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Oxygen isotope seasonality in a temperate estuarine shell midden: a case study from CA-ALA-17 on the San Francisco Bay, California

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A B S T R A C T

Seasonality determination using stable oxygen isotope ($\delta^{18}O$) analyses in archaeological mollusk shell has been largely limited to aquatic settings where one of the two factors that control shell $\delta^{18}O$ – water $\delta^{18}O$ (or salinity) and temperature – is assumed to be constant. Open coastal marine environments reflect the former situation, and tropical estuaries constitute the latter. In an effort to expand stable isotope seasonality to an ecological setting where neither variable remains constant, we present a model of annual shell $\delta^{18}O$ cycle of aragonite deposition derived from instrumental data on salinity and temperature from San Francisco Bay, California. The predicted range of modeled shell $\delta^{18}O$ is consistent with observed $\delta^{18}O$ values in prehistoric and modern shells when local conditions are considered. Measurements of $\delta^{18}O$ taken at 0 mm and 2 mm from the terminal growth margin were made on 36 archaeological specimens of *Macoma nasuta* from a late Holocene hunter-gatherer site CA-ALA-17, and season of collection was inferred using the shell $\delta^{18}O$ model. We conclude that shellfish exploitation occurred through the year with the exception of fall, which may indicate scheduling conflicts with acorn harvesting or other seasonally abundant resources elsewhere. The model supports the feasibility of stable isotope seasonality studies in temperate estuaries, provided that instrumental records are available to quantify the relevant water conditions at appropriate spatial and temporal scales.

1. Introduction

Characterizing seasonal resource use among prehistoric foragers is fundamental to reconstructing changing land use patterns across time and space, and opens paths of inquiry into broader behavioral and social issues, including settlement mobility, territorial circumscription, resource intensification, and emergence of status differentiation. Seasonality can be inferred from the presence of migratory species in faunal materials (e.g., anadromous fish, waterfowl; Broughton, 1999; Hildebrandt, 1993), processing implements or macrobotanical remains indicating seasonally available plant resources (e.g., berry and seed crops; Riley, 2008), or through isotopic analysis of incremental growth structures in fish otoliths or mollusk shells (e.g., Andrews et al., 2003; Bailey et al., 1983; Glassow et al., 1994; Jones et al., 2008; Kennett, 2005; Kennett and Voorhies, 1996; Killingley, 1981). Each of these indicators is drawn from subsistence remains, and therefore are variably represented at any particular site depending on the site's function within a settlement system (e.g., specialized foraging or processing camps vs. central bases), its ecological setting (e.g., aquatic vs. terrestrial habitats), and taphonomic processes. Because each indicator only reflects one aspect of a broader subsistence regime, archaeologists ideally employ all available data sets for each site and determine seasonality for sites in every ecological setting within the annual foraging range. Expanding the range of materials amenable to analysis, and the variety of ecological settings subject to investigation, contributes to more comprehensive models of regional settlement behavior and seasonal mobility patterns.

Stable isotope analysis of mollusk shells has become a staple seasonality indicator at coastal archaeological sites owing to the abundance and durability of shells, and the relative ease of sampling and measurement afforded by modern mass spectrometers. The method takes advantage of the relationship between water temperature and shell carbonate oxygen isotope ratio to indicate season of death (Epstein et al., 1951, 1953; Shackleton, 1973). In contrast, seasonality at shell-rich sites in estuarine settings is less frequently studied because periodic inputs of isotopically depleted freshwater alter the resulting carbonate isotope values, making the seasonal signal more difficult to

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interpret. In cases where the freshwater input is itself seasonal, relatively predictable, and quantifiable, an isotope seasonality model based on salinity rather than temperature may be employed. Kennett and Voorhies (1995, 1996) had success with this approach at several Archaic Period shellmounds in the Acapetahua estuary in southern Chiapas, Mexico. There, relatively stable water temperatures through the year limit the use of the oxygen isotope seasonality technique in marine settings, but in estuaries this has the advantage of isolating the salinity variable in the carbonate $\delta^{18}O$ equation by holding temperature constant.

Outside of the tropics an estuarine model must account for both seasonal change in water salinity *and* temperature that each contribute to the oxygen isotope values of shell carbonate formed in that water. This paper reports such a model for San Francisco Bay, using available instrumental data and empirically derived relationships between water temperature, salinity and shell isotope values. We then apply the model to a sample of isotope measurements on archaeological *Macoma nasuta* shells to investigate shellfish exploitation at CA-ALA-17, a hunter-gatherer midden site occupied between ca. 4000 and 1500 cal BP. This first attempt to develop a stable oxygen isotope seasonality model shows promise for new settlement and mobility research for a region renowned for massive prehistoric shellmounds (Gifford, 1916; Lightfoot, 1997; Nelson, 1909).

2. Site description

CA-ALA-17 was one of the first San Francisco Bay shellmounds recorded by Nels Nelson in 1909. Situated near the northeastern shoreline of San Francisco Bay in the city of Oakland, CA-ALA-17 is marked by a highly disturbed shell midden mostly covered by paved roads, parking lots, and structures, including an office of the United States Postal Service. The site was within the direct impact area of the Cypress Replacement Project that was developed to restore roadways that collapsed during the 1989 Loma Prieta Earthquake, and it was initially tested by the California Department of Transportation (Caltrans) in the early 1990s (Hylkema, 1997). Subsequently, it was subjected to an extensive data recovery (114 m^3 of recovery volume) in 1998 (Jones and Darcangelo, 2007). Excavation showed that the site was a heavily disturbed remnant of a larger midden deposit that extended to a maximum depth of 120 cm below the surface. The deposit consisted primarily of shell remains, dominated by oyster (*Ostrea lurida*) and bent-nosed clam (*M. nasuta*) although it also produced vertebrate remains, intact features, and a modest assemblage of formal artifacts. A total of 24 radiocarbon dates from marine shells and animal bone collagen shows that the portion of the deposit investigated by Caltrans was occupied between 4000 and 1500 cal BP, marking portions of the Early (5000–2600 cal BP) and Middle (2600–1000 cal BP) periods in the San Francisco Bay cultural sequence (Milliken et al., 2007). Direct dates on 16 *M. nasuta* shells from the site span this range (Table 1), though the period from ~3000 to 2000 cal BP is poorly represented, perhaps suggesting two periods focused on shellfishing. The cultural inventory was very similar to that of the well-known West Berkeley site (CA-ALA-307; Wallace and Lathrap, 1975) and it conforms well with Early and Middle Period expressions of Fredrickson's (1974) Berkeley Pattern. Unfortunately, the deposit at CA-ALA-17 was homogeneous and unstratified so that discrete components marking these individual periods could not be delineated.

