# RECONSTRUCTING NEARSHORE AND KELP FOREST HABITATS FROM TRANS-HOLOCENE OCCUPATIONS AT BAY POINT, SAN MIGUEL ISLAND, CALIFORNIA: THE ARCHAEOLOGY AND HISTORICAL ECOLOGY OF DAISY CAVE AND CAVE OF THE CHIMNEYS

by

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A DISSERTATION

Presented to the Department of Anthropology
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
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# DISSERTATION APPROVAL PAGE

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# DISSERTATION ABSTRACT

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**Title:** Reconstructing Nearshore and Kelp Forest Habitats from Trans-Holocene Occupations at Bay Point, San Miguel Island, California: The Archaeology and Historical Ecology of Daisy Cave and Cave of the Chimneys

This dissertation examines the archaeology and historical ecology of Bay Point, San Miguel Island, through archaeometric and zooarchaeological analyses. Stable isotopes ($\delta^{13}$C and $\delta^{18}$O) from archaeological mussel shells spanning much of the Holocene are used to reconstruct a localized nearshore sea surface temperature (SST) sequence and explore correlations between ancient SST patterns and archaeological data from two multicomponent rockshelter sites. I focus on the role of primary producers (Macrophytes) and primary consumers (i.e., sea urchins) in structuring nearshore marine ecosystems and develop two methods to examine ancient kelp forest and rocky shore habitats. In one case, seaweed and sea grass shellfish commensals provide a wealth of untapped data about nearshore ecology and serve as a proxy for identifying the harvest of seaweeds and sea grasses in archaeological contexts. Another case study focuses on sea urchins, which are algal grazers and, if left unchecked, can wipe out entire forests. I used analyses of covariance (ANCOVA) to develop a formula that infers sea urchin size based on hemipyramid morphometrics, allowing me to reconstruct size/age frequencies spanning thousands of years of sea urchin harvesting.

My dissertation contributes to a growing database of coastal historical and ecological studies that help decipher the complex nature of intertidal foraging and marine fishing over the course of human history across the globe. By providing new methods of analysis, and primary zooarchaeological and archaeometric data on some of the oldest, most intact, and best-preserved archaeological sequences on the Channel Islands, my dissertation contributes to broad anthropological and paleoenvironmental research questions for the region and beyond. It provides datasets and interpretations fundamental for addressing long-standing questions about the nature and antiquity of aquatic resource use, shifts in harvesting practices and human impacts to marine ecosystems, the perceived marginality of island environments, mobility, settlement, and land use patterns, as well as other topics of transdisciplinary interest. As the first long-term reconstructed nearshore SST sequence for the region, the results have significant implications for a variety of local research questions in archaeology, historical ecology, paleoecology, marine biology, oceanography, conservation biology, and fisheries management.

This dissertation contains previously published and/or co-authored material.

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Dedicated to my little sister, Victoria (R.I.P.),
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# CHAPTER 1
# INTRODUCTION AND PROJECT OVERVIEW

## Introduction

Despite earlier doubts about the extent and antiquity of human use of marine resources (see Osborn 1977; Yesner 1980), archaeological research in coastal areas over the past few decades has demonstrated a deep history and variability of maritime adaptations around the world. It is now evident that coastal environments attracted human populations since the inception of our species (Avery et al. 2008; Erlandson 2001, 2010; Klein et al. 2004; Klein and Steele 2013; Marean 2011; Marean et al. 2007), with aquatic resources seen by some as critical to human evolution and encephalization (see Cunnane and Stewart 2010). Evidence for human use of marine resources extends to the Middle Stone Age in South Africa, with the earliest site dated to ~194,000 years ago (Henshilwood et al. 2001). In addition, increasing evidence suggests that other members of the genus *Homo* also utilized marine resources (Balbo et al. 2011; Colonese et al. 2011; Cortés-Sánchez et al. 2010; Stiner 1994; Szabó and Amesbury 2011) with a recent synthesis demonstrating the many similarities in systematic use of marine resources and coastal habitation for Neanderthals and *Homo sapiens* during the European Middle Paleolithic and African Middle Stone Age (Will et al. 2019).

Although the use of marine resources is now clearly documented in our earliest history, the nature of marine resource utilization varies to the degree that littoral environments differ along coastlines within and between continental landmasses. The development and diversity of coastal/maritime adaptations, including technological innovation, subsistence patterns, settlement and seasonality of site occupation, and socio-cultural trajectories are conducive to a framework based in historical ecology (see Baleé 1998, 2006; Crumley 1994; Kirch and Hunt 1997), which fosters investigations into the wide range of dynamic interactions between people and the coastal environments they inhabited. Although littoral shellbeds and other nearshore ecosystems were clearly utilized by our early ancestors, there is little evidence that human foraging resulted in depression or depletion of harvested species at this time, likely due to low population numbers (Klein and Steele 2013). However, archaeological evidence suggests that human use of marine resources and resultant impacts on marine and littoral ecosystems intensified and accelerated as human populations grew and expanded geographically through time (Erlandson 2001; Erlandson and Fitzpatrick 2006; Milner et al. 2007; Bailey and Milner 2008; Boivin and Fuller 2009; Erlandson and Rick 2010; Rick et al. 2013).

Recently, there has been a major shift in dominant views concerning the initial colonization and peopling of the New World (see Erlandson and Braje 2011). Several key sites have yielded radiocarbon dates for Paleocoastal settlement and use of marine resources that rival inland Clovis and Folsom sites (Dillehay 1997; Erlandson et al. 2008a,c, 2011b; Johnson et al. 2002), and in the Pacific Northwest coastal habitation has been deemed possible several millennia prior to the ice-free corridor (Fedje and Christensen 1999; Mandryk et al. 2001; Misarti et al. 2012; Munyikwa et al. 2011). Multiple sites have now been found to contain credible evidence of pre-Clovis occupations (Dillehay et al. 2008; Gilbert et al. 2008a; Joyce 2006; Overstreet 2005; Waters et al. 2011b; Williams et al. 2018) with several revealing cultural strata underlying and differing from Clovis deposits, suggesting a Paleo-Indian tradition predating and contemporaneous with Clovis in North and South America. A refining of Clovis chronology has lowered the time range of what was once thought to be the oldest human population in the Americas by several hundred years; the revised age of 11,050 – 10,800 $^{14}$C yr B.P. now overlaps with multiple non-Clovis sites, implying people were well established in the New World before the development of this specialized cultural adaptation (Waters and Stafford 2007). Genetic evidence supports the pre-Clovis colonization of the Americas, but there is debate concerning the number of early migrations (see Achilli et al. 2018; Lesnek et al. 2018; Neves et al. 2004; Scheib et al. 2018). Recent studies do not provide evidence for the occurrence of multiple human migrations during the Terminal Pleistocene at this time (Chatters et al. 2014; Goebel et al. 2008), but future research might prove otherwise.

Archaeological sites on the islands off the Pacific Coast of Alta and Baja California are providing evidence that people were engaged in seafaring and maritime lifeways earlier than once thought (Des Lauriers 2006; Erlandson and Braje 2011;

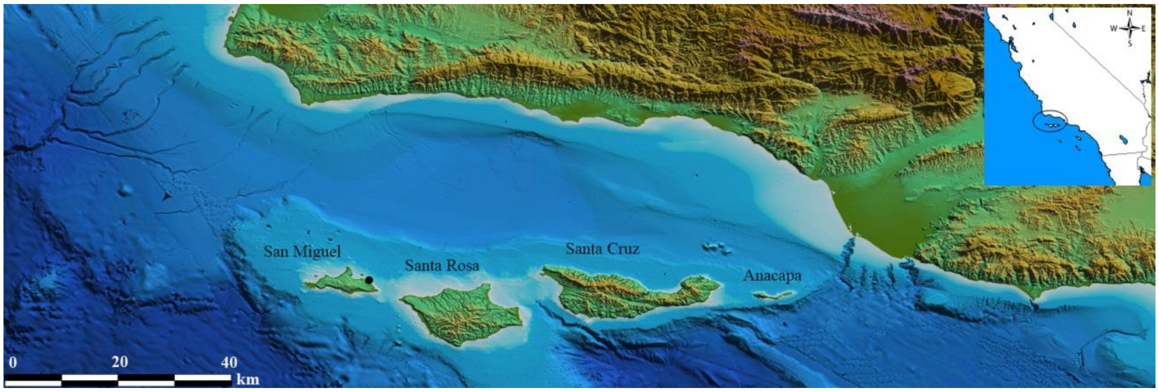

**Figure 1.1.** Map of the Northern Channel Islands (left to right: San Miguel, Santa Rosa, Santa Cruz, and Anacapa islands) showing surrounding ocean bathymetry. Bay Point, on San Miguel Island, is demarcated with a black dot.

Erlandson et al. 2007, 2008a, 2011b; Fujita and Ainis 2018; Fujita and Melgar 2014; Johnson et al. 2002). The Arlington Springs and Radio Point sites on Santa Rosa Island (Johnson et al. 2002; see also Reeder et al. 2008), Daisy Cave (Erlandson 2007; Erlandson et al. 1996; Rick et al. 2001, 2013) and recently discovered Paleocoastal sites at Caldwell Bluffs on San Miguel Island (Erlandson et al. 2011b), sites on Cedros Island off the Pacific Coast of Baja California (Des Lauriers 2006) and on Espíritu Santo Island in the bay of La Paz (Fujita and Ainis 2018; Fujita and Melgar 2014) have contributed significantly to major shifts in our views concerning the timing and nature of initial colonization of the New World, providing evidence that people were engaged in fully maritime lifeways much earlier than previously thought. Human remains at the Arlington Springs site demonstrate that people were employing watercraft during the same time that Clovis technology was produced and utilized, and Paleocoastal middens on the Northern Channel Islands demonstrate the existence of a maritime lifeway by at least 12,000 years ago.

In particular, excavations and analyses of the extraordinarily well-preserved multi-component sites of Daisy Cave (CA-SMI-261) and Cave of the Chimneys (CA-SMI-603) have provided a wealth of archaeological, paleontological, and historical ecological data that are illuminating the deep history of the terrestrial and marine ecosystems of the Channel Islands and the dynamic relationship between islanders and the landscapes they inhabited, influenced, and adapted to throughout at least 13,000 years of co-existence. My dissertation examines the nature of nearshore paleoenvironmental conditions and maritime adaptations on the Channel Islands through archaeometric and zooarchaeological analyses of archaeological remains from these two adjacent multi-component rockshelter and cave sites on the northeastern coast of San Miguel Island (Figure 1.1). This study elucidates the lifeways and ecodynamics of island inhabitants from the Terminal Pleistocene to the Late Holocene, investigating oceanographic trends and diachronic patterns in the procurement and use of intertidal, nearshore, and kelp forest resources. Archaeological assemblages included in this study range from some of the earliest known deposits on the islands (~12,500 cal BP) to roughly 2,000 years ago.

I use the framework of historical ecology to investigate and interpret the nature and history of maritime adaptations and human impacts on coastal resources formed from multiple lines of archaeological, environmental, ecological, and paleobiological evidence (Erlandson and Fitzpatrick 2006; Rick and Erlandson 2008; Rick and Lockwood 2012). Historical ecology has been increasingly employed by marine scientists (McClenachan et al. 2015) and coastal and island archaeologists studying long-term interactions between ancient people and the ecosystems they subsisted on, including discussions of anthropogenic impacts, climatic and environmental fluctuations and adaptive strategies and responses by human societies, landscape management in coastal settings, and other factors affecting change in maritime hunter-gatherer-fisher lifeways in a variety of contexts (e.g., Habu and Hall 2013; Kirch and Hunt 1997; Milner 2013; Rick 2013; Rick and Erlandson 2008). The wide array of faunal remains in coastal shell middens provide evidence of ecological and environmental fluctuations, shifts in subsistence practices, and local histories of human interactions with marine and terrestrial ecosystems (Erlandson and Rick 2008).

A plethora of archaeological data has been synthesized under an historical ecology approach, imbedding site-specific historical analyses in studies of regional scale. Such studies provide long-term developmental histories of human impacts on marine fauna as well as sustained use of marine resources in coastal and island settings (e.g., Braje et al. 2012; Carlson and Keegan 2004; Fitzpatrick and Donaldson 2007; Fitzpatrick and Intoh 2009; Fitzpatrick and Keegan 2007; Jerardino et al. 2008; Kirch and Hunt 1997; Rick 2013; Rick et al. 2008, 2014; Thomas 2009; Thompson et al. 2013). Being bounded environments, islands are particularly susceptible to the effects of extended resource extraction and the introduction of exotic biota by humans, providing valuable examples of human interactions with fragile ecosystems over extended periods of time (Braje et al. 2015; Erlandson and Fitzpatrick 2006; Fitzpatrick and Erlandson 2018; Fitzpatrick and Keegan 2007; Kirch and Hunt 1997; Rick et al. 2013).

Approaches grounded in historical ecology have guided many archaeological investigations on the Northern Channel Islands for the past decade. This framework has been used to explore the antiquity of endemic terrestrial taxa, examine dispersal histories of terrestrial fauna, reconstruct island paleoenvironments, and investigate the nature of human interactions with nearshore and terrestrial ecosystems (e.g., Braje 2010; Braje et al. 2009, 2011; Erlandson et al. 2008d, 2009, 2011a, 2015a; Rick 2013; Rick et al. 2008, 2009, 2014).

