Central place foraging and shellfish processing on California’s Northern Channel Islands

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We use a central place forager model for shellfish processing to understand Middle Holocene (7550–3600 cal BP) human settlement patterns on California’s Northern Channel Islands. This period was associated with increasing sedentism and special purpose sites. We examine the processing and transport costs of two high-ranked shellfish species collected during the Middle Holocene, red abalone (Haliotis rufescens) and California mussel (Mytilus californianus), and how these costs influence archaeological assemblages at coastal and interior settlements. Experimental data and the biology of these species suggest that red abalones are less likely than mussels to be transported long distances (~2 km) without field processing. Consistent with these expectations, coastal red abalone midden sites (CA-SRI-109 and -338) are dominated by large red abalone shells and California mussels are most abundant at contemporaneous inland sites (e.g., CA-SRI-50). Large coastal settlement sites (CA-SRI-5, -19, -116, and -821) had the highest overall shellfish diversity. A stable oxygen isotope study suggests that special purpose sites were occupied seasonally and large coastal settlements were more likely to be inhabited year-round. Our study suggests that transportation and processing costs of food resources were important variables in the development of early hunter–gatherer settlement patterns.

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1. Introduction

Among human populations, there is a fundamental trade-off between sedentism and access to diverse environmental resources. Decisions must be made about mobility, investments in transportation, which resources to prioritize, and scheduling of resource procurement activities (e.g., Bettinger, 1991, 2009; Metcalfe and Barlow, 1992; Smith and Winterhalder, 1992; Madsen, 1993; Barlow and Metcalfe, 1996; Bettinger et al., 1997; Bird and Bliege Bird, 1997; Madsen and Schmitt, 1998; Winterhalder and Smith, 2000; Nagaoka, 2002; Cannon, 2003; Bird and O’Connell, 2006; Kennett et al., 2009; Winterhalder et al., 2010). Among modern industrial populations, efficient forms of long-distance transportation and refrigeration allow people to be almost exclusively sedentary while maintaining access to a broad range of resources. Among hunter–gatherer populations, seasonal and long-term mobility and the conditions in which certain resources are collected and transported back to residential bases are much more variable and related to a series of environmental and social factors.

Changes in population size or density, sea level rise, seasonal water availability, distribution of food resources, and weather patterns all play a role in shaping settlement systems. Human Behavioral Ecology (HBE) is an effective approach for exploring the decisions that people make about settlement location, mobility, and resource acquisition because it allows for models that can be tested with archaeological data (e.g., Smith, 1983; Stephens and Krebs, 1986; Madsen, 1993; Bird and O’Connell, 2006).

One model of particular use for understanding early settlement systems is the central place forager model (Bettinger, 1991). This model predicts that when collecting a resource, decisions about whether to field process prior to transportation back to a central location should be made to maximize energetic and other returns (e.g., Charnov, 1976; Smith, 1983: 631–634; Ugan et al., 2003; Burger et al., 2005; Metcalfe and Barlow, 1992; Barlow and Metcalfe, 1996; Bird and Bliege Bird, 1997; Cannon, 2003; Bettinger et al., 1997). These decisions become necessary when people occupy one location and must travel substantial distances to collect resources not available locally. This, in turn, can lead to the development of regional settlement systems that include special purpose sites (e.g., Binford, 1980). Decisions about shellfish processing have been addressed in coastal environments such as the South Pacific to understand fundamental questions about...
human subsistence (e.g., Bird et al., 2002; Thomas, 2007; Codding et al., 2014). Patterns of shellfish remains in archaeological contexts also can provide important information about population size and movement during the initial colonization of new locations (see Codding et al., 2014).

In this paper, we use a central place forager model to understand the distribution of permanent and special purpose sites on Santa Rosa Island, California, during the Middle Holocene (~7550–3600 cal BP). At this time, people collected shellfish from special purpose coastal sites for transport back to permanent coastal settlements or interior residential bases. The faunal record supports a field processing model in which red abalones (Haliotis rufescens) are preferentially processed at or near collection sites because they are easily removed from their heavy shells. California mussels (Mytilus californianus) were transported unprocessed because their shells are lighter and more time consuming to remove, and because the meat preserves better in the shell. This model describes a settlement system in which decisions about where to establish a central base, seasonal movement, and patterns of field processing are made to take advantage of disparate resources across the landscape. It helps explain differing archaeological assemblages between sites that were likely seasonally occupied by the same groups of people.

2. Theoretical background

When modeling human subsistence behavior, it is important to consider not only which resources hunter–gatherers choose to exploit, but also how long is spent processing and collecting those resources before transporting them back to a central base. This is often modeled using the marginal value theorem, an optimization model borrowed from biology (Charnov, 1976; Smith, 1983: 631–634; Ugan et al., 2003; Burger et al., 2005), or through the use of utility functions, defined by Metcalfe and Barlow (1992; Barlow and Metcalfe, 1996) as the relationship between the time spent processing and the resulting increase in the utility of the transported load. This model predicts that collectors will spend the amount of time field processing that maximizes the net calories per hour from a resource after traveling to a resource patch, collecting and field processing the resource, and transporting it back to camp (Barlow and Metcalfe, 1996: 355). Metcalfe and Barlow divided the processing of pinyon and pickleweed into steps, for example, with total utility calculated for field processing after each step. They then used this model to predict the degree of field processing of each species based on distance from a base camp (Barlow and Metcalfe, 1996: 358–368). Bettinger et al. (1997) used a similar calculation to model field processing of acorns, arguing that because stages of acorn processing subsequent to drying are disproportionately time consuming, field processing would only be done under extreme circumstances (i.e., one-way travel time greater than 24.95 h), but that field drying was often a preferred strategy. Similarly, Cannon (2003) argued that for large mammal hunting, processing time should increase when more distant resources are being processed. This also occurs when the availability of high-ranked species is depressed and average search time increases.

Shellfish processing differs from that of plants and large mammals in that removing the meat from the shell (shucking) is the only step in the process other than cooking. When collecting shellfish at long distances from a central base, foragers are confronted with the decision to either shuck shellfish in the field or to transport unprocessed shellfish back to their home bases. The benefits to field processing are clear; by removing the shell and, for some species, the guts from the meat, the forager can collect more meat during a single trip because the parts that cannot be consumed do not contribute to the maximum weight that can be carried or the space available in baskets or bags used for transport. In their ethnographic and archaeological study of shellfish collecting among the Merriam Islanders of the eastern Torres Strait in Australia, Bird and Bliege Bird (1997) observed field collection and processing strategies in conjunction with the archaeological record of dietary shellfish species. They found that because of differential field processing and transport, some species were more likely to be over-represented and others under-represented in shellfish assemblages relative to their dietary importance. Using a central place foraging model to predict field processing behaviors, Bird and Bliege Bird (1997) observed consistent relationships between the predictions of their model and observed patterns of transport for five species. They found that resources with high-energy yield (per processing time), such as Hippopus and Tridacna spp., were likely to be under-represented in residential deposits and low-ranked shellfish (e.g., rocky shore resources) were likely to be over-represented relative to their dietary importance (Bird and Bliege Bird, 1997).