Seasonality, settlement, and mobility have been major issues in the investigation of San Francisco Bay mounds for much of the 20th century. In 1955 Beardsley described the Bay mounds as markers of a system of "central-based wandering," in which a community would "spend part of each year wandering and the rest at a settlement or central base to which it may or may not consistently return in subsequent years" (Beardsley, 1955:138). Since then, the most influential model for local settlement suggests a "periodically mobile home base" system, in which local groups had two or three contemporaneous semi-permanent villages together with numerous seasonal special purpose camps and locations (Banks and Orlins, 1981). Developed on the basis of settlement practices observed at the time of European contact, the model supposes that semi-permanent villages could be moved every few years within the community territory because investment in structures was minimal (Milliken et al., 2007). Furthermore, "the duration of stay at each site may have been influenced by the available supplies of such localized, not easily transported items as firewood, fresh water, and molluscan food resources, as well as hygienic conditions" (Banks and Orlins, 1981:9). Others have suggested that settlement systems in the Bay area were essentially sedentary by as early as 4500 cal BP (Moratto, 1984:263).

3. Background to the method

Mollusks precipitate calcium carbonate during shell formation in isotopic equilibrium with surrounding water, thus recording habitat conditions during growth (Wefer and Berger, 1991). The ratio of stable oxygen isotopes ($^{18}O/^{16}O$, expressed as $\delta^{18}O$) in shell carbonate reflects the interaction of water temperature and isotopic content (Epstein et al., 1951, 1953; Grossman and Ku, 1986). Because water $\delta^{18}O$ tracks salinity in a near-linear fashion, the relationship may also be understood in terms of salinity. In marine settings, water $\delta^{18}O$ and salinity are generally assumed to be constant during the life of an organism, so changes in shell $\delta^{18}O$ primarily record changes in water temperature, where higher $\delta^{18}O$ (enriched in ^{18}O) corresponds to colder water, and lower $\delta^{18}O$ (depleted in ^{18}O) indicates warmer water. In environments with clear seasonal variation in water temperature, the oxygen isotope value at a shell's terminal margin can be used to determine water temperature, and hence, season of death (i.e., collection). In one of the earlier archaeological applications of the oxygen isotope technique, Shackleton (1973:134–135) identified several conditions to be met for successful seasonality determination (summarized below):

a) The animal must deposit shell carbonate in equilibrium with water in a temperature-dependent fashion.
b) The isotopic composition of the water should remain constant through the season. This would exclude animals in rock pools (because of evaporative enrichment) and possibly sand-burrowing animals.
c) The temperature at which shell deposition takes place must be sea surface temperature. Rock pools, etc., will have erratic temperature excursions not necessarily related to season.
d) The shell must deposit carbonate continuously through the year.
e) The growth rate of the shell must be high enough to record variations in temperature up to the growth edge. Longer-lived specimens often grow very slowly later in life, which can compress seasonal variations beyond the sampling resolution.
f) The annual range of mean water temperature should be an order of magnitude greater than the week-to-week variability in temperature.

Conditions b) and c) are usually violated in estuarine settings, where varying inputs of freshwater discharge change both water $\delta^{18}O$ (salinity) and temperature, often superimposed on (but out of synch with) insolation-driven temperature and evaporative enrichment signals. In tropical estuaries, nearly constant water

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Table 1
Radiocarbon dates on CA-ALA-17 *Macoma nasuta*.

Lab number (Beta-)	Provenience	Method	Measured ^{14}C age	δ^{13}C (PDB)	Conventional ^{14}C age	Calibrated 1–σ range (cal BP) $\Delta R = 290 \pm 35$	Calibrated 1–σ range (cal BP) $\Delta R = 365 \pm 35$
119722	Unit 33, 90–100 cm	Conventional	3790 ± 70	−0.7	4190 ± 70	3990–3750	3890–3670
134734	Unit 15, 100–110 cm	AMS	3640 ± 40	0.9	4070 ± 40	3810–3650	3700–3540
119726	Unit 13, 80–90 cm	Conventional	3660 ± 110	0.3	4070 ± 120	3890–3550	3800–3460
134726	Unit 11, 110–120 cm	AMS	3640 ± 40	−0.7	4040 ± 40	3770–3600	3670–3510
119729	Unit 19, 60–70 cm	Conventional	3460 ± 100	−1.3	3850 ± 100	3590–3330	3500–3230
119725	Unit 19, 90–100 cm	Conventional	3400 ± 60	−0.2	3810 ± 60	3490–3320	3410–3230
119731	Unit 19, 50–60 cm	Conventional	3360 ± 70	0.9	3770 ± 80	3470–3250	3380–3160
119723	Unit 45, 40–50 cm	Conventional	3150 ± 100	−0.7	3550 ± 110	3250–2930	3150–2840
134735	Unit 15, 110–120 cm	AMS	2620 ± 50	0.3	3040 ± 50	2560–2340	2470–2290
134725	Unit 11, 100–110 cm	AMS	2500 ± 40	−1.1	2900 ± 40	2350–2190	2290–2140
134729	Unit 19, 100–110 cm	AMS	2130 ± 40	0.2	2550 ± 40	1940–1800	1850–1710
134732	Unit 23, 70–80 cm	AMS	2120 ± 50	0.4	2540 ± 50	1940–1780	1850–1690
119730	Unit 5, 100–110 cm	Conventional	2100 ± 40	0.9	2520 ± 40	1910–1760	1830–1680
119728	Unit 27, 50–60 cm	Conventional	2110 ± 90	−0.9	2510 ± 90	1940–1690	1850–1610
119724	Unit 13, 50–60 cm	Conventional	2000 ± 110	−0.5	2400 ± 120	1840–1540	1770–1460
119727	Unit 48, 40–50 cm	Conventional	1940 ± 130	−0.3	2350 ± 140	1820–1470	1710–1370