Integrating archaeology, paleobiology, and ecology under the framework of historical ecology provides deep contexts for current management, marine conservation, and restoration efforts (Braje 2010; Jackson et al. 2001; Rick 2013; Rick and Erlandson 2008; Rick and Lockwood 2012). Historical ecology has become a promising tool in conservation biology, helping to guide ecosystem management and providing insight into conservation decisions with long-term multifaceted perspectives fostered through interdisciplinary research (i.e., Rick et al. 2014). Marine conservation efforts are increasingly employing historical ecological data to assess extinction risks and set baselines and parameters for fisheries management (e.g., McClenachan et al. 2012).

Long sequences of sustained and significant human foraging in intertidal habitats on island environments, such as California’s Channel Islands, suggest by their nature that people had a deep understanding of the life-cycles and ecological interactions of the species they harvested (Braje et al. 2012; Rick 2011). Biocultural approaches to conservation biology increasingly recognize the wealth of information contained in indigenous socioecological knowledge or “biocultural heritage” (e.g., Gavin et al. 2015). Ancient communities clearly had similar interwoven, socioecological practices in place based on accumulated knowledge about the environments they lived in. Although identifying particular management practices has not yet been achieved, more complete ecological and biological understanding of the distributions, life-cycles, and predator-prey relationships of primarily targeted taxa may allow archaeologists to discover faunal indicators of conscious management by ancient coastal forager-fishers.

Faunal and floral remains and artifacts from Daisy Cave and Cave of the Chimneys have already contributed significantly to theories about the peopling of the New World and the antiquity of maritime adaptations on the west coast of North America. Woven artifacts from these sites are the oldest described for the region (Connolly et al. 1995; Norris 1997; Vellanoweth et al. 2003), lithic artifacts have contributed to our understanding of Paleocoastal maritime biface technology (Erlandson and Braje 2011; Erlandson and Jew 2009; Erlandson et al. 2011b; Jew et al. 2013c), macrobotanical remains reveal evidence that people were harvesting edible geophytes throughout the Holocene (Reddy and Erlandson 2012), and faunal assemblages represent some of the earliest evidence for intensive fishing on the islands (Rick et al. 2001). Collagen fingerprinting has recently been used to identify marine mammal bones from Terminal Pleistocene and Early Holocene components at Daisy Cave, making these specimens some of the earliest evidence for marine mammal hunting in the Americas (Hoffman et al. 2018). In addition, paleontological assemblages from these sites have contributed to discussions concerning the endemic giant island deer mouse (Ainis and Vellanoweth 2012; Shirazi et al. 2018) and historic changes in the presence of avian fauna on the islands (Collins et al. 2018). Although a significant amount of data has been gleaned from these assemblages, even more can be learned concerning maritime lifeways, technological trajectories, subsistence patterns, and human-environmental interactions on San Miguel Island throughout the past ~12,000 years.

My research explores the nature of human-environmental dynamics in an island/coastal setting by reconstructing paleoenvironmental conditions using climatic proxy data (i.e., sea surface temperatures [SST]) and investigating patterns in subsistence practices and resource selection, including size/age profiles of harvested specimens and seasonality of shellfish harvesting on San Miguel Island. I focus on the trans-Holocene record of human interactions with marine ecosystems at Bay Point through analysis of archaeological materials from Daisy Cave and Cave of the Chimneys. Stable isotope (ʒ$^{13}$C and ʒ$^{18}$O) analysis of modern and archaeological California mussel shells from these two sites contribute to questions concerning the nature of island settlement and residential seasonality and how these patterns shifted through time. The potential of seaweed harvesting in the past is explored through ethnographic and ethnohistoric analogies along with ecological, biological, and nutritional data, setting the stage for discussions of nearshore and kelp forest ecology in the Southern California Bight. Identifying small non-dietary marine gastropods that are known associates of kelp forest ecosystems provides a method for inferring the harvesting of highly perishable marine macroalgae in the past. Reconstructing size and age profiles of tens of thousands of harvested sea urchins contributes to an understanding of kelp forest health throughout the Holocene. Combined, these studies improve our understanding of trans-Holocene maritime adaptations on the Northern Channel Islands and provide an exceptional case study of both continuity and change over 12,000 years of human occupation.

## Geographic, Environmental, and Oceanographic Background

Alta California's Channel Islands consist of eight islands divided into northern and southern groups located off the coast of southern California. The northern islands of San Miguel, Santa Rosa, Santa Cruz, and Anacapa represent the western extent of the Transverse Ranges, which were connected in a single 125 km long island known as Santarosae during and after the Last Glacial Maximum (LGM) (Erlandson 1994, 2016; Kennett et al. 2008; Orr 1968). Although Santarosae was only 6 to 8 km from the mainland coast, the depths of the Santa Barbara Basin (200-500 m below mean sea level) separated the island(s) from the mainland continental shelf during the Late Pleistocene (Peterson et al. 2017). Sea-level rise over the past 20,000 years has significantly altered the island's sizes, configurations, and habitable land areas, which only reached their approximate current shapes and sizes after ~7000 cal BP (Clark et al. 2014; Glassow et al. 2010; Kennett et al. 2008; Muhs et al. 2012; Reeder-Myers et al. 2015). It is estimated that roughly 70 percent of Santarosae's landmass was lost since the end of the LGM (Muhs et al. 2012). Based on the most recent estimate, the eastern tip of San Miguel Island separated from the western extension of Santa Rosa Island between ~9400 and 9100 cal BP (Reeder-Myers et al. 2015: Figure 4), after which the extent of subtidal surface area available for securing kelp forest holdfasts and rocky coast intertidal areas

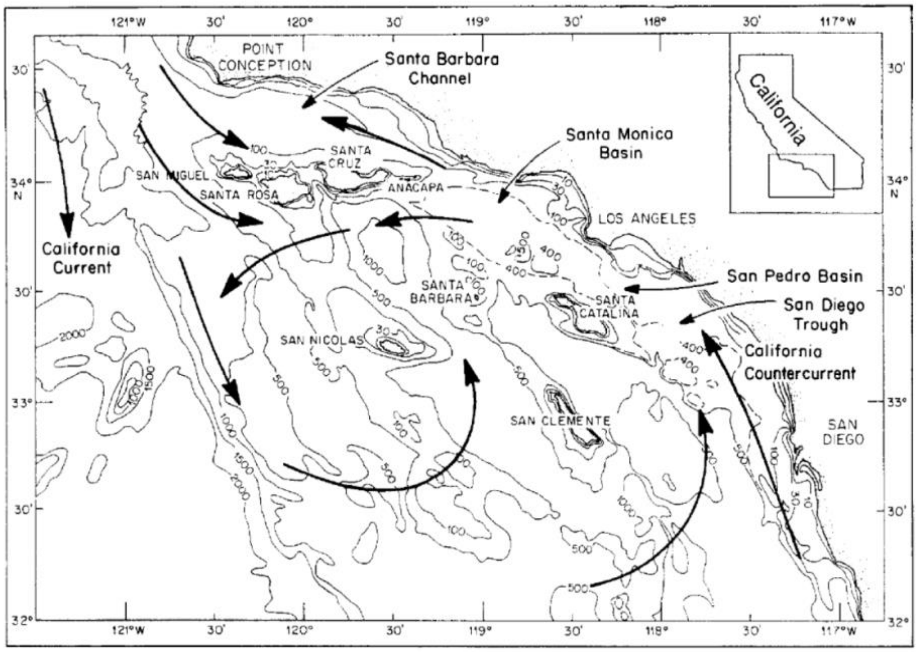

**Figure 1.2.** Map of the Southern California Bight, including the Channel Islands, depicting ocean floor bathymetry and ocean circulation patterns (contours in fathoms, figure from Hickey 1992:39).

around the island steadily diminished through time until current proportions were attained (Reeder-Myers et al. 2015: Table 1).

The northern islands underwent considerable paleoclimatic changes during the Terminal Pleistocene/Holocene boundary and significant vegetative shifts during the Middle-Late Holocene, some of which might be attributed to human fire-management practices. Pollen/pond cores from San Miguel and Santa Rosa islands reveal significant changes in vegetative communities during the past ~12,000 years (Anderson et al. 2010; Erlandson et al. 1996; West and Erlandson 1994). Coastal conifer forests that dominated Late Pleistocene highlands shifted to pine, sage, and grasslands between ~11,800 and 9150 cal BP as the climate warmed. Coastal sage scrub dominated the hill slopes until ~6900 cal BP, after which grasslands become the dominant vegetative communities.

The complex interaction of underwater topography, island-specific geography, island wakes (wind and current induced), wind and wave effects, and large-scale oceanographic currents and upwelling patterns contribute to the dynamic and complex forces that propel water circulation in the Southern California Bight (Figure 1.2; Caldeira

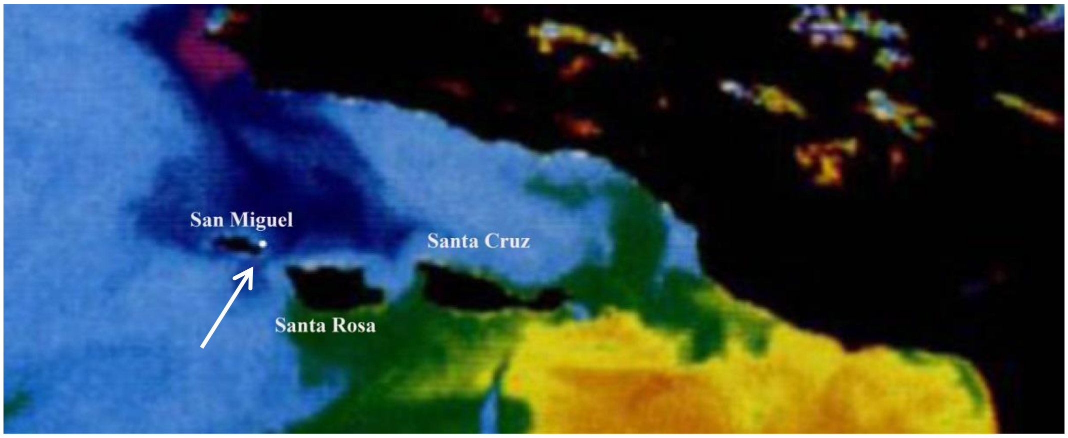

**Figure 1.3.** Map of the Northern Channel Islands showing satellite derived variations in SST around the Northern Channel Islands (adapted from Hickey 1992:41). The location of Bay Point is demarcated by the white arrow and dot. Temperature range: orange (warmest) – dark blue (coldest).

et al. 2005; Dong and McWilliams 2007; Hendershott and Winant 1996; Hickey et al. 2003; Winant et al. 2003). The regional hydrographic regime is dominated by a semi-permanent cyclonic gyre incorporating cool water from the south flowing California Current with warmer waters from the California Countercurrent, which intrude from the southeast (Hickey 1992). Wind patterns and mixing water currents cause seasonal oscillations in SST and upwelling in the channel (see Browne 1994; Kennett 2005). In the Southern California Bight, oceanographic circulation processes vary from east-to-west, creating a thermal gradient with warmer SSTs associated with subtropical water in the southeast and cooler waters associated with the upwelling center at Point Conception in the northwestern channel (Broitman et al. 2005; Fewings et al. 2015; Hickey 1992; Otero and Siegel 2004; Winant et al. 1999, 2003). The California Current flows in a southerly direction at the western edge of the islands, bringing cold waters down from the Gulf of Alaska. The Southern California countercurrent flows northward, bringing warmer waters up from Baja California, causing varying degrees of mixing around the islands depending on seasonal and ENSO conditions. The California Current is most fully developed and strongest in late summer and early fall, and the Countercurrent is weakest in spring (Hickey et al. 2003).

The maintenance of intertidal and littoral ecosystems is dependent on the influx of deeper, offshore waters that bring in nutrients, larvae, and biogenic particles, which is accomplished through cross-isobath transport processes like wind-driven upwelling in the outer Southern California Bight, and internal waves and eddies within the bight and along the mainland coast (Bassin et al. 2005; Winant and Dorman 1997). Internal waves are essential for sustaining kelp growth during warmer summer months and El Niño years, transporting nutrients and larvae to kelp forests on the inner shelf (Zimmerman and Kremer 1984). Analysis of sub-mesoscale eddies in the Southern California Bight, south of Point Conception (directly north and east of San Miguel Island) indicate they transport high concentrations of nutrients and particles from deeper waters to the shallower waters of the inner shelf and may be responsible for sustaining kelp bed productivity during nutrient limiting conditions like El Niño events (Bassin et al. 2005), which might explain the resiliency of kelp forest habitats in the Southern California Bight to warm water events in the past (see Chapters 2 and 5). Regional studies have also shown that deep-water winter wave climates are relatively consistent during La Niña (PDO cool phase) intervals but much more variable during El Niño (PDO warm phase) intervals (Adams et al. 2008).

