INVESTIGATION OF POSTMARITAL RESIDENCE DURING THE EARLY PERIOD IN CENTRAL CALIFORNIA: A STABLE SULFUR ISOTOPIC STUDY OF SEX-BIASED DISPERAL AT CA-SJO-68

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Previously published isotopic studies of paleomobility and postmarital residence reveal varied patterns and dynamic marriage networks for the Early Period (ca. 4,050-2,550 cal BP) in central California. Expansion of research on synchronic patterns of postmarital residence during the Early Period is necessary to foster understanding of marriage-exchange spheres and how it covaries with other aspects of cultural systems for precontact California. This study reconstructs sex-biased mobility profiles using stable sulfur isotopes of human skeletal tissues of 12 females and 14 males from archaeological site CA-SJO-68, dated to the Early Period, to interpret hypothesized postmarital residence patterns. Results are consistent with a preference for endogamous marriage and show a slight bias towards female immigration, suggesting an inclination for patrilocality in cases of exogamy.

Postmarital residence affects the regularity of interactions within a kinship system, the number of individuals within a household, and the complexion of domestic units. These configurations shape the sociality, obligations, and roles espoused by kin and have far-reaching consequences for the group’s broader social organization. Therefore, investigation and understanding of regional and diachronic postmarital residence patterns can elucidate other aspects of human behavior and society. Isotopic evidence from human skeletal tissues can inform on ancient human geolocation, mobility, and sex-biased dispersal patterns (e.g., Bartelink 2006; Burns et al. 2012; Harold et al. 2016; Jorgenson 2012; Laffoon et al. 2017, 2019; Price et al. 2008; Prowse 2016; Sullivan 2018; Winter-Schuh and Makarewicz 2019). This study investigates postmarital residence at an Early Period (ca. 4,050-2,550 cal B.P.) burial population from CA-SJO-68 in central California using stable sulfur isotopes of bone, first molar, and third molar collagen. This research produces a valuable data set of a rarely used isotopic system that will contribute to previously reported and future multi-isotopic studies that aim to understand precontact mobility and the social organization of indigenous California.

BACKGROUND

This study focuses on stable sulfur analysis of the collagen fraction of bone and teeth to ascertain individual-level mobility and to interpret sex-biased mobility profiles of a population from archaeological site CA-SJO-68. The sections below provide an overview of the study site, reviews the approach to tracking human geolocation using stable sulfur isotopes, and reflects on studies using other isotopic systems to investigate postmarital residence in central California.
Characterization of the Windmiller Pattern of the Early Period (ca. 4,050-2,550 cal BP) in central California was based, in part, on seminal research conducted at CA-SJO-68, also known as the Blossom Mound (Bennyhoff 1994; Bennyhoff and Hughes 1987; Groza et al. 2011; Heizer 1949; Moratto 1984). The site was located on a natural clay knoll near Thornton, California, about two kilometers north of the Mokelumne River (Ragir 1972:27; Figure 1). The location of the Blossom Mound comports with other Early Period sites found on old levee ridges within riparian zones and near freshwater marshes (Heizer 1949; Lillard et al. 1939; Ragir 1972; Moratto 1984). E. J. Dawson, an amateur archaeologist from the Lodi area (Ragir 1972:1), initially explored the site in the 1920s, and excavations were later conducted by the University of California Archaeological Survey (UCAS) beginning in the 1940s.

Early excavations at CA-SJO-68 were focused on burial recovery and analysis, lacked adequate screening, and likely led to midden constituents being systematically missed (Meighan 1987; Moratto 1984; Ragir 1972). Blossom Mound shows a relatively high density of graves (Meighan 1987) that, in conjunction with a dearth of recovered domestic debris, initially led Heizer (1949, 1974) to conclude that the site served primarily as a cemetery. The majority of burials recovered during UCAS excavations are ventral extensions (~55 percent), oriented towards the west (~73 percent), and 54 percent were accompanied by grave goods (Ragir 1972:Tables 16 and 19a). These observations associate the site with the Windmiller Pattern of central California (ventral extensions, oriented towards the west, and with a high frequency of grave-associated objects) (Heizer 1949, 1974; Meighan 1987; Moratto 1984; Ragir 1972). Among the grave accoutrements, well-crafted charmstones manufactured from various materials (e.g., translucent marble, schist, and igneous or metamorphic rock) have been reported (Ragir 1972:Table 39). Stone projectiles, predominantly made of obsidian (~84 percent), include large-stemmed points (Ragir 1972:Tables 40 and 42). Other grave goods recovered include *Olivella* and *Haliotis* shell beads and ornaments, quartz crystals, and bone artifacts (e.g., awls, gorges, fishhooks, and miscellaneous worked bone) (Ragir 1972:Tables 46a and 47).

Ragir (1972) analyzed and tabulated artifacts from previous excavations and demonstrated that there is more evidence for domestic objects than previously reported. These include fragments of mortars and metates.
(n = 13), manos/pestles (n = 17), baked-clay objects (n = 8), and bone implements (n = 13). Flaked stone debitage has generally been overlooked (Heizer 1974; Meighan 1987; Moratto 1984); Ragir (1972) tabulated 116 flaked stone objects such as flakes, pebbles, scrapers, and choppers. Faunal remains have also been largely ignored; however, those recovered during UCAS excavations reveal that many of the mammals and birds common to the area are represented at the site (Heizer 1974; Meighan 1987; Moratto 1984; Ragir 1972).