Conventional ^{14}C ages are corrected for isotopic fractionation with measured δ^{13}C values according to the conventions of Stuiver and Polach (1977). Calibrations were made with OxCal 3.10 (Bronk Ramsey, 1995, 2001) using the Marine04 curve (Hughen et al., 2004). Results are presented with two local reservoir corrections (ΔR) for the central California Coast reported by Ingram and Southon (1996) for comparative purposes.

temperature might be assumed or empirically demonstrated, allowing for a strictly δ^{18}O (or salinity)-based seasonal model (e.g., Kennett and Voorhies, 1995, 1996; Voorhies, 2004:13). Constant water temperature cannot usually be assumed for temperate estuaries, however, which necessitates a model to predict shell δ^{18}O values through the year that incorporates annual water temperature and salinity cycles. This makes for a more complex model than is usually applied to archaeological situations, but one that comprises the variables that govern shell carbonate geochemistry (Epstein et al., 1951, 1953; Grossman and Ku, 1986). Because the classic marine model assumes constant salinity, and the tropical estuarine model assumes constant temperature, they can be understood as special cases of the generalized carbonate δ^{18}O model. That is, they are end members of a spectrum of aquatic environments in which water salinity and temperature influence seasonal shell carbonate δ^{18}O values to different degrees depending on local conditions. It follows then that a δ^{18}O seasonality model applied to a specific site should be built from proximate environmental data where possible, and that a model built for one part of an estuary may not be applicable to the entire system. In the following section we describe the process of constructing a shell δ^{18}O seasonality model for site CA-ALA-17 on the San Francisco Bay, and subsequently apply it to the interpretation of oxygen isotope data in the marsh clam *M. nasuta* found in this site and in the larger shellmounds that surrounded the bay.

4. Modeling the annual shell δ^{18}O cycle

A model of seasonal shell δ^{18}O is derived from modern instrumental data and empirically derived relationships between water temperature, salinity and shell δ^{18}O in San Francisco Bay (see Fig. 1 for locations discussed in text). Because of the Bay's historical importance in the study of estuarine and climate processes (e.g., Conomos, 1979a), there is a wealth of available data from which to characterize the relevant parameters. Water salinity (expressed as practical salinity units [psu] in ‰) ranges from oceanic (~32‰) at Golden Gate to fresh (~1‰) at the Sacramento–San Joaquin Delta, and the shape of the gradient changes depending on Delta outflow (Conomos, 1979b; Peterson et al., 1989). In the wetter winter months (January through March) high freshwater inputs push the mixing zone seaward, depressing salinity markedly throughout the northern reach of the Bay. Salinity is highest from July to November, after the spring snowmelt pulse from Sierra Nevada rivers has passed and before the onset of winter storms. Water temperature is primarily driven by insolation. At Alameda, water is coldest (~9 °C) in January and warmest (~20 °C) in July and August (Conomos, 1979b:63).

The combination of changing salinity and temperature through the year is reflected in shell δ^{18}O. Like many clams, members of the genus *Macoma* generate an aragonitic (as opposed to calcitic) calcium carbonate shell (Aberhan et al., 2004) and so the aragonite precipitation equation of Grossman and Ku (1986) is used to describe this relationship:

$$\delta^{18}O_{arag(PDB)} = [(T - 20.6/-4.34)] + \delta^{18}O_{water(SMOW)} \quad (1)$$

where T is water temperature in °C, aragonite δ^{18}O is in terms of the PDB scale, and water δ^{18}O is in terms of SMOW (Standard Mean Ocean Water). Because salinity data near CA-ALA-17 are more abundant than δ^{18}O measurements, the model is made more robust by restating it in terms of salinity. Ingram et al. (1996a,b) found a linear relationship between water δ^{18}O and salinity in the northern reach of the Bay described by the equation

Fig. 1. A portion of San Francisco Bay noting locations discussed in the text. (Satellite image downloaded from USGS/PG&E site: http://www.sfbayquakes.org.)

