

# Shellfish, Seasonality, and Stable Isotope Sampling: $\delta^{18}\text{O}$ Analysis of Mussel Shells From an 8,800-Year-Old Shell Midden on California's Channel Islands

Nicholas P. Jew,<sup>1,2</sup> Jon M. Erlandson,<sup>1,2</sup> Jack Watts,<sup>1,3</sup>  
and Frances J. White<sup>2</sup>

<sup>1</sup>*Museum of Natural and Cultural History, University of Oregon, Eugene, Oregon, USA*

<sup>2</sup>*Department of Anthropology, University of Oregon, Eugene, Oregon, USA*

<sup>3</sup>*Kellogg College, Oxford University, Oxford, UK*

## ABSTRACT

*Analyzing stable isotopes in mollusk shells allows archaeologists to address issues ranging from seasonality of harvest, to settlement and subsistence strategies, sea surface temperatures, and nearshore paleoecology. Studying California mussel shells from an ~8,800-year-old shell midden on San Miguel Island, we investigate how mollusk growth rates influence sampling strategies for determining seasonality. Using a fully profiled shell as a standard to interpret more limited measurements (terminal growth band plus one) on 39 additional shells, we identified what appeared to be a multi-seasonal occupation. Sampling 20 of the 39 shells more intensively, however, changed our conclusions about season of harvest for 35 percent of the analyzed shells, producing data more consistent with other evidence for a short-term occupation of CA-SMI-693. Sampling strategies for determining seasonality from marine*

---

Received 2 August 2012; accepted 30 August 2012.

Address correspondence to Nicholas P. Jew, Department of Anthropology, University of Oregon, Eugene, OR 97403-1224, USA. E-mail: njew@uoregon.edu

*mollusks should carefully consider the ecology of individual species, particularly for fast-growing shellfish such as California mussels.*

*[Supplementary material is available for this article. Go to the publisher's online edition of **Journal of Island & Coastal Archaeology** for the following free supplemental resource(s): Appendix 1. Reported  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  and inferred temperature values for all isotopic determinations from forty analyzed California mussel shells from CA-SMI-693.]*

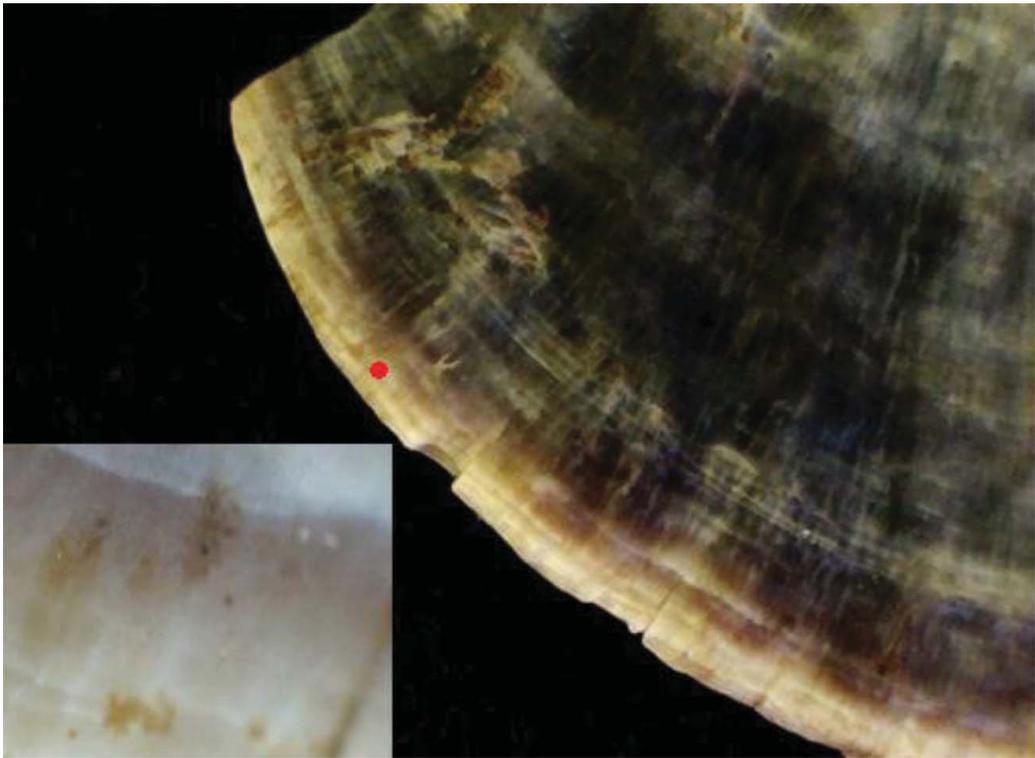
**Keywords** Early Holocene, stable oxygen isotopes, *Mytilus californianus*, San Miguel Island

Archaeologists have used stable oxygen isotope analysis of marine mollusk shells for several decades to study past environments and human adaptations, including the seasonality of shellfish harvest, human settlement and mobility patterns, nearshore ecology, and sea surface temperature (SST) (see Andrus 2011, 2012; Bailey et al. 1983; Eerkens et al. 2010; Glassow et al. 1994; Jones et al. 2008; Kennett 2005; Kennett and Voorhies 1995, 1996; Killingley 1981; Kimball et al. 2009; Rick et al. 2006; Shackleton 1973; Schweikhardt et al. 2011). The ratio between stable oxygen isotopes  $^{18}\text{O}$  and  $^{16}\text{O}$  (reported as  $\delta^{18}\text{O}$ ) reveal enriched or depleted values (Epstein et al. 1951, 1953; Killingley and Berger 1979) that provide a proxy for inferring SST for a given period of calcium precipitation during mollusk growth. Recent studies have examined the relationships among the rate of growth, calcium carbonate precipitation, and the effects of estimating season of harvest for various species (e.g., Andrus 2012; Quitmyer and DePrater 2012; Quitmyer and Jones 2012). Researchers have also employed a variety of sampling techniques to extract calcium carbonate ( $\text{CaCO}_3$ ) for isotopic research from mollusks (see Bailey et al. 1983; Glassow et al. 1994, 2012; Jones and Kennett 1999; Kennett 1998; Kennett and Voorhies 1995; Rick et al. 2006; and others), which frequently includes sampling the terminal growth band (TGB) and additional increments along the growth axis (Figure 1). The total number of isotopic determinations varies between researchers, with different strategies developed to address tensions between adequate sampling of individual shells, the total number of shells to be

sampled, analytical time, expenses, and available funding.

In shell middens along the California Coast, where California mussels (*Mytilus californianus*) are commonly used for  $\delta^{18}\text{O}$  analysis, a small number of shells typically are extensively profiled in  $\sim 2$  mm increments, with additional shells characterized through more limited sampling of the TGB and increments ranging anywhere from one (usually 2 mm from the TGB) to several measurements (e.g., Glassow et al. 1994; Kennett 2005; Jones et al. 2008; Rick et al. 2006). For fast-growing mollusks such as California mussels (see below), however, 2 or 3 isotopic determinations spanning  $\sim 2$ –5 mm of growth may not represent a full season (three months) of growth. During periods of rapid growth, such small sampling increments may capture just a week or month of growth (see Bailey et al. 1983:394), while for slower growing mollusks this method may capture one or more seasons of growth. Ideally, seasonal determinations should be based on isotopic records spanning at least one or more season of growth (Bailey et al. 1983).

A sampling method designed to document at least one season of growth for a mollusk may vary depending on species, lifespan, growth rate, age, size, water salinity, food availability, habitat, SST, sex of an organism, and other factors (Goodwin et al. 2003). For California mussels, several studies (e.g., Culleton et al. 2009; Glassow et al. 1994; Jones and Kennett 1999; Kennett 1998; Killingley and Berger 1979; Rick et al. 2006; and others) employed a 2 mm interval sampling strategy as a standard unit of measure when conducting oxygen isotope analysis.



**Figure 1.** 20× and 200× (inset) magnification of a California mussel shell from CA-SMI-693, illustrating ~2 mm of growth (represented by the red dot) inward from the terminal edge. The inset shows the lighter and darker layers typically identified as growth bands (color figure available online).

The number of isotopic determinations per shell ranges from two samples (TGB + 1) to extended profiles that sample 30 mm or more of shell growth. See Figure 1.

On Santa Cruz Island, Glassow et al. (1994) fully profiled (~15–24 samples per shell) seven California mussels from a Middle Holocene shell midden, sampling ~28–48 mm of growth. Later, using mussels from Santa Rosa Island shell middens, Rick et al. (2006; Robbins and Rick 2007) sampled 4–5 increments at 2 mm intervals for every analyzed mussel shell, sampling ~8–10 mm along the growth axis. Increasingly, California archaeologists have relied on full profiles for one or more shells from each site or component, with additional shells sampled using a TGB + 1 method (see Jones et al. 2008; Kennett 2005).