In general, Early Period sites in central California contain a sophisticated material culture and varied dietary and technological assemblages (Heizer 1949, 1974; Lillard et al. 1939; Meighan 1987; Moratto 1984; Ragir 1972; Rosenthal et al. 2007; Wohlgemuth 1996). Botanical, faunal, and technological evidence suggests that Early Period populations took advantage of the developing grasslands, marshes, and riparian forests that appeared during the Middle Holocene (ca. 8,000 years ago) in central California (Moratto 1984; Rosenthal et al. 2007; Wohlgemuth 1996). Overall, Early Period sites, including CA-SJ0-68, demonstrate evidence consistent with residentially stable settlements and logistically organized subsistence practices adapted to valley and riverine environs.

**STUDY APPROACH**

The reconstruction of human geolocation and mobility profiles using isotopic tracers of geography relies on the principle that isotopic values in human skeletal tissues (e.g., bone and dentinal collagen) reflect those from regional substrates in the environment (Katzenberg 2008; Makarewicz and Sealy 2015; Nehlich 2015). The fraction of skeletal tissues commonly used in stable isotope studies includes the protein and mineral components of bone, collagen, hydroxyapatite, dentinal collagen, and enamel from teeth. Bone tissue undergoes a process known as remodeling during which skeletal tissues are resorbed and reconstructed, resulting in an 18 percent annual turnover of adult human bone (Steele and Bramblett 1988:10-20; White et al. 2012:35-37). Typically, completion of this process occurs between every five and 25 years and varies depending on the type of element sampled (Hedges et al. 2007).

Teeth consist of three distinct tissues: enamel, cementum, and dentine (Hillson 1996). Unlike bone, these dental tissues do not remodel. Deciduous and permanent teeth begin development between 14 and 16 weeks, and 28 and 32 weeks after fertilization, respectively (Hillson 1996; White et al. 2012:385-386). Tooth growth starts with the crown and terminates at the root apex. The crown of the permanent first molar develops around birth and finishes between 2.5 and 3 years of age. The growth of dentine persists until the completion of the apical tip of the root between 9 and 10 years of age. In the case of the permanent third molar, the crown begins to form between 7 and 10 years of age and completes between 12 and 16 years with the dentine continually growing through about 18 to 25 years. Therefore, the isotopic values of first molars, third molars, and bone evaluated in this study serve as proxies for residence during childhood, late adolescence/early adulthood, and later adulthood. Once potential dietary differences between individuals are considered, a person’s change in residence can be determined if the isotopic values from tissues that form during childhood, late adolescence/early adulthood, and adulthood differ. Furthermore, when the sex of individuals is known, the mobility profiles of females versus males can be compared, and sex-biased movement assessed to investigate postmarital residence.

This study focuses on stable sulfur of the collagen fraction of bone and teeth to ascertain individual-level mobility. Reservoirs of sulfur in nature are varied and include pyrite in the geosphere, dissolved sulfates in the hydrosphere, and evaporitic sulfates in certain soils (Bottrell and Newton 2006; Nehlich 2015). The relative abundance of sulfur-34 ($^{34}$S) to sulfur-32 ($^{32}$S) is conventionally measured for use in human mobility and paleodietary studies. The $^{34}$S/$^{32}$S ratio is reported using the delta notation ($\delta^{34}$S) and in permil notation (‰; parts per thousand). Sulfur is incorporated in the amino acid, methionine, which performs an essential function in the protein structure of organismal tissues (Ingenbleek 2006). Methionine cannot be produced by animals and is an essential amino acid for humans, and must be assimilated from food. A study conducted by Nehlich and Richards (2009) demonstrated that the amount of sulfur in mammalian bone collagen is 0.28 ± 0.07 percent by weight.
Figure 2. $\delta^{13}$C and $\delta^{15}$N values of CA-SJO-68 samples included in this study, and other Early Period components of sites in central California reported in the literature (Bartelink 2009 [CA-ALA-307]; Barton et al. 2020 [CA-SJO-112]; Beasley et al. 2013 [CA-CCO-295]; Eerkens et al. 2015 [CA-YOL-171]; Mikkelsen et al. 2008 [CA-SFR-4]; Ralston et al. 2016 [CA-CCO-696]; Ralston 2020 [CA-SAC-107, CA-SJO-68]).

In addition to providing geolocational information as a feature of local geology, stable sulfur is also useful for investigating diets and, in particular, marine resource consumption (Bartelink and Chesson 2019; Nehlich and Richards 2009). Marine $\delta^{34}$S is higher than that reported from terrestrial environments. Higher $\delta^{34}$S values in human tissues may indicate that marine protein is an important component of the diet. It is crucial to incorporate other elements used to reconstruct paleodiets (carbon and nitrogen) to help distinguish between marine-sourced foods or local geology as the driver for variation in collagen $\delta^{34}$S values. Dietary isotopic evidence from CA-SJO-68 are consistent with freshwater-riverine and terrestrial food webs and, therefore, sulfur values are not expected to be significantly influenced by marine contributions. For example, Figure 2 plots previously published carbon ($\delta^{13}$C) and nitrogen ($\delta^{15}$N) values from several Early Period sites in central California, showing that sites close to San Francisco Bay have quite high values, consistent with significant marine food input, while those from the California Delta and Sacramento Valley have much lower values.