Bettinger et al. (1997) used experimental data for returns on collecting and processing of California mussels obtained by Jones and Richman (1995) to calculate travel thresholds for field processing. Experimental data are available for mussels collected from two environments, pristine and depleted beds, and using two collection strategies, plucking and stripping. Bettinger et al. (1997) calculated these travel thresholds for two load sizes, 15 kg and 36 kg. These were based on the two primary burden basket sizes in the C. Hart Merriam Ethnographic collection at the University of California, Davis. They found that: (1) predicted return rates are higher in depleted beds than pristine ones; (2) plucking is more efficient than stripping; and (3) the one-way travel limit for 15 kg loads is less than the 2 h radius within which most hunter–gatherers confine their daily foraging. Because of this, Bettinger et al. (1997) predicted that field processing of mussels should occur in some cases, namely when the distance to the resources exceeds this travel threshold. For our study, we combine the results from Bettinger et al. (1997) with an experimental study of abalone processing utility to assess differential processing of the two most common shellfish species in Middle Holocene archaeological sites on Santa Rosa Island.

Our central place forager model incorporates three different site types: coastal red abalone middens, coastal settlement sites, and interior residential bases (Fig. 1). We predict that when people seasonally occupied interior residential bases several kilometers from the coast, they occasionally traveled to coastal red abalone sites to collect shellfish. When they did, they preferentially processed red abalones, discarded the shells, and transported the meat to the interior, whereas mussels were more likely to be transported whole and unprocessed (A). When local shellfish resources were depleted at permanent coastal settlement sites, there may have been a similar pattern of field processing abalones that were transported from red abalone sites to permanent sites (B). Additionally, seasonal movement between coastal settlement sites and interior residential bases involved the transportation of shellfish from the coast to the interior and plant foods and other terrestrial resources from the interior to the coast (C). In this model, the three different site types should have distinctive faunal assemblages which reflect their roles in the overall settlement system, including the decisions that people made regarding where to access subsistence resources and whether those resources should be processed prior to transportation.

3. The Middle Holocene on Santa Rosa Island

On California’s Northern Channel Islands (NCI), a distinct Middle Holocene settlement pattern developed that included...
permanent coastal settlements, interior residential bases, and distinctive red abalone (*H. rufescens*) middens (Braje et al., 2009; Kennett, 2005; Glassow, 2013). Evidence of human occupation on the NCI dates back to ∼13,000 cal BP (Erlandson et al., 2007, 2008, 2011; Johnson et al., 2002; Kennett, 2005; Kennett et al., 2008), but it is during the Middle Holocene that we see an elaboration of diverse settlement and special purpose sites (Kennett, 2005). By investigating the full range of Middle Holocene settlement patterns on the NCI, we can better understand the formation of permanent settlements and how people exploited subsistence resources across regional landscapes.

The NCI include four islands, Anacapa, Santa Cruz, Santa Rosa, and San Miguel, located off the coast of Santa Barbara. These islands were occupied by the Chumash and their ancestors from the terminal Pleistocene through the Spanish colonial period in the early 1800s (Fig. 2). The subsistence economy of the Island Chumash was heavily reliant on shellfish and other marine resources throughout the occupation of the islands, although recent efforts have recognized the important role of plant resources in island diets (e.g., Timbrook, 2007; Erlandson et al., 2011; Perry and Hoppa, 2012; Gill, 2013, 2014; Gill and Erlandson, 2014; Jazwa and Perry, 2013). The Middle Holocene in particular is associated with large interior shell middens, likely related to the seasonal collection of plant resources given the absence of large terrestrial mammals on these islands (Perry, 2003; Kennett and Clifford, 2004; Kennett, 2005; Perry and Delaney-Rivera, 2011). By historic contact, the Island Chumash had established a complex sociopolitical structure unlike most

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**Fig. 1.** The central place forager model. According to this model, (A) people will collect shellfish at red abalone sites, where they will preferentially process abalones rather than mussels, and transport the product to interior residential bases. (B) Occupants of coastal settlement sites may travel to red abalone sites to collect abalones after local resources have been depleted. (C) Some occupants of coastal settlement sites may travel to interior residential bases seasonally.

**Fig. 2.** California’s Channel Islands with the sites of interest indicated.
other hunter–gatherer populations. The roots of many economic and social hallmarks of this system extend back to at least the Middle Holocene (e.g., Erlandson, 1997; Erlandson and Rick, 2002; Glassow, 1997; Kennett, 1998, 2005; Arnold, 2001; Rick et al., 2005; Jazwa and Perry, 2013).

The prevalence of red abalone shells in many midden sites throughout the NCI is a distinct dietary trend that occurred during parts of the Middle Holocene (Braje et al., 2009; Kennett, 2005). Red abalones are a large marine gastropod that, along with mussels and black abalones, are the highest-ranked shellfish species on the NCI (Braje et al., 2007). In a study of shellfish sizes from archaeological assemblages, Erlandson et al. (2008) calculated a Middle Holocene average of 166.3 mm for red abalones and 41.7 mm for California mussels on San Miguel Island. Historically, red abalones prefer to live in subtidal environments in southern California, but will live in intertidal regions in cooler areas during periods of cooler water (Raab, 1992). Glassow (1993, 2013; Glassow et al., 1988, 1994, 2008, 2012; also Hubbs, 1967; Raab, 1992; Salls, 1992) argued that red abalone middens on Santa Cruz Island dating between 6300 and 5300 cal BP were related to cooler sea surface temperatures during this interval (Kennett, 2005: 66; Kennett et al., 2007: 354). He also suggested that the comparatively low human population densities during this period would have limited the depletion of stocks of abalone and other large gastropods from over-predation by island inhabitants, while the later expansion of human populations may have had deleterious effects on these high-ranked resources (Glassow, 2013). Recent radiocarbon evidence suggests that the substantial collection of red abalones persisted on western Santa Cruz Island until 4170–3810 cal BP (SCRI-333; Jazwa et al., 2013a). Braje et al. (2009; see also Erlandson et al., 2004, 2005, 2008) have argued that the primary reason that red abalone middens were formed during this period across the islands was that the abalones were released from predation pressure from otters, whose numbers were reduced by human hunting.

Red abalone middens occur on the islands and adjacent mainland, with most dating to between about 8000 and 3500 cal BP (Braje et al., 2009; Braje, 2010). On Santa Rosa and San Miguel Islands, which are farther west and therefore in cooler water than Santa Cruz Island, the presence of red abalone middens extends over a longer time period, including terminal Pleistocene examples dated to ~11,500 cal BP (Erlandson et al., 2011). Similar trends are evident in the faunal assemblages of these sites through time, with large red abalone replaced by smaller black abalone in the archaeological record during most of the Early Holocene and again at the end of the Middle Holocene (Wilcoxon, 1993; Kennett, 1998, 2005; Walker et al., 2000; Braje et al., 2007). Several researchers have suggested that red abalone middens were specialized foraging locations (Glassow, 1993; Glassow et al., 1994; Kennett et al., 2007) because this large species of abalone dominates these assemblages. Kennett (2005; Kennett et al., 2007) argued that they were logistical shellfish collecting and processing camps to obtain meat for transportation back to central bases. Large red abalone shells also occur in the middens of some large residential bases (Kennett, 2005) and the artifact assemblages from some red abalone middens suggest that they were not always specialized, short-term, or limited activity sites (Braje, 2010: 63).