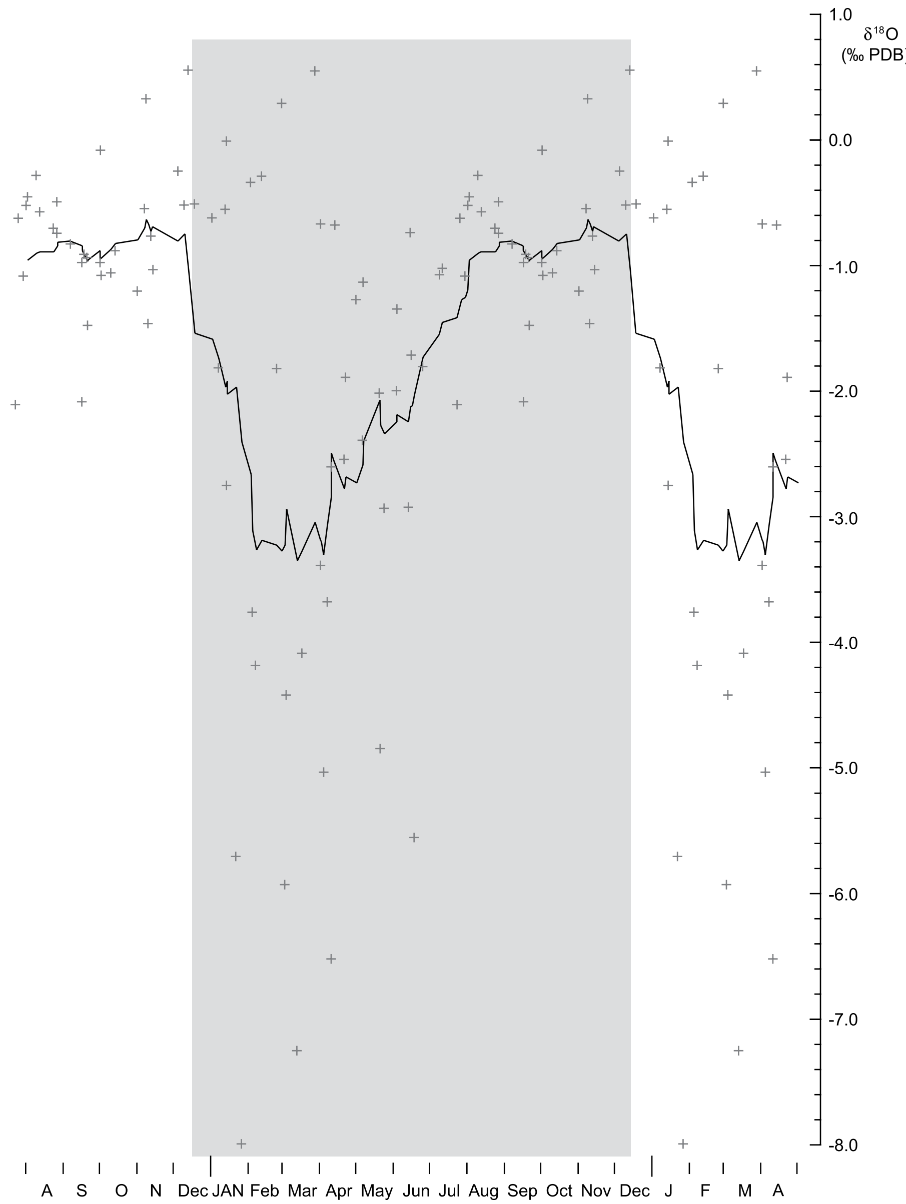

Fig. 2. Annual cycle of shell $\delta^{18}O$ values modeled from diversion-corrected salinity and temperature measurements at USGS Hydrologic Station 21 from 1969 to 1988. Crosses are the $\delta^{18}O$ values predicted from a modified aragonite precipitation equation (Grossman and Ku, 1986). The mean (solid line) is a 15-term moving average of these values. The extremely negative values represent freshwater pulses from winter and spring storms.

$$\delta^{18}O_{water(SMOW)} = 0.34S - 11.6 \tag{2}$$

where S is salinity in practical salinity units (psu; ‰). In rough terms, a 3‰ change in salinity results in a 1‰ change in $\delta^{18}O$ (Ingram et al., 1996b). By substituting eq. (2) for the $\delta^{18}O_{water}$ term in eq. (1), the aragonite $\delta^{18}O$ equation is recast in terms of temperature and salinity in the equation

$$\delta^{18}O_{arag(PDB)} = [(T - 20.6/-4.34)] + (0.34S - 11.6) \tag{3}$$

which allows the seasonal shell $\delta^{18}O$ cycle for *M. nasuta* to be modeled from available instrumental data.

Surface temperature and salinity data (i.e., at a depth of 0.5 m) for the model were obtained for Hydrographic Station 21 through the USGS online database (http://sfbay.wr.usgs.gov/access/wqdata). Station 21 is located in the center of the channel near the Bay Bridge, and was chosen for its relative proximity to CA-ALA-17. Data are recorded at near-monthly frequency from 1969 to the early 1980s, and at biweekly frequency until 1987. Salinity values were reduced 1.79‰ psu to account for historic water diversion (i.e., post ca. AD 1875) in the Sacramento–San Joaquin Delta and the Central Valley using the mixing equation derived for Point Orient:

$$S = 33\ e^{-0.00028*Q} \tag{4}$$

where Q is discharge in m^3/s (Peterson et al., 1989, Figure 15). The offset assumes that average Delta flow is reduced from ca. 1100 m^3/s to 600 m^3/s since AD 1850 (see Ingram et al., 1996a,b; Byrne et al., 2001).

A typical year was modeled by arranging the paired temperature and salinity data for Station 21 by month and day, generating the aragonite $\delta^{18}O$ value according to eq. (3) and taking a 15-term running mean to smooth the curve. As can be seen in Fig. 2, individual predicted $\delta^{18}O$ values vary most during winter and early

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Table 2
Stable isotope values from CA-ALA-17 *Macoma nasuta*.