San Miguel, influenced primarily by the California Current, has the coolest ocean water regime of any of the Channel Islands and is situated near the boundary of two major biogeographic provinces, the Oregonian and the Panamanian, just south of Point Conception. San Miguel and Santa Rosa islands are also in the direct path of the prevailing upwelling-favorable winds in summer (Caldwell et al. 1986). Although upwelling winds are known to relax during summer within the Bight, they remain strong in offshore regions (like San Miguel Island) as a result of the continental slope which creates a “positive wind-stress curl condition” that is reinforced by proximity to Point Conception (Di Lorenzo 2003:2371). The cooler California Current is the primary influence on nearshore habitats around San Miguel Island, with warmer water temperatures along its eastern shores (Figure 1.3).

Point Conception is a major biogeographic boundary with strong upwelling and nearshore habitats dominated by marine macrophytes to the north, and intertidal habitats dominated by filter feeders sustained by weaker and sporadic upwelling in the channel to the south (Atkinson et al. 1986; Blanchette and Gaines 2007; Brink et al. 1984; Hickey

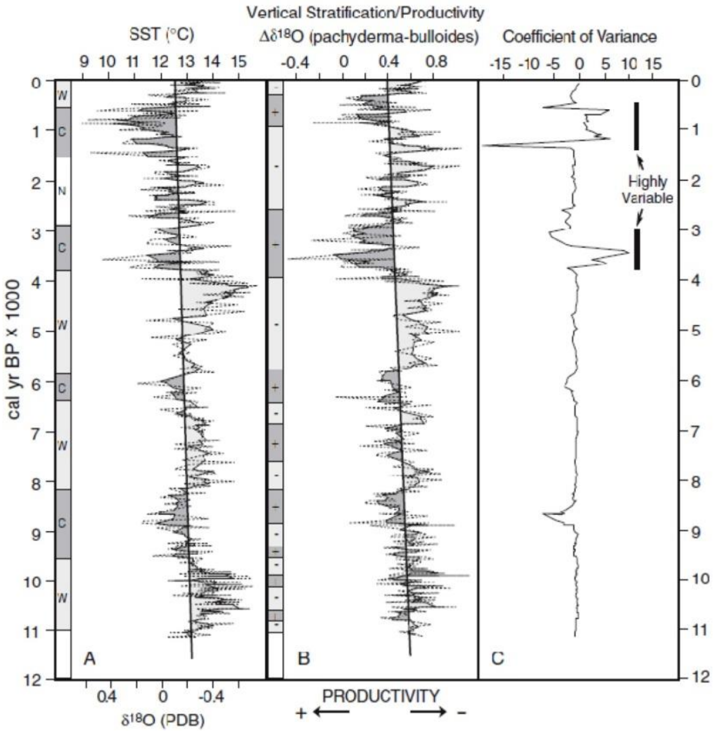

**Figure 1.4.** Holocene climate record for the Santa Barbara Basin (Kennett 2005:66,67). (A) SST curve based on oxygen isotopic composition of surface-dwelling foraminifera (*Globigerina bulloides*) from varved sediments. Bar on left side represents warm (w), cold (c), and neutral (n) water cycles. (B) Vertical stratification/productivity record based on differing isotopic composition of surface-dwelling (*G. bulloides*) and deeper-dwelling (*Neogloboquadrina pachyderma*) foraminifera. Bar on left shows intervals inferred as high (=+) or low (-) productivity. (C) Water cycles through the Holocene.

1993). In general, marine habitats of the Northern Channel Islands are highly productive and enhanced by extensive upwelling and kelp forests. However, intertidal shellfish beds are influenced by small-scale ecological and oceanographic characteristics, producing unique habitats shaped by tidal gradients and local fluctuations in water temperature and upwelling, requiring an understanding of these influences on the shellfish people harvested (Blanchette et al. 2007, 2009a; Schoenherr et al. 1999).

Reconstructing submerged coastlines is complex, but recent paleogeographic studies are producing improved models of submerged landscapes, refining our knowledge of landmass changes on the Northern Channel Islands since the LGM and highlighting the importance of site-specific reconstructions to account for island-specific departures from eustatic records (see Clark et al. 2014; Reeder-Myers et al. 2015). SST reconstructions for the Santa Barbara Bight using isotopic analysis of planktonic foraminifera (ODP Site 893) have revealed general oceanographic patterns for the Holocene (Figure 1.4; Kennett 2005; Kennett et al. 2007) showing increased interannual variability at ~4.2 kya (Fisler and Hendy 2008). This reconstruction is based on averaged data from 50 and 25 year composite samples of annual varves, however, and discrepancies between faunal and geochemical records of a proposed Late Holocene ‘warming trend’ between AD 1200 and 1700 illuminate the need for more intricate interpretations of past conditions (Fisler and Hendy 2008).

Regional SST reconstructions from deep sea cores taken from the Santa Barbara Bight provide invaluable data on generalized climatic and oceanographic conditions, but it seems increasingly clear that they are not fully representative of localized nearshore SST and productivity patterns that account for small-scale oceanographic variations affecting intertidal shellfish beds (Flores 2017). Composite SST sequences (e.g., Kennett and Kennett 2000) may also blur localized variation within and between islands by combining values from shells collected from both cooler and warmer coastal areas (Flores 2017). Recent archaeometric studies identified nearshore SST patterns around the Northern Channel Islands (Glassow 2015; Glassow et al. 2012; Jew et al. 2013a, b, 2014; Rick et al. 2006; Robbins and Rick 2007; Robbins et al. 2013; Thakar 2014), revealing localized departures from the generalized Santa Barbara Basin sequence and demonstrating the need to reconstruct additional nearshore sequences from archaeological shell middens.

Latitudinal variation in the degree and spatial extent of currents, upwelling, and substrate affects larval transport processes with implications for shifts in the relative abundances of intertidal shellfish populations harvested by humans (Blanchette and Gaines 2007; Blanchette et al. 2007; Flores 2017). Mesoscale circulation processes are the primary sources of variability in these nearshore environments and studies have shown an association between spatial variability in invertebrate larval recruitment and variation in temporal dynamics of SST (Broitman et al. 2005). Mussel growth rates are predominantly contingent on environmental factors, including water temperature and the littoral gradient in wave exposure with elevated wave action and air exposure affecting predator rates and displacing populations higher in the intertidal (Blanchette and Gaines 2007; Blanchette et al. 2007; Coe and Fox 1942).

The dynamic nature of nearshore marine environments in the Southern California Bight suggests that changes in currents, wave effects, upwelling patterns, shoreline configuration, sedimentation, SSTs and other factors have continuously reshaped kelp forest, estuarine, and other coastal ecosystems for millennia. However, marine ecosystems surrounding the islands are highly productive, enhanced by the upwelling of nutrient-rich currents and extensive kelp forests. Pelagic and nearshore habitats teem with diverse vertebrate, invertebrate, and algal communities. An extensive background on kelp forest ecosystems is presented in Chapter 3 of this dissertation.

## Terrestrial Background

San Miguel Island is the most westerly of the Northern Channel Islands, now located ~42 km from the mainland. It contains a land area of about 37 km$^2$ with a maximum length and width of ~13 and 7 km respectively. Intertidal substrates along the coastline of San Miguel are predominantly composed of rocky shores (~33 km, 64%) and sandy beaches (~19 km, 36%), with a small amount of boulder beach (>1 km, >1%) (Littler and Littler 1979). Central tablelands, consisting of a series of ancient marine terraces, are separated from the coast by steep escarpments, except for two hills (Green Mountain and San Miguel Hill) that rise to elevations of 254 and 229 m, respectively. Postglacial dune development characterizes the surface of the island (Johnson 1980) as Pleistocene sand dunes formed over dense caliche horizons that are heavily cemented (Erlandson et al. 2005c; Peterson and Erlandson 2018). Holocene dunes, being younger, range from unconsolidated loose sand to partially indurated dunes studded with calichified root casts (Erlandson et al. 2005c). Sand-ramp deposits from the Late Pleistocene are generally thicker than those accrued during the Holocene, likely due to the much longer duration of low-stand marine conditions and the more restricted sand-ramp development during the shorter mid-late Holocene period (Peterson et al. 2017). Dramatic environmental changes swept the islands during the Terminal Pleistocene and first half of the Holocene as climate oscillated and sea levels rose, shrinking habitable land, and affecting the distribution, availability, and productivity of terrestrial and marine resources (Kennett et al. 2007; Kinlan et al. 2005)–all of which significantly influenced human settlement and subsistence strategies on the island.

As the Channel Islands were reshaped and habitats restructured, islanders were faced with the challenges of adapting to a changing environment. The archaeological record provides clues about the nature of resource distributions and diversification through time and the adaptive responses of islanders to these dynamic changes. Still, understanding the specifics of how, when, and where terrestrial and marine resource use changed is one of the challenges facing Channel Island researchers. Distinguishing between natural environmental changes and the effects of human impacts on local ecosystems further complicates our understanding of the dynamic nature of human-environmental interactions on these islands throughout the past 13,000 years or more.

Columbian (*Mammuthus columbi*) and pygmy (*M. exilis*) mammoths roamed the Northern Channel Islands near the time of initial human colonization (Agenbroad et al. 2005), no other terrestrial mammals larger than a now extinct giant mouse (*Peromyscus nesodytes*; Ainis and Vellanoweth 2012; Guthrie 1993; Shirazi et al. 2018; Walker 1980) lived on San Miguel Island until dogs, foxes, and skunks were introduced by humans along with a smaller mouse species (*Peromyscus maniculatus*) (see Rick et al. 2009). Endemic terrestrial fauna also include the California bat (*Myotis californicus*), the ornate shrew (*Sorex ornatus*), one species of amphibian (Channel Islands slender salamander, *Batrachoseps pacificus pacificus*), and three reptiles (Island western fence lizard, *Sceloporus occidentalis becki*; Southern alligator lizard, *Elgaria multicarinatus;* and the Island gopher snake, *Pituophis melanoleucus*).

At least 17 species of land birds breed on San Miguel Island today and 14 species of marine birds frequent the shores of the island (Collins et al. 2018; Guthrie 1993; Schoenherr et al. 2009; Walker 1980). A now extinct flightless duck (*Chendytes lawii*) and vampire bat (*Desmodus stockii*) are also known from fossil deposits and archaeological sites on the island (Agenbroad 1998; Agenbroad et al. 2005; Ainis and Vellanoweth 2012; Guthrie 1993, 2005; Rick et al. 2012; Shirazi et al. 2018; Walker 1980; Wilson 1936; White 1966). San Miguel Island also serves as a rookery for marine birds and six species of pinnipeds numbering in the tens of thousands use the islands coasts for haul-outs and breeding (Schoenherr et al. 1999).

Vegetation communities on the islands are like those from the adjacent southern California mainland coast and carbonate (caliche) casts of tree trunks, fossil cones, and pollen demonstrate that forests and woodlands were widespread prior to the Terminal Pleistocene (Johnson 1980; West and Erlandson 1994). Although native vegetation is abundant on the islands, taxonomic diversity is relatively low on San Miguel when compared to the other islands. Less than 200 native plant taxa are known for San Miguel Island, compared to almost 400 for its much larger neighbor Santa Rosa Island (Schoenherr et al. 1999). Diversity and distribution of vegetative communities vary between the islands with San Miguel being dominated by Coastal Sage Scrub and Coastal Grassland species, which are found predominantly on marine terraces. Coastal Dune vegetation can also be found on the extensive sand dunes that cover much of the island and Coastal Bluff Scrub varieties inhabit north-facing cliffs (Schoenherr et al. 1999; Junak 1995). As they recover from a century of historical overgrazing, island grasslands are supporting prodigious numbers of geophytes, especially bluedicks (*Dichelostemma capitatum*) that were an important food source for the Island Chumash and their ancestors and archaeobotanical studies demonstrate higher diversity and abundance than previously considered (Gill 2013, 2014; Gill and Erlandson 2014; Gill and Hoppa 2016; Gill et al. 2019a; Reddy and Erlandson 2012).

Although Native Islanders most certainly altered island ecosystems to some extent during ~13,000 years of habitation, the scale of ecological impacts was unlike the drastic changes that occurred during the Historic Era (late-18th to mid-20th centuries; Rick et al. 2014; Braje et al. 2019). Commercial hunting of whales, sea otters, pinnipeds, and fish by Russian, Spanish, American, and English companies severely altered fragile marine ecosystems around the islands decimating most marine mammal populations (Bartholomew 1967; Scammon 1968). Some of the islands were sporadically inhabited by Chinese abalone fishers during the mid-to-late19th century when the extermination of otter populations led to a temporary expansion of abalone and a short-lived but lucrative industry harvesting and processing the large meaty gastropods (Braje 2016; Ogden 1941). In addition, terrestrial landscapes were significantly altered by ranching enterprises during the 19th and 20th centuries when overgrazing and trampling by introduced herbivores (e.g., sheep, goats, pigs, cattle, horses, deer, elk) led to widespread erosion, the loss of organic soil layers, and the introduction of non-native flora which replaced native perennial scrub (see Johnson 1980; Junak et al. 1997). This historic destabilization of previously vegetated sand-ramp and hill deposits created an active sand supply that migrated across San Miguel Island in the mid-1900s (Johnson 1980; Rick 2002).