MOBILITY AND POSTMARITAL RESIDENCE IN CENTRAL CALIFORNIA

Ethnographic evidence suggests that virtually all indigenous Californians practiced patrilocal residence, characterized by married couples living with or near the husband’s family (Bettinger 2015; Jorgensen 1980). Data reported by Jorgensen (1980:variable #308) demonstrates that 85 percent of societies in the Sacramento Valley and 77 percent in the San Joaquin Valley show a preference for patrilocal residence. However, approximately half of ethnographic populations in California also allowed alternative practices when individuals needed or desired them, with matrilocal (residence with or near the wife’s family) being the most common (Jorgensen 1980:174-190). Additionally, even for societies that did not permit alternative forms, matri-patrilocal, in which a couple lives initially with the wife’s family immediately after marriage (e.g., until the birth of the first child), followed by a permanent shift to patrilocal, was common (Jorgensen 1980:174-190). Since stable isotope evidence permits comparison between male and female mobility profiles, it is increasingly employed to investigate to what extent observed ethnographic patterns of mobility and postmarital residence apply to...

Burns et al. (2012) employed an ANOVA analysis on δ¹⁸O of bone apatite from four Early Period (CA-SJO-142, CA-SJO-68, CA-SJO-56, and CA-ALA-307), six Middle Period (CA-SAC-43, CA-SAC-60, CA-SJO-154, CA-ALA-309, CA-ALA-329, and CA-ALA-328), and five Late Period (CA-SAC-43, CA-SAC-60, CA-SAC-06, CA-SAC-309, and CA-ALA-329) components in central California to investigate diachronic and regional postmarital residence patterns. Evidence from that study demonstrates that endogamy was typical among Early Period populations in the Central Valley. In contrast, those from the Bay region during the same period are characterized by matrilocality (Burns et al. 2012). Beginning in the Middle Period, populations living near the San Francisco Bay show a shift from matrilocality to patrilocality, while those in the Central Valley demonstrate a strong patrilocal preference; evidence for greater endogamy emerges for Bay area populations during the Late Period (Burns et al. 2012).

Two studies use strontium isotopes (⁸⁷Sr/⁸⁶Sr) to reconstruct individual mobility profiles and investigate postmarital residence practices for Early Period populations in central California (Harold et al. 2016; Jorgenson 2012). Harold et al. (2016) examined early-forming teeth (e.g., first molars, incisors, and canines), third molars, and bone for females (n = 8) and males (n = 10) from CA-SJO-112 and showed a pattern consistent with patrilocality. The majority of males (60 percent) showed “local” ⁸⁷Sr/⁸⁶Sr values of enamel from early-forming teeth but “nonlocal” values of third molars. Two males (20 percent) showed “local” ³⁷Sr/³⁶Sr values of all sampled tooth enamel. Taken together, 80 percent of males were local during their early childhood and adult years. In comparison, most females (75 percent) show “nonlocal” values of teeth enamel. This pattern suggests a system of female dispersal with women leaving their natal homes to live as adults at CA-SJO-112. Furthermore, the range of ⁸⁷Sr/³⁶Sr values of tooth enamel for females suggests that they immigrated from environments with similarly available strontium sources, indicating that they likely came from similar regions as opposed to a range of locations. Also, males (60 percent) with a local → nonlocal → local mobility profile showed ⁸⁷Sr/³⁶Sr values of third molars consistent with the natal environment for females. This suggests that males left the immediate vicinity of CA-SJO-112 during late childhood or early adolescence to live within the home range of migrating females and later returned to the site as adults. This pattern is consistent with males leaving to live in villages where their future wives resided to perform bride service duties starting around puberty and until the age of 16.

Jorgenson (2012) assessed postmarital residence of a burial population from CA-CCO-548 (the Marsh Creek site) using strontium isotopes of tooth enamel and bone apatite. Evidence from her study showed that for individuals who lived between 3,340 and 3,900 cal BP (Marsh Creek 3), 40 percent of males (n = 35) had “nonlocal” signatures compared to about 22 percent of females (n = 23) (Jorgenson 2012:149-150). In other words, about 74 percent of immigrants to the site were male. Individuals dated between 2,900 and 3,300 BP (Marsh Creek 4) showed about 54 percent of males (n = 13) and 41 percent of females (n = 17) with “nonlocal” ⁸⁷Sr/³⁶Sr values; both males and females represent 50 percent of immigrants to the site (Jorgenson 2012:149-150). These results are consistent with a slight preference for matrilocality during the Marsh Creek 3 phase, with a shift towards ambilocality during the Marsh Creek 4 phase at CA-CCO-548 (Jorgenson 2012). Additionally, there is a greater percentage of “nonlocals” reported for Marsh Creek 4 and less variation in ⁸⁷Sr/³⁶Sr values (Jorgenson 2012:148). This suggests that individuals migrating to CA-CCO-548 during Marsh Creek 3 originated from a wider range of locations than immigrants during the Marsh Creek 4 period.

The above demonstrates the complicated picture of marriage systems during the Early Period in California and points to the importance of building on isotopic studies of sex-biased dispersal patterns and postmarital residence. We expect that sulfur values of bone and tooth collagen from the CA-SJO-68 burial population to reflect sedentism (constricted variation) and a bias towards marriage-endogamy. The proposed sulfur range for the Sacramento Valley and the Sacramento-San Joaquin Delta, based on bone sulfur values collected from 37 sites throughout California, is between -1.5 and 6.3‰ and -5.6 to 4.2‰ (Table 1). We expect stable sulfur analysis of skeletal remains from the Blossom Mound population to reflect values from those environs.
Table 1. Expected δ\textsuperscript{34}S (‰) Regional Values.