4. Methods

4.1. Experimental methods

Our analysis incorporates data from experimental studies of the collection and extraction of meat from two shellfish species, California mussel (M. californianus) and red abalone (H. rufescens). Data for total weight, meat weight, collection time, and extraction time of California mussel were obtained by Jones and Richman (1995) and analyzed by Bettinger et al. (1997). We performed an experimental study to obtain analogous data for red abalone. Unfortunately, because the collapse of abalone populations along the California coast has limited the number of wild red abalone that can be collected, it was not possible to experimentally obtain data about collection time similar to those presented by Jones and Richman (1995) for the rate of collection by plucking and stripping mussels.

Twenty live abalones were obtained for this study from The Abalone Farm, Inc. in Cayucos, California. They were shipped overnight to Eugene, Oregon, where they were soaked to reverse shrinking from drying during shipment. Commercial abalone farms tend to harvest and sell shellfish at a relatively small size, generally about 10 cm long, so our meat yields may be smaller than would be expected for larger wild populations. Processing time, however, should remain consistent. Abalones comparable to those found in Middle Holocene middens were shucked in two batches of ten using a pry bar, with processing times for each batch measured. Data for the total weight of each individual, the shell weight, the meat weight, and the guts weight were recorded.

For our analysis, we calculated the average total weight and average meat weight for the twenty experimental red abalones. We also calculated the average processing time per abalone. Bettinger et al. (1997) did not calculate travel thresholds based on collection times of individual mussels because they were plucked or stripped in batches. Abalone, however, are typically collected individually. Since in both cases the weight and time of extraction are consistent with each other (i.e., both are either for an individual abalone or for a batch of mussels), the calculated time in minutes per kilogram and the utility $u_j$ are consistent between the two experiments.

As Bettinger et al. (1997) did for mussels, we used Eq. (1) to calculate $z_j$, the round-trip travel threshold for red abalones:

$$z_j = p_j \left( \frac{u_{j-1}}{u_j - u_{j-1}} \right)$$

where $p_j$ is processing time per kilogram, $u_{j-1}$ is the initial utility before processing, and $u_j$ is the utility after processing. Bettinger et al. (1997: 888–891) provide a derivation for this equation and justification for its use. For values greater than $z_j$, people would choose to extract abalones in the field and bring back shucked meat, and for values less than $z_j$, people would bring back whole shells. For consistency, and because there is no evidence to suggest that basket sizes on the NCI were much different, we used the same two load sizes Bettinger et al. (1997) described in their study. To calculate one-way travel thresholds in hours from $z_j$, we multiplied $z_j$ by the load size $L$, divided by 60 to convert minutes to hours, and halved this to convert from the round-trip to one-way travel threshold, as in Eq. (2):

$$T_h = \frac{(z_j/L)}{120}$$

where $T_h$ is the one-way travel threshold in hours and $L$ is the load size in kg. We use a walking speed of 2.86 km/h derived from observations of adult foragers on the Meriam Islands of northern Australia by Bird and Biege Bird (2002). This is a slower speed than the 5 km/h assumed by Bettinger et al. (1997) and can be used to calculate the one-way travel thresholds in kilometers for each load size from $T_h$.

4.2. Santa Rosa Island midden data

We used chronological and dietary data to test the predictions of the central place forager model determined from the
et al., 2013. We incorporated faunal data from excavations at an interior residential base (CA-SRI-50), two coastal red abalone midden sites (CA-SRI-109 and -338), and four permanent coastal sites (CA-SRI-5, -19, -116, and -821). To determine whether the inland and coastal sites analyzed for this project were part of the same overall subsistence pattern, it was necessary to first assess whether they were contemporaneous. We incorporated nine previously published radiocarbon dates from CA-SRI-5, -50, -109, and -116, which were submitted to Beta Analytic, Inc. for standard radiometric dating, and eight new dates from CA-SRI-19, -338, and -821, which were cleaned and reduced to carbon dioxide at Pennsylvania State University and submitted to the Keck Carbon Cycle AMS Facility at the University of California, Irvine (UCI), to be graphitized and AMS dated (Table 1). We calibrated all dates in OxCal 4.1 (Bronk Ramsey, 2009) using the most recent marine calibration curve, Marine13 (Reimer et al., 2013). We used an updated ΔR value for the Santa Barbara Channel region (261 ± 21 ^14C yr; Brendan Culleton, personal communication, 2012; see also Jazwa et al., 2012).

In 1996, Kennett and Don Morris excavated one 25 × 25 cm column sample at CA-SRI-5, three 25 × 25 cm column samples at CA-SRI-50, one 25 × 25 cm column sample at CA-SRI-109, and one 25 × 25 cm column sample at CA-SRI-116 from eroding natural exposures in arbitrary 10 cm levels from the surface to the base of the cultural deposits. All excavated materials were transported to the University of California, Santa Barbara (UCSB), to be water screened, dried, and then size sorted (1/2-, 1/4-, and 1/8-in. mesh) to assist with the identification process. Material from each successive screen size was sorted separately. More detailed sorting and checking was later conducted at California State University, Long Beach (CSULB), and the University of Oregon (UO). During the summer of 2013, Jazwa excavated three 25 × 25 cm column samples at CA-SRI-19, one of which dates to the Middle Holocene and is included in this study, one 25 × 25 cm column sample at CA-SRI-338, and one 25 × 25 cm column sample at CA-SRI-821, also in arbitrary 10 cm levels. Excavated materials were screened, size sorted, and sorted by species in similar fashion at Pennsylvania State University (PSU).

Shellfish, other faunal constituents, and cultural materials were separated and quantified by trained undergraduate and graduate students. All midden data for the three units from CA-SRI-50 were first compiled by Clifford (2001: 146–152). We checked and recomposed these data and compiled the data for CA-SRI-5, -19, -109, -116, -338, and -821. All material was sorted as in Jazwa et al. (2012; see also Jazwa et al., 2013b). We calculated the percentage of the total shell weight for each species and combined the data for each of the three units from CA-SRI-50. The 2σ ranges from the two dates from Unit 2 have a large overlap (4800–4420 cal BP for 23 cmbs and 4830–4450 for 10–20 cmbs), and they also overlap with the 2σ range from Unit 1 (4555–4140 for 30–40 cmbs), suggesting that combining the data from these units is appropriate for investigating differences in dietary patterns between the sites. The other sites only have material from one excavation unit each, which we combined because initial and terminal radiocarbon dates all fall within the Middle Holocene.