## Archaeological Background for San Miguel Island

Recent research based on stable isotope analysis of archaeological shell remains suggests that the Northern Channel Islands were inhabited year-round by at least 10,000 years ago (Jew et al. 2013c; Watts 2013). Sites dated to the Terminal Pleistocene and Early Holocene have yielded lithic assemblages containing finely crafted points (i.e., Channel Island Barbed and Amol points) and crescents, suggesting a sophisticated maritime hunting technology was well established at the time of initial colonization (Braje et al. 2013; Erlandson 2013; Erlandson and Jew 2009; Erlandson et al. 2011b; Glassow et al. 2008; Jew et al. 2013c). Faunal remains from Terminal Pleistocene sites on San Miguel (Daisy Cave, Cardwell Bluffs) and Santa Rosa (CA-SRI-512) islands show evidence of waterfowl hunting, shellfish collecting, fishing and marine mammal hunting, with emphasis on red abalone and California mussel. Early Holocene sites are often dominated by black abalone, California mussel, and black turban shells, with other rocky intertidal species collected in varying amounts (see Erlandson et al. 1999, 2004, 2005a). Research also revealed evidence for protected paleoestuaries and the collection of estuarine molluscs during this time period on Santa Rosa Island (e.g., CA-SRI-666; Erlandson 1994; Erlandson et al. 2019; Rick et al. 2003).

Middle Holocene middens reveal the remains of a wide variety of shellfish and fish taxa, showing that a cornucopia of marine resources were being harvested in varying amounts throughout this time period (see Braje 2010; Rick et al. 2005a; Sharp 2000; Vellanoweth and Erlandson 1999). Red abalone middens, most of them dated to between ~7500 and ~3300 years ago, are common features on the Northern Channel Islands and San Nicolas Island, with some researchers suggesting that cooler ocean waters during this time allowed this species to flourish (see Glassow 1993b; Sharp 2000). Others suggest that cooler temperatures coupled with infrequent El Niños, might have fostered the proliferation of this species (Kennett 2005:147), or that increased sea otter hunting, driven by human population growth, may have freed red abalone populations from their primary predators, increasing sizes and abundances (Erlandson et al. 2005b; see also Braje et al. 2009). The stable isotope results from my study greatly improve our understanding of oceanographic conditions during this dynamic time period, contributing a wealth of data pertinent to this debate.

The Late Holocene archaeological record for the Channel Islands in general contains evidence of high population densities, demographic expansion, increased sedentism and craft specialization, economic intensification and intensive trade with other islands and the mainland facilitated by a shell bead economy (see below), and resource diversification with increased emphasis on fishing (see Kennett 2005; Rick et al. 2005a). Throughout the Late Holocene and until the onset of European contact the Northern Channel Islands were inhabited by the Island Chumash, who lived in large sedentary villages, manufactured circular shell fishhooks (Rick et al. 2001) and *tomols* (sewn planked canoes; Hudson et al. 1978) and engaged in intensive use of highly productive marine fisheries. Island Chumash also took part in extensive trade networks between islands and with mainland groups and participated in a well-developed regional economy based on shell bead money made from the purple olive (*Olivella biplicata*) shell (see Arnold 2001; Kennett 2005).

Contact between the Chumash and Europeans occurred in AD 1542, when Cabrillo’s three Spanish ships wintered for five weeks at Cuyler Harbor on the northern coast of San Miguel, possibly introducing Old World diseases to Island Chumash populations (Erlandson et al. 2001). The Chumash were clearly thriving when the Spanish colonization of Alta California began in AD 1769, however, until Spanish settlement on the mainland coast devastated Chumash populations through a combination of disease and political and religious domination that severely damaged traditional lifestyles and regional economic networks. An AD 1793 census by the Spanish recorded only 55 Chumash residing on San Miguel Island, and by around AD 1820, the last of the Island Chumash were removed to the mainland. Soon after, ranches were established on the Northern Channel Islands, introducing a variety of livestock that fundamentally changed the vegetative communities and terrestrial landscapes of the islands.

Simultaneously, the colonial fur trade and advent of commercial whaling and fisheries led to severe alterations of marine ecosystems surrounding the islands by depleting stocks of key species, such as sea otter, pinnipeds, and black abalone.

## Archaeological Research on San Miguel

Multiple authors have summarized the history and extent of archaeological investigations on the Channel Islands (Benson 1997; Glassow et al. 2010; Kennett 2005; Rick et al. 2005a; and others), so I provide only a brief synopsis. In the late 1800s and early 1900s, initial research was spurred by the antiquarian quest to increase museum collections. These early investigations focused on cemeteries and removed large quantities of artifacts and human remains from the islands with little or no provenience for collected items (e.g., Bowers 1890; Benson 1997; Glidden 1919; Heye 1921; Schumacher 1875, 1877). After the 1920s, researchers were more focused on the research potential of archaeological assemblages, resulting in extensive museum collections containing thousands of artifacts with some provenience but only general stratigraphic and chronological correlation (e.g., Orr 1968; Rogers 1929). Excavation methods often relied on arbitrary levels and screening through large mesh (1/4-inch) screens, limiting subsequent interpretations (e.g., Rozaire 1965, 1976, 1978). Archaeological methods improved later in the 20th Century, as researchers became more concerned with the context of archaeological remains, the collecting of detailed provenience, and thorough analysis of excavated samples (e.g., Arnold 2001; Glassow 1993a; Meighan 1959).

Recent investigators have explored a wide array of archaeological topics including: the perceived marginality of California island environments (Gill et al. 2019c); evidence for the earliest occupations of the islands and lifeways of early islanders (e.g., Braje et al. 2013; Erlandson et al. 2011b; Gusick 2013; Rick et al. 2013); social and political elaboration during the latter part of the Late Holocene prior to European contact (e.g., Arnold 1992, 2001), craft specialization (Arnold and Graesch 2001; Arnold and Munns 1994), trade and exchange (e.g., Bennyhoff and Hughes 1987; Gill et al. 2019b; King 1971; Raab and Howard 2002; Vellanoweth 2001; Vellanoweth et al. 2014); lithic material distributions on the islands (e.g., Erlandson et al. 1997, 2008b, 2012; Jew et al.

2013c; Perry and Jazwa 2010); historical ecology and human impacts (e.g., Braje et al. 2012; Erlandson et al. 2008d, 2011a, 2015a); seasonality of site occupation (e.g., Jew et al 2013a, b, 2014); settlement systems and land-use patterns (e.g., Glassow 2013; Jazwa et al. 2013; Perry 2004, 2005); theoretical perspectives and methodological approaches to faunal analysis (e.g., Glassow and Joslin 2012; Raab 1992; Pletka 2012); with increasing focus on the distribution and use of terrestrial plant resources (e.g., Gill 2013, 2014; Hoppa and Gill 2016; Gill et al. 2019a; Reddy and Erlandson 2012), and potential evidence for the harvesting of marine macrophytes (Ainis et al. 2014, 2019).

More than 700 archaeological sites have been recorded on San Miguel Island, creating a relatively extensive record of human occupation beginning in the Terminal Pleistocene and spanning the Holocene. The island stands out as an exemplar for applying historical ecology perspectives to the interpretation of archaeological data on an island wide scale. Studies incorporating archaeological data from a wide array of sites, including Daisy Cave and Cave of the Chimneys, have examined diachronic trends in ecological dynamics between humans and keystone predators of kelp forest ecosystems (Erlandson et al. 2005b) and human impacts on favored shellfish taxa through more than 10,000 years of predation (Erlandson et al. 2008d, 2011a, 2015a). In addition, data from these two sites have contributed to regional syntheses of the historical ecological records of marine resource extraction on the Northern Channel Islands (Braje et al. 2012; Erlandson et al. 2009) and in the California Bight (Rick et al. 2008). These studies have demonstrated that despite decreasing sizes in some key species and switching of resources to include greater diversity through time, there is significant resilience of primarily harvested shellfish taxa until the Historic Era. Furthermore, researchers have emphasized that the deep history of human interaction with marine environments and the ecological baselines provided by the archaeological record have much to contribute to modern management and restoration of declining fisheries and nearshore environments (Braje 2010; Erlandson and Rick 2010; Erlandson et al. 2009; Rick et al. 2008).

Multi-component sites such as Daisy Cave and Cave of the Chimneys have the potential to reveal finer-grained patterns at the site-specific scale and contribute to our knowledge of human exploitation and potential management of nearshore habitats at Bay Point through more than 12,000 years of repeated use. Regional syntheses are based on local case studies, and these multi-component sites provide the opportunity to understand localized, within-site patterns over the long-term. Studies showing that localized trends may differ considerably from regional trends in other areas of the world (e.g., Otaola et al. 2015) indicate that scale is an issue we need to mindful of when deciphering archaeological trends and patterns. Unraveling the causes of possible long-term human impacts on shellfish beds can be best explored through intensive analysis of diachronic components from a single location where localized geographic, oceanographic, and ecological variables that influence shellfish populations can be deciphered. Utilizing various scales of analysis when interpreting archaeological sequences allows a wider array of inquiry and explanation, as well as the ability to address research questions at different levels. Quantifying the variability that is present at several spatial and temporal scales provides in-depth insights and a more holistic understanding of the past as a multi-faceted and dynamic "human ecosystem" people lived in and interacted with (as per Butzer 1982).

## The Sites: Context and Previous Research

Daisy Cave (CA-SMI-261) and Cave of the Chimneys (CA-SMI-603) are rock shelter and cave sites located on a rugged stretch of rocky coastline on the northeast coast of San Miguel Island near Bay Point (see Figure 1.1). The sites are within 100 meters of each other, with the closest fresh water source currently less than a kilometer away at Willow Canyon, although it is possible that other sources existed at various times in the past. Daisy Cave is located at the base of a steep and prominent bedrock escarpment, while Cave of the Chimneys is located on a coastal ledge; both sites overlook steep slopes above rocky intertidal areas. Today, these sites reside in a vegetated but largely treeless landscape, speckled with giant coreopsis (*Coreopsis gigantea*), live-forever succulents (*Dudleyi greenei*), blue dick and other geophytes, a mix of introduced and native grasses, ice plant (*Mesembryanthemum crystallinum*), and other shrubs. The island fox (*Urocyon littoralis*) and deer mouse (*Peromyscus maniculatus*) are the only terrestrial mammals on the island today and were likely introduced by Native Islanders (see Rick et al. 2009; Hofman et al. 2015). A weathered mandible of a domestic dog (*Canis* *familiaris*) was uncovered by Rozaire deep in the sequence at Daisy Cave (Walker et al. 1978); suggesting that people also brought this trusty companion to the islands. Although the exact stratigraphic origin and current location of the dog bone is unknown, it implies the presence of dogs on the island in the past, potentially during the Early Holocene (Forgeng 1992:16).

Nearly 100 radiocarbon ($^{14}C$) dates now provide an extensive chronology for human use of these rock shelters, revealing intermittent human occupations ranging from around 12,000 to 700 cal BP (see Ainis and Vellanoweth 2012; Erlandson et al. 1996; this dissertation). However, some dates for Daisy Cave are from other areas of the site (i.e., Cave A) and some of the Cave of the Chimneys dates are not associated with a stratum (i.e., Probe samples) or from Stratum I, which did not contain much cultural material and will not be included here. This study combines dates from all the main cultural components from both sites into a single Bay Point chronological sequence (Figure 1.5). Radiocarbon dates imply an alternating pattern of use during the Holocene, suggesting that for the most part when one site was occupied the other was vacant, although $^{14}C$ dates beginning in the later part of the Early Holocene show overlapping occupations between sites. The degree of testing varies greatly between sites, however, as Daisy Cave has been extensively excavated, unlike Cave of the Chimneys where only one unit and one column of bulk samples were excavated from the northeast wall of the site. It is possible that additional earlier components lie buried in other areas of this well-preserved site.

Nevertheless, the presence of multiple clearly defined and discrete cultural strata dated between the Terminal Pleistocene and the Late Holocene offer an unprecedented opportunity to examine the interactions of coastal foragers with a changing environment using high-resolution data from neighboring sites that stretch across a broad temporal expanse. Caution must be used, however, when interpreting faunal remains from such exceptionally preserved sites, where paleontological and natural accumulation from raptors and other animals can be mixed with cultural deposits (i.e., Collins et al. 2018).