<table>
<thead>
<tr>
<th>Region</th>
<th># Sites*</th>
<th>Mean</th>
<th>SD</th>
<th>Proposed δ\textsuperscript{34}S Range (‰)†</th>
</tr>
</thead>
<tbody>
<tr>
<td>South San Francisco Bay‡</td>
<td>5</td>
<td>-1.8</td>
<td>4.8</td>
<td>-6.6 to 3.0</td>
</tr>
<tr>
<td>East San Francisco Bay‡</td>
<td>4</td>
<td>2.9</td>
<td>2.2</td>
<td>0.7 to 5.1</td>
</tr>
<tr>
<td>Sacramento-San Joaquin Delta</td>
<td>3</td>
<td>-0.7</td>
<td>2.4</td>
<td>-5.6 to 4.2</td>
</tr>
<tr>
<td>Sacramento Valley</td>
<td>16</td>
<td>2.4</td>
<td>3.9</td>
<td>-1.5 to 6.3</td>
</tr>
<tr>
<td>Sierra Nevada</td>
<td>9</td>
<td>5.8</td>
<td>2.6</td>
<td>3.2 to 8.4</td>
</tr>
</tbody>
</table>

*Data from the U.C. Davis Archaeometry Laboratory (Jelmer Eerkens, personal communication 2020), Gardner (2013; CA-SCL-34), and Talcott (2019; CA-AMA-56); † Mean ± 2 SD; ‡ Does not include data from burial populations with isotopic evidence of marine and brackish contributions to the diet.

MATERIALS AND METHODS

Individuals from CA-SJO-68 are curated at the Phoebe A. Hearst Museum of Anthropology (PAHMA) at U.C. Berkeley. PAHMA granted permission to conduct isotopic analyses on human skeletal remains, including the samples reported in this study. In consultation with museum staff, we selected adult individuals with confident sex estimates to investigate potential sex-biased mobility using stable isotope analysis. Sex was assessed by previous researchers using diagnostic features of the pelvis and cranium (Buikstra and Ubelaker 1994; White et al. 2012). The primary author of this article reevaluated osteological assessments as part of sample selection. When selecting individuals, skeletal remains had to be complete enough to dependably assess sex and ideally to have a first and third molar and bone fragment available for study. Samples also had to meet the selection criteria established by PAHMA (e.g., teeth must be loose and lack pathology, preferential selection of rib fragments). This study focuses on a subset of samples selected during this process and includes 26 individuals, of which 12 are female and 14 are male.

Two to three grams of bone were sampled for the δ\textsuperscript{34}S analysis reported in this study, as well as for use in other isotopic studies (to be reported elsewhere). Collagen extraction followed a modified Longin method (Longin 1971). To mitigate potential diagenetic contamination, the outermost layer of bone was removed using a diamond-grit drill followed by ultrasonic cleaning of samples in deionized H\textsubscript{2}O with at least three five-minute baths and replacement of deionized H\textsubscript{2}O after each rotation. Samples were demineralized in 0.5 M hydrochloric acid (HCl); the 0.5 M HCl was changed every other day until demineralization was complete. After rinsing samples with deionized H\textsubscript{2}O three times, 0.125 M sodium hydroxide (NaOH) solution was added to samples and allowed to sit for 24 hours to remove potential soil humic contaminants. Samples were then centrifuged, and the supernatant decanted and discarded. Samples were then placed in water at pH3 (10-3 M hydrochloric acid) and heated in an oven at 70°C for at least 48 hours to solubilize collagen. The pH3 solution was decanted (and deposited in a clean vial) and replaced every 24-48 hours until samples were completely solubilized. Solubilized collagen was frozen, followed by freeze-drying to isolate the collagen fraction.

Approximately 10 mg of collagen from each bone and tooth sample was submitted to the U.C. Davis Stable Isotope Facility (SIF) to be measured with an Elementar Vario ISOTOPE cube interfaced to a SerCon 20-20 IRMS. The SIF monitors and corrects for possible drift and linearity by interspersing samples with duplicates of various laboratory reference materials. These materials have been calibrated directly against several international standards (IAEA S-1, S-2, and S-3; NBS-127, SO-5, and SO-6). This method has a long-term reproducibility of ± 0.4‰.