Here, given what is known about the growth rates of California mussels, we examine how many isotopic determinations per shell are required to ensure the sampling of at least one full season of growth—generally considered to be a minimum for accurate estimates of the season of harvest. Specifically, we consider the ecology and variable growth rates of California mussels in evaluating two different sampling strategies used to acquire isotope and seasonality data. We use the TGB + 1 method and a modified TGB + 6 method to evaluate seasonality determinations on California mussels from a discrete, 8,800-year-old shell midden feature at CA-SMI-693 located near Point Bennett on San Miguel Island. We evaluate the  $\delta^{18}\text{O}$  results in relation to other archaeological evidence for the structure, function, and

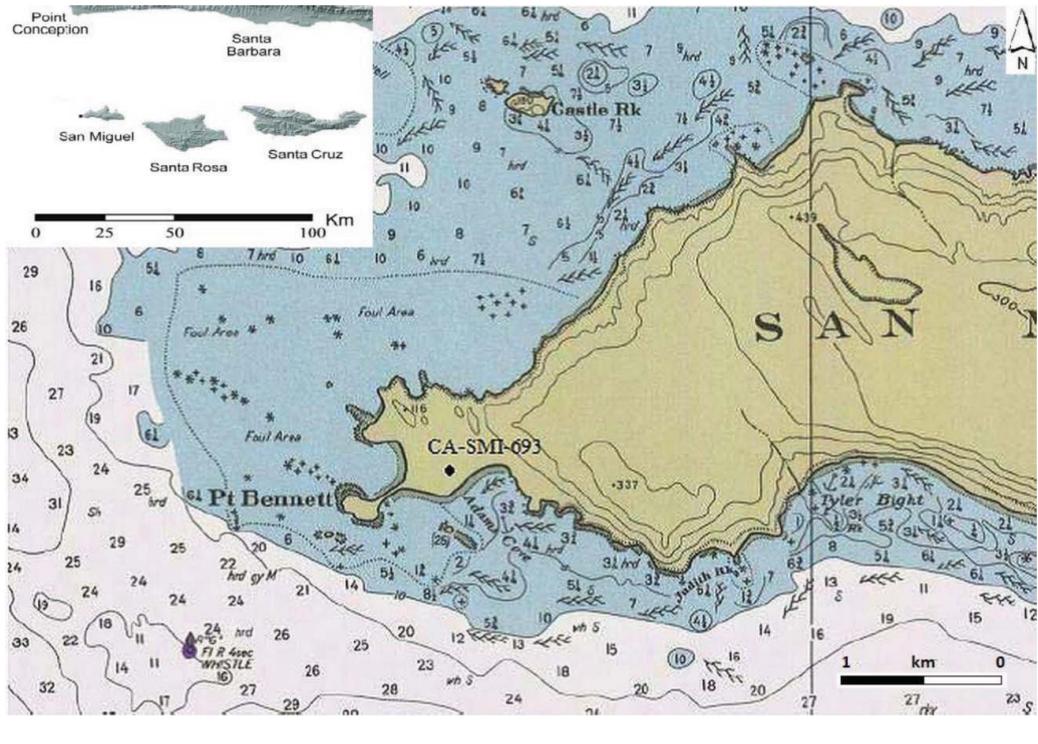
seasonality of CA-SMI-693. First, however, we provide background data that contextualizes the site, the paleoecology of the ancient Point Bennett area, and the ecology of California mussels.

BACKGROUND AND  
ARCHAEOLOGICAL SETTING

On California's Channel Islands (Figure 2), the last decade has seen considerable progress on understanding the antiquity and nature of human settlement during the Paleo-coastal period, from ~13,000 to 8,500 years ago (see Cassidy et al. 2004; Erlandson et al. 2011; Glassow et al. 2008; Johnson et al. 2012; Kennett 2005; Kennett et al. 2008; Rick et al. 2001). More than 75 Terminal Pleistocene and Early Holocene sites have been

identified on the northern islands alone, most of them on San Miguel and Santa Rosa islands. Less than one-third of these early sites have been tested, and most of these have seen very limited excavations.

It is often assumed that most Paleo-coastal sites on the Channel Islands were short-term or seasonal campsites (see Balter 2011; Erlandson et al. 2008a; Fitzhugh and Kennett 2010; Rick et al. 2005). Rising postglacial sea levels have submerged the coastal lowlands where early maritime people probably spent most of their time (see Kennett et al. 2008) and most known Paleo-coastal sites are located around peri-coastal geographic features (caves, springs, chert sources) that drew ancient maritime peoples into the interior. Other than an inferred winter/early spring occupation (based on the presence of migratory waterfowl) at



**Figure 2.** Map of Santa Cruz, Santa Rosa, and San Miguel Islands including the approximate location of CA-SMI-693 relative to the onshore and offshore topography of western San Miguel Island, including the 10-fathom submarine contour that approximates the location of the paleo-shoreline about ~8500 cal BP (from NOAA 1987 navigation chart for San Miguel Passage) (color figure available online).

Downloaded by [University of Oregon] at 12:47 18 July 2013

the 11,700 year old CA-SRI-512 on Santa Rosa Island (Erlandson et al. 2011), there is little or no evidence for the seasonality of occupation at Paleocoastal sites. There is considerable diversity in the size, depth, density, and contents of such sites, however, suggesting that Paleocoastal peoples may have occupied the larger islands yearround.

CA-SMI-693 was discovered during a search for early sites near the west end of San Miguel Island. The site appeared to have been recently exposed by the erosion of overlying Holocene dune sand and was being destroyed by a combination of wind erosion and the activities of pinnipeds hauling out on the site. In response to this damage, the site was thoroughly surveyed in 1–2 meter transects to identify exposed artifacts, faunal remains, and features. Much of the site was heavily disturbed, leaving a deflated scatter of marine shells and occasional artifacts visible over an area about 80 m long and 30 m wide. Here, we identified three loci (north, central, and south) where remnants of intact shell midden deposits were still concentrated. Very few artifacts were observed on the site surface and only two tools were noted still embedded in the site soil: a lightly used hammer stone and a flaked cobble core. No animal bones were observed in situ either, and excavation of a 1 × 1 m wide test pit in an intact midden feature in the central locus produced just two tiny unidentifiable bone fragments.

The shell midden at CA-SMI-693 was only 3–8 cm thick, but the excavation of Test Unit 1 produced more than 4.6 kg of marine shell from California mussels and other rocky intertidal shellfish taxa. These included the remains of over 400 California mussels, including scores of whole and still articulated mussel shells. California mussels dominated the shellfish assemblage, comprising more than 80% of the shellfish MNI, 91% of the shell weight, and 96% of the estimated meat yield for the excavated sample. Aside from small amounts of black abalone (*Haliotis cracherodii*), black turban (*Chlorostoma funebris*), and sea urchin (*Strongylocentrotus* spp.) shell, the other shellfish taxa represented appear to be mostly epifauna, including tiny limpets and barnacles often found attached to mussels (Jones and Richman 1995).

Three well-preserved California mussel shells from the intact remnants of the central and southern loci were submitted for radiocarbon ( $^{14}\text{C}$ ) dating and calibrated using a  $\Delta R$  of  $225 \pm 35$  within a 1 sigma range. At the UO, the  $^{14}\text{C}$  samples were cleaned and etched with hydrochloric acid (HCl) to remove potential contaminants, and sent to two labs for dating. First, two samples were submitted to Beta Analytic for analysis via conventional liquid scintillation counting. This resulted in  $^{14}\text{C}$  dates of  $8,540 \pm 50$  RYBP (Beta-255083) for the southern locus and  $8,150 \pm 100$  RYBP (Beta-255084) for the central locus, with calibrated age ranges of 8,980–8,780 cal BP and 8,510–8,290 cal BP, respectively (see Stuiver and Reimer 1993). A second mussel shell (Mc33) from the central locus was later submitted to DirectAMS for dating via accelerator mass spectrometry and produced a conventional age of  $8,440 \pm 40$  RYBP (DAMS-1217–174; J. Chatters, p.c., 2012) and a calibrated age range of 8,810–8,620 cal BP. This date is consistent with Beta-255083 and suggests that CA-SMI-693 resulted from a single short-term occupation  $\sim 8,800 \pm 100$  years ago.

A variety of evidence—including the dearth of artifacts and vertebrate remains, the thin and ephemeral nature of the midden deposits, and the limited diversity of shellfish represented—supports the conclusion that occupation of CA-SMI-693 was relatively brief and focused on the harvest and processing of California mussels. The dearth of artifacts and vertebrate remains at the site is reminiscent of several nearby Early Holocene sites that have been interpreted as short-term camps focused on shellfish collecting and processing (e.g., Erlandson et al. 2004). Because well-preserved mussel shells were abundant in the small and shallow shell feature excavated at the site, they provided an excellent opportunity to examine the seasonality of the site occupation.