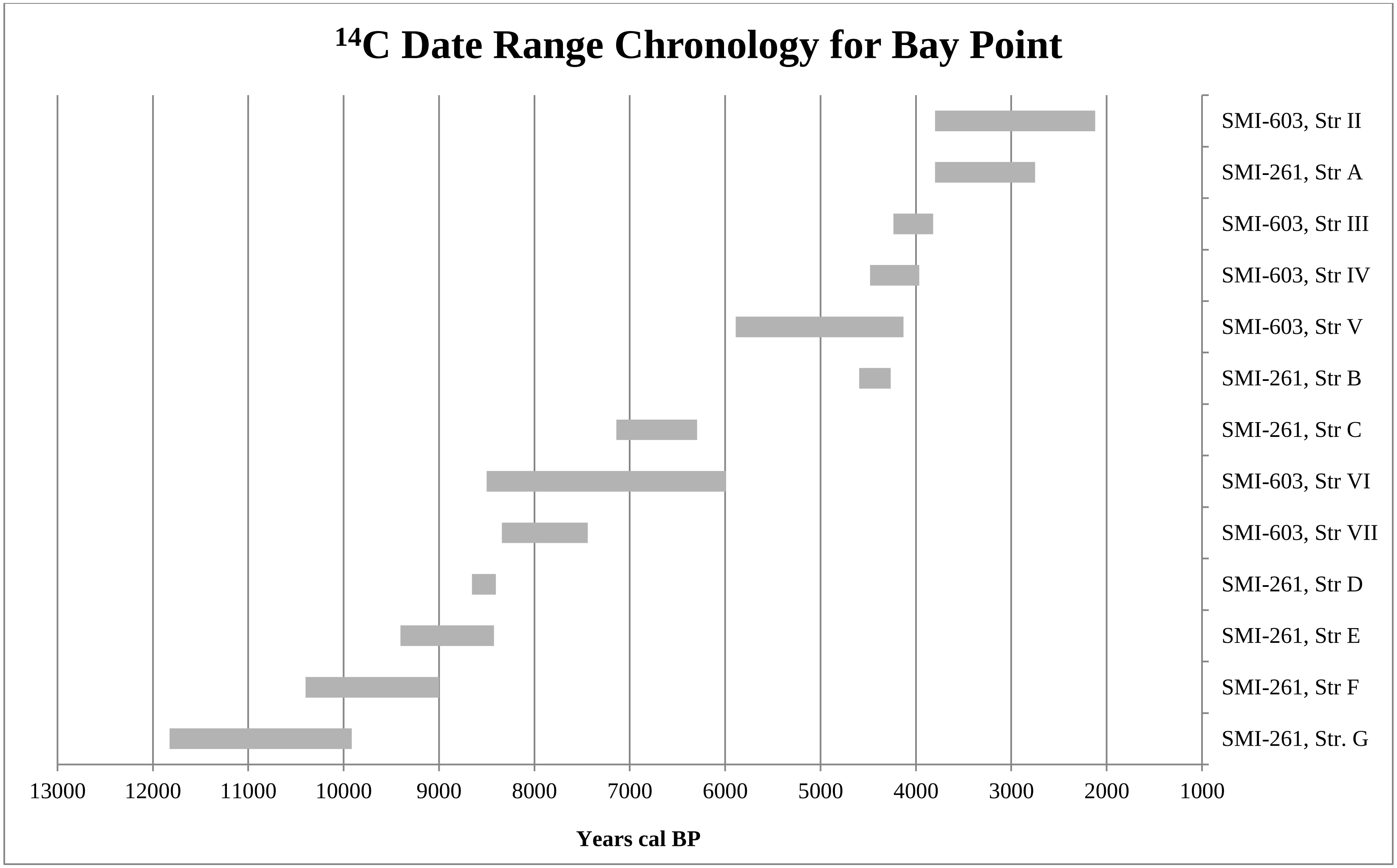

**Figure 1.5.** Traditional and AMS $^{14}$C date ranges for Bay Point components discussed in this study. Graph was compiled using all calibrated $^{14}$C date ranges from charcoal, twig, and marine shell samples presented in Tables 1.1 and 1.2 of this chapter.

Both sites contain remains of the extinct giant island deer mouse (*Peromyscus nesodytes*). Although their bones are predominantly found in Terminal Pleistocene and Early Holocene layers at Daisy Cave (Guthrie 1993, 1998; Shirazi et al. 2018; Walker 1980), they are found in significant amounts throughout all the anthropological strata at Cave of the Chimneys (Ainis and Vellanoweth 2012; Allen 2013). The difference in accumulation of giant mouse bones between these roughly adjacent sites is an issue that requires further taphonomic investigations and direct radiocarbon $^{14}C$ dating of giant mouse bones, which has so far proven difficult (T. Rick, pers. comm. 2018).

### *Daisy Cave: Description, History of Investigation, Stratigraphy, and Chronology*

Daisy Cave received much acclaim as the oldest documented coastal shell midden in North America (Erlandson 2007; Erlandson et al. 1996) -- although slightly older sites have now been identified at nearby Cardwell Bluffs and on Cedros Island in Baja California (Des Lauriers 2006; Erlandson and Braje 2011; Erlandson et al. 2008c, 2011b) -- providing a significant contribution to our understanding of early maritime people in the region and the earliest evidence of an intensive fishing tradition in North America (Rick et al. 2001). The cave, rockshelter, and slope below hold dense midden deposits, testifying to the repeated use of this site by people in the past.

Daisy Cave is formed in massive marine conglomerate bedrock composed of rounded pebble and cobble-sized volcanic rocks cemented in a fine-grained sandy matrix. Sediments at the site consist of various sized particles weathered from the cave walls and ceiling in addition to wind-blown sediments, naturally deposited organic materials from animals that used the site and anthropogenic soils containing artifacts and organic remains accumulated during repeated human occupations. The relatively steep bathymetry off the east end of San Miguel Island puts Daisy Cave roughly 1-2 km from terminal Pleistocene and Early Holocene shorelines (Erlandson et al. 1996:369). The site now sits less than 10 m from the shore and 10 meters above sea level.

The Daisy Cave site complex consists of a slender fissure-like cave, Cave A, likely formed by marine erosion during the Last Interglacial. Cave A developed along a fault extending from northeast to southwest through the cliff above, it is around 12 m long and contains three small chambers no more than 1-3 m wide and approximately >2 m high in the central chamber. All three chambers contain archaeological and paleontological materials including human remains, as the Chumash and their ancestors used this portion of the site for a burial chamber. Crystalline gypsum flowers encrust the walls of the inner chamber in high densities – possibly inspiring the name of the site. Although not very large, this cave is one of the few locations on San Miguel that provides shelter from the strong northwesterly winds that buffet the island and occasional rainstorms. Cave A opens towards the east into a rockshelter about 4 m deep and 6 m wide, which once held extensive stratified deposits of archaeological materials. These were almost entirely removed by a team led by Rozaire in the late 1960s (see below), and the floor of the rockshelter now consists of irregular bedrock perched about a meter above a large apron of midden deposited by site occupants on the slope below. To the north of the rockshelter, the ground slopes steeply down to the sea cliff and rocky intertidal below. This slope contains an extensive apron of shell midden extending across an area ca. 20-25 m long, 12 m wide, and roughly 40-50 cm thick. Basal midden deposits dated to the Terminal Pleistocene and Early Holocene cover the slope between the rockshelter and sea cliff forming a discrete, compact, relatively homogenous lens. At the top of the talus, along the rock shelter drip line, finely stratified deposits reach a depth of 1.5 m, with evidence for Middle and Late Holocene occupations overlying the earlier deposits.

Collectors and amateurs conducted the earliest excavations at Daisy Cave in the late 1800s and early 1900s, when the site was plundered with little or no documentation (see Daly 1990; Heye 1921). Charles Rozaire (Los Angeles County Museum of Natural History) led systematic excavations of around 20 percent of the site deposits in 1967 and 1968, including a trench through the midden on the slope in front of the rock shelter opening, the entire interior of the rock shelter, and a test pit in the central chamber of Cave A. A large assemblage of artifacts and faunal remains was uncovered along with the disturbed remains of at least 26 people laid to rest in the Cave A (Rozaire 1978). No $^{14}$C dates were obtained at this time, but Rozaire hypothesized that occupations of Daisy Cave dated to roughly 3-4,000 years ago based on comparative analysis of artifacts. Because the cultural strata are relatively thin and slope downward to the north and east, Rozaire's excavation using arbitrary 6-inch horizontal levels preclude most of the materials he recovered from being assigned to specific cultural components (Erlandson et al. 1996). In addition, the use of relatively large screens (1/4-inch) likely resulted in the loss of many smaller artifacts and faunal remains, such as shell beads and fish bone. Pandora Snethkamp (University of California, Santa Barbara), Daniel Guthrie (Claremont Colleges), and Don Morris (Channel Islands National Park) revisited the site in 1985 and 1986. At this time artifacts were collected from the surface and profiles, sections of Rozaire's trench were cleared and redocumented, two small test pits were excavated inside the cave, and column samples were collected from the walls of one of Rozaire's units near the dripline of the rockshelter. This research effort produced the first stratigraphically controlled excavations at Daisy Cave and the first $^{14}C$ dates for the site, establishing that it was occupied in the Early Holocene and potentially the Terminal Pleistocene.

Further work at Daisy Cave was directed by Erlandson from 1992 to 1998 in response to the National Park Service's concerns about erosion of the site. These investigations were intent on collecting archaeological and paleontological materials, including woven artifacts uncovered in the Early Holocene strata (see Connolly et al. 1995; Norris 1997), and further exploring the lowest levels of human occupation at the site dated to the Terminal Pleistocene. At this time, several 50×100 cm test units were meticulously excavated in the midden deposited in front of the rockshelter, paying close attention to stratigraphic distinctions, and limited explorations were conducted in the walls of Rozaire's unit in Cave A.

More than 60 $^{14}C$ dates securely establish the antiquity of archaeological and paleontological deposits at Daisy Cave (see Erlandson et al. 1996; Erlandson unpublished data). Although these dates span the past 36,000 years, some of these represent paleontological deposits. Owls and other raptors were likely responsible for paleontological deposits underlying archaeological strata in which fossil bird bones and remains of the extinct giant island deer mouse were found in quantity (Collins et al. 2018; Guthrie 1993; Walker 1980). Archaeological materials are present in the upper 50-200 cm of sediments in all areas of the site, representing domestic activities during multiple occupations spanning at least the past 12,000 years (Erlandson et al. 1996). Multiple

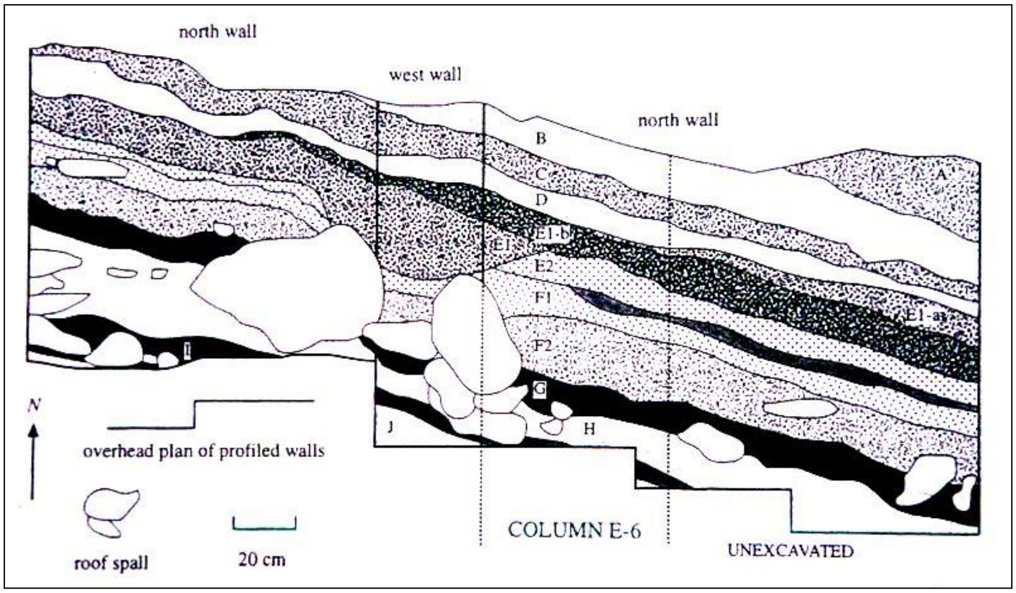

**Figure 1.6.** Stratigraphic profile along the drip line of the Daisy Cave rockshelter (drawn by M. Tveskov; reproduced from Erlandson et al. 1996).

cultural strata identified along the drip-line of the rockshelter have delineated six cultural components (Table 1.1) including one dated to the Terminal Pleistocene (~12,600-10,700 cal BP, Stratum G), two dated to the Early Holocene (~10,290-8500 cal BP, Strata F and E), two dated to the Middle Holocene (~6900 and 4400 cal BP, Strata C and B), and one to the beginning of the Late Holocene (~3600-2800 cal BP, Stratum A) (Figure 1.6). Dating of materials recovered from the upper levels of Rozaire's excavation of the rock shelter interior have identified additional Late Holocene occupations, the youngest of which dates to ~700 cal BP (Erlandson et al. 1996).