### 4.3. Seasonality from M. californianus

The measurement of oxygen isotopes (δ^{18}O) in shell carbonate is a well-established technique for determining sea surface temperature (SST; see Glassow et al., 1994, 2012; Jazwa et al., 2012; Jew et al., 2013a, 2013b; Jones and Kennett, 1999; Kennett, 2005; Kennett and Voorhies, 1996; Killingley and Berger, 1979; Shackleton, 1973; Thakar, 2014). Oxygen isotope ratios in shell contain information about the physical and chemical environment at the time of their growth. The two primary factors that contribute to this are the isotopic composition of seawater (including salinity) and water temperature (Wefer and Berger, 1991). The stable oxygen isotopic composition of the calcium carbonate of marine mussels reflects past SST because salinity remains constant throughout the year (Urey, 1947). Shackleton (1973) showed that by sampling a shell along its growth axis, it is possible to track the sinusoidal pattern of δ^{18}O values over the lifetime of the individual. This can be translated into a measure of annual SST range (Epstein et al., 1951, 1953; Hoibe and Oba, 1972).

Once the annual range of SST is available for a given location at a particular time, it is possible to estimate the season of death for a collection of shells and statistically obtain information about seasonality of shellfish collection (Killingley, 1980, 1981; Killingley and Berger, 1979; Glassow et al., 1994; Kennett and Voorhies, 1996; Culleton et al., 2009). Traditionally, season of death has been determined by placing the value for the most recent growth band of an individual shell on the annual temperature range. Culleton et al. (2009) argued that it is necessary to also collect a second sample from 2 mm from the edge of the shell to determine

<table>
<thead>
<tr>
<th>Site #</th>
<th>Lab #</th>
<th>Provenience</th>
<th>Material</th>
<th>Conventional</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>CA-SRI-5</td>
<td>Beta-96866</td>
<td>Unit 1, 50–70 cmbs</td>
<td>Haliotis rufescens</td>
<td>4670 ± 70</td>
<td>4800–4400</td>
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<td>CA-SRI-19</td>
<td>UCAMS-130883</td>
<td>Unit 2, 3 cmbs</td>
<td>Mytilus californianus</td>
<td>4620 ± 15</td>
<td>4580–4405</td>
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<td>CA-SRI-19</td>
<td>UCAMS-130884</td>
<td>Unit 2, 77 cmbs</td>
<td>Mytilus californianus</td>
<td>5220 ± 20</td>
<td>5425–5240</td>
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<td>CA-SRI-50</td>
<td>Beta-96961</td>
<td>Unit 1, 30–40 cmbs</td>
<td>Haliotis rufescens</td>
<td>4510 ± 70</td>
<td>4560–4140</td>
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<tr>
<td>CA-SRI-109</td>
<td>Beta-49664</td>
<td>Eroding Wall</td>
<td>Haliotis rufescens</td>
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<td>4810–4420</td>
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<td>Beta-92059</td>
<td>Unit 1, 10 cmbs</td>
<td>Haliotis rufescens</td>
<td>5570 ± 70</td>
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<td>CA-SRI-338</td>
<td>UCAMS-130896</td>
<td>Unit 1, 4 cmbs</td>
<td>Haliotis rufescens</td>
<td>5670 ± 20</td>
<td>5880–5905</td>
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<td>CA-SRI-338</td>
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<td>Unit 1, 20–24 cmbs</td>
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<td>5755 ± 20</td>
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whether the shell was collected during a period when SST was increasing or decreasing, and the rate of change, to better associate it with a time of year. Recently, several researchers argued that even more samples should be taken to characterize season of collection more accurately (e.g., Glassow et al., 2012; Jew et al., 2013a, 2013b; Eerkens et al., 2014; Thakar, 2014). We selected two samples from each shell to maximize the number of levels and sites that could be tested with our limited funding and to maintain consistency with previous studies for the sites analyzed (e.g., Kennett, 1998, 2005; Jazwa et al., 2012).

California mussel has been used to determine the seasonality of site occupation because it meets the criteria established by Shackleton (1973: 134–135), and it is the most abundant species represented in island shell middens. Furthermore, California mussels grow in a marine environment rather than estuaries or coastal lagoons (e.g., Kennett and Voorhies, 1996; Culleton et al., 2009). We therefore treat SST as the driving force in unstable isotope mass spectrometry with instrument precision for carbon isotope measurements of ±0.26‰. Two samples were collected for each shell from both sides along the growth band (Fig. 3). Approximately 12.16 kg of sample powder was collected for analysis. All shells were first manually cleaned to remove any visible contaminants. Whole shells were subjected to a 20% hydrochloric acid etch at room temperature to remove any remaining macroscopic contaminants. Whole shells were subjected to a 20% hydrochloric acid etch in a bath of 70 °C to expedite the reaction. After drying overnight in an oven set at 60 °C, samples were collected using a .8 mm diameter drill bit mounted on a Lucas Model 9804 dental drill or a battery powered Dremel tool to obtain powder from the shell at the terminal growth margin and at 2 mm from the edge along the growth band (Culleton et al., 2009). Approximately .2 mg of sample powder was collected for each shell from both locations during drilling. Samples were weighed out to ±0.15 mg for analysis.

Samples were analyzed in two laboratories. Samples analyzed in the 1990s were run at UCSB using a Finnegan/MAT-251 light stable isotopic mass spectrometer with instrument precision for δ18O of ±1.1‰ (PDB; see Kennett, 1998: 497–504, 509–524). Samples analyzed in 2014 were run at the Union College Department of Geology Stable Isotope Lab via a Thermo Gas Bench II connected to a Thermo Delta Advantage mass spectrometer in continuous flow mode, with an uncertainty for δ18O of ±0.06‰ (VPDB).

5. Results

5.1. Middle Holocene site chronology

Radiocarbon dates from the six sites strongly suggest a substantial overlap in the occupation of these sites, supporting the argument that they were part of the same Middle Holocene settlement system (Table 1; Fig. 3). The overall date range is from 6380–6020 cal BP (2σ range; CA-SRI-116, 60–65 cmbs) to 3390–3220 cal BP (2σ range; CA-SRI-821, Unit 1, 30–35 cmbs). Except for the latest date, which is associated with a less dense midden lens, the rest of the occupation of these sites ended by 4560–4140 cal BP (2σ range; CA-SRI-50, Unit 1, 30–40 cmbs). This places the occupation of these sites within the Middle Holocene and within the general range of dates for the formation of red abalone middens on the NCI (Braje, 2010; Braje et al., 2007, 2009; Glassow, 1993, 2013; Glassow et al., 1988, 1994, 2008, 2012; Jazwa et al., 2013a; Kennett, 1998: 462, 2005). The red abalone midden sites span nearly the entire range, particularly at CA-SRI-109, which produced dates ranging from 5870 to 4420. CA-SRI-338 was occupied for a much shorter time, with dates ranging from 5905 to 5695 cal BP. Permanent coastal settlement sites also span the entire range of occupation. CA-SRI-116 was occupied during the earlier part of the range, with dates from 6380 to 4870 cal BP, and CA-SRI-5 (4790–4400; 2σ range; 50–70 cmbs) was occupied latest. CA-SRI-19 overlaps with both of these sites, with dates ranging from 5425 to 4405 cal BP. The bulk of occupation at CA-SRI-821 occurred between 5945–5760 cal BP and 5560–5330 cal BP, but less dense midden deposits persist until 3390–3220 cal BP. The interior residential base, CA-SRI-50, spans the later part of the overall range, from 4830 to 4140 cal BP, but these dates overlap with both red abalone sites and permanent coastal settlements.