RESULTS AND DISCUSSION

Table 2 reports the individuals (n =26) from CA-SJO-68 that provided collagen for sulfur isotope analysis and reports their respective δ\textsuperscript{34}S data. From the population used in this study, 22 had bones (female = 10; male = 11), 18 had first molars (female = 10; male = 8), and 13 had third molars that met the PAHMA sampling criteria (female = 5; male = 8).
The δ³⁴S values for the CA-SJO-68 population for bone collagen range from 2.4 to 6.5‰ (range = 4.1), 1.8 to 6.4‰ (range = 4.6) for first molar dentinal collagen, and 2.6 to 6.8‰ (range = 4.2) for third molar dentinal collagen (Table 3). The δ³⁴S population mean for bone collagen is 4.2‰ (SD = 1.01), 4.3‰ (SD = 1.47) for first molar dentinal collagen, and 4.7‰ (SD = 1.36) for third molar dentinal collagen (Table 3). Since bone collagen represents diet and mobility for the last five to 25 years of life (Hedges et al. 2007) and individuals are most likely interred within locations where they lived before death, we argue that bone δ³⁴S values provide something of a proxy for the “local” signature at CA-SJO-68. Two standard deviations around the mean (2.2‰ to 6.2‰) delineate the “local” δ³⁴S range for the immediate area. The “local” δ³⁴S signature for CA-SJO-68 overlaps with the higher end of the previously recorded California Delta values and falls within the Sacramento Valley δ³⁴S range (Table 1). This “local” range is consistent with other populations living within the Delta, albeit on the higher end of the spectrum. While contributions of marine protein to the diet could account for the enrichment of δ³⁴S values at CA-SJO-68, δ¹³C and δ¹⁵N bone collagen values are consistent with freshwater-riverine and terrestrial foragers (Figure 2) and show that marine protein is not a significant contributor to the population’s dietary protein. Since the samples in this study are limited to one archaeological site, the enriched δ³⁴S values and constrained range reported likely represent the more immediate area surrounding CA-SJO-68 (e.g., within a 15- to 20-mile foraging radius of the site). Figure 3 shows boxplots comparing CA-SJO-68 δ³⁴S bone collagen values to other sites from the east San Francisco Bay, south San Francisco Bay, Sacramento-San Joaquin Delta, Sierra Nevada, and Sacramento Valley.

Table 2. δ³⁴S Values in Collagen of Individuals from CA-SJO-68.

<table>
<thead>
<tr>
<th>PAHMA #</th>
<th>Sex</th>
<th>Rib Sampled</th>
<th>Bone δ³⁴S (%)</th>
<th>M1 Sampled</th>
<th>M1 δ³⁴S (%)</th>
<th>M3 Sampled</th>
<th>M3 δ³⁴S (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-6472(0)</td>
<td>Female</td>
<td>Left</td>
<td>4.0</td>
<td>M1</td>
<td>2.1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-7569(0)</td>
<td>Female</td>
<td>Left</td>
<td>3.9</td>
<td>M¹</td>
<td>3.6</td>
<td>M³</td>
<td>3.2</td>
</tr>
<tr>
<td>12-7575(0)</td>
<td>Female</td>
<td>Right</td>
<td>4.9</td>
<td>M1</td>
<td>6.3</td>
<td>M³</td>
<td>6.3</td>
</tr>
<tr>
<td>12-7577(0)</td>
<td>Female</td>
<td>--</td>
<td>--</td>
<td>M¹</td>
<td>6.3</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-7581.1</td>
<td>Female</td>
<td>Left</td>
<td>2.7</td>
<td>M¹</td>
<td>5.3</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-7588(0)</td>
<td>Female</td>
<td>Right</td>
<td>4.4</td>
<td>M1</td>
<td>5.4</td>
<td>M³</td>
<td>6.3</td>
</tr>
<tr>
<td>12-7598(0)</td>
<td>Female</td>
<td>Left</td>
<td>3.8</td>
<td>M¹</td>
<td>5.1</td>
<td>--</td>
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<tr>
<td>12-7608(0)</td>
<td>Female</td>
<td>Right</td>
<td>4.6</td>
<td>M1</td>
<td>4.2</td>
<td>M³</td>
<td>4.3</td>
</tr>
<tr>
<td>12-7622.1</td>
<td>Female</td>
<td>Left</td>
<td>5.3</td>
<td>M¹</td>
<td>5.9</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-7638.1</td>
<td>Female</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>M³</td>
<td>5.2</td>
</tr>
<tr>
<td>12-8024(0)</td>
<td>Female</td>
<td>Right</td>
<td>3.6</td>
<td>M1</td>
<td>2.1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-8025(0)</td>
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<td>Left</td>
<td>3.5</td>
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</tr>
<tr>
<td>12-5824(0)</td>
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<td>Left</td>
<td>3.4</td>
<td>--</td>
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<tr>
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<td>Right</td>
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<td>M1</td>
<td>3.2</td>
<td>M³</td>
<td>4.3</td>
</tr>
<tr>
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<td>--</td>
<td>--</td>
<td>M¹</td>
<td>1.8</td>
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</tr>
<tr>
<td>12-7582(0)</td>
<td>Male</td>
<td>Right</td>
<td>4.6</td>
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<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-7603(0)</td>
<td>Male</td>
<td>Not sided</td>
<td>4.7</td>
<td>M1</td>
<td>4.1</td>
<td>M³</td>
<td>4.4</td>
</tr>
<tr>
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<td>Left</td>
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<td>--</td>
<td>--</td>
<td>M³</td>
<td>2.6</td>
</tr>
<tr>
<td>12-7614.1</td>
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<tr>
<td>12-7621(0)</td>
<td>Male</td>
<td>Left</td>
<td>4.6</td>
<td>M1</td>
<td>3.7</td>
<td>M³</td>
<td>4.3</td>
</tr>
<tr>
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<td>--</td>
<td>--</td>
<td>M¹</td>
<td>3.4</td>
<td>M³</td>
<td>5.6</td>
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<tr>
<td>12-7634(0)</td>
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<td>Right</td>
<td>5.6</td>
<td>M¹</td>
<td>4.5</td>
<td>M³</td>
<td>4.9</td>
</tr>
<tr>
<td>12-7640.1</td>
<td>Male</td>
<td>--</td>
<td>--</td>
<td>M¹</td>
<td>6.4</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-7646(0)</td>
<td>Male</td>
<td>Right</td>
<td>6.5</td>
<td>--</td>
<td>--</td>
<td>M³</td>
<td>6.8</td>
</tr>
<tr>
<td>12-7652(0)</td>
<td>Male</td>
<td>Left</td>
<td>2.4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>12-8022(0)</td>
<td>Male</td>
<td>Left</td>
<td>3.2</td>
<td>M1</td>
<td>3.8</td>
<td>M³</td>
<td>2.6</td>
</tr>
</tbody>
</table>