Stratum G has been identified along the rockshelter dripline. This Terminal Pleistocene component consists of a low-density shell midden comprised of rocky coast shellfish remains, along with a small assemblage of chipped stone artifacts. Stratum G contains the earliest definitive evidence for human use of the site. Strata E and F overlay Stratum G along the rockshelter dripline. These clearly cultural strata appear to have accumulated during several discrete occupations and consist of dense midden deposits including a wide array of faunal remains, a diverse lithic assemblage, and shell, bone, and woven artifacts (Connolly et al. 1995; Erlandson and Jew 2009; Norris 1997; Rick et al. 2001). Overlying Stratum E, Stratum D consists of a thin soil that is mostly devoid of

**Table 1.1.** $^{14}$C dates for Daisy Cave (CA-SMI-261) components used in this study

| **Provenience** | | **Lab number** | **Material dated** | **Measured $^{14}$C age** | **Calendar age range* (cal BP, 2 sigma)** |
|---|---|---|---|---|---|
| **Unit** | **Stratum** | | | | |
| Col. E-6 | A3 | Beta-15619 | Red abalone | 3430±90 | 3200-2750 |
| Col. E-6 | A1 | Beta-49997 | Black abalone | 3510±80 | 3300-2850 |
| Col. E-6 | A3 | CAMS-9095 | Charred twig | 3110±60 | 3450-3170 |
| Col. E-6 | A3 | CAMS-14358 | California mussel | 3820±80 | 3660-3245 |
| Col. E-6 | A1 | CAMS-8864 | Charred twig | 3220±70 | 3610-3255 |
| Col. E-6 | A3 | CAMS-14359 | California mussel | 3940±70 | 3800-3415 |
| TU C/5-6 | B | Beta-122710 | Black abalone | 4570±50 | 4595-4265 |
| Col. E-6 | C | Beta-15620 | Black abalone | 6380±110 | 6800-6295 |
| Col. E-6 | C | Beta-52359 | California mussel | 6500±80 | 6890-6480 |
| Col. E-6 | C | CAMS-8862 | Charred twig | 6000±70 | 7140-6665 |
| Col. D-6 | D | D-AMS 027662 | California mussel | 8340±41 | 8655-8405 |
| Col. E-6 | E1 | CAMS-8866 | Charred twig | 7810±60 | 8850-8425 |
| TU C/5-6 | E1 | Beta-122711 | California mussel | 8370±80 | 8855-8385 |
| Col. E-6 | E1 | CAMS-14379 | California mussel | 8380±60 | 8830-8410 |
| Col. E-6 | E1 | CAMS-14380 | California mussel | 8400±60 | 8850-8440 |
| Col. E-6 | E1 | CAMS-14360 | California mussel | 8440±80 | 8950-8470 |
| Col. E-6 | E1 | Beta-15621 | Black abalone | 8460±100 | 8985-8455 |
| Col. E-6 | E1 | CAMS-14361 | California mussel | 8500±80 | 8990-8545 |
| Unit D6 | E3 | D-AMS 028373 | California mussel | 8647±35 | 9115-8805 |
| Unit D6 | E3 | D-AMS 028372 | California mussel | 8654±33 | 9115-8855 |
| Unit D6 | E4 | D-AMS 028375 | California mussel | 8680±40 | 9190-8895 |
| Col. E-6 | E4 | CAMS-8865 | Charred twig | 8040±60 | 9090-8650 |
| Unit D6 | E4 | D-AMS 028374 | California mussel | 8704±36 | 9205-8955 |
| Col. E-6 | E4 | Beta-15622 | Black abalone | 8730±120 | 9405-8725 |
| Col. E-6 | F1 | Beta-15623 | California mussel | 8900±120 | 9515-9000 |
| Col. E-6 | F1 | CAMS-8867 | Charred twig | 8600±60 | 9695-9484 |
| Unit D-6 | F2 | CAMS-33374 | Marine shell | 9190±60 | 9785-9455 |
| Col. E-6 | F3 | Beta-49948 | California mussel | 9360±90 | 10120-9560 |
| Col. E-6 | F3 | CAMS-8863 | Charred twig | 8810±80 | 10165-9600 |
| Unit D-6 | F2 | CAMS-33519 | Charcoal | 8920±70 | 10225-9780 |
| Col. E-6 | F-G | CAMS-33368 | Charcoal | 8970±60 | 10235-9915 |
| Col. E-6 | F-G | CAMS-33375 | Marine shell | 9620±70 | 10400-9955 |
| Unit 94-E6 | G | CAMS-33369 | Charcoal | 9580±60 | 11150-10725 |
| Unit 94-E6 | G | CAMS-33376 | Marine shell | 10400±60 | 11265-10965 |
| Col. E-6 | G | Beta-52360 | Black turban | 10600±70 | 11730-11180 |
| Col. E-6 | G | Beta-14660 | Red abalone | 10700±90 | 11935-11235 |
| Col. E-6 | G | CAMS-9094 | Charcoal | 10390±130 | 12635-11775 |

*All dates were calibrated using Calib 7.0.4 (IntCal13 and Marine13; Stuiver and Reimer 1993, 2014), and adjusted with a ΔR of 261±21 (Jazwa et al. 2012). All calibrated date ranges were rounded to the nearest five.

cultural material, representing a hiatus in human occupation at Daisy Cave that lasted nearly 2,000 years. Stratum C is a relatively thin (5-15 cm thick) shell midden lens that resulted from a relatively brief human occupation of the site about 6700 years ago. This component encompasses a smaller area than the more extensive strata E and F, but has produced an abundance of faunal remains and a small assemblage of lithic, shell, and bone artifacts, along with a small amount of sea grass cordage. Stratum B is a largely sterile layer separating Strata C and A that marks another occupational hiatus, except for a localized and thin lens of shell midden deposited during a brief occupation dated to ~4450 years ago. Stratum A, dated between 3600 and 2800 years ago, consists of a dense midden deposit that once covered much of the northern slope in front of the site and the rockshelter portion of the site up to a depth of 40 cm. Much of this stratum was removed by Rozaire in the 1960s, but column samples were collected from it by Snethkamp, Guthrie, and Morris in the 1980s. Most of Stratum A had been lost to erosion by the 1990s, but Erlandson's excavations managed to salvage small amounts of additional data that contribute to the analyses presented here. Even younger Late Holocene components, dated between ~1600 and 700 years ago, were once present inside the rock shelter but were completely removed by Rozaire's excavations. Exceptional artifacts from this layer, including a rare cache feature referred to as a Chumash "bead-maker's kit" (Rozaire 1993), are curated at the Los Angeles County Museum of Natural History.

Multiple researchers and numerous publications have investigated aspects of the Daisy Cave assemblage. An extensive radiocarbon chronology for Daisy Cave was published more than 20 years ago (Erlandson et al. 1996). Carbonized macrobotanical remains from Column E-6 were described by Reddy and Erlandson (2012), revealing the presence of unidentified charcoal in cultural and non-cultural strata, along with fragments of geophytes (Brodiaea-type corms) in Strata A, E, and F. The presence of these charred edible plant remains suggests that Paleocoastal and Island Chumash people utilized geophytes and other plants for at least 10,000 years. Lithic artifacts from the Early Holocene layers reveal information concerning early biface technologies on the Channel Islands, contributing to our understanding of Paleocoastal maritime technologies (Erlandson and Jew 2009). Woven eelgrass artifacts, knots, and cordage from Early Holocene components provide some of the only known examples for the region due to the exceptional preservation at this site (Connolly et al. 1995; Norris 1997). Analysis of a select sample of Early Holocene fish bone revealed some of the earliest evidence for intensive fisheries in the Americas (Rick et al. 2001) and direct dates on circular shell fishhooks from this and other Channel Island sites helped define the Late Holocene chronology for the introduction of this specialized technology (Rick et al. 2002). Paleontological deposits, including bird remains (Collins et al. 2018) and bones of the extinct giant island deer mouse (Shirazi et al. 2018) have also been recently analyzed. Additional analyses and publications pertinent to specific research projects examined in this dissertation are discussed in the sections below.

### *Cave of the Chimneys: Description, History of Investigation, Stratigraphy, and Chronology*

Cave of the Chimneys is located on the northeast side of Bay Point, roughly 100 m southeast of Daisy Cave. The site consists of a large open rockshelter facing the sea to the east, with a steep drop roughly 12 m to a wave swept rocky intertidal area below. Marine erosion under a high interglacial sea stand likely shaped the rockshelter during the Pleistocene. The geologic composition of the rockshelter includes cobble and pebble conglomerate cemented in a sandy matrix with numerous cracks and fissures along the ceiling and walls. The 10 × 12 m rockshelter is open and well-lit by a large opening at the mouth and a 1.5 m wide “chimney,” or skylight, in the roof. The site is accessible via a narrow ledge at the southeast edge of the rockshelter. Sediments fill the site to within a meter of the roof in the back and extend beyond the drip-line, spilling down slope at the mouth of the shelter. Human remains were found on the surface of the site, in the innermost portion of the shelter and the eroded slope below. Archaeological deposits are extremely well-preserved and finely stratified despite being somewhat reduced by erosion, natural disturbances, and taphonomic processes.

Archaeological excavations at Cave of the Chimneys have been limited in comparison to Daisy Cave, but a thorough analysis of virtually all recovered materials has resulted in a high-resolution record of more than 7,000 years of near-continuous use of the site, from roughly 8,400 to 1,000 years ago (Ainis 2012). In 1994, Erlandson and

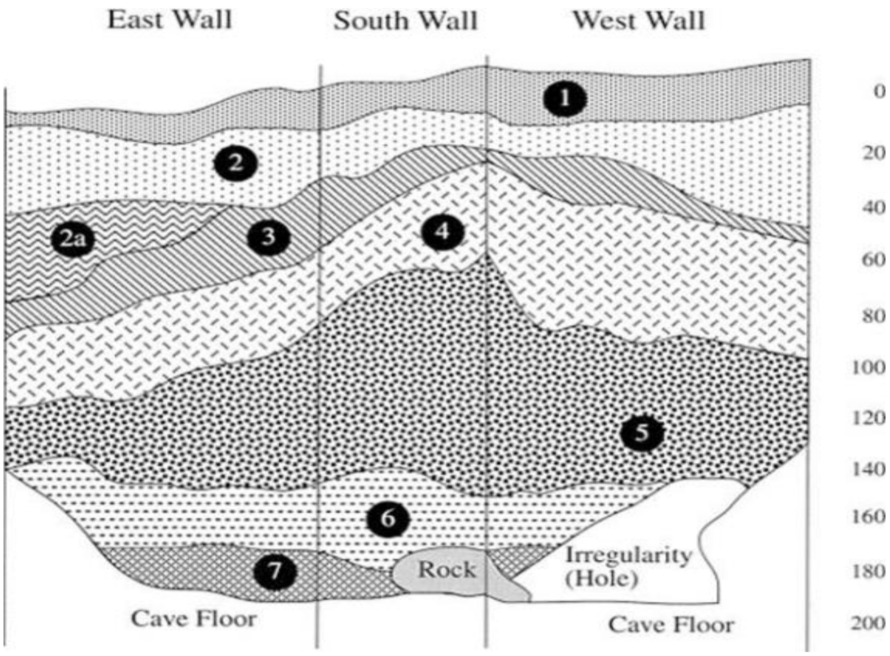

**Figure 1.7.** Stratigraphic profiles from Unit 1, Cave of the Chimneys (Reproduced from Vellanoweth et al. 2003).

Kennett excavated three 20 × 20 cm wide exploratory probes to determine site chronology, extending to a depth of no more than 50 cm and $^{14}$C samples dated to roughly 4400 cal BP (Kennett 1998). In 1997-1998 a 0.5 × 1 m unit (Unit 1) was excavated by René Vellanoweth, Jon Erlandson, Torben Rick, and colleagues under a rock overhang along the northwest wall of the rockshelter. Excavations followed depositional strata, with thicker components being further divided into 10 cm levels. All sediments from Unit 1 were screened over 1/8-inch mesh in the field and all residuals were retained along with 4-liter bulk samples collected from each stratum and level, which were processed over finer sieves under laboratory conditions (see Ainis et al. 2011).

Seven strata were identified in Unit 1 at Cave of the Chimneys (Figure 1.7), with the uppermost stratum (Stratum I) containing only a very small amount of faunal remains. Stratum II is a dense cultural midden with abundant faunal and artifactual remains. It was excavated in four 10 cm levels and $^{14}$C results from each level reveal stratified dates of ~3800 to 2200 cal BP. Stratum III is a thin cultural deposit with abundant charcoal and midden remains that dated to ~4100 cal BP. Stratum IV was dated between ~4000 and 4300 cal BP and is unique in the large amount of sea urchin tests comprising the bulk of

**Table 1.2.** $^{14}$C dates for Cave of the Chimneys (CA-SMI-603) components used in this study

| Provenience | | Lab number | Material dated | Measured $^{14}$C age | Calendar age range* (cal BP, 2 sigma) |
|---|---|---|---|---|---|
| Unit | Stratum/ Level | | | | |
| 1 | I | OS-86232 | California mussel | 1700±25 | 1065-910 |
| 1 | II/1 | OS-86059 | Marine shell | 2800±25 | 2300-2120 |
| 1 | II/2 | OS-86060 | Marine shell | 2930±30 | 2481-2285 |
| 1 | II | Beta-115556 | Red abalone | 2980±60 | 2660-2300 |
| 1 | II/3 | OS-86061 | Marine shell | 3560±25 | 3245-3015 |
| 1 | II/4 | OS-86062 | Marine shell | 4010±25 | 3800-3580 |
| 1 | III | Beta-115557 | Red abalone | 4270±70 | 4235-3820 |
| 1 | IV/1 | D-AMS 32265 | California mussel | 4329±34 | 4230-3965 |
| 1 | IV/2 | Beta-115558 | Red abalone | 4450±70 | 4480-4070 |
| 1 | V | Beta-115559 | Red abalone | 4480±60 | 4495-4130 |
| 1 | V | Beta-129100 | Red abalone | 4490±60 | 4500-4140 |
| Bulk Sample | VC | D-AMS 27655 | California mussel | 4527±28 | 4495-4260 |
| 1 | VB | Beta-136694 | California mussel | 4570±70 | 4675-4215 |
| Bulk Sample | VC/VI | D-AMS 12491 | California mussel | 5675±28 | 5890-5690 |
| 1 | VI | D-AMS 27658 | California mussel | 5972±29 | 6220-5995 |
| 1 | VI | D-AMS 27657 | California mussel | 5997±31 | 6260-6025 |
| 1 | VI | Beta-129101 | Red abalone | 6390±70 | 6730-6390 |
| 1 | VII | UCIAMS 206754 | Eel grass knot | 7280±20 | 7570-7440 |
| 1 | VI | Beta-136694 | *Olivella* bead | 7300±70 | 7655-7410 |
| 1 | VI | D-AMS 27656 | California mussel | 7620±35 | 7925-7720 |
| 1 | VII | Beta-122713 | Abalone | 7650±70 | 7985-7685 |
| 1 | VII | D-AMS 27659 | California mussel | 7762±32 | 8050-7860 |
| 1 | VII | Beta-136696 | California mussel | 7740±80 | 8135-7765 |
| 1 | VII | D-AMS 27661 | California mussel | 7785±36 | 8110-7895 |
| 1 | VI | Beta-136695 | California mussel | 7880±60 | 8215-7935 |
| 1 | VII | D-AMS 27660 | California mussel | 8041±35 | 8340-8160 |
| 1 | VI | Beta-122712 | California mussel | 8120±80 | 8500-8150 |