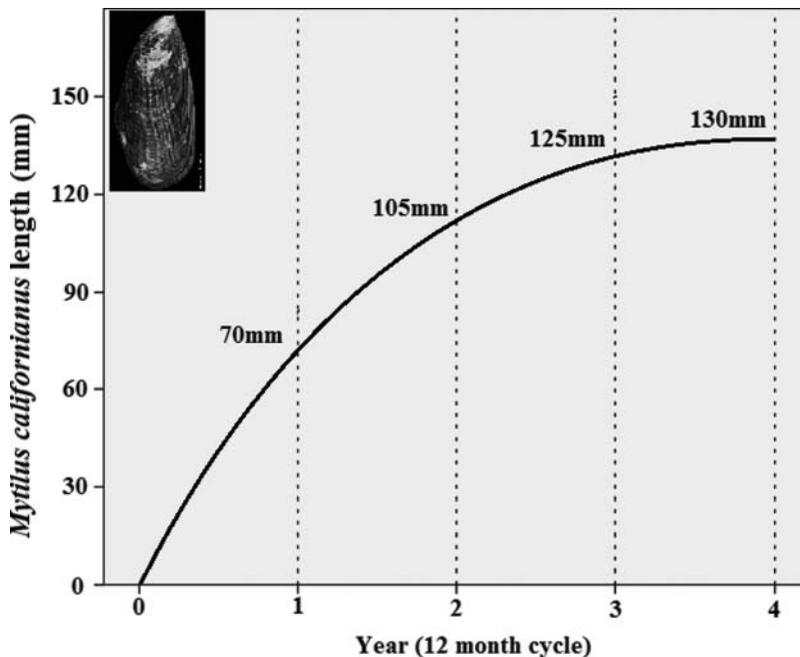
#### MYTILUS CALIFORNIANUS ECOLOGY AND GROWTH

California mussels are filter-feeding bivalves that inhabit intertidal and (less commonly) subtidal zones of North America's Pacific

Coast, from the Aleutians and Alaska to Alta and Baja California (Bayne 1976; Killingley and Berger 1979:187). California mussels are relatively long-lived bivalves that can live up to 20 years. They are found in rocky intertidal areas in water temperatures that can range between  $\sim 8$  and  $26^{\circ}\text{C}$  (Bayne 1976; Coe and Fox 1942:66). California mussels along the Southern California Coast spawn throughout the year (see Suchanek 1981) with breeding peaks between July and December (Morris et al. 1980) and can begin reproducing as early as 4 months old or between 25 and 30 mm long (Shaw et al. 1988). Environmental influences such as water temperature, salinity, wave action, food (dinoflagellates, kelp spores, etc.) availability, surface exposure, sedimentation, and upwelling can vary depending on geographic location, changing growth rates of mussels by the hour, day, month, and season (Coe and Fox 1942, 1944; Dehnel 1956; Fox and Coe 1943; Menge et al. 2008; Rao 1953; Richards 1946; Richards et al. 1990). As a response to heavy preda-

tion, California mussels generally grow very rapidly during their first year, adding as much as 6 mm of shell length per month and reaching total lengths of  $\sim 70$  mm (Coe and Fox 1942). In subsequent years, growth slows significantly as more metabolic energy goes to reproduction, with shell growth averaging  $\sim 35$  mm in the second year, 20 mm in the third year, and just 5 mm in the fourth year (Figure 3). Depending on environmental conditions and the age of an individual mussel, monthly growth rates can vary dramatically, from less than 1 mm to more than 5 mm per month (Coe and Fox 1942:60). In waters south of Point Conception, where growth tends to be relatively rapid (Phillips 2005), California mussels less than  $\sim 70$  mm long may grow 18 mm or more in a single season.

On the Northern Channel Islands (NCI), California mussels were harvested by humans for at least 12,000 years (see Erlandson et al. 2011) and are the most abundant type of shellfish found in most island shell middens. California mussels are nearly ubiquitous in



**Figure 3.** Estimated mean growth curve for  $>1000$  California mussels over a four-year period at Scripps Institute of Oceanography in La Jolla, California (after Coe and Fox 1942).

the mid-to-low intertidal zone of rocky island shores. They attach to rocky substrates via strong byssal threads, often forming dense clusters or extensive mussel beds. Because they are abundant, readily accessible, grow rapidly, and can be easily harvested in large clumps or stripped from rocks in dense mats, they are generally considered the top-ranked shellfish on the islands (see Braje et al. 2007).

Trans-Holocene studies of mussel harvesting on San Miguel and Santa Rosa islands have shown a long-term and island-wide reduction in mean California mussel size, with most Late Holocene shell middens containing relatively small mussels averaging just 35–50 mm long (Erlandson et al. 2008b). As a result, although the Island Chumash harvested millions of mussels annually from Channel Island waters, most of these were small and less than one year old when harvested (see Figure 3). At CA-SMI-693, the mean length of 100 measured mussel valves was 67.8 mm, with a range of 35 to 102 mm. Growth curves for California mussels in southern California waters suggest that all of these mussels were probably harvested before they were two years old, with more than half being one year old or less. How might the very rapid growth of California mussels during their first year of life affect oxygen isotope sampling methods and the inferred seasonality of mussel harvest?

#### OXYGEN ISOTOPE ANALYSIS

The rapid growth of California mussels during their first year suggests that shells ~70 mm long require sampling of at least ~15–25 mm along the growth axis to adequately characterize a full season of growth. With average growth rates slowing to ~35 mm during their second year, however, mussels >70 to 105 mm long should require considerably less sampling (~9–12 mm) to span a full season of growth. The very different growth rates for California mussels in their first few years of life suggest that different isotopic sampling strategies might be appropriate for shells of different sizes. To test this, we analyzed whole California mussel shells of varying sizes using two different sampling methods.

First we selected 40 whole or nearly whole California mussels between 45 mm and 102 mm long. All shells were scraped, rinsed in deionized water, and etched in diluted HCl (0.5 M) to remove foreign substances and diagenetically altered carbonate (see Bailey et al. 1983; Culleton et al. 2006; McCrea 1950; Robbins and Rick 2007). Each shell was mounted onto a Sherline 5410 Micromill and drilled at low speeds (see Robbins and Rick 2007:29) using a carbide (.05 mm) drill bit, carefully sampling in transects following the visible growth lines while ensuring that only the exterior calcite was sampled. Powdered samples were weighed and placed in an autosampler that flushed exetainers with helium to exclude atmospheric carbon dioxide and injected with several drops of orthophosphoric acid to release carbon dioxide from each sample.  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  were measured using a Finnigan MAT253 mass spectrometer using continuous helium flow with precision oxygen and carbon isotopic ratios at  $\pm 0.1\%$  measured at 1 sigma and calibrated by repeated direct measurement against NBS-19. All isotopic determinations are reported in  $\delta$ -notation in per mil (‰) using the Vienna PeeDee Belemnite (VPDB or PDB) standard and inferred SST is based on oxygen isotope signature conversion (see Epstein et al. 1951, 1953; Killingley 1981) where:

$$T(^{\circ}\text{C}) = 16.4 - 4.2 (\delta^{18}\text{O}_{\text{cc(PDB)}} - \delta^{18}\text{O}_{\text{water(smow)}}) + .13 (\delta^{18}\text{O}_{\text{cc(PDB)}} - \delta^{18}\text{O}_{\text{water(smow)}})^2$$

The selected  $\Delta_{0m} \delta^{18}\text{O}_{\text{sw(‰)}}$  for the Early Holocene period ~8,800 cal BP in the Pacific (see LeGrande and Schmidt 2009; Martinson et al. 1987) is ~.47‰ and was adjusted from an ocean water sample of .32‰ taken from Santa Rosa Island (see Robbins and Rick 2007) providing an ice volume correction ( $\delta^{18}\text{O}_{\text{water(smow)}}$ ) of .15‰. The minimum and maximum temperatures in the terminal edge series represent the warmest and coldest months of harvesting (see Kimball et al. 2009).

Initially, we analyzed 95 carbonate samples including one fully profiled shell (Mc21, 77 mm long) and two measurements each for the other 39 shells (TGB + 1; sampling the terminal growth band plus one sample 2 mm from the TGB). For our second approach (TGB + 6 method), we measured 120 isotopic signatures from 20 of the previously sampled shells, 10 shells from 45 to 67 mm long and 10 larger shells from 71 to 100 mm long. Shells were sampled at 3 mm intervals for at least 18 mm of growth extending from the TGB to ensure at least 3–4 months of growth for smaller mussels, based on estimates of California mussel growth (see Coe and Fox 1942, 1944).

provided a standard range of SST variation over most or all of an annual cycle and was used to estimate seasonal variability in paleo-SST for waters around the western end of San Miguel Island ~8,800 years ago (Figure 5). Subsequent isotopic measurements were converted into estimated temperature values and compared to the paleo-SST model, adjusted from modern monthly SST averages recorded for ten years off the coast of San Miguel Island (Kennett 2005:56,66–68). Modern SST averages off San Miguel place the coldest water temperatures (~12.5°C) during March–May (spring), with increasing temperatures (~14–16°C) between June and September (summer–early fall), declining temperatures (16–14°C) from October to December (late fall–early winter), and further decline during January and February (winter). Because SSTs around western San Miguel during the Early Holocene appear to be characterized by seasonal temperature variations of ~6°C (see Appendix 1, available online) the range of seasonal variation was adjusted to compensate for this

A Paleo-SST Model for Western San Miguel Island

For the extensively profiled shell (Mc21), we analyzed 17 samples taken in 3 mm intervals, for a total of 48 mm of growth. This extended profile (Figure 4)