Sample number	Distance from edge (mm)	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	Sample number	Distance from edge (mm)	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)
01-17a	0	−1.08	0.09	20-16a	0	−3.20	−1.59
01-17b	2	−2.52	0.15	20-16b	2	−2.46	−0.33
01-37a	0	−1.39	0.20	25-17a	0	−1.82	−0.70
01-37b	2	−3.13	−0.28	25-17b	2	−4.16	−0.73
02-40a	0	−1.42	0.20	30-14a	0	−0.85	−0.40
02-40b	2	−1.28	0.00	30-14b	2	−2.33	0.16
02-41a	0	−4.33	−1.71	31-14a	0	−0.34	0.83
02-41b	2	−2.81	0.42	31-14b	2	−1.41	0.20
03-33a	0	−2.61	−0.89	32-04a	0	−0.11	0.50
03-33b	2	−0.81	0.85	32-04b	2	−1.70	0.24
05-08a	0	−2.40	−0.70	36-19a	0	−0.72	0.22
05-08b	2	−0.89	0.62	36-19b	2	−2.18	−0.22
05-11a	0	−2.58	−0.71	39-24a	0	−1.28	−1.15
05-11b	2	−3.84	−1.06	39-24b	2	−0.36	1.33
08-13a	0	−0.60	−0.22	40-04a	0	−3.49	0.75
08-13b	2	−1.22	0.52	40-04b	2	−3.58	−0.09
08-14a	0	−0.61	0.78	40-11a	0	−2.62	0.14
08-14b	2	−2.87	−0.59	40-11b	2	−2.05	0.42
08-41a	0	−1.30	−0.24	41-05a	0	−2.18	−1.34
08-41b	2	−3.67	−0.82	41-05b	2	−1.53	−0.92
10-18a	0	−1.16	−0.25	42-08a	0	−0.34	−0.18
10-18b	2	−1.92	0.50	42-08b	2	−2.58	−0.05
10-26a	0	−3.71	−0.23	43-04a	0	−3.59	0.13
10-26b	2	−2.26	−0.36	43-04b	2	−2.67	0.43
11-68c	0	−2.10	0.82	43-17a	0	−4.69	−1.47
11-68d	2	−2.51	0.31	43-17b	2	−4.00	−1.25
15-40a	0	−4.29	−0.42	48-07a	0	−2.86	−0.55
15-40b	2	−0.87	1.39	48-07b	2	−4.30	−1.49
18-04a	0	−2.52	0.07	48-10a	0	−0.93	−1.89
18-04b	2	−2.52	−0.25	48-10b	2	−1.26	−3.31
19-24a	0	−2.24	0.88	49-12a	0	−2.01	−1.66
19-24b	2	−0.96	1.17	49-12b	2	−1.45	−0.81
20-03a	0	−0.66	0.09	50-10a	0	−2.29	−0.17
20-03b	2	−2.19	0.43	50-10b	2	−3.61	−0.36
20-12a	0	−2.04	−0.45				
20-12b	2	−3.37	0.17				

spring months depending on the timing of the onset of winter storms. We assume that the running mean is a good first approximation of the shell $\delta^{18}O$ cycle despite this variability because shell deposition rates and sampling resolution are probably not high enough to record individual storm events. That the ranges of observed shell $\delta^{18}O$ and predicted mean $\delta^{18}O$ are similar lends support to this assumption.

5. Laboratory methods

5.1. Sampling methods

Thirty-six valves of *M. nasuta* were selected for analysis. *M. nasuta* is an infaunal clam widely distributed in shallow water, muddy-bottomed bays and estuaries of the Pacific Coast of North

Table 3
Stable isotope profiles from prehistoric and modern *Macoma nasuta*.

Sample number	Distance from edge (mm)	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	Sample number	Distance from edge (mm)	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)
Prehistoric *M. nasuta*				Modern *M. nasuta*			
19-27a	0	−2.81	−0.67	1A	0	−1.61	−1.06
19-27b	2	−2.09	0.06	1B	2	−2.57	−0.91
19-27c	4	−0.27	0.96	1C	4	−1.73	−1.23
19-27d	6	−1.31	0.49	1D	6	−2.16	−0.50
19-27e	8	−0.54	1.06	1E	8	−2.55	−0.67
19-27f	10	−0.72	1.37	1F	10	−2.83	−1.15
19-27g	12	−3.33	−0.49	1G	12	−2.29	−1.50
19-27h	14	−2.29	−0.78	1H	14	−4.03	−1.22
19-27i	16	−0.72	0.76	1I	16	−2.34	−0.76
19-27j	18	−0.60	0.77	1J	18	−4.58	−1.36
19-27k	20	−1.31	0.19	1K	20	−3.72	−1.06
19-27l	22	−2.46	−0.20	1L	22	−2.46	−0.76
19-27m	24	−3.10	−0.28	1M	24	−1.65	−1.10
19-27n	26	−2.80	−0.35	1N	26	−1.52	−0.91
19-27o	28	−1.56	0.34	1O	28	−2.18	−1.25
19-27p	30	−0.61	0.53	1P	30	−2.47	−1.16
19-27q	32	−0.17	0.67	1Q	32	−2.71	−1.39
19-27r	34	−1.83	−0.50	1S	36	−2.55	−1.63
19-27s	36	−3.23	−0.23	1T	38	−2.60	−1.49
19-27t	38	−4.08	−0.79				
19-27u	40	−3.80	−0.63				
19-27v	42	−2.70	0.14				

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America (Morris, 1980). Members of the genus filter-feed on microalgae, and food availability has been shown to control growth rate in the related species *M. balthica* in San Francisco Bay (Thompson and Nichols, 1988).

The specimens were robust and appeared to be well preserved. Shells were scrubbed with a brush in distilled water to remove adhering sediment. Surfaces were treated with 0.1 N HCl to remove contaminants and altered carbonate, rinsed in distilled water and dried overnight at 50 °C. Samples were obtained from the exterior surface of the shells at 2 mm increments from the margin using a dental drill. After inspecting the sample under the microscope and removing any foreign material, the powder was placed in a labeled glass vial. The drill bit was cleaned in a sonicated ethanol bath between samples to avoid cross-contamination.

Paired samples were taken at the shell edge and 2 mm from the edge to determine season of harvest. This approach allows times of year with similar isotope values to be distinguished by noting the isotopic trend during several weeks of growth preceding collection (e.g., decreasing to −1.5‰ in early winter vs. increasing to −1.5‰ in early summer). Profiles of one prehistoric shell from CA-ALA-17 and one modern shell collected from Pt. Richmond, CA, in September 2003 were taken to help put the terminal growth samples in context.

5.2. Analytical methods

Two rounds of sampling were submitted to isotope labs in the departments of geology at UC Santa Barbara and UC Davis. Samples (~0.3 mg) processed at UC Santa Barbara were heated at 375 °C under vacuum for 1 h to volatilize organic compounds. After cooling to room temperature, the samples were reacted with orthophosphoric acid at 90 °C using a Fairbanks common acid bath auto-sampling device. $\delta^{18}O$ and $\delta^{13}C$ of the evolved CO_2 were measured using a Finnegan/MAT 251 Mass Spectrometer. All measurements are expressed in δ notation as the deviation from the PeeDee Belemnite (PDB) using the laboratory standard NBS-19. The precision of $\delta^{13}C$ and $\delta^{18}O$ measurements is 0.1‰.