*All dates were calibrated using Calib 7.0.4 (Marine13; Stuiver and Reimer 1993, 2014), and adjusted with a ΔR of 261±21 (Jazwa et al. 2012). All calibrated date ranges were rounded to the nearest five.

the deposit with almost no soil matrix. Stratum V is a substantial cultural deposit, ranging from 20-50 cm thick and dated between ~4200 and 5800 cal BP. Strata VI and VII contained 341 fiber artifacts, in the form of sea grass (*Phyllospadix* spp.) knots and cordage fragments, along with 25 spire-ground *Olivella biplicata* beads (Vellanoweth et al. 2003). These two strata are very similar in faunal constituents and radiocarbon dates range from ~8400 to 6000 cal BP showing some unconformity in deposition at the base of the deposits in materials dated to between ~8400 and 8100 cal BP. Recent AMS radiocarbon analysis conducted for this dissertation suggests that Stratum VII is more narrowly defined as ranging from ~8300 to 7800 cal BP, with dated samples from Stratum VI ranging from ~8400 to 6000 cal BP.

Previously published research from Cave of the Chimneys includes analysis of Early Holocene cordage and shell artifacts (Vellanoweth et al. 2003), quantification of select vertebrate remains from the Early Holocene strata (Rick et al. 2005b), quantification of a sample of faunal remains from Strata II-IV (Vellanoweth et al. 2002), and analysis of faunal remains from column samples representing all cultural strata (Ainis et al. 2011). An impressive collection of sea grass cordage from the Early Holocene strata at Cave of the Chimneys constitutes the earliest evidence for a predominantly S-twist assemblage on the Northern Channel Islands, a style perceived as more common on the southern islands and contrasting with patterns from the Daisy Cave assemblage which was dominated by Z-twist remains (Vellanoweth et al. 2003). Preliminary results for the faunal assemblage from the Early Holocene strata at Cave of the Chimneys revealed an emphasis on rocky intertidal shellfish and fish from nearshore rocky and kelp forest habitats. Faunal remains presented in Vellanoweth et al. (2002) and Ainis et al. (2011) follow the general economic trends for the islands, although the relative importance of primary taxa varies between samples underscoring the inherent bias represented by different degrees of faunal sampling.

## **Project Overview**

Evidence that the New World was populated in part by maritime peoples who followed a coastal migration route has grown in recent decades. My examination of islander lifeways and shifts in maritime subsistence and mobility patterns at Bay Point will contribute to larger questions related to the antiquity and diversity of aquatic resource use, the perceived marginality of island environments, and some of the earliest maritime people of the Pacific Coast. Archaeological research has demonstrated that the Northern Channel Islands were colonized at least 13,000 years ago by seafaring Paleoindians, whose descendants occupied the islands until the early 1800s. Questions remain however, about individual site function, seasonality of occupation, mobility patterns, changes in resource harvesting practices, and human impacts on marine ecosystems. I explore these topics through research that uses AMS $^{14}C$ dating and stable isotope analysis of marine shells, detailed zooarchaeological analysis incorporating biological and ecological data, and statistical measures. My research combines archaeological, archaeometric, ecological, and paleoenvironmental data to evaluate a range of site specific and regional hypotheses concerning cultural and ecological shifts in the Bay Point area throughout more than 11,000 years of human occupation.

With some of the oldest shell middens in North America and the earliest record of intensive fishing in the region, these assemblages have contributed to reconstructing trans-Holocene records of cultural, technological, and ecological change along the Pacific Coast. Stable isotope analysis ($\delta^{18}O$ and $\delta^{13}C$) provides inferences about human occupation cycles, seasonality of mussel collecting, ecological changes, and the adaptive shifts of coastal foragers by providing a proxy for small-scale oceanographic variability in nearshore habitats where human harvesting was occurring. These data provide a historical ecological context for investigating cultural and environmental changes on northeastern San Miguel Island throughout the Holocene and comparison of site-specific trends to broader regional patterns. In addition, this dataset has broad potential to contribute to current management and conservation challenges facing marine ecologists in this era of rapid climatic change by providing a long-term baseline for Terminal Pleistocene and Holocene shifts in species composition and the structure of local ecosystems.

As noted previously in this chapter, various investigations have occurred at these sites over the past 100 years, but materials analyzed in this study are from careful excavations undertaken in the 1980s and 1990s. In addition to several site-specific studies, selected data from Cave of the Chimneys and Daisy Cave have been incorporated into island-wide studies documenting regional patterns on the Channel Islands. These studies include changes in maritime technologies and subsistence through time (Connolly et al. 1995; Rick et al. 2002, Vellanoweth et al. 2003), ecological interactions between human harvesters and nearshore marine ecosystems (Erlandson et al. 2005b), analyses demonstrating patterns in human induced impacts on key shellfish species through time

(Erlandson et al. 2008d, 2011b, 2015a), long-term resiliency of shellfish taxa on the Northern Channel Islands (Braje et al. 2009, 2012; Erlandson et al. 2009), and region-wide syntheses of archaeological patterning (e.g., Erlandson et al. 2004; Kennett 2005; Rick et al. 2005).

The goal of my study is to add to previously published analyses by identifying and analyzing materials that were not previously reported. The hope is that this study results in a narrative capable of filling in the gaps of previous research, telling the tale of these important sites with all available information. The specific aspects of my study are outlined in the sections that follow. In planned post-doctoral research, I will also add comprehensive analyses of shellfish and fish remains from the two sites, detailed studies that will help in the production of a published monograph detailing the wealth of information they have provided for understanding the archaeology and historical ecology of California's Channel Islands.

## Trans-Holocene SST Reconstruction, Settlement, and Seasonality at Bay Point

Stable isotope (e.g., $\delta^{18}\mathrm{O}$) analysis of marine mollusks is a proven method for reconstructing local nearshore oceanographic conditions (e.g., SST and salinity) and for defining the seasonality of shellfish harvesting. When combined with other faunal and artifactual data sets, such analyses expand the types of information that can be gleaned from shellfish remains and are useful for reconstructing settlement patterns and nearshore paleoecology (e.g., Andrus 2011; Colonese et al. 2011; Jew et al 2013a, b, 2014; Kennett and Voorhies 1995; Mannino et al. 2003; Shackleton 1973). On the Northern Channel Islands, recent $\delta^{18}\mathrm{O}$ analyses have contributed to reconstructions of SST, seasonality of mussel and abalone harvesting, and duration of site occupation, including evidence suggesting that the islands were inhabited year round in the Early Holocene (Flores 2014, 2016; Glassow et al. 2012; Jew et al. 2013 a, b, 2014; Kennett 2005; Rick et al. 2006; Robbins et al. 2013; Thakar 2014; Watts 2013). Recent research has commented on the differential effects of nearshore SST and marine productivity on harvested shellfish when undertaking human impact studies (Flores 2017; Thakar et al. 2015). The extensive temporal depth and localized nature of my study will provide a detailed data set to examine the interwoven effects of small-scale oceanographic characteristics (i.e., nearshore SST), variations in intertidal environments, and their influence on the ecology of harvested shellfish species to better understand the effects of human foraging.

My dissertation research includes a ~10,000-year sequence of stable isotope data showing localized variation in nearshore SST from two adjacent sites at Bay Point. In Chapter II, I use stable isotope analysis of mussel shells from archaeological assemblages to construct a site-specific nearshore sequence for Bay Point and explore correlations between local paleo-SST and archaeological data. Through an integrative approach using isotopic analysis, radiocarbon chronologies, and statistical analysis, I will: 1) construct a high resolution trans-Holocene nearshore SST record for the area; 2) compare and evaluate the relationship between nearshore SST and the Santa Barbara Basin cores; 3) examine potential relationships between $\delta^{18}O$ and $\delta^{13}C$ in archaeological and modern mussel shells; and 4) evaluate potential evidence for shifts in site function through time. Species-specific biological and ecological data are synthesized in my interpretation of correlations between archaeological shellfish data and results of isotopic analysis such as SST. This inclusive approach, combining biological, ecological, oceanographic and archaeological datasets contributes to our understanding of the complex and dynamic interactions between small-scale variation in localized nearshore environments and archaeological patterns of long-term intertidal foraging.

Previous analysis of mussel shells from one of the Early Holocene components at Daisy Cave (Stratum E1 ~8600 cal BP) suggested the site was occupied primarily in summer and fall, and to a lesser degree in winter; with SST up to 4° warmer than the 50 year running average recorded in the Santa Barbara Bight marine core (Jew et al. 2013c:6). I conducted stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) analysis on a sample of modern mussels from the Bay Point intertidal area and more than 100 archaeological mussel shells from all the cultural strata at Daisy Cave and Cave of the Chimneys; creating a high resolution, trans-Holocene nearshore SST reconstruction for northeast San Miguel Island. The occupational histories of these sites contribute to our understanding of settlement and mobility patterns on the islands and potential shifts in seasonality of use between the Early and Late Holocene occupations.

Evidence for diachronic shifts in seasonal procurement patterns of marine mollusks may indicate changes in site function and occupation cycles, which might be tied to changes in mobility patterns on the island and shifts in behavioral adaptations to dynamic environmental conditions. For instance, the Middle Holocene (~7-3 kya) has been highlighted as containing the warmest climatic phase (peak at ~7.5 kya, but extends to ~3 kya) and the most variability in ocean temperatures (~5.5 to 3.5 kya, with peak at ~4.2 kya) represented in Santa Barbara Basin cores (Fisler and Hendy 2008; Friddell et al. 2003). Archaeologically, this is a time of human population growth on the islands, development of innovative technologies, and a broadening of diet breadth (Kennett 2005). Isotopic records and shifts in site use and harvesting patterns at Bay Point will add to our understanding of this and other climatically and culturally dynamic periods on the Channel Islands. As these data are compared to other isotopic studies for the Northern Channel Islands, they contribute to a growing data set that will help archaeologists decipher the nature of site occupation histories, mobility patterns, and settlement on the islands during the ~12,000 years of Native habitation.

## Potential Use of Marine Macrophytes by Native Islanders

Being surrounded by some of the lushest and most extensive kelp forests on the planet fostered the expansion and growth of Native Channel Islander populations throughout the Holocene. Although terrestrial faunal and floral communities are more limited in diversity when compared to the neighboring mainland (but see Gill et al. 2019a), the marine ecosystems of the Southern California Bight provided a wealth of resources that clearly sustained island populations for millennia. The widespread and abundant shell middens of the Channel Islands attest to the prolific harvesting and use of marine mammals and birds, fish, and a variety of mollusks, crustaceans, and echinoderms from nearshore and kelp forest habitats. The easily accessible array of kelps, seaweeds, and seagrasses were also likely harvested and utilized for a variety of dietary, medicinal, and technological purposes.

In chapter III, I summarize the extent of human use of seaweeds on a global scale for thousands of years and highlight the nutritional characteristics of some of the more common seaweeds in the region, suggesting the likelihood they were used by Native Islanders despite sparse evidence. Although Dillehay et al. (2007) identified several types of seaweeds at the ~14,000 year old site of Monte Verde near Chile’s Pacific Coast, archaeologists have paid scant attention to the potential dietary importance of seaweeds on the Channel Islands and around the world, in part because they preserve poorly in most archaeological contexts. I review a wealth of ethnographic and ethnohistoric accounts from the west coast of the Americas alluding to the dietary and technological uses of seaweeds along the Pacific Coast. Potential methods for identifying kelps, seaweeds, and seagrasses in the archaeological record are also explored. In the rare instance of exceptional preservation, direct identification of marine macrophytes may be possible; but indirect evidence inferring their use is also explored as required by organic preservation biases.