5.2. Experimental results

We compared the data obtained for the experimental extraction of red abalones to those obtained by Jones and Richman (1995) to calculate the relative utility of the two species. We use their data for mussel plucking rather than stripping, since this minimizes processing times and the transportation of very small mussels. Using the calculations for one-way travel thresholds for distance by Bettinger et al. (1997), and walking speed of 2.86 km/h from Bird and Bleige Bird (2002), one-way travel thresholds from a pristine mussel bed are .91 h and 2.60 km for a 15 kg load and 2.19 h and 6.26 km for a 36 kg load. One-way travel thresholds from a depleted environment are 1.77 h and 5.06 km for a 15 kg load and 4.25 h and 12.16 kg for a 36 kg load (Table 2). Bettinger et al. (1997) argued that return rates are higher in depleted beds than pristine ones because, by thinning mussel colonies, human predation increased growth rates while decreasing the efficiency of byssal attachment, allowing for easier collection. Furthermore, they argued that for the 15 kg load size, thresholds are below the 2-h one-way travel time radius within which many hunter–gatherers confine their daily foraging. This suggests that mussel processing may occur within this radius (Bettinger et al., 1997: 896).

Unlike mussels, abalones cannot be harvested in different ways like plucking and stripping. The efficiency of abalone search and collection is related to the density of individuals. A model that incorporates collection time, analogous to plucking or stripping, should include variants for low, medium, and high density of abalone. Similarly, factors such as depth below the water could also be taken into account. Red abalone is typically found at lower depths than mussels, and may have required diving to be collected (Kennett, 2005). Specimens from the Middle Holocene were typically large, suggesting that variations based on the shell size of available individuals is a less important factor for field processing.
Unfortunately, the collapse of California abalone populations and regulations by the state of California limiting abalone fishing prevent any sort of systematic experiment to collect abalone under these conditions. Additionally, serial overfishing and withering foot syndrome have decreased modern communities of red abalones, which would influence modern measurements (Braje et al., 2009). For this study, we compare the utility of abalone with and without field processing, assuming that it would take the same amount of time to collect the individuals in either case. Although this is an oversimplification, it provides a first pass at estimating the travel threshold for field processing abalone.

We processed abalone in two batches of ten individuals each. The first batch took 8.11 min, total weight of the abalones was 2.61 kg, and the total meat weight was 1.31 kg. The second batch took 6.36 min to process, total weight of the abalones was 3.03 kg, and the total meat weight was 1.46 kg. The overall averages for individual abalones were 0.72 min to process, overall weight of 0.282 kg, and meat weight of 0.139 kg (Table 3). It is likely that the reason that the first batch took longer to process than the
second was because of lack of shucking experience. As more experience was gained in shucking the abalones, the processing speed increased. It is likely that experienced abalone fishers on the Channel Islands processed them more efficiently, decreasing the distance at which people would start field processing abalones.

Two clear patterns emerged from our experimental work: (1) that unshucked abalone has much higher calculated utility than unshucked mussels (i.e., greater ratio of meat to non-meat weight); and (2) that the travel thresholds for field processing abalone are lower than for mussels in all cases. We assign a value for $u_j$ of 1 for both mussels and red abalone since all of the meat can be consumed. Then, $u_j \rightarrow$ for abalone is .49, whereas $u_j \rightarrow$ for plucked mussels is .08 in pristine beds and .3 in depleted beds. When mussels are stripped, $u_j \rightarrow$ is even lower: .06 in pristine beds and .07 in depleted beds (Table 2). It is still more beneficial, however, to shuck red abalone prior to transportation than it is for mussels because it takes much less time to extract abalone meat. Abalone was extracted in our experiment at 5.22 min per kilogram, while the fastest rate at which mussel was extracted was 32.48 min per kilogram (plucking, depleted). Values for mussel ranged up to 264.54 min per kg (pristine, stripped; Bettinger et al., 1997).

Because of this discrepancy, it is economically more advantageous to shuck red abalone than mussel and travel thresholds should be shorter for the former than for the latter. Using the same Eq. (1) that Bettinger et al. (1997) used for mussels and the walking rate of 2.86 km/h, we calculate a one-way travel threshold for red abalone of .63 km and 1.81 km for a 15 kg load and 1.52 h and 4.33 km for a 36 kg load (Table 2). Each of these is lower than for the analogous values for mussels under all collection conditions. It is likely that these values for abalones are still higher than the actual travel thresholds for Middle Holocene foragers, both because of rugged terrain that slowed walking speeds and because of ineffectiveness in abalone shucking during our experiments (see Bird and Bliege Bird, 1997; Bird et al., 2002). Abalones are collected individually rather than in groups like mussels, so Chumash abalone fishers could have preferentially selected for large individuals. The archaeological record, however, suggests that it is more likely that the Chumash harvested red abalone of a variety of sizes (Braje, 2010; Braje et al., 2007). This might alter the rate at which abalone meat could be obtained, but it would nonetheless outpace mussels. Given the lower travel thresholds for red abalones than mussels, we expect inland sites to contain more mussel shell than red abalone shell, and coastal shucking sites should contain more red abalone shell than mussel shell.

5.3. Faunal data

For all of the assemblages included in this study, shellfish are by far the dominant subsistence component, comprising at least 96% of the total faunal weight. In more than half the levels, shellfish comprised over 99% of the total faunal weight (Table 4, SOM Table 1), reflecting the relative importance of shellfish and their low ratio of edible flesh to shell weight. The four most abundant species throughout the units from these sites are M. californianus, H. rufescens, Chlororostoma funebralis (black turban snail), and Balanus spp. (barnacles). Other species are present but they generally made up very small proportions of the overall shellfish assemblage. The only other species that comprised more than 1% of the overall assemblage were Ischnochiton conspicus (small chiton) and Septifer bifurcatus (platform mussels). When red and black abalone shell fragments could not be distinguished (i.e., we designated undiagnostic nacre as Haliotis spp.), we used the proportion of weights of abalone identified to the species level to estimate the relative proportion of each species from this weight.

There is a clear distinction in the relative contribution of mussel and abalone between the permanent coastal sites, red abalone middens, and interior residential bases (Fig. 4). For all three units of CA-SRI-50, mussel is the dominant species, comprising more than 80% of the total shell weight (and overall faunal assemblage). Conversely, abalone comprise less than 1% of the total shell weight for each of the units from CA-SRI-50. The remaining shell weight is primarily composed of black turban snail and barnacles. For the red abalone midden, CA-SRI-109, in contrast, California mussels comprised 30.3% of the shellfish assemblage, red abalones 31.9%, and black turban snails 34.6%. The difference is even more pronounced at CA-SRI-338, where red abalones comprise 70.1% of the shellfish assemblage, mussels only 6.5%, and black turban snails 6.7%.