Samples processed at the UC Davis isotope lab were evolved to CO_2 using a common 100% phosphoric acid bath at 90 °C. 20–50 μg of sample were reacted and analyzed in the directly coupled dual inlet of a GV Instruments Optima mass spectrometer. Isotope values are reported relative to V-PDB through the use of the UC Davis working standard, a Carrara marble. Expected values of this standard are $\delta^{13}C = +2.10$‰ and $\delta^{18}O = -1.94$‰. It has been calibrated by repeated direct measurement against NBS-19 (D. Winter, pers. comm., 2006). The samples were not roasted before processing.

6. Results

Results from prehistoric *M. nasuta* from CA-ALA-17 and modern *M. nasuta* from Pt. Richmond are presented in Tables 2 and 3. Sample numbers refer to the catalog lots from which the specimens were derived. Isotope profiles for the modern and prehistoric *M. nasuta* samples are depicted in Fig. 3. Oscillations in $\delta^{18}O$ values consistent with annual cycles are apparent in both, though the magnitude is greater in the prehistoric sample. $\delta^{13}C$ tracks $\delta^{18}O$ in the prehistoric specimen, but shows little patterned variation in the modern sample. Ingram et al. (1996a) argue that $\delta^{13}C$ (as well as $\delta^{18}O$) is largely controlled by salinity in *M. nasuta*. While this explains the covariation in $\delta^{13}C$ and $\delta^{18}O$ in the prehistoric specimen, the lack of agreement in the modern specimen suggests that some other factor influences $\delta^{13}C$, perhaps related to local nutrient inputs (e.g., municipal or industrial effluent) that alter *in situ* production of dissolved inorganic carbon near Pt. Richmond (Spiker, 1980). Ideally, multiple additional specimens collected with direct measurements

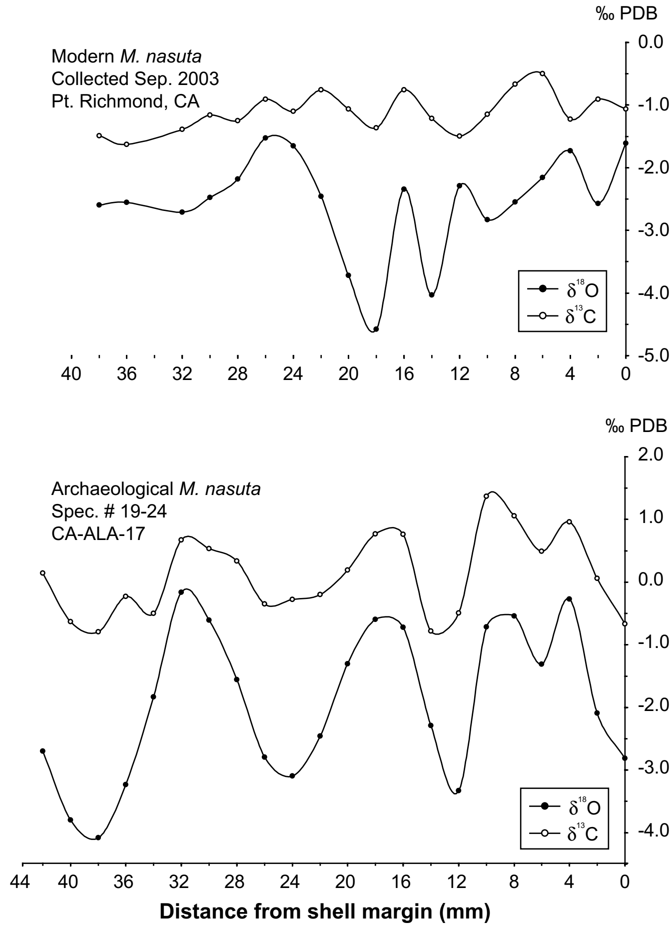

Fig. 3. Isotope profiles for modern and archaeological *Macoma nasuta*.

of salinity and water temperature for the years before death would clarify this issue. On average, prehistoric $\delta^{13}C$ and $\delta^{18}O$ are higher than the modern values (even without a salinity correction), indicating lower mean temperature, greater salinity, or a combination of both during the life of the prehistoric *M. nasuta* compared to the modern specimen. The closer proximity of CA-ALA-17 to the Golden Gate is consistent with cooler water and higher salinity. Accounting for the differing local conditions, the fact that the observed $\delta^{18}O$ ranges in these specimens is similar to the range predicted by the model suggests the model is a good first approximation of the average annual $\delta^{18}O$ cycle in the vicinity of CA-ALA-17.

Season of harvest is determined by plotting the $\delta^{18}O$ values at 2 mm (open circles) and at the shell margin (closed circles) for each shell against the modeled annual $\delta^{18}O$ curve (Fig. 4). 2 mm of shell growth in *M. nasuta* is scaled here to represent about 6 weeks, though the rate changes through the year depending primarily on food availability, and generally slows as mollusks age (Krantz et al., 1987; Thompson and Nichols, 1988). Samples are tied to the curve using the terminal value where possible, though a few points are plotted using the 2 mm value or the slope of the curve (mainly those terminating in late summer and early fall). Seasonality estimates are summarized in Table 4 and Fig. 4 in 3-month and 6-week intervals. The majority of the specimens show fairly steep slope between the 2 mm and terminal measurements, indicating large changes in salinity and temperature in the period before collection consistent with sharp decline in shell $\delta^{18}O$ going into winter and the rise from late spring to summer. There are few specimens with relatively flat and high paired $\delta^{18}O$ values that are predicted for a fall collection.