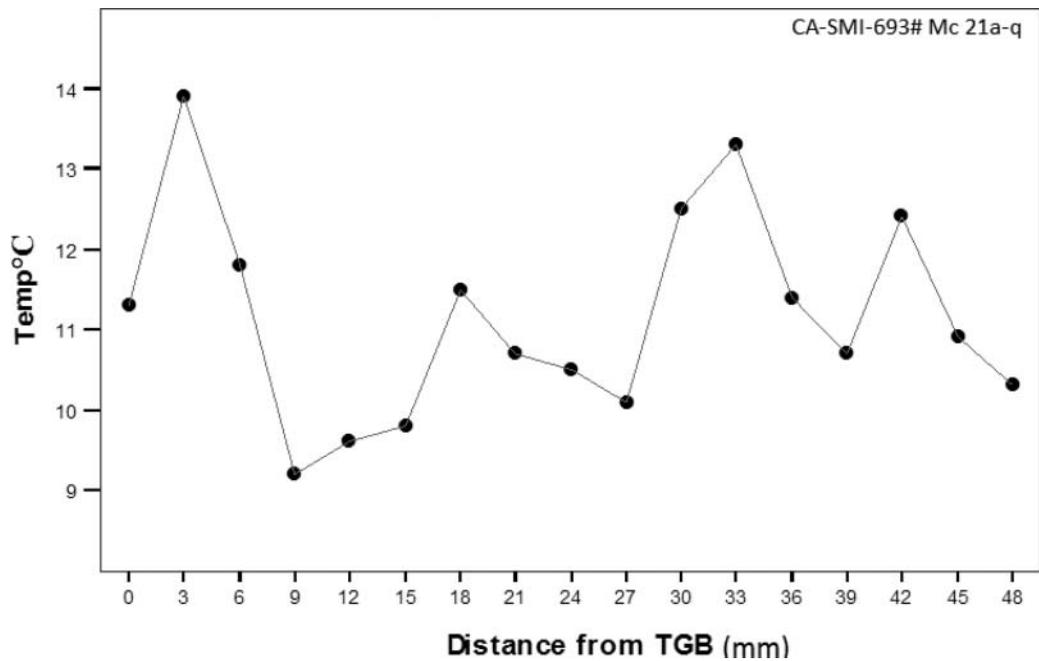
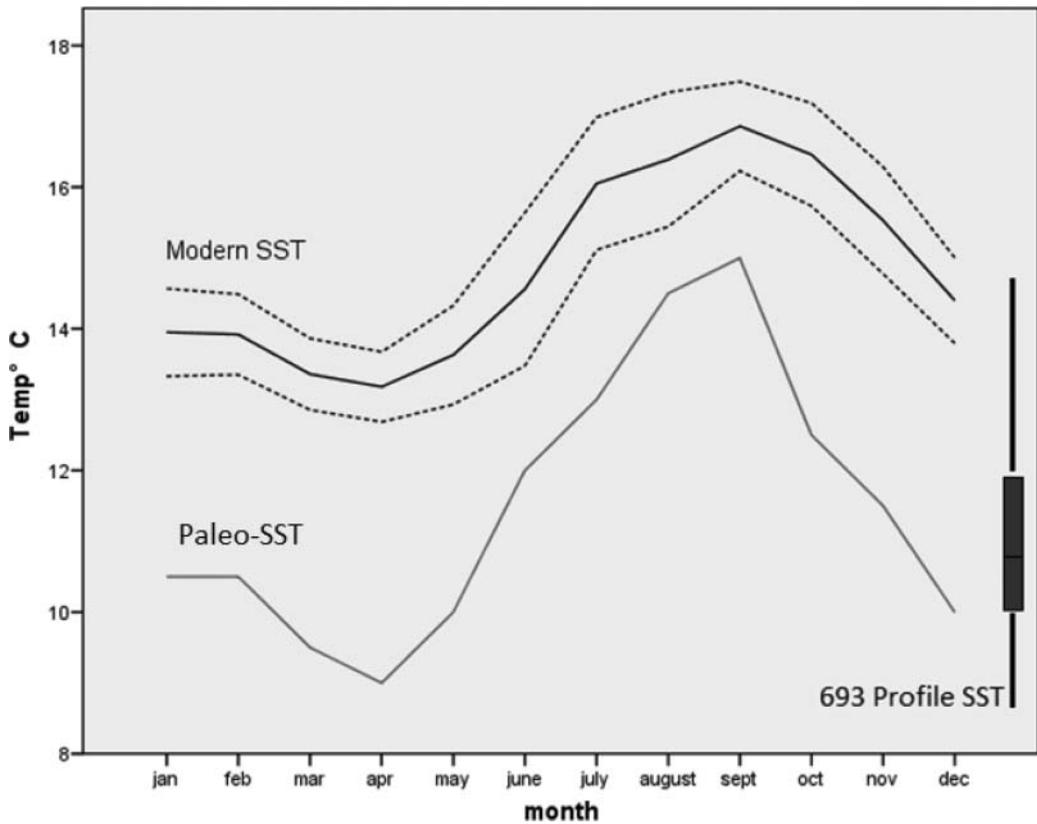


Figure 4. Shell profile for Mc21, showing changes in inferred temperatures through 48 mm of growth.



**Figure 5.** Modern estimated seasonal SST variation for San Miguel Island (top, adapted from 10 years of recorded sea surface temperatures, including 95% confidence intervals (dashed lines; see Kennett 2005:56) compared to estimated seasonal SST variation for the Point Bennett area ~8,800 years ago. (The boxplot, quartiles, and whiskers indicate the range of SST variation for the fully profiled mussel shell (Mc21), demonstrating the overall lower temperature ranges consistent with cooling trends during this period.

increased variability. Overall, recent  $\delta^{18}\text{O}$  values range between 0.852 and  $-0.283$  (PDB) for the Santa Barbara Channel region (see Kennett 1998:451, 2005:66; Kennett and Kennett 2000:384) where Early Holocene  $\delta^{18}\text{O}$  values for ~8,700 cal BP fall between  $-0.2$  and  $-0.4$  with cooler temperatures during this period (see Kennett 2005:66). As a result, our modeled temperatures were adjusted between 2 and 4°C, skewed towards colder water temperatures.

We classified the season of harvest for each analyzed shell using the parameters listed below: where  $X$  represents the value

for the TGB (season of capture) and  $Y$  equals the value for the comparative growth band(s) and season prior to capture, and directionality is the difference (change) between these two values. Based on these estimates, seasonal paleo-SST near San Miguel ~8,800 cal BP can be divided as follows:

Summer (June–September):  $X \geq 12^\circ\text{C}$  and  $Y < X$  (increasing warm temperatures above  $\sim 12^\circ\text{C}$ );

Fall (September–December):  $X \geq \sim 10^\circ\text{C}$  and  $Y > X$  (with decreasing warm temperatures);

Winter–Early Spring (*December–March*):  $X \leq \sim 10^{\circ}\text{C}$  and  $Y > X$  (*coldest waters*);  
and  
Spring (*March–May*):  $X \leq \sim 12^{\circ}\text{C}$  and  $Y < X$  (*with colder temperatures*).

Figure 5 also shows at least two extended periods of relatively stable temperatures represented in the modern 10-year averages for waters off San Miguel, one during 5–6 months between December and May (winter/spring), and another of 2–3 months duration from July to September (summer). Given the overlap in SSTs between winter and early spring, these seasons were indistinguishable except in shells that contained high variability between the terminal edge and adjacent growth bands, suggesting either a dramatic warming or cooling from the prior season. Given instrumentation precision of  $\pm 0.1\%$ , approximate temperature values and assigned seasons are influenced by the isotopic determination of the comparative sampled interval. For example, temperatures on the border between two seasons were assigned based on the temperature of the previous season. Therefore a shell with a TGB temperature of  $9.9^{\circ}\text{C}$  could be either late fall, winter, or early spring depending on the temperature of the previous season. If the temperature of the comparative sample interval was  $10.2^{\circ}\text{C}$  it would be attributed to a winter or early spring harvest, while a shell with a comparative sample interval of  $15^{\circ}\text{C}$  would be attributed to a fall–late fall harvest as it is unlikely this high temperature would occur in late winter. Shells that contained lower SST variances between the TGB and comparative 2 mm of growth were assigned a single season as this suggests that it was harvested well into the season. Alternately, if the TGB and comparative sample interval contained high SST variances, these were assigned a corresponding season as they were most likely harvested towards the end of the previous seasons and in the early months of the season of capture.

Initially, we assigned a prior season and season of harvest for each shell using the results from the TGB + 1 sampling method. We then reassigned seasonality to 20 re-tested

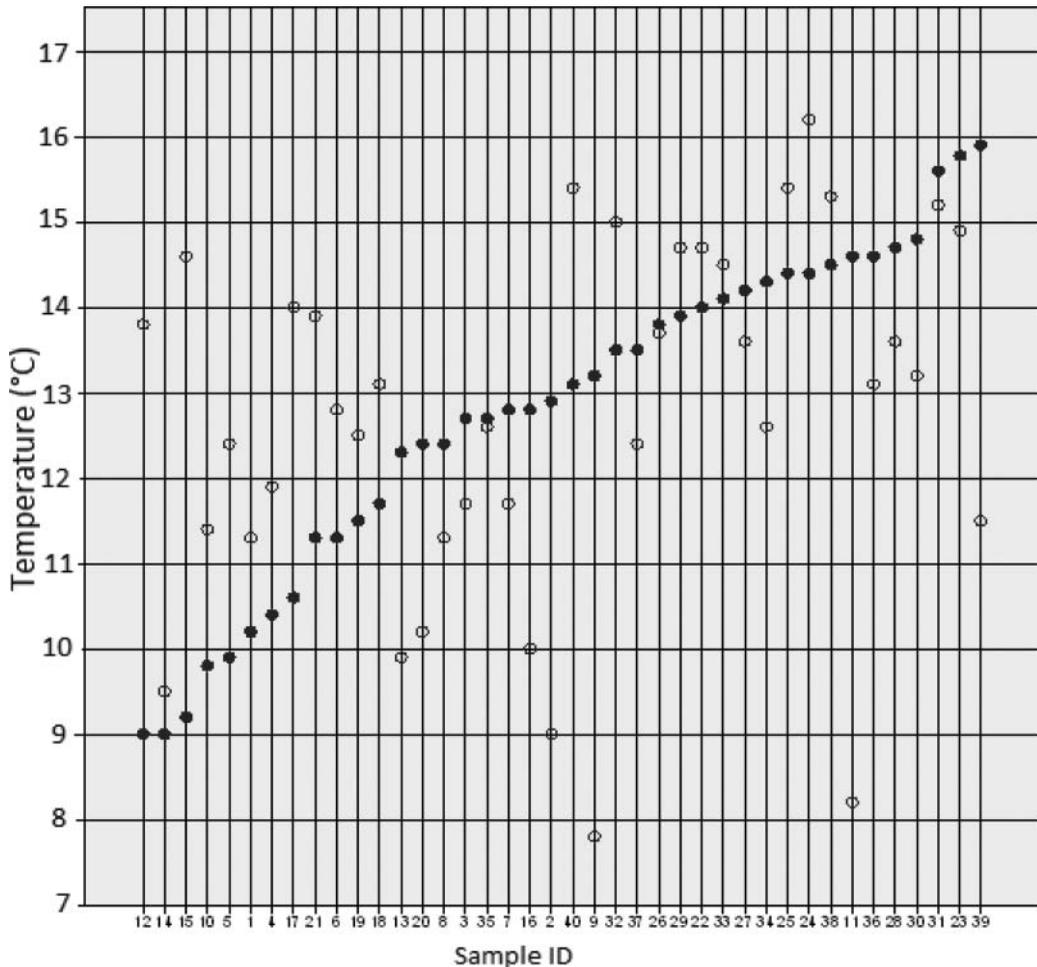
shells using the TGB + 6 method, with sampling intervals of 3 mm capturing at least 18 mm of growth for each mussel. Comparing the two data sets, we identified where differences lie between the 2 mm vs. 18 mm sampling intervals for larger and smaller mussels. From these comparisons we discuss the efficacy of seasonality determinations for California mussels from CA-SMI-693 using the two methods.