Not only were people depositing more red abalone shell at CA-SRI-109 and -338 compared with CA-SRI-50, they were also depositing less mussel. This makes sense within the central place forager model; people are more likely to shuck red abalone on the coast before transporting the meat inland and they are more likely to transport whole mussels inland. Black turban snails should also be transported whole because of their difficulty of extraction. There is no permanent settlement in the vicinity of CA-SRI-338 during the Middle Holocene (Kennett et al., 2009; Winterhalder et al., 2010). The remoteness of CA-SRI-338 from the hub of settlement on the northern coast of the island is perhaps the reason that the faunal record is even more skewed toward abalone than at CA-SRI-109.

Coastal village sites have more diverse faunal assemblages, with a higher proportion of California mussels and lower proportion of red abalone than the red abalone middens and a lower proportion of California mussels and higher proportion of red abalone than the interior residential base. To assess the taxonomic diversity of faunal assemblages, we used the Shannon–Weaver function (Shannon and Weaver, 1949), as discussed by Reitz and Wing (1999: 235):

$$H' = - \sum p_i \ln(p_i)$$  \hspace{1cm} (4)

where $p_i$ is the proportion of each taxon per stratum, level, or time period in terms of the contribution of shell weight corrected for volume. Using this measurement, it is clear that the most diverse assemblages are at the coastal settlement sites, and the lowest are at the interior residential base (Fig. 5; Table 4). The only exception to this pattern is CA-SRI-116, which has a slightly lower diversity than either of the red abalone middens. This reflects the high proportion of mussels at the site (~73%), which is likely related to

### Table 3

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Shell wt. (g)</th>
<th>Meat wt. (g)</th>
<th>Guts wt. (g)</th>
<th>Total wt. (g)</th>
<th>Shucking time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>82.41</td>
<td>150.69</td>
<td>28.92</td>
<td>262.02</td>
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</tr>
<tr>
<td>2</td>
<td>100.10</td>
<td>136.43</td>
<td>30.80</td>
<td>278.75</td>
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<tr>
<td>3</td>
<td>84.28</td>
<td>95.98</td>
<td>23.40</td>
<td>205.64</td>
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</tr>
<tr>
<td>4</td>
<td>89.54</td>
<td>151.21</td>
<td>34.66</td>
<td>276.55</td>
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</tr>
<tr>
<td>5</td>
<td>88.90</td>
<td>137.55</td>
<td>28.29</td>
<td>261.56</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>96.04</td>
<td>137.60</td>
<td>19.93</td>
<td>259.03</td>
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<tr>
<td>7</td>
<td>108.74</td>
<td>117.41</td>
<td>29.80</td>
<td>264.96</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>114.28</td>
<td>159.49</td>
<td>32.74</td>
<td>325.33</td>
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</tr>
<tr>
<td>9</td>
<td>100.27</td>
<td>103.65</td>
<td>23.82</td>
<td>238.77</td>
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</tr>
<tr>
<td>10</td>
<td>86.77</td>
<td>117.24</td>
<td>23.90</td>
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<td>11</td>
<td>88.86</td>
<td>172.62</td>
<td>29.04</td>
<td>296.82</td>
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<tr>
<td>12</td>
<td>97.88</td>
<td>149.54</td>
<td>28.53</td>
<td>284.25</td>
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</tr>
<tr>
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<td>117.84</td>
<td>152.54</td>
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<tr>
<td>14</td>
<td>108.86</td>
<td>149.33</td>
<td>33.75</td>
<td>298.35</td>
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<tr>
<td>15</td>
<td>109.63</td>
<td>151.00</td>
<td>25.49</td>
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</tr>
<tr>
<td>16</td>
<td>105.29</td>
<td>153.50</td>
<td>25.26</td>
<td>291.03</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>110.55</td>
<td>125.00</td>
<td>34.24</td>
<td>278.07</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>143.81</td>
<td>131.94</td>
<td>40.66</td>
<td>338.69</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>103.04</td>
<td>134.22</td>
<td>35.16</td>
<td>313.94</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>107.73</td>
<td>144.86</td>
<td>35.63</td>
<td>319.12</td>
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</tr>
</tbody>
</table>

Mean per shell | 102.34 | 138.59 | 29.78 | 281.81 | 0.72
the local availability of shellfish species. In all, one would expect to find the highest shellfish diversity at permanent sites that are occupied year-round, as people exploited a broader range of resources. The central place forager model predicts that the interior sites should have the lowest diversity because people would process some resources in the field and only bring a subset of low utility parts (shells, bones, etc.), despite the fact that they consumed a diverse diet.

5.4. Site seasonality

To further explore these issues, we used δ¹⁸O data to generate seasonality profiles of California mussel collection from each of the sites in this study (SOM Table 2). We created one profile for each site except for CA-SRI-116, where we tested two different levels. To do so, we created a model of daily variation in modern SST for Santa Rosa Island. We plotted the δ¹⁸O data against a model of daily average SST obtained from modern instrumental data collected from a buoy near Santa Rosa Island by J. Engle approximately twice per week from April 1981 through December 1992. SST data were measured to the nearest .5 °C. Over the twelve-year span during which data were collected, at least one value was available for each day except December 25 and January 1. Values for each day were averaged; a value for December 25 was obtained by averaging December 18–24 and 26–31, and a value for January 1 was obtained by averaging December 26–31 and January 2–8. We then smoothed the curve using a 15-day running average (Fig. 6).

To adjust the generalized curve for each of the levels we tested, we collected data from a profile from one of the shells from each collection. Kennett (1998) collected δ¹⁸O data for full profiles of one shell from CA-SRI-5, -50, -109, and 50–60 cmbs from CA-SRI-116 at 2 mm increments of the shell. We collected similar data from CA-SRI-19, -338, and 20–30 cmbs from CA-SRI-116 (SOM Table 3). For adult, non-senescent California mussel shells, 2 mm of shell deposition represents approximately one month of growth (Jones and Richman, 1995: 40). We used Eq. (1) to estimate SST for each of these δ¹⁸O data points. We then stretched the