The δ³⁴S values for the CA-SJO-68 population for bone collagen range from 2.4 to 6.5‰ (range = 4.1), 1.8 to 6.4‰ (range = 4.6) for first molar dentinal collagen, and 2.6 to 6.8‰ (range = 4.2) for third molar dentinal collagen (Table 3). The δ³⁴S population mean for bone collagen is 4.2‰ (SD = 1.01), 4.3‰ (SD = 1.47) for first molar dentinal collagen, and 4.7‰ (SD = 1.36) for third molar dentinal collagen (Table 3). Since bone collagen represents diet and mobility for the last five to 25 years of life (Hedges et al. 2007) and individuals are most likely interred within locations where they lived before death, we argue that bone δ³⁴S values provide something of a proxy for the “local” signature at CA-SJO-68. Two standard deviations around the mean (2.2‰ to 6.2‰) delineate the “local” δ³⁴S range for the immediate area. The “local” δ³⁴S signature for CA-SJO-68 overlaps with the higher end of the previously recorded California Delta values and falls within the Sacramento Valley δ³⁴S range (Table 1). This “local” range is consistent with other populations living within the Delta, albeit on the higher end of the spectrum. While contributions of marine protein to the diet could account for the enrichment of δ³⁴S values at CA-SJO-68, δ¹³C and δ¹⁵N bone collagen values are consistent with freshwater-riverine and terrestrial foragers (Figure 2) and show that marine protein is not a significant contributor to the population’s dietary protein. Since the samples in this study are limited to one archaeological site, the enriched δ³⁴S values and constrained range reported likely represent the more immediate area surrounding CA-SJO-68 (e.g., within a 15- to 20-mile foraging radius of the site). Figure 3 shows boxplots comparing CA-SJO-68 δ³⁴S bone collagen values to other sites from the east San Francisco Bay, south San Francisco Bay, Sacramento-San Joaquin Delta, Sierra Nevada, and Sacramento Valley.
Table 3. Summary Statistics of $\delta^{34}$S Values at CA-SJO-68.

<table>
<thead>
<tr>
<th>δ$^{34}$S Breakdown</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
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<tr>
<td>Bone Collagen $\delta^{34}$S</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Population</td>
<td>21</td>
<td>4.2</td>
<td>1.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Female</td>
<td>10</td>
<td>4.1</td>
<td>0.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Male</td>
<td>11</td>
<td>4.3</td>
<td>1.2</td>
<td>4.1</td>
</tr>
<tr>
<td>M1 Collagen $\delta^{34}$S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>18</td>
<td>4.3</td>
<td>1.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Female</td>
<td>10</td>
<td>4.6</td>
<td>1.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Male</td>
<td>8</td>
<td>3.8</td>
<td>1.3</td>
<td>4.6</td>
</tr>
<tr>
<td>M3 Collagen $\delta^{34}$S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>13</td>
<td>4.7</td>
<td>1.4</td>
<td>4.3</td>
</tr>
<tr>
<td>Female</td>
<td>5</td>
<td>5.1</td>
<td>1.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Male</td>
<td>8</td>
<td>4.4</td>
<td>1.4</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Figure 3. Boxplots comparing $\delta^{34}$S in bone collagen from CA-SJO-68 to data from regions in central California: the east San Francisco Bay, south San Francisco Bay, Sacramento-San Joaquin Delta, Sierra Nevada, and Sacramento Valley.

The mean $\delta^{34}$S values at CA-SJO-68 for bone, first molars, and third molars are similar, with teeth values showing slightly higher $\delta^{34}$S and a larger range (Table 2, Figure 4). The $\delta^{34}$S values of first molars indicate a modestly greater range (range = 4.6) than $\delta^{34}$S values of bone (range = 4.1) and third molars (range = 4.3). This suggests that the population from CA-SJO-68 foraged from a moderately more diverse landscape in their childhood with varying sources of available sulfur when compared to their later years. The mean $\delta^{34}$S values of both first and third molars, taken together, indicate slightly greater mobility during childhood and teenage years when compared to adulthood.

The one-tailed Levene’s test for equality of variance comparing bone versus teeth is presented in Table 4. We predict that variation in first molars should be higher, since some people married in exogamously, while bone should be lower since it represents adults who lived at the site. None of the $p$-values are significant at an alpha of 0.05. However, the lower $p$-value comparing $\text{var}(\text{bone})$ and $\text{var}(\text{M1})$, relative to comparing $\text{var}(\text{bone})$ and $\text{var}(\text{M3})$, is interesting. Overall, based on the Levene’s test results, we cannot reject the null hypothesis.
that bone and teeth variance are equal at the $p = 0.05$ level. This suggests that individuals from CA-SJO-68 foraged in locales with a similar range of available sulfur during the time frames in which sampled tissues developed. The convergence of mean $\delta^{34}S$ teeth values with mean $\delta^{34}S$ bone values suggest that the population from CA-SJO-68 foraged in or consume resources from the same region in adulthood as they had in their youth.