## RESULTS

The extended isotopic profile for shell Mc21 (77 mm long) includes 48 mm of growth, with temperatures ranging from  $9.2^{\circ}\text{C}$  to  $14^{\circ}\text{C}$ , with an average of  $\sim 12^{\circ}\text{C}$ . The lowest temperature for the profiled shell is  $\sim 2$  degrees cooler than modern SST, consistent with cooling trends identified for the Early Holocene (see Kennett 2005:66). Figure 4 plots the temperature distribution of the profiled shell, which span  $\sim 48$  mm along the growth axis of the shell, which match up well with a full annual cycle of modern SST variation for San Miguel Island waters (Figure 5). For a shell a total of 77 mm long, this suggests that growth rates near Point Bennett  $\sim 8,800$  years ago were somewhat slower than those recorded for the warmer waters of La Jolla in the 1940s.

### TGB + 1 Sampling

Isotopic determinations from 39 additional California mussel shells (Appendix 1, available online) utilized the TGB + 1 method, analyzing samples from the terminal growth band and 2 mm for each shell. We then interpreted season of harvest on SST, the direction of change (warming vs. cooling) for each shell, and comparison to our paleo-SST model. The results show a wide range of enriched and depleted  $\delta^{18}\text{O}$  values. TGB values varied significantly, with an overall range of  $\sim 9$ – $16^{\circ}\text{C}$  and an average of  $12.5^{\circ}\text{C}$ , suggesting that the shells were harvested in a wide range of water temperatures. Our results suggest that 25 of the shells were collected in waters warmer than the  $12.5^{\circ}\text{C}$



**Figure 6.** Inferred temperature distribution for 40 mussels from CA-SMI-693 analyzed with the TGB + 1 sampling method including the terminal growth band (solid circles) and one adjacent band (at 2 mm; open circles); samples are ordered from lowest to highest temperature at the point of harvest. Note that mussels appear to have been harvested in waters ranging from 9–16°C and that shells are almost evenly split between specimens harvested during warming vs. cooling trends.

average and 15 shells in cooler waters. Comparing the TGB and 2 mm samples, 19 shells show harvesting from warmer to colder periods, 17 from colder to warmer periods, and four from moderate periods of little or no temperature change (Figure 6). Compared to our paleo-SST model, these distributions suggested a pattern of multi-seasonal shellfish harvesting and site use at CA-SMI-693,

focused on summer ( $n = 22$ , 55%) and fall ( $n = 13$ , 32.5%), with only limited harvesting during winter or early spring ( $n = 5$ , 12.5%). These percentages could reasonably be interpreted as evidence for a year-round site occupation (see Jones et al. 2008:2292) with reduced collection in the winter–spring and mussel harvesting focused primarily on the warmer and calmer summer and fall months.

Differences between the TGB and 2 mm samples vary from  $\sim 5^{\circ}\text{C}$  to  $6^{\circ}\text{C}$ . The higher SST fluctuations represented in only 2 mm of shell growth may result from long periods of slow growth for larger mussels or episodic events dramatically changing SST within a single season for smaller mussels. Similar high variances of SST have also been identified in Middle Holocene assemblages on Santa Cruz (Glassow et al. 1994) and Santa Rosa islands (Rick et al. 2006) and can also occur in modern SST in a single month (see Kennett 2005). For both smaller and larger mussels, temperature changes (and their directionality) between the TGB and 2 mm samples may represent as little as one or two weeks of growth, short periods that may be particularly susceptible to short-term episodic events (wave activity, wind-driven upwelling, local variation in currents, etc.).

The TGB + 1 evidence for mussel harvesting at CA-SMI-693 through much of the year seemed to contradict other archaeological evidence that the site occupation was relatively brief, especially given that all the mussels analyzed came from a  $1 \times 1$  m area within a small and discrete shell midden feature. Consequently, we decided to conduct additional analysis to test these initial results. The decision to conduct further testing was also fueled by our suspicion that nearshore oceanic conditions around western San Miguel Island might be particularly complex oceanographically due to unusually strong wind regimes, high wave energy, and the interaction of complex ocean currents.

#### TGB + 6 Sampling

To test the results of our TGB + 1 analysis, we designed a second round of  $\delta^{18}\text{O}$  analysis, based on more extended sampling of 20 of the original 40 shells, including 10 shells 70 mm or longer and 10 shells smaller than 70 mm. For each of these 20 shells, we analyzed six additional sampling intervals at 3, 6, 9, 12, 15, and 18 mm from the TGB. The longer profile for these 20 shells show longer time depth with slightly higher SST variances between growth periods. Overall, however, they are comparable

to the general range of water temperatures established earlier for paleo-SSTs off western San Miguel  $\sim 8,800$  years ago. The TGB + 6 method provides an extended view of water temperatures before the season of capture (TGB), including multiple periods of growth for each shell. This approach allowed us to identify SST variations across 18 mm of shell growth—spanning one or more seasons of growth for both smaller and rapidly growing mussels and larger mussels that were likely to be growing much more slowly.

When comparing TGB values to those from six adjacent 3 mm increments, our estimated seasons of capture for smaller mussels range through summer ( $n = 3$ ), summer-fall or late fall ( $n = 5$ ), and winter ( $n = 2$ ). For the 10 larger mussels, our seasonality estimates all fell during spring-summer or summer periods. The extended isotopic determinations per shell demonstrate that water temperatures over 18 mm of growth fluctuate between  $\pm 3$  and  $7^{\circ}\text{C}$  suggesting that seasonal variations off western San Miguel Island were relatively high. In contrast, SST between the terminal edge and 3 mm samples fluctuated a maximum of  $5^{\circ}\text{C}$  and on average  $\sim \pm 2^{\circ}\text{C}$ . For example, the inferred SST for the last 18 mm of growth for shell Mc5 fluctuates between  $9.9$  and  $14.8^{\circ}\text{C}$  which suggest warming and cooling waters comparable to those proposed in our paleo-SST model.

#### Comparison of TGB + 1 and TGB + 6 Results

Overall 70% of the twenty shells reanalyzed after the initial TGB + 1 sampling were assigned different seasonal ranges based on sampling of additional growth bands (Table 1). For the 10 larger shells, more intensive analysis yielded different seasonal ranges for six shells and four were assigned different harvest seasons. All four of the latter changed from fall to summer, further concentrating the seasonality of shellfish harvesting at CA-SMI-693 in the summer months. Among the larger mussels, half also showed rapid changes in SST between the 2 mm and 3 mm samples. Reconstructed SST for the

**Table 1. Estimated season of harvest for California mussels from CA-SMI-693, including 20 samples reanalyzed with extended-measurements.**

Shell ID#	Length (mm)	TGB + 1 (0–2 mm)	TGB + 6 (0–18 mm)
1	73	Fall-fall	—
6	71	Summer-fall	—
8	49	Spring-summer	—
9	60	Spring-summer	—
11	55	Spring-summer	—
13	62	Spring-summer	—
15	102	Fall-early winter	—
18	71	Summer-fall	—
19	58	Summer-fall	—
20	72	Spring-summer	—
23	60	Summer-summer	—
24	72	Summer-fall	—
25	55	Summer-fall	—
26	60	Summer-summer	—
27	62	Summer-summer	—
33	70	Summer-summer	—
36	54	Summer-summer	—
37	60	Spring-summer	—
38	92	Summer-summer	—
21	77	Summer-fall	—
22	74	Summer-fall	Spring*-summer*
28	88	Summer-summer	Spring*-summer*
29	87	Summer-fall	Spring*-summer*
30	80	Summer-summer	Summer-summer
31	71	Summer-summer	Spring*-summer
32	85	Summer-fall	Spring*-summer*
34	77	Spring-summer	Spring-summer
35	86	Summer-summer	Summer-summer
39	76	Spring-summer	Summer*-summer
40	100	Summer-fall	Spring*-summer*
2	62	Spring-summer	Summer*-summer
3	50	Spring-summer	Summer*-summer
4	63	Summer-fall	Summer-fall
5	45	Fall-winter	Fall-late fall*
7	65	Spring-summer	Summer*-summer
10	65	Winter-early spring	Fall*-late fall*
12	62	Fall-early winter	Fall-early winter
14	61	Winter-winter	Fall*-winter
16	66	Spring-summer	Summer*-fall*
17	67	Summer-fall	Summer-fall

*Note:* Asterisks indicate where sampling methods led to different seasonality conclusions.