<table>
<thead>
<tr>
<th>Site type</th>
<th>CA-SRI-50</th>
<th>CA-SRI-109</th>
<th>CA-SRI-338</th>
<th>CA-SRI-5</th>
<th>CA-SRI-19</th>
<th>CA-SRI-116</th>
<th>CA-SRI-821</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell diversity</td>
<td>0.73</td>
<td>1.25</td>
<td>1.20</td>
<td>1.57</td>
<td>1.81</td>
<td>1.13</td>
<td>1.90</td>
</tr>
<tr>
<td>Taxon wt.%</td>
<td>7.21</td>
<td>0.62</td>
<td>0.54</td>
<td>1.33</td>
<td>1.94</td>
<td>3.44</td>
<td>3.00</td>
</tr>
<tr>
<td>Balanus spp.</td>
<td>3.87</td>
<td>34.62</td>
<td>6.65</td>
<td>1.66</td>
<td>25.75</td>
<td>9.11</td>
<td>14.49</td>
</tr>
<tr>
<td>Chlorostoma funebralis</td>
<td>0.44</td>
<td>31.88</td>
<td>70.05</td>
<td>5.72</td>
<td>7.67</td>
<td>2.66</td>
<td>8.80</td>
</tr>
<tr>
<td>Haliotis rufescens</td>
<td>1.20</td>
<td>0.00</td>
<td>1.11</td>
<td>4.53</td>
<td>6.07</td>
<td>1.23</td>
<td>10.20</td>
</tr>
<tr>
<td>Mytilus californianus</td>
<td>83.40</td>
<td>30.25</td>
<td>6.45</td>
<td>45.21</td>
<td>38.93</td>
<td>73.13</td>
<td>38.54</td>
</tr>
<tr>
<td>Septifer bifurcatus</td>
<td>1.13</td>
<td>0.26</td>
<td>0.25</td>
<td>0.22</td>
<td>6.24</td>
<td>4.53</td>
<td>5.04</td>
</tr>
</tbody>
</table>
The overall range of SST from the shell profiles in this study was from 9.65 to 19.65 °C (Table 5). Both of these measurements were from the same shell from CA-SRI-338. Therefore, we assigned this site the highest SST range. The smallest SST ranges were from CA-SRI-5 (12.58–16.17 °C) and CA-SRI-116, 50–60 cmbs (11.93–15.55 °C). CA-SRI-19, -50, -109, and 20–30 cmbs from CA-SRI-116 all had intermediate SST ranges. After using each of these values to stretch the modern SST curve, we used the calculated SST values from the terminal growth band samples along with the direction and rate of change from the second sample 2 mm from the edge to place each shell on the curve. CA-SRI-19 is an example of year-round occupation and CA-SRI-109 is an example of seasonal occupation (Fig. 7; see SOM Figs. 1–5 for the other levels). For CA-SRI-19, although there are more samples that can be associated with the fall than with any other season, the samples are spread throughout the curve. For CA-SRI-109, on the other hand, there is a clear cluster of samples during the beginning and middle of summer, with very few associated with any other time of the year. We then generated histograms for each of the seven levels that we tested, assigning each shell to a specific season of collection (Fig. 8). Mussel collection was assigned conservatively to specific seasons rather than more precise time ranges to accommodate error in this method (see Culleton et al., 2009).

The most apparent pattern in the δ¹⁸O data is that red abalone sites and interior residential bases have a seasonal signature of mussel collection and that this species was collected year-round at large permanent coastal sites. The exception to this is CA-SRI-5, which does not have deposits as extensive as at either CA-SRI-19 or the later deposit (20–30 cmbs) from CA-SRI-116. It appears that the deposits at CA-SRI-5 were not from a long-term occupation, although the faunal density and diversity in the assemblage suggest that it was not a special purpose site like the red abalone middens. This site appears to have one of the most seasonal signatures, with most of the mussel collection occurring during the fall. Another interesting pattern is that the two red abalone sites, CA-SRI-109 and -338, both have seasonal patterns, but are opposite each other, suggesting that occupation of these sites is likely not dictated by any seasonal availability of abalones.

Occupation of CA-SRI-109 is strongly associated with the summer, as is CA-SRI-50. While the occupants of these two sites in particular may not be directly related (i.e., the occupants of CA-SRI-50 may have traveled to a different coastal site for abalone and CA-SRI-109 may be associated with a different interior base), this result suggests that the occupation of these sites was seasonally contemporaneous, supporting the mobility patterns suggested in Fig. 1. A possible explanation for this summer occupation could be that people moved to the interior to collect blue dicks (Dickelostemma sp.) and other interior plant species that are highly visible at this time of year (Timbrook, 2007; Gill, 2013, 2014). The reverse signature at CA-SRI-338 suggests a different pattern. The west coast of the island has a larger number of red abalone sites than any other part of the island and could have been a focal point for collecting abalones during most of the year. The exception may have been during the summer, when people spent more time in the interior, particularly in the flat areas to the north of the main ridge. This increased activity in the interior could have reduced the time that they had available to travel to the west coast. Instead, they more exclusively harvested shellfish from the north coast sites.

6. Discussion

The data presented in this paper support a central place foraging model during the Middle Holocene on California’s Northern Channel Islands. We argue that the occupants of interior residential bases traveled to the coast to collect shellfish and differentially field processed California mussels and red abalones. Our study uses archaeological data to provide support for patterns of field processing among shellfish that have been observed ethnographically, providing a deep time confirmation of ethnographic principles in other coastal settings (e.g., Bird and Bliege Bird, 1997). The central place foraging model provides a framework for understanding decisions the Island Chumash of northern Santa Rosa Island made about collecting, field processing, and transporting economically valuable shellfish species during the Middle Holocene. In particular, it helps interpret how faunal records from various archaeological sites may over- or under-represent certain species with respect to their actual dietary contribution.

Excavation data from an interior site (CA-SRI-50) and two coastal red abalone middens (CA-SRI-109 and -338) represent two sides of the Middle Holocene subsistence system. Experimental data suggest that the distance at which field processing becomes the energetically preferred strategy is shorter for red abalones than for mussels. Red abalone is more likely to be processed near the point of collection than mussels. Faunal data from our study sites suggest that foragers traveled from interior bases at sites like CA-SRI-50 to coastal locations like CA-SRI-109 and -338, where they collected both of these high-ranked shellfish species. Red abalones appear to have been preferentially processed in the field, resulting in an over-representation of this species at coastal sites and an under-representation at interior sites compared to their dietary significance. Mussels, with longer one-way travel thresholds, would be preferentially transported in their shells, and therefore under-represented at special purpose coastal processing sites and over-represented at interior sites. This is reflected in the midden data by an overwhelming dominance of mussels at
Fig. 7. Seasonal profile of *Mytilus californianus* shells from (a) CA-SRI-19, an example of a site with a year-round occupation signature; and (b) CA-SRI-109, an example of a site with a seasonal (summer–fall) occupation signature. The curve was stretched and shifted to the range of temperatures from the profile of a single shell drilled at 2 mm increments. The terminal growth band and 1 month (2 mm) prior are plotted to estimate season of collection.
CA-SRI-50, a more even balance between these two species at CA-SRI-109, and a dominance of red abalones at CA-SRI-338 (Fig. 4).

These special purpose sites make up an important part of an increasingly diverse settlement system during the Middle Holocene. At this time, people developed a complex pattern of seasonal and year-round movements to access resources that were not adequately abundant near their permanent sites. Large permanent coastal sites like CA-SRI-19 and -116 have thick midden deposits, diverse artifact and faunal assemblages, and evidence of year-round occupation. CA-SRI-5, a smaller coastal site, also has a diverse assemblage, although it has a highly seasonal signature. Especially during the summer and potentially to collect plant foods and other interior resources, subsets of this population moved to large interior residential bases like CA-SRI-50 (Kennett and Clifford, 2004). When they occupied the interior, they had to travel to the coast to collect shellfish, and their processing decisions are reflected in the faunal assemblage. Finally, the red abalone sites on the west coast of the island perhaps reflect special purpose collection of abalones to a greater extent than on the north coast. West coast sites like CA-SRI-338 were occupied for longer segments of the year with the primary purpose of collecting abalones. This part of the island was resource poor compared to the rest of the island, particularly with respect to fresh water availability (Kennett et al., 2009; Winterhalder et al., 2010; Jazwa, 2015). Islanders, therefore, traveled from distant locations to these sites to collect and shuck abalones before transporting the meat back to base camps. During the summer, when people were more focused on interior resources, abalone collection likely shifted more to the north coast at sites like CA-SRI-109.