The low observed inter-individual variation and lack of evidence for individuals migrating to the site (as evidenced by comparable mean bone and teeth values) are consistent with a limitedly mobile population who likely resided in sedentary villages. Contributors of $\delta^{34}S$ variation to this population likely originated from the amount of time and frequency that individuals spent away from their village on logistical foraging trips to obtain food and other resources. Alternatively, inter-individual differences in dietary sources (e.g., marine versus terrestrial protein) could account for variation in $\delta^{34}S$ values. However, $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen from individuals at CA-SJO-68 show that the population foraged within terrestrial and riverine food webs, and marine protein was not a significant contributor to the diet. Furthermore, the limited evidence for nonlocals migrating to the site suggests that population size may have been sufficient for village-endogamy or people to marry others from nearby sites with similar underlying sulfur isotopic values.

The $\delta^{34}S$ values for females from CA-SJO-68 for bone span from 2.7 to 6.5‰ (range = 2.7; $n = 10$), 2.1 to 6.3‰ for first molars (range = 4.2; $n = 10$), and 3.2 to 6.3‰ for third molars (range = 3.1; $n = 5$) (Table 2, 

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**Figure 4.** Boxplots comparing female (F) versus male (M) $\delta^{34}S$ in bone collagen (B), 1st molar dentinal collagen (M1), and 3rd molar dentinal collagen (M3) from CA-SJO-68.

**Table 4.** Levene’s* Test (One-Tailed) Results for Comparison of $\delta^{34}S$ Values at CA-SJO-68.

<table>
<thead>
<tr>
<th>Type</th>
<th>df</th>
<th>$F$</th>
<th>$p$ value†</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{var(bone)}$ vs. $\text{var(M1)}$</td>
<td>37</td>
<td>2.951</td>
<td>0.094</td>
</tr>
<tr>
<td>$\text{var(bone)}$ vs. $\text{var(M3)}$</td>
<td>32</td>
<td>1.087</td>
<td>0.305</td>
</tr>
<tr>
<td>$\text{var(M1)}$ vs. $\text{var(M3)}$</td>
<td>29</td>
<td>0.213</td>
<td>0.648</td>
</tr>
</tbody>
</table>

* center = median; † $\alpha = 0.05$. 

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* $\delta^{34}S$ denotes sulfur stable isotope ratio in parts per thousand (‰).
Figure 5). The mean δ³⁴S values for females are 4.1‰ (SD = 0.8), 4.6‰ (SD = 1.6), and 5.1‰ (SD = 1.4) for bone, first molars, and third molars, respectively. Comparatively, the δ³⁴S values for males from CA-SJO-68 vary from 2.4 to 4.3‰ for bone (range = 4.1; n = 11), 1.8 to 6.4‰ for first molars (range = 4.6; n = 8), and 2.6 to 6.8‰ for third molars (range = 4.2, n = 8) (Table 2, Figure 5). The mean δ³⁴S values for males are 4.3‰ (SD = 1.2), 3.8‰ (SD = 1.3), and 4.4‰ (SD = 1.4) for bone, first molars, and third molars, respectively.

Thus, overall, males show higher δ³⁴S values and greater inter-individual variation. This result is mostly driven by one male individual (12-7646(0)) who had a relatively high δ³⁴S bone collagen value (6.5‰) that falls outside the aforementioned “local” range (2.2 to 6.2‰) (Table 2, Figure 5). This evidence suggests that 12-7646(0) was a recent immigrant. Once the bone δ³⁴S value from 12-7646(0) is removed from the calculation of statistics for males, the resulting average (4.1‰) and range (3.2‰) are more congruous with those observed for females at CA-SJO-68. The Mann-Whitney U test reveals no statistical difference between female and male δ³⁴S bone collagen values (Table 5).

Females show higher δ³⁴S values in first molar dentinal collagen on average compared to males, while males have a slightly greater range. However, results from the Mann-Whitney U test shows that at the 0.05 confidence level, we are unable to state that female and male first molar δ³⁴S values are drawn from different underlying populations (Table 5). The greater inter-individual variation observed for male first molars is driven by two males (12-7640.1 and 12-7568(0)) whose δ³⁴S values fall outside the “local” range (Table 2, Figure 5). Four females (12-7575(0), 12-7577(0), 12-8024(0), and 12-6472(0)) also show δ³⁴S values that fall outside the “local” range (Figure 5). These females and one male (12-7640.1) had “nonlocal” δ³⁴S first molar values that suggests they spent their childhoods living outside the vicinity of archaeological site CA-SJO-68. The other “nonlocal” male, 12-7568(0), has a less enriched δ³⁴S first molar value (1.76‰) that is well outside the “local” range and suggests that this individual lived in a distinct area from the rest of the CA-SJO-68 population as a juvenile. Of the available first molars analyzed in this study, 60 percent of females and 75 percent of males show “local” δ³⁴S first molar values, consistent with being native to the site. However, the Fisher’s exact test does not reach the 0.05 statistical significance level when nonlocals and locals are compared by sex (Table 6). This suggests that the population’s juvenile-adult mobility profile is not significantly sex-biased. This finding is inconsistent with unilocal postmarital residence.