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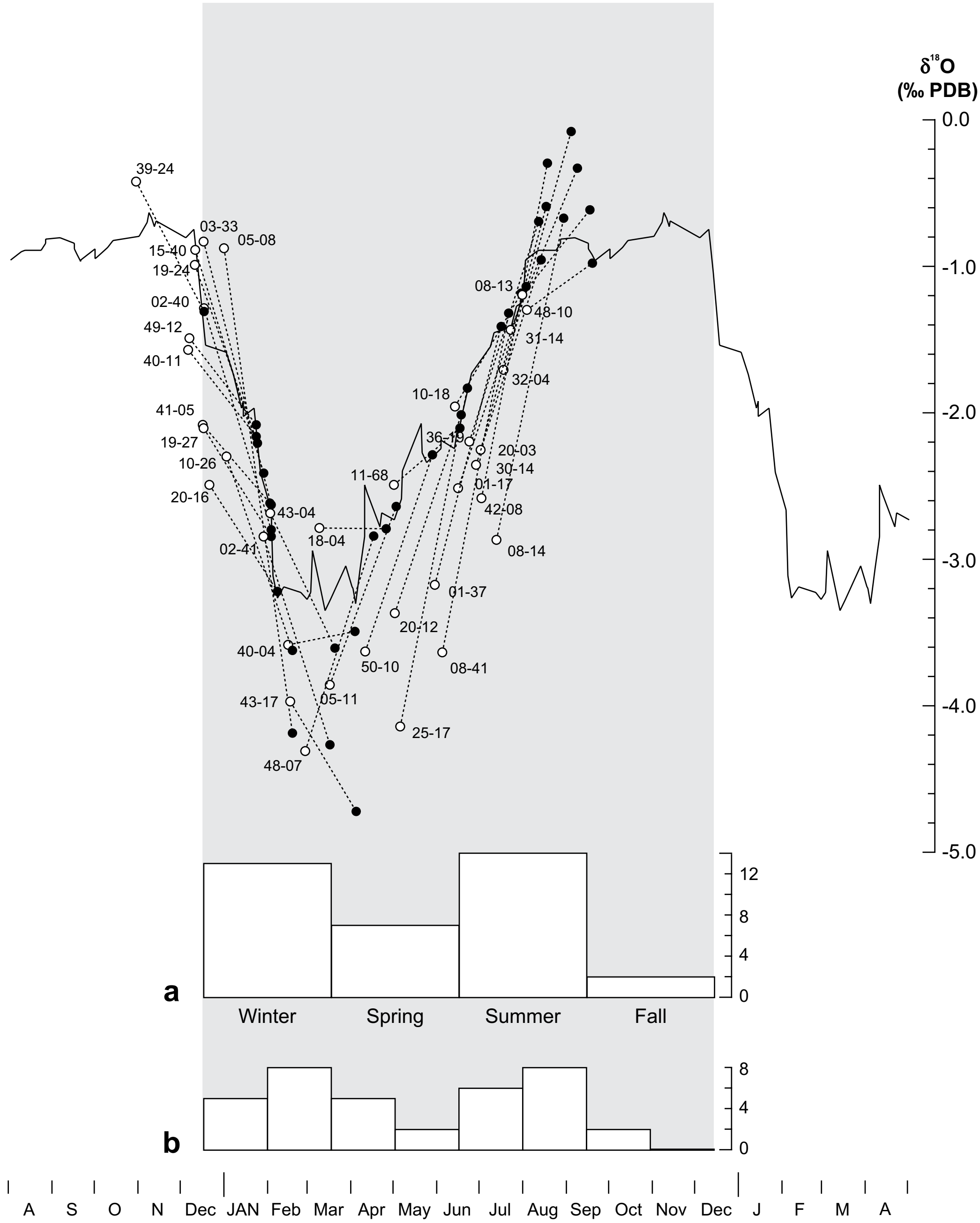

Fig. 4. Estimated season of harvest of *M. nasuta* from CA-ALA-17. Shell $\delta^{18}O$ values at 2 mm from margin (open circles) and shell margin (closed circles) are plotted against $\delta^{18}O$ modeled from diversion-corrected salinity and temperature (modified from Grossman and Ku, 1986). Histograms summarize a) 3-month (seasonal) and b) 6-week frequency distributions of season of harvest. *M. nasuta* appear to have been collected primarily from winter to summer, and rarely during fall.

The distribution of terminal growth increments suggests that *M. nasuta* at CA-ALA-17 were collected from winter through summer, but were rarely exploited during fall. Breaking the seasons out into 6-week blocks may also point out less shellfish harvesting in late spring, but given the assumptions involved in modeling it is probably unwise to attribute that level of precision to the estimate (see e.g., Bailey et al., 1983 vs. Killingley, 1981, 1983 for a discussion on the limits of isotope seasonality).

Diachronic salinity change is a concern for a deposit like CA-ALA-17, where stratigraphic components cannot be defined within the ~2500 year span of *M. nasuta* procurement indicated by the suite of direct radiocarbon measurements (Table 1). Freshwater

Table 4
Summary of seasonality estimates for CA-ALA-17 *Macoma nasuta* ($n = 36$).

Season	*n*	%	Season	*n*	%
Winter	13	36.1	Early Winter	5	13.9
			Late Winter	8	22.2
Spring	7	19.4	Early Spring	5	13.9
			Late Spring	2	5.6
Summer	14	38.9	Early Summer	6	16.7
			Late Summer	8	22.2
Fall	2	6.6	Early Fall	2	5.6
			Late Fall	0	0.0