TGB of shell Mc39 (Figure 6) is 15.9°C, for example, followed by 11.5°C (2 mm), 15.9°C (3 mm), and 15.0°C (6 mm). The extended isotopic profile for this shell suggests a gradual warming—interrupted by a single relatively rapid cooling episode—over 18 mm of growth (from 10.5°C to 15.9°C) which suggests a summer collection when waters were warmer. The high variance between closely spaced growth bands 2 and 3 mm from the TGB in this and other shells (Figure 6) probably represents short-term and episodic SST fluctuations off western San Miguel Island in the Early Holocene. If such dramatic changes in SST represented a full season of growth, ~1 mm of growth would have to represent at least 4 months, contradicting what is known of mussel ecology and growth rates even in the poorest conditions (see Coe and Fox 1942). In many such cases, without a more extended profiling of the shells, season-of-harvest estimations would be misinterpreted.

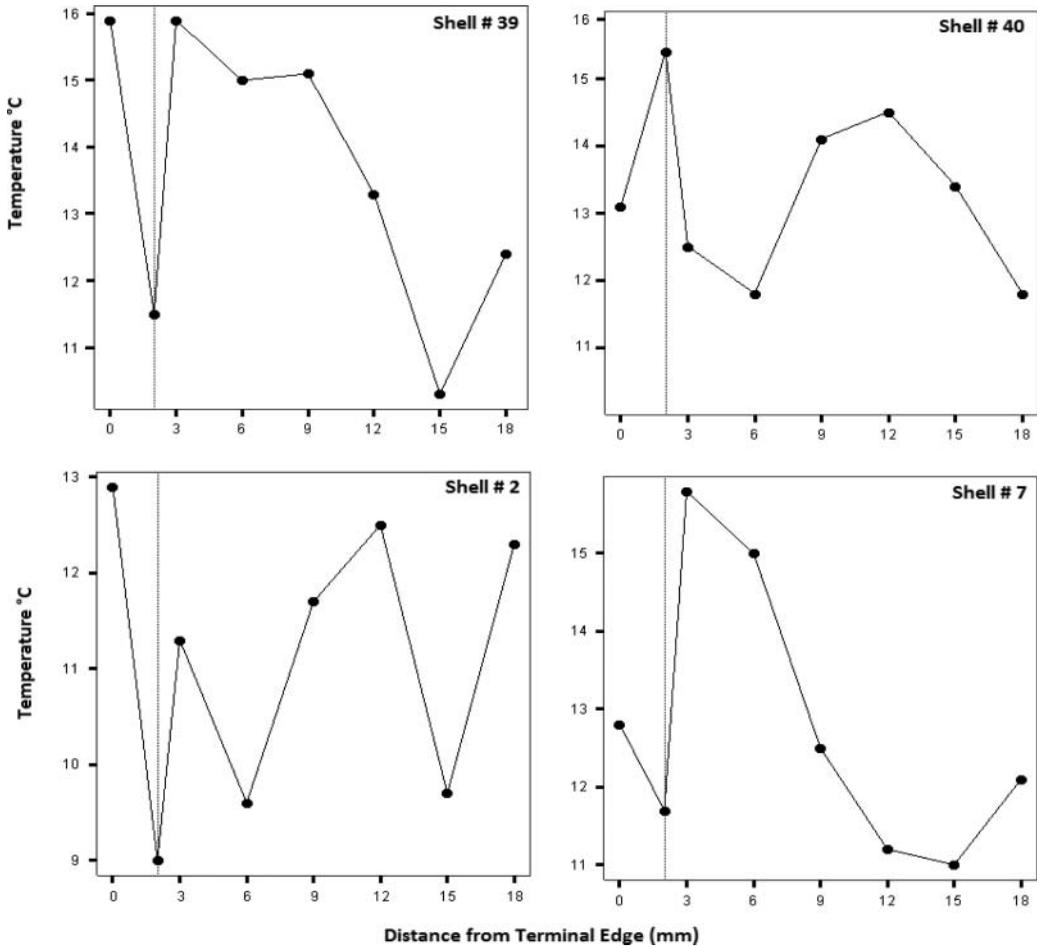
For the 10 smaller (<70 mm) mussel shells, analysis of the TGB + 6 samples resulted in seasonal range changes for seven (70%,  $n = 7/10$ ) shells and different harvest seasons for three (30%,  $n = 3/10$ ). Shell Mc2 (Figure 7) was originally assigned a spring-summer range because the 2 mm growth band was 3 degrees colder than the TGB (12.9°C), suggesting that it was harvested as cool waters warmed. The 18 mm growth band is 12.3°C with three dramatic decreases in temperature up to the terminal edge. This likely represents seasonal fluctuation in temperatures within summer of  $\pm 4^\circ\text{C}$  which is consistent with modern temperature variation within a single season of  $\pm 5^\circ\text{C}$  (Glassow et al. 1994:227; Kennett 2005:56) and also during the Middle Holocene on Santa Cruz (see Glassow et al. 1994:226) and Santa Rosa islands (Rick et al. 2006:246). The most significant differences can be seen in shell Mc7 (Figure 7) where isotopic data for the 2 and 3 mm growth bands produced different directional changes in temperatures and thus different interpretations for season of capture. Shell Mc7 was originally identified as a spring-summer harvest based on the TGB + 1 sampling strategy. The 3 mm growth band was 3°C warmer than the termi-

nal edge, suggesting a fall season of harvest. The temperature for the 18 mm of growth was 0.7°C cooler than the terminal edge but warm enough to have been well into summer harvesting. These differences can be explained as either intraseasonal temperature fluctuations or multiple seasonal signatures for slower growing mussels. Given the range of temperatures between the 2 mm and 3 mm growth bands, once again the isotopic data most likely represent relatively short-term intra-seasonal fluctuations.

## DISCUSSION

For the 20 California mussel shells from CA-SMI-693 analyzed with both the TGB + 1 and TGB + 6 methods, our results were substantially different—with the more intensive method changing the estimated season of harvest for 35% of the shells, 40% of those >70 mm long, and 30% of those <70 mm long. Assuming that the 18 mm method (TGB + 6) is a more accurate measure of the seasons represented at and before harvest, the TGB + 1 method appears to be significantly less reliable than our TGB + 6 method—at least for western San Miguel Island about 8,800 years ago.

The results also significantly narrow the seasonal harvest signature for those 20 shells, with 90% falling within the summer ( $n = 13$ ) or fall ( $n = 5$ ), and just two shells attributed to a winter harvest. In contrast, with the TGB + 1 sampling method, just 80% of the shells were identified as being harvested in summer ( $n = 10$ ) or fall ( $n = 6$ ) and 20% were identified as either winter ( $n = 3$ ) or spring ( $n = 1$ ). Applying a 35% error rate to the full sample of 40 shells (Figure 8) significantly changes the reconstructed seasonal patterns of mussel harvesting and the inferred season(s) of site occupation. With just 10% of the analyzed shells falling outside of a summer/fall harvest, moreover, it is considerably easier to explain the outliers as resulting from another ecological problem rarely discussed in seasonality analyses for California mussels. This has to do with the typical aggregation of California mussels, human mussel harvesting techniques, and

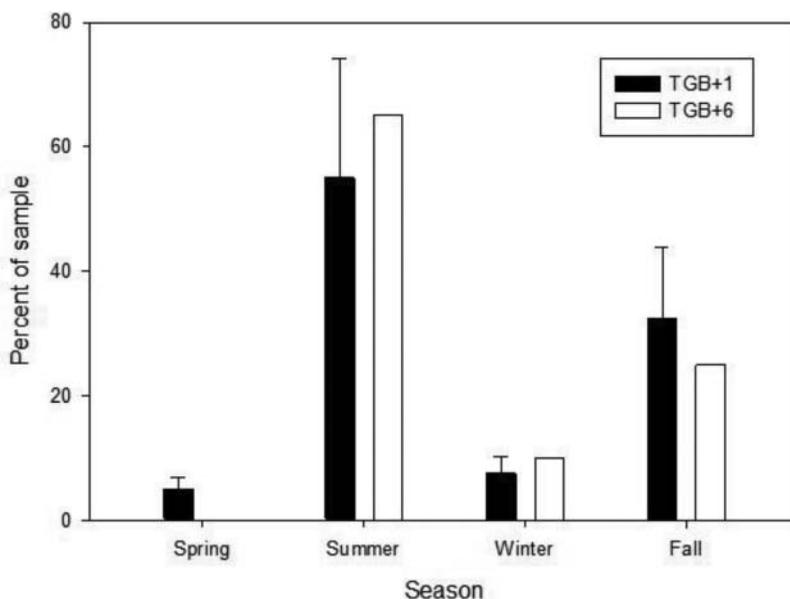


**Figure 7.** Profiled temperature estimates from shells tested using both sampling strategies, illustrating some inconsistencies and seasonal discontinuities. The 2 mm value is represented in each graph by a vertical line through the x-axis. All four shells were harvested in summer based on  $TGB + 6$  values.

year-round predation on mussels by seastars (*Pisaster ochraeus*) and other non-human predators. If people harvested clusters of intertwined mussels from rocky intertidal areas (see Jones and Richman 1995), occasional shells of dead mussels may have been brought back to the site along with live ones.