The δ³⁴S values of third molar dentinal collagen reflect the same patterns observed for first molars; females show higher average δ³⁴S values, while males show greater inter-individual variation. The Mann-Whitney U test reveals no statistical difference at the 0.05 level between female and male δ³⁴S values of third molars (Table 5). The range of δ³⁴S values of third molars for males, like that of first molars, is largely affected
by one individual with a “nonlocal” signature (Figure 5). In this case, the aforementioned “immigrant” male’s (12-7646(0)) third molar value (6.8‰) is more enriched in δ^{34}S relative to other males in the sample and is the source of this higher variation. The higher δ^{34}S values of third molars for females is primarily driven by two individuals (12-7575(0) and 12-7588(0)) whose values fall outside the “local” range (Table 2, Figure 5). One of these females, 12-7575(0), also had a nonlocal signature for her first molar (the other females with nonlocal signatures for first molars, 12-7577(0), -8024(0), and -6472(0), did not have third molars available for study). Interestingly, the second female, 12-7588(0), shows “local” δ^{34}S values for her first molar and bone. This suggests that she is native to CA-SJO-68, spent her teenage years elsewhere, and returned to live in the vicinity of the site as an adult. Of the available third molars analyzed in this study, 60 percent of females and about 88 percent of males show “local” δ^{34}S first molar values, consistent with being native to the site.

While the proportion of nonlocals seems to be biased towards females, the Fisher’s exact test does not allow us to state that this difference is less than 5 percent due to chance alone (Table 6). Given the small sample size available for third molars, especially for females (n = 5), these results should be interpreted with caution. In summary, δ^{34}S data of bone, first, and third molars at CA-SJO-68 provides evidence for a few migrating individuals to the site. Results are most consistent with a sedentary population practicing village (or within the immediate area) marriage-endogamy. While the patterns are consistent with a slight preference for female immigration (i.e., patrilocality) among those who did immigrate to the site, we are unable to demonstrate statistical significance in this bias at the 0.05 level, likely due to small sample sizes.

**CONCLUSIONS**

Previous isotopic studies in central California (Burns et al. 2012; Eerkens and Bartelink 2020; Harold et al. 2016; Jorgenson 2012) suggest that Early Period populations show preference for endogamous marriage, but both matrilocality and patrilocality were also practiced. For example, isotopic evidence from archaeological sites CA-SJO-112 and CA-CCO-548 (Harold et al. 2016; Jorgenson 2012) demonstrated...
distinct sex-biased dispersal patterns, one consistent with patrilocality and the other showing shifts from matrilocality to ambilocality. These results are unexpected since the sites are proximal to each other and date to the Early Period. We would expect nearby populations to intermarry and practice compatible postmarital residence rules. Instead, the data reflect two different marriage exchange networks for populations from CA-SJO-112 and CA-CCO-548. Differing marriage-interaction spheres reported for these sites, as well as differences noted for the San Francisco Bay Area and the Sacramento-San Joaquin Delta, have important implications for the broader cultural landscape, especially when coupled with demographic evidence and inter-regional migration (Eerkens and Bartelink 2020).

This study produced new isotopic evidence for postmarital residence that builds upon previous research and hopefully will encourage future isotopic investigations of Early Period paleomobility and evaluations of marriage-interaction spheres. Results conform to prior studies that have suggested endogamous marriage practices during the Early Period in the Central Valley (e.g., Burns et al. 2012). The burial population from CA-SJO-68 indicates a slight bias of female immigration, and hence, a preference for patrilocality. Marriage between individuals living in locales with similar available sulfur or village endogamy may obfuscate sex-biased mobility profiles. For instance, marriage-endogamy does not preclude unilocal residence practice; a spouse could live with or near the wife’s/husband’s family within the same home region instead of migrating between sites with different sulfur systems. This pattern would not be captured using isotopic evidence.

Our isotopic investigation of postmarital residence of a burial population at CA-SJO-68 highlights an isotopic system that has been scarcely employed in the literature. Initially, the application of sulfur isotope research was constrained due to large sample size requirements and its associated expense; however, this limitation has lessened in recent decades (Bartelink and Chesson 2019; Katzenberg 2008; Nehlich 2015). Now the onus is on researchers to refine understandings of what impacts the isotopic constitution of sulfur in human tissues and the geologic factors that drive δ34S variation. Research that models the influence of soil and geologic features, environmental attributes, and covariance with other isotopic values (δ13C and δ15N) on δ34S of human bone collagen is currently underway at the U.C. Davis Archaeometry Lab. We hope this study encourages other scholars to expand on the isotopic systems employed in research to develop nuanced, multi-isotopic research programs focused on human mobility and sex-biased dispersal patterns.

Stable isotope analysis produces a unique source of individual-level data that can be used to reconstruct paleomobility and investigate hypothesized postmarital residence practices. This evidence is important for evaluations of the intersection of social organization and other facets of human behavior and the cultural systems of ancient societies. Investigation and understanding of regional and diachronic postmarital residence patterns, especially when coupled with research on how it covaries with temporal trends such as subsistence and demography, provides vital information to elucidate sociocultural change in central California.

ACKNOWLEDGEMENTS

The authors thank the staff and volunteers at the Phoebe A. Hearst Museum of Anthropology for access to archives and collections, as well as assistance with sample collection. We also thank Joy Matthews and the staff at the U.C. Davis Stable Isotope Facility for their services. Finally, we thank the undergraduate and graduate students of the Archaeometry Lab at U.C. Davis for their assistance with data collection and analysis of bone collagen sulfur values used for regional comparisons. This study was made possible with partial funding from the Sacramento Archeological Society Scholarship and NSF Doctoral Dissertation Research Improvement Grant to the lead author (CER) (No. 1933469).

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