To establish applicable variants of central place foraging models, experimental processing studies provide a means to assess the foraging and transport strategies for different shellfish species. Experimental studies performed by Jones and Richman (1995) for the energy return of mussels in different environmental settings and using different collection techniques provide an effective way to think about how utility and travel time thresholds are influenced by these factors. For example, the utility for mussels obtained by stripping is lower than for plucking because it yields many more small mussels with little meat that take as long to extract as larger mussels with more meat (Bettinger et al., 1997: 896). Similar patterns can be interpreted for other species with similar colonizing and growth patterns to mussels (e.g., oysters). Analogous experimental studies for these other species can yield more precise model predictions that can be used in similar contexts.

Abalones are gastropods with very different life histories than mussels. Rather than attaching to rocks and growing in colonies, red abalones are able to move around and can be found in varying densities in tide pools or on the sea floor. Our experimental study was not able to test for variations in abalone density during collection because we used farmed abalones out of necessity. However, one would expect travel time thresholds to vary with density. The less densely distributed the individuals, the longer it would take to collect a given amount of meat (or the less meat that could be collected in a unit of time). There is no reason to suggest that individual abalones would differ in terms of energetic return from processing when they occur in different densities, except for the possibility that in very low densities, collectors may be more likely to settle for smaller individuals, which could decrease the return. As abalone density and rate of collection increases, travel thresholds should decrease to maximize the return of each load.

Other factors could act to reduce the travel distance at which people on Santa Rosa Island should field process shellfish.
Interior sites are in upland regions that require people to ascend steep coastal bluffs or canyon walls. To access CA-SRI-50 from the coast, for example, walking through the canyon is a shorter distance (~2.75 km), but it requires traveling along or through stream beds and potentially thick vegetation. To walk along the ridgetop, it is necessary to walk around two side branches of the canyon and then down a steep hill to the coast (~3.15 km). The mussel beds along the north coast of the island likely have been depleted by frequent collection. The estimated thresholds of 1.81 km for abalones and 5.06 km for mussels are consistent with the faunal data from CA-SRI-50.

Factors other than energetic/nutritional return may also have influenced whether shells were shucked before being transported inland. The shells of bivalves like mussels completely enclose the organism, allowing them to survive longer out of water and preserving the meat for longer than if it was removed. Because abalones have only one shell, there is not the same benefit from leaving the organism in the shell. This would magnify the difference in transport threshold distances between mussels and abalones, and perhaps explain the presence of mussels further inland than the 5.06 km predicted by the Bettinger et al. (1997) model. On the other hand, there are reasons that abalones may have been transported inland without first being processed. Beads, ornaments, and containers were made from red abalone shells during the Middle Holocene (e.g., Bennyhoff and Hughes, 1987; King, 1990), which could be a reason to not shock some abalones before transportation.

The seasonality record for the north coast of Santa Rosa Island supports the central place forager model. CA-SRI-50 and -109 have similar signatures; both are focused in the summer, with evidence for occupation from the spring through the fall. The seasonal contemporaneity between this interior residential base and coastal red abalone midden suggest that the red abalone site could have been accessed for resources directly by people occupying the interior site. The permanent coastal settlement sites were likely occupied year-round, particularly CA-SRI-19 and the later deposits at CA-SRI-116. CA-SRI-338 has a different seasonal signature, with evidence for use during every season but the summer, when CA-SRI-50 and -109 experienced their most intensive occupation. The faunal record from CA-SRI-338 also has a much higher proportion of red abalone shell than CA-SRI-109, suggesting that it may have had even more limited activities. A possible explanation is that during the Middle Holocene, residents of the north coast of Santa Rosa Island may have traveled to the west coast to collect abundant red abalones. During the summer, this activity may have been reduced, with people focusing more of their efforts on collecting interior resources like plants, and traveling to the north coast for shellfish.

Abalones are high-ranked food resources in many coastal locations throughout the world (Bird and Bliege Bird, 1997, 2002; Bird et al., 2002; Glassow, 2013; Coddington et al., 2014). This article provides data from an experimental study on abalone processing that supplements data from Jones and Richman (1995) on mussel collecting and processing. This was an initial attempt to understand the utility of removing abalone meat from its shell in the field. Additional experiments could expand upon these results. First, the experiment should be repeated because further expertise in abalone processing could result in decreased processing times. Professional abalone processors working at abalone farms or restaurants may be able to process shellfish more quickly. Further studies could also include abalones of different sizes and the utility of different types of shucking implements could also be tested. Finally, the cultural framework of abalone processing could be explored further. We assume here that shellfish collecting was the primary subsistence pursuit when people traveled to special-purpose sites along the coast because other forms of marine subsistence were limited in the archaeological record at that time. If more than just adult males made these trips and other activities were embedded, this also may have influenced decisions regarding field processing.

7. Conclusion

In this study, we used a central place foraging model to explore the effects of field processing and transport decisions on the structure of three distinct site types during the Middle Holocene on Santa Rosa Island. We used experimental and archaeological data to argue that the abundance of two high-ranked shellfish species, California mussels and red abalones, is influenced by site location through differential field processing.

Our model predicts that it is energetically beneficial to field process red abalones when they are collected closer to residential bases than mussels, and both coastal red abalone sites and inland residential bases should have quantities of these two species inconsistent with their relative dietary importance. Because an equivalent amount of meat can be extracted from abalones much more quickly than it can from mussels, red abalone should be preferentially field processed compared to mussels. Therefore, red abalone is over-represented at Middle Holocene coastal red abalone middens and under-represented at inland sites. These results support a long-standing assumption that many red abalone middens on the NCI are relatively specialized shellfish processing localities. At permanent coastal village sites, more diverse faunal assemblages reflect the local collection, processing, and consumption of a wider diversity of shellfish and other resources, providing a more representative view of subsistence. At these coastal sites, transport of shellfish may also have involved the use of boats, which would alter processing and transport decisions. Additionally, our study suggests that as island populations grew larger and more permanent coastal villages were established, at least a segment of the population continued seasonal movements to the interior during summer to collect plant foods and to make logistical trips to the west end of the island to collect abalones during other seasons.

Our findings also have important implications for understanding the earliest record of New World Pacific Coast colonization. A vast paleocoastal landscape along the NCI and the larger Pacific Coast has been submerged by rising sea level since the initial colonization of the region. It is increasingly likely that the first Americans followed these coastlines into the New World (see Erlandson, 2002; Erlandson et al., 2011). A better understanding of the types of faunal remains these coastal foragers may have left along the paleocoastal interior can help us locate, track, and interpret the fragmentary record of terminal Pleistocene occupations. Our study, along with field processing models in general, has important implications for interpreting the archaeological record. Within a single subsistence system in which occupants are consuming a similar diet, the faunal record can suggest substantial dietary differences based largely on the travel costs required to obtain those resources. Central place forager models can provide a framework for understanding these differences and offer more informed interpretations of the archaeological record. By understanding human foraging and processing decisions, we can better interpret subsistence systems and the interaction of past humans with their environments.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.jaa.2015.05.005.

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