From a methodological standpoint, if shell growth is  $\sim 15$ – $18$  mm per season for smaller mussels and  $\sim 9$ – $12$  mm for larger mussels, then the variation between

0 and 2 mm of growth represents short-term (intra-seasonal) SST fluctuations rather than broader seasonal signatures prior to harvest. This suggests that for California mussels and other rapidly growing molluscs, archaeologists should carefully consider growth rates—which vary significantly through the life history of many species—in devising  $\delta^{18}\text{O}$  sampling strategies. Based on our analysis, it seems clear that sampling strategies should vary depending on the age and size of the shell being analyzed.



**Figure 8.** Seasonality reconstructions including error bars (whiskers) for 40 analyzed shells, based on an extrapolation from reassignments between the TGB + 1 and TGB + 6 samples (a 35% error rate for TGB + 1 samples was applied to the larger sample).

## CONCLUSIONS

Archaeologists have identified scores of Terminal Pleistocene and Early Holocene sites on California's NCI, but there is still little known about the nature of Paleocoastal settlement in general or the seasonality of specific site occupations. In this paper, we reported the first detailed evidence for the seasonality of a Paleocoastal site based on  $\delta^{18}\text{O}$  analysis of marine shells. The structure and contents of this 8,800-year-old shell midden on western San Miguel Island strongly suggested that site occupation was relatively brief, seasonal in nature, and focused on the harvesting of California mussels and other rocky shore shellfish. When initial  $\delta^{18}\text{O}$  results for 40 California mussel shells seemed at odds with this archaeological evidence, we conducted more intensive isotope sampling for 20 of the same shells. For 35% of the shells, the results were significantly different and produced seasonality data more consistent with a summer-fall occupation of the site. The revised results, when combined

with other archaeological evidence, lead us to conclude that CA-SMI-693 was a seasonal camp occupied during the summer and to a lesser extent the fall—possibly a satellite for a larger residential base located elsewhere on San Miguel or Santa Rosa islands. This hypothesis is supported by the isotopic signatures and inferred SST values, the high frequency of California mussels at the site, and a near absence of artifacts and vertebrate faunal remains.

More extended profiles for mussel shells from CA-SMI-693 also provided SST estimates that identified several short-term temperature fluctuations suggestive of episodic events potentially related to storm activity, wind-driven upwelling events, or the complexity of ocean currents and microhabitats in the ancient Point Bennett area. Whatever the cause, these short-term fluctuations in SST revised several of the seasonality determinations obtained with the TGB + 1 sampling method after more intensive sampling was done. Given the rapid growth of California mussels, particularly in their first year

or two of life, we recommend more extensive sampling of shells to obtain higher resolution data on paleo-SSTs, seasonality, site function, and human subsistence and settlement strategies. Ideally, we recommend that more than one whole shell should be fully profiled per assemblage—the more the better—in intervals ranging from 1 to 3 mm along the growth axis to provide a range of SST throughout an annual cycle. The resulting data can be compared to modern water temperatures and seasonal variances to create paleo-SST models that facilitate seasonal studies.

Our study also suggests that growth rates of shellfish should be carefully considered before selecting samples for isotopic analysis (see also Andrus 2011). Rather than a single “one size fits all” methodological approach, sampling strategies should be tailored to the nature of the assemblage being studied, including the primary size range of mussels available for analysis. Since growth rates for many shellfish taxa vary dramatically through their life cycle, the size of each shell analyzed should be reported so other researchers can more effectively estimate the period of growth represented in the sampling of each shell. Finally, although whole shells are not necessarily required (see Schweikhardt et al. 2011), fragments large enough to preserve a terminal growth band and a full season of growth (~15–20 mm in length) prior to harvest are recommended for reliably determining seasonality. Reconstructing the full range of annual variation in paleo-SSTs may require an even longer sequence to insure sampling of one full year of growth.

Stable isotope analysis continues to be a powerful tool in determining paleo-SSTs, the seasonality of shellfish harvesting, site occupation, and settlement patterns in many coastal and island settings (Andrus 2011). As numerous studies have shown, however, the ecology and life history of individual molluscan taxa should be carefully considered in designing effective sampling strategies. In areas such as Point Bennett, where complex currents and variable oceanic conditions are known to occur, detailed analysis of modern shells and local water temperatures may also

help interpret isotopic signatures in ancient shells.

#### ACKNOWLEDGEMENTS

*Our  $\delta^{18}O$  samples reported were prepared by the senior author in the Coastal Archaeology and Human Ecology Lab, then analyzed in the Department of Geological Sciences Stable Isotope Lab at the University of Oregon (UO). We thank Jim Palandri and Ilya Bindeman for their help in analyzing the samples. We also thank Torben Rick, Tracy Garcia, Brendan Culleton, Douglas Kennett, and John Robbins for their intellectual contributions to our research, which was supported by the National Science Foundation (BCS 0917677 to Erlandson and Rick), the Edna English Trust, the National Parks Service, and UO. Finally, we thank DirectAMS for providing a free AMS  $^{14}C$  date from CA-SMI-693, the anonymous reviewers, and the editors of JICA for comments that significantly improved this article.*

#### REFERENCES

- Andrus, C. F. T. 2011. Shell midden sclerochronology. *Quaternary Science Reviews* 30:2892–2905.
- Andrus, C. F. T. 2012. Mollusks as oxygen-isotope season-of-capture proxies in southeastern United States archaeology. In *Seasonality and Human Mobility along the Georgia Bight* (E. Reitz, I. Quitmyer, and D. Thomas, eds.):123–132. New York: Scientific Publications of the American Museum of Natural History.
- Bailey, G., M. Deith, and N. Shackleton. 1983. Oxygen isotope analysis and seasonality determinations: Limits and potential of a new technique. *American Antiquity* 48:390–398.
- Balter, M. 2011. Do island sites suggest a coastal route to the Americas? *Science* 331(6021): 1122.
- Bayne, B. L. (ed.). 1976. *Marine Mussels, Their Ecology and Physiology*. Cambridge, London: Cambridge University Press.
- Braje, T., D. J. Kennett, J. M. Erlandson, and B. J. Culleton. 2007. Human impacts on nearshore shellfish taxa: A 7,000 year record from Santa

