. 2014). An interesting hypothesis for future research is to test whether marriage patterns slowly shifted after the Middle Period (ca. 1,500 B.P.) in response to increasing rates of inter-personal violence.

At the same time, the archaeological data from SCL-287 also suggest flexible post-marital residence strategies. Thus, while the majority of males were born outside SCL-287, suggesting a preference for matrilocality, some men have isotopic signatures suggesting SCL-287 was their natal village. Likewise, while all women appear to have lived in their natal village as adults, they seem to have moved frequently in their early teenage years. This suggests that post-marital residence did not necessarily follow rigid rules, but could be modified to suit individual preferences.

Indeed, based on the isotopic data, residence shifts seem to have been common. Of the nine individuals in this study with $^{87}\text{Sr}/^{86}\text{Sr}$ values for M1, M3, and bone, only two (04-09 and 04-13), or 22%, have isotopic data

suggesting they were born and lived their entire lives in the same location. In this respect, the archaeological data are consistent with ethnographic reports, where couples could decide to follow or not follow societal norms depending on individual circumstances. It also suggests that despite the presence of “sedentary” villages that were occupied by some people year-round, individual mobility between such villages was still high.

In closing, we hope this study inspires others to continue building a database of $^{87}\text{Sr}/^{86}\text{Sr}$ values for a range of archaeological sites in California. By building such a database, we will be able to better determine how people moved across the landscape at different points in their lives and how this varied by sex, age, status, and other factors. Moreover, with additional site-intensive studies, we will be able to rule out certain regions as possible natal villages for individuals who did immigrate during the course of their lives, and hopefully, trace ancient marriage networks. Such work will provide an important baseline context for understanding gene flow and genetic variation observed in other studies (e.g., Eshleman and Smith 2007; Johnson and Lorenz 2006; Johnson et al. 2012). As well, with larger samples of males and females, we may be able to examine preferences for post-marital residency and changes over time in such preferences.

Finally, the isotopic data allow us to reconstruct certain aspects of the life histories of particular individuals in the past. Doing so gives some agency to the dead, allowing the deceased to reach out to the living and tell us parts of their life histories. In this respect, although the native people of California did not have a written language, parts of their individual stories are “written” isotopically in their teeth and bone. We believe that such information is not only relevant to anthropological and archaeological research, but also hope it is relevant to living descendants by helping them reconnect with specific ancestors.

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