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discharge into San Francisco Bay, and therefore salinity, have fluctuated throughout the Holocene in response to precipitation in the Sacramento and San Joaquin river watersheds (see Malamud-Roam et al., 2006 and references within). Salinity proxies have been developed from cores at several sites in tidal marshes and open water in the northern reach of the bay using stable isotopes (Sr, C, O) in mollusks, ostracods and organic matter, as well as pollen indices of salt-tolerant marsh plants (Byrne et al., 2001; Goman and Wells, 2000; Ingram and DePaolo, 1993; Ingram et al., 1996a,b; Malamud-Roam and Ingram, 2004; Malamud-Roam et al., 2006). The records vary between each site due to local conditions in the estuary and the proxy employed, but it appears that, for example, the period from 3600 to 2000 cal BP was characterized by fresher conditions associated with higher flows during the neoglacial period (Malamud-Roam et al., 2006; but see Byrne et al., 2001). The salinity change is not consistently quantified and would vary depending on the distance from the Golden Gate, but would result in lowering the annual curve of predicted shell $\delta^{18}O$ in our model. With decreasing average salinity, fewer shells would be estimated to have been collected in late winter and early spring. However, the decline in salinity in the habitats exploited prehistorically is not likely to have been more than ca. 3‰ psu (i.e., a 1‰ decrease in shell $\delta^{18}O$), because this would put many of the highest observed shell $\delta^{18}O$ values well above the modeled range. This suggests that for a first approximation the pre-diversion salinity estimate is adequate for CA-ALA-17. As San Francisco Bay salinity proxies are refined and quantified more precisely, it will be important to revisit the assumptions of the model.

7. Discussion

Shellfish were collected at CA-ALA-17 primarily during winter, spring and summer from ca. 4000 cal BP to 1500 cal BP. This suggests persistent use of the site except during the fall when other resources, perhaps at more interior locations, were more focal to the subsistence economy. Residential mobility related to acorn harvesting is an obvious candidate, in which case the lack of shellfish gathering in the fall could be explained in terms of scheduling conflicts (cf. Kennett and Voorhies, 1996). It is also possible that other seasonal aquatic resources such as waterfowl or salmon dominated the diet during fall, and clams were less favored. In this case, there would be site use throughout the year, but no indication of fall *Macoma* procurement. The variety of artifacts recovered (e.g., bone tools, groundstone, lithic tools) reflects a broad range of domestic activities consistent with year-round (or nearly year-round) site use, but the low artifact density and few isolated burials suggest a fairly low intensity occupation. We must also keep in mind that the span of time represented by these shells (i.e., ~2500 years) could obscure seasonality shifts throughout this period, for example from winter in 4000 cal BP through spring to summer in 1500 cal BP. Without the ability to place the measured shells into temporally discrete components during the span of site use this possibility cannot be ruled out at CA-ALA-17. However, the interpretation of the site as a year-round residential base accords with the conclusions of Banks and Orlins (1981) and Holson et al. (2000), who argued for a periodically mobile home base or semi-permanent settlement system in the central Bay Area. Such a system envisions year-round settlements that persist for several years at a time but are periodically relocated in response to local resource depression or other factors. There is the potential to test this model at the regional scale with further stable isotope seasonality work at better stratified sites coupled with more traditional archaeological inference at multiple locations around the Bay Area.

Regional tests of seasonal resource procurement and settlement patterns would require the temperature/salinity model developed here to be modified to conform to spatially and temporally varying local conditions. The network of hydrographic stations from the Golden Gate to the Sacramento–San Joaquin Delta provides the necessary empirical data and is readily accessible online. *M. nasuta* is relatively common in later archaeological components, including the upper strata of several of the larger shellmounds, but less abundant in deposits before ca. 2000 cal BP where *Ostrea* sp. (oyster) and *Mytilus* sp. (mussel) dominate (Broughton, 1999; Ingram, 1998; Milliken et al., 2007). Extending seasonality studies to include these species would require a calcite form of the carbonate precipitation equation be used (e.g., Horibe and Oba, 1972) rather than the aragonite equation used here (Grossman and Ku, 1986).

Ideally, the seasonality model would also account for diachronic shifts in water temperature and salinity in the San Francisco Bay, whether the focus is on a single archaeological component at some specific time in the Holocene, or seasonal shellfish procurement is being traced through a deep shellmound sequence. Documented salinity changes in the late Holocene San Francisco Bay reflect discharge at the Delta, and therefore correlate with precipitation anomalies recorded in lake and tree-ring climate records in western North America (e.g., Byrne et al., 2001; Goman and Wells, 2000; Graumlich, 1993; Ingram and DePaolo, 1993; Ingram et al., 1996a,b; Ingram, 1998; Malamud-Roam and Ingram, 2004; Malamud-Roam et al., 2006; Stine, 1994). Human response to late Holocene climate change continues to be a key research focus of California archaeology, with settlement disruption and reorganization being one hypothesized consequence of prolonged droughts (Jones et al., 1999; Kennett and Kennett, 2000; Kennett et al., 2007). It is interesting to consider these climate proxies being used to build a diachronic seasonality model that in turn is used to test hypotheses about the social consequences of the environmental changes they reveal.

8. Conclusions

As archaeologists have gained technical familiarity with stable isotope analyses and increased collaboration with isotope geochemists over the last two decades, seasonality determination in temperate marine and tropical estuarine shell-bearing sites has become a common tool in the archaeologist's kit. Although the data inform us about one aspect of coastal foraging lifeways – the seasonality of shellfish harvesting – when combined with other lines of archaeological evidence they provide valuable insights into other behaviors and their social outcomes: resource procurement scheduling conflicts, foraging decisions, mobility patterns, and regional settlement systems (e.g., Jones et al., 2008; Kennett, 2005; Kennett and Voorhies, 1995, 1996). The seasonal oxygen isotope model presented here for the San Francisco Bay demonstrates one approach to expanding the method to temperate estuarine sites, which despite providing abundant shellfish remains have been under-examined because of a lack of appropriate salinity and temperature models to interpret the shell isotope data in terms of seasonality. The CA-ALA-17 test case indicates that where long-term instrumental water quality records exist, and empirical relationships between salinity, water $\delta^{18}O$, and temperature are established for the target species, a suitable model can be developed to overcome these difficulties. Such models should reflect local site-specific conditions in the estuary, and where relevant climate data are available it may be possible to account for diachronic changes in water conditions as well. Broader application of isotope seasonality studies holds great potential for elucidating prehistoric resource use and settlement patterns in estuarine archaeological sites in diverse geographic and temporal contexts.

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