- Rosa Island, California. *American Antiquity* 72:735–756.
- Cassidy, J., L. M. Raab, and N. A. Kononenko. 2004. Boats, bones, and biface bias: The Early Holocene mariners of Eel Point, San Clemente Island, California. *American Antiquity* 69:109–130.
- Coe, W. and D. L. Fox. 1942. Biology of the California sea-mussel (*Mytilus californianus*). I influence of temperature, food supply, sex, and age on the rate of growth. *Journal of Experimental Zoology* 90(1):1–30.
- Coe, W. and D. L. Fox. 1944. Biology of the California sea-mussel (*Mytilus californianus*). III environmental conditions and rate of growth. *Biological Bulletin* 87:59–72.
- Culleton, B. J., D. J. Kennett, B. L. Ingram, and J. M. Erlandson. 2006. Intrashell radiocarbon variability in marine mollusks. *Radiocarbon* 48:387–400.
- Culleton, B. J., D. J. Kennett, and T. Jones. 2009. Oxygen isotope seasonality in a temperate estuarine shell midden: A case study from CA-ALA-17 on the San Francisco Bay, California. *Journal of Archaeological Science* 36:1354–1363.
- Dehnel, P. A. 1956. Growth rates in latitudinally and vertically separated populations of *Mytilus californianus*. *Biological Bulletin* 110:43–53.
- Eerkens, J. W., Rosenthal, J. S., Stevens, N. E., Cannon, E. L. Brown, and H. J. Spero. 2010. Stable isotope provenance analysis of Olivella shell beads from the Los Angeles Basin and San Nicolas Island. *Journal of Island and Coastal Archaeology* 5:105–119.
- Epstein, S., R. Buchsbaun, H. Lowenstam, and H. Urey. 1951. Carbonate-water isotopic temperature scale. *Bulletin of the Geological Society of America* 62:417–426.
- Epstein, S., R. Buchsbaun, H. Lowenstam, and H. Urey. 1953. Revised carbonate-water isotopic temperature scale. *Bulletin of the Geological Society of America* 64:1315–1326.
- Erlandson, J. M., M. L. Moss, and M. Des Lauriers. 2008a. Life on the edge: Early maritime cultures of the Pacific Coast of North America. *Quaternary Science Reviews* 27:2232–2245.
- Erlandson, J., T. Rick, and M. Batterson. 2004. Busted Balls Shell Midden (CA-SMI-606) an early coastal site on San Miguel Island, California. *North American Archaeologist* 25:251–272.
- Erlandson, J. M., T. C. Rick, T. J. Braje, M. Caspersen, B. Fulfrost, T. Garcia, D. A. Guthrie, et al. 2011. Paleoindian seafaring, shell middens, and maritime technologies on California's Northern Channel Islands. *Science* 331 (6021):1181–1185.
- Erlandson, J. M., T. C. Rick, T. J. Braje, A. Steinberg, and R. Vellanoweth. 2008b. Human impacts on ancient shellfish: A 10,000 year record from San Miguel Island, California. *Journal of Archaeological Science* 35:2144–2152.
- Fitzhugh, B. and D. J. Kennett. 2010. Seafaring intensity and island-mainland interaction along the Pacific Coast of North America. In *The Global Origins and Development of Seafaring* (A. Anderson, J. Barrett, and K. Boyle, eds.):69–80. Cambridge: McDonald Institute for Archaeological Research, University of Cambridge.
- Fox, D. and W. Coe. 1943. Biology of the California sea-mussel (*Mytilus californianus*). II. Nutrition, metabolism, growth and calcium deposition. *Journal of Experimental Zoology* 93:205–249.
- Glassow, M. A., D. J. Kennett, J. P. Kennett, and L. R. Wilcoxon. 1994. Confirmation of Middle Holocene ocean cooling inferred from stable isotopic analysis of prehistoric shells from Santa Cruz Island, California. In *The Fourth California Islands Symposium: Update on the Status Resources* (W. L. Halvorson and G. J. Maender, eds.):223–232. Santa Barbara: Santa Barbara Museum of Natural History.
- Glassow, M. A., P. Paige, and J. Perry. 2008. *The Punta Arena site and Early and Middle Holocene cultural development on Santa Cruz Island, California*. Santa Barbara: Anthropological Papers, Santa Barbara Museum of Natural History.
- Glassow, M. A., H. B. Thakar, and D. J. Kennett. 2012. Red abalone collecting and marine water temperature during the Middle Holocene occupation of Santa Cruz Island, California. *Journal of Archaeological Science* 39:2574–2582.
- Goodwin, D. H., B. R. Schone, and D. L. Dettman. 2003. Resolution and fidelity of oxygen isotopes as paleotemperature proxies in bivalve mollusk shells: Models and observations. *PALAIOS* 18:110–125.
- Johnson, J. R., T. W. Stafford, Jr., H. O. Ajie, and D. P. Morris. 2012. Arlington Springs revisited. In *Proceedings of the 5th California Island Symposium* (D. Browne, K. Mitchell, and H. Chaney, eds.): 541–545. Santa Barbara: Santa Barbara Museum of Natural History.
- Jones, T. and D. Kennett. 1999. Late Holocene sea temperatures along the central California Coast. *Quaternary Research* 51:74–82.
- Jones, T., D. Kennett, J. Kennett, and B. Coddling. 2008. Seasonal stability in Late Holocene shellfish harvesting on the central California Coast. *Journal of Archaeological Science* 35:2286–2294.
- Jones, T. and J. R. Richman. 1995. On mussels: *Mytilus californianus* as a prehistoric resource. *North American Archaeologist* 16:33–58.

- Kennett, D. J. 1998. *Behavioral Ecology and the Evolution of Hunter-Gatherer Societies on the Northern Channel Islands, California*. Ph.D. Dissertation. Santa Barbara: University of California, Santa Barbara.
- Kennett, D. J. 2005. *The Island Chumash: Behavioral Ecology of a Maritime Society*. Berkeley: University of California Press.
- Kennett, D. and J. Kennett. 2000. Competitive and cooperative responses to climatic instability in coastal southern California. *American Antiquity* 65:379–395.
- Kennett, D. J., J. P. Kennett, G. J. West, J. M. Erlandson, J. R. Johnson, I. L. Hendy, A. West, B. J. Culleton, T. L. Jones, and T. W. Stafford, Jr. 2008. Wildfire and abrupt ecosystem disruption of California's Northern Channel Islands at Allerød-Younger Dryas Boundary (13.0–12.9 ka). *Quaternary Science Reviews* 27/28: 2530–2545.
- Kennett, D. J. and B. Voorhies. 1995. Middle Holocene periodicities in rainfall inferred from oxygen and carbon isotopic fluctuations in prehistoric tropical estuarine mollusk shells. *Archaeometry* 37(1):157–170.
- Kennett, D. J. and B. Voorhies. 1996. Oxygen isotopic analysis of archaeological shells to detect seasonal use of wetlands on the southern Pacific Coast of Mexico. *Journal of Archaeological Science* 23:689–704.
- Killingley, J. S. 1981. Seasonality of mollusk collecting determined from O-18 profiles of shells. *American Antiquity* 46:152–158.
- Killingley, J. S. and W. H. Berger. 1979. Stable isotopes in a mollusk shell: Detection of upwelling events. *Science* 205:186–188.
- Kimball, M. J., W. Showers, S. McCartan, and B. J. Genna. 2009.  $^{18}\text{O}$  analysis of *Littorina littorea* shells from Ferriter's Cove, Dingle Peninsula: Preliminary results and interpretations. In *From Bann Flakes to Bushmills* (N. Finlay, S. McCartan, N. Milner, and C. Wickham-Jones, eds.):190–197. Oxford: Oxbow Books.
- LaGrande, A. N. and G. A. Schmidt. 2009. Sources of Holocene variability of oxygen isotopes in paleoclimate archives. *Climate of the Past* 5:441–455.
- Martinson, D. G., N. G. Pisias, J. D. Hays, J. Imbrie, T. C. Moore, and N. J. Shackleton. 1987. Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research* 27:1–29.
- McCrea, J. M. 1950. On the isotopic chemistry of carbonates and a paleotemperature scale. *Journal of Chemical Physics* 18:849–857.
- Menge, B. A., C. Chan, and J. Lubchenco. 2008. Response of a rocky intertidal ecosystem engineer and community dominant to climate change. *Ecology Letters* 11:151–162.
- Morris, R. H., D. P. Abbot, and E. C. Harderlie. 1980. *Intertidal Invertebrates of California*. Stanford: Stanford University Press.
- Phillips, N. E. 2005. Growth of filter-feeding benthic invertebrates from a region with variable upwelling intensity. *Marine Ecological Progress Series* 259:79–89.
- Quitmyer, I. R. and C. B. DePrater. 2012. Validation of annual shell increments and shifting population dynamics in modern and zooarchaeological hard clams (*Mercenaria mercenaria*) from the Litchfield Beach Region, South Carolina. In *Seasonality and Human Mobility along the Georgia Bight* (E. Reitz, I. Quitmyer, and D. Thomas, eds.):149–164. New York: Scientific Publications of the American Museum of Natural History.
- Quitmyer, I. R. and D. S. Jones. 2012. Annual incremental shell growth patterns in hard clams (*Mercenaria* spp.) from St. Catherines Island, Georgia: A record of seasonal and anthropogenic impact on zooarchaeological resources. In *Seasonality and Human Mobility along the Georgia Bight* (E. Reitz, I. Quitmyer, and D. Thomas, eds.):135–148. New York: Scientific Publications of the American Museum of Natural History.
- Rao, K. P. 1953. Rate of water propulsion in *Mytilus californianus* as a function of latitude. *Biological Bulletin* 104:171–181.
- Richards, C. A., R. Seed, and E. Naylor. 1990. Use of internal growth bands for measuring individual and population growth rates in *Mytilus edulis* from offshore production platforms. *Marine Ecology Progress Series* 66:259–265.
- Richards, O. W. 1946. Comparative growth of *Mytilus californianus* at La Jolla, California and *Mytilus edulis* at Wood Hole, Massachusetts. *Ecology* 24:370–372.
- Rick, T. C., J. M. Erlandson, and R. Vellanoweth. 2001. Paleocoastal marine fishing on the Pacific coast of the Americas: Perspectives from Daisy Cave, California. *American Antiquity* 66:595–613.
- Rick, T. C., J. M. Erlandson, R. L. Vellanoweth, and T. J. Braje. 2005. From Pleistocene mariners to complex hunter-gatherers: The archaeology of the California Channel Islands. *Journal of World Prehistory* 19:169–228.
- Rick, T. C., J. A. Robbins, and K. M. Ferguson. 2006. Stable isotopes from marine shells, ancient environments, and human subsistence on Middle Holocene Santa Rosa Island, California, USA. *Journal of Island and Coastal Archaeology* 1:233–254.

## Shellfish, Seasonality, and Stable Isotope Sampling

- Robbins, J. and T. Rick. 2007. The analysis of stable isotopes from California coastal archaeological sites: Implications for understanding human cultural developments and environmental change. *Proceedings of the Society for California Archaeology* 20:29-33.
- Schweikhardt, P. L, Ingram, K. Lightfoot, and E. Libby. 2011. Geochemical methods for inferring seasonal occupation of an estuarine shellmound: A case study from San Francisco Bay. *Journal of Archaeological Science* 38:2301-2312.
- Shackleton, N. J. 1973. Oxygen isotope analysis as a means of determining season of occupation of prehistoric middens. *Archaeometry* 15(1):133-141.
- Shaw, W. N., T. Hassler, and D. Moran 1988. *Species Profiles: life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Southwest): California Sea Mussel and Bay Mussel*. U. S. Fish and Wildlife Service Biological Report 82 (11.84). Vicksburg, MS: U.S. Army Corps of Engineers, TR EL-82-4.
- Stuiver, M. and P. J. Reimer. 1993. Calib 6.0 radiocarbon calibration program. *Radiocarbon* 35:215-230.
- Suchanek, T. 1981. The role of disturbance in the evolution of life history strategies in the intertidal mussels *Mytilus edulis* and *Mytilus californianus*. *Oecologia* 50:143-152.