## Indirect Evidence for Human Harvesting of Seaweeds and Seagrasses

In chapter IV, I present a previously published study in which I identified small non-dietary shells that are known kelp and seagrass associates, suggesting they may be used to infer human harvesting of these perishable resources in the past. The fragile nature of marine macrophytes lacking in hard parts capable of preserving in most archaeological contexts requires novel approaches and the creation of methods whereby we may infer the harvesting and use of these important and plentiful resources in the past. My detailed analysis and identification of dozens of species of non-dietary marine mollusks in archaeological assemblages from Cave of the Chimneys and a large Middle Holocene midden site on San Nicolas Island revealed several taxa that are known kelp and seagrass associates. The presence of these species in a rockshelter lead me to infer the harvesting and transport of seaweeds and seagrasses to the site and their densities and relative abundances suggest shifting patterns in the procurement and use of these resources through time. I argue that the presence of these small seaweed and seagrass associates can be used as proxies for the collection and use of marine macrophytes in the past.

In this study, identified small gastropods were placed into four categories based on habitat and ecological association. This allows these specimens to be used as paleoenvironmental proxies, representing the types of intertidal habitats human foragers were collecting resources from. In addition to those associated with seaweeds and seagrasses, species associated with rocky boulders, sand and gravel substrate, and several mollusk commensals were also identified and quantified. Although no drastic shifts in nearshore habitats were noted for Bay Point between the Early and Late Holocene in this study, this method has the potential to reveal significant changes in nearshore habitats through time when they occur. Identified taxa will change along various coastlines, but the approach and method can be utilized anywhere.

## Sea Urchins: Historical Ecology and Morphometrics

In chapter V, I present a morphometric and statistical analysis of sea urchins that can be used to reconstruct harvested populations of this key kelp forest inhabitant in the past. Shellfish such as abalone and mussel are often found whole in well preserved contexts on California's Channel Islands, but the fragile shells (tests) of echinoderms like sea urchins are difficult to excavate without extensive fragmentation. Two main species of urchin (red and purple, *Mesocentrotus franciscanus* and *Strongylocentrotus purpuratus*) inhabit nearshore island waters but distinguishing their remains in archaeological contexts has long been problematic. Being that sea urchins can be a high ranking shellfish at many coastal middens, with extensive "urchin lenses" occurring in many Channel Island sites (Erlandson et al. 2004; Sharp 2000) including Cave of the Chimneys (Stratum IV; Ainis 2012), constructing a formula for species differentiation and individual size estimates greatly contributes to regional studies.

I developed a method for estimating sizes of harvested sea urchin from archaeological middens using measurements of sea urchin hemipyramids. There are 10 hemipyramids making up five pyramids in the area known as the Aristotle's Lantern in the interior of each urchin. These are often found in archaeological contexts in fair condition, intact enough to allow for a length measurement. I purchased, macerated, and measured more than 2100 hemipyramids from 238 modern purple and red sea urchins of varying sizes. I use analyses of covariance (ANCOVAs) based on these measurements to create a regression formula that is used to estimate the sizes of harvested sea urchin found in archaeological contexts at Cave of the Chimneys.

This project assesses concerns about identifying sea urchin species in the archaeological record and quantifies harvested sea urchin using size and age profiles to examine harvesting trends through time and the relative health of nearshore kelp forest ecosystems at Bay Point. The creation of a formula for estimating sizes of harvested sea urchin has significant implications for archaeological and biological researchers working on the Channel Islands and elsewhere. Being a keystone species of the kelp forest ecosystem, sea urchins play a pivotal role in the health of kelp patches, which form the basal habitat for the highly productive nearshore environments encircling the islands. Archaeological data sets such as the ones I analyze here can provide deep historical perspectives of sea urchin harvesting that can inform current management strategies.

### A Holocene Record of Human Interactions with Nearshore Ecosystems at Bay Point, San Miguel Island

In my final chapter, I summarize the broader implications of my findings for understanding the archaeology and historical ecology of the Bay Point area and San Miguel Island, as well as the broader Channel Islands region throughout the last ~12,000 years. These include the implications for a wide range of topics, ranging from the general productivity of marine ecosystems and resources (including seaweeds) for human foragers, the Kelp Highway Hypothesis and the peopling of the Americas, to the methods utilized to reconstruct the past, and the importance of archaeological data for historical ecology, restoration biology, and conservation efforts in island and coastal regions today. Methods refining sea urchin identification and quantification are combined with data acquired through zooarchaeological and archaeometric studies to piece together as much of this fragmented record as possible. Suggestions for incorporating archaeological faunal data sets into modern kelp forest data platforms (i.e., data websites) is also discussed as a viable way for creating baseline data for specific kelp forest ecosystems using the archaeological record.

The following chapter presents a proxy for paleoenvironmental reconstruction (i.e., SST) of nearshore environments spanning the Holocene through an extensive stable isotope ($\delta^{18}$O and $\delta^{13}$C) analysis of marine shells from all cultural components at Daisy Cave and Cave of the Chimneys. This chapter sets the stage for discussion of long-term changes in kelp forest and other nearshore ecosystems around the Channel Islands and more detailed discussion of select faunal remains from these archaeological sites.

# CHAPTER II:

## A TRANS-HOLOCENE NEARSHORE PALEO-SEA SURFACE TEMPERATURE RECORD FOR BAY POINT, SAN MIGUEL ISLAND, CALIFORNIA

### Introduction

Complex oceanographic factors in the Southern California Bight foster some of the most productive kelp forest and nearshore intertidal habitats along the Pacific Coast of North America (Blanchette and Gaines 2007; Blanchette et al. 2007), and may have facilitated the southward dispersal of early coastal inhabitants into the New World (Erlandson et al. 2007, 2015b). Human colonization of the Americas occurred during the Terminal Pleistocene, a time of extreme environmental and climatic fluctuations as the global climate transitioned from the Last Glacial Maximum (LGM) to more moderate Holocene climates. Analysis of cores drilled through seafloor sediments off the Pacific Coast provide some data on fluctuations in general marine productivity through time (Friddell et al. 2003, 2004; Kennett 2005; Kennett and Kennett 2000; Mortyn et al. 1996; Pak et al. 2004), but it is not clear to what degree such changes impacted maritime peoples relying on a mix of nearshore and terrestrial resources.

Our understanding of human adaptations to coastal environments during this time period is limited by uncertainties about the nature of localized paleo-oceanographic shifts in nearshore ecosystems. Geochemical analyses, including determining stable isotope composition of marine and freshwater mollusks, have become an essential component of environmental archaeology. Seen as “paleoarchives,” mollusk shells from coastal shell middens are providing a wealth of information on paleo-environments and human behavioral adaptations (see Leng and Lewis 2016 for comprehensive review of this literature). Specifically, comparative analyses of stable isotope composition of modern and archaeological mollusks are proving to be a powerful tool for reconstructing aspects of nearshore oceanographic variability along the Pacific Coast of the Americas throughout the Holocene (Carré et al. 2005; Flores et al. 2018; Galimberti et al. 2017).

Incremental samples taken along a shell's growth axis enable reconstruction of oxygen isotopic ratios, which can be utilized as a proxy for seasonal water temperature changes through the life of a mollusk. In addition, readings from the final growth increment of a mussel's shell indicate surface water temperature at the time the mollusk died or was collected by human foragers. Comparing such values with contemporary seasonal shifts in sea surface temperatures (SST) and archaeological ranges indicates the season of the shell's collection. Archaeologists working in coastal settings around the globe use stable isotope analysis of marine mollusks to investigate paleo-oceanographic conditions related to nearshore ecology such as SST and examine the relationships between these physical conditions and human cultural adaptations including patterns in marine resource procurement and seasonality of harvest (e.g., Andrus 2011, 2012; Carré et al. 2012; Colonese et al. 2012; Flores et al. 2018; Jew et al. 2014; Jew and Fitzpatrick 2015; Mannino et al. 2008).

For several decades, data on SST changes in the Santa Barbara Channel region have been based primarily on the analysis of submarine cores that sampled long sequences of varved sediments from the anoxic offshore Santa Barbara Basin (SBB; see Pisias 1978; Kennett 2005; Kennett and Kennett 2002). For years, archaeologists interpreted cultural changes by comparing them to these generalized records (e.g., Glassow et al. 1984), which were usually based, at best, on the analysis of foraminifera from 50-year or 25-year running averages. Kennett (2005) demonstrated that the Pisias (1978) SST records were problematic, however, and he pioneered the use of revised and higher resolution seafloor core data paired with $\delta^{18}$O data from archaeological shells to reinterpret cultural and paleoecological changes in the Santa Barbara Channel through time. For archaeologists, analyzing marine shells from coastal archaeological sites has two clear advantages to seafloor core studies: (1) the shells come directly from the middens that record cultural changes; and (2) they record SST and other ecological changes in the nearshore habitats that coastal foragers obtain the majority of their marine resources from.

Archaeologists have increasingly used stable isotope analyses of California mussel (*Mytilus californianus*) shells from archaeological contexts as proxies for paleo-SST around California's Channel Islands and as indicators of season of harvest for intertidal shellfish (Jew et al. 2013a, b, 2014; Glassow 1994; Glassow et al. 2012; Flores 2016; Jazwa et al. 2012, 2015; Rick et al. 2006; Robbins et al. 2013). Isotopic analysis of mussel shells from middens on Santa Rosa and San Miguel islands revealed short-term extreme temporal fluctuations in SST that may indicate greater frequencies of El Niño events after 4500 cal BP (Rick et al. 2006) as proposed by Kennett et al. (2007). Strata V-III (~5800-3900 cal BP) at Cave of the Chimneys have been dated to this time period, providing an ideal opportunity to evaluate hypotheses about mid-Holocene increases in the frequency and intensity of El Niño events.

Isotopic signatures of ENSO events are challenging to tease out, but Carré et al. (2005) found negative isotopic peaks ($\delta^{18}$O amplitudes of 1.3‰ and 3.5‰) followed by cycles of low amplitude (≤0.8‰ and 1-1.3‰) in isotopic signatures of the surf clam (*Mesodesma donacium*), suggestive of extreme short-term spikes in SST along the Pacific Coast of Chile, potentially signaling ENSO events. This potential has not been examined with California mussel shells. However, both species are characterized by rapid growth in the first three years with a potential lifespan of over 10 years (Coe and Fox 1942; Tarifeño 1980) and exhibit general similarities in life cycle patterns that might allow similar signals to be recorded in mussel shells. Furthermore, studies using spectral and wavelet analyses of $\delta^{18}$O data have shown that surface ocean variability is greatest during warmer climatic phases (Friddell et al. 2003), suggesting that we should see more localized variation in nearshore SST reconstructions during warmer periods. Glassow et al.'s (2012) results, however, suggest that variation in annual temperature ranges was greater during periods of lower overall water temperatures. The lengthy temporal nature of the Bay Point datasets, encompassing the full range of trans-Holocene climatic shifts, makes it ideally suited to evaluate long-term patterns in nearshore SST.

In this study, I analyzed stable oxygen ($\delta^{18}$O) and carbon ($\delta^{13}$C) composition of two modern and 55 California mussel shells from ten chronologically discrete archaeological components preserved in two adjacent rockshelter sites on the northeast coast of San Miguel Island. These data are used to reconstruct the longest nearshore SST sequence for the region. Coupling these isotopic data with zooarchaeological data reflecting shifts in human harvesting intensity through time (i.e., changes in sizes, relative abundances, and types of harvested mollusks, and oscillations in fishing intensity) allows me to test to what degree such changes resulted from human harvesting pressure, environmental shifts (i.e., regional SST, ENSO events), or variability in small-scale oceanographic forces (i.e., nearshore SST and upwelling). Data on variation in mean shell sizes at Daisy Cave and Cave of the Chimneys through time have contributed to several papers examining the impacts of human harvesting of shellfish and other nearshore organisms through time (Erlandson et al. 2008d, 2012; Rick et al. 2008). Recent research has commented on the differential effects of nearshore SST and marine productivity on harvested shellfish when undertaking human impact studies (Flores 2016; Thakar et al. 2017). The extensive temporal depth and localized nature of my study provides a detailed dataset to examine the interwoven effects of small-scale oceanographic characteristics (nearshore SST), variations in intertidal environments, and their influence on the ecology of harvested shellfish species to better understand the effects of human foraging.

My research tests hypotheses evaluating the relationship between temporal changes in nearshore SST and upwelling and in the future will be compared to shifts in density and composition of faunal assemblages and used to reconstruct season of harvest data for mussel shells from multiple components at Bay Point spanning ~10,100 to 2000 cal BP (see Tables 1.1 and 1.2). SBB SST curves have been widely used as a proxy for past water temperature fluctuations around the Channel Islands, but isotopic studies in this area have noted up to 5º differences in seasonal patterning of SST at different depths in the water column (Pak et al. 2004:7). Recent archaeological research on Santa Cruz, Santa Rosa, and San Miguel islands has also identified localized SST variations around the islands (Flores 2016; Glassow et al. 2012; Jew et al. 2013a, 2014; Rick et al. 2006), suggesting that similar trends exist on all of California's Channel Islands. At the onset of this research, I hypothesized that the Bay Point paleo-SST sequence, which considers nearshore variability and shallower waters, would vary independent of the SBB sequence. Ocean floor bathymetry, colliding currents and variable upwelling around the islands, the latitudinal gradient of colder to warmer ocean temperatures from northwest to southeast in the Santa Barbara Channel region, and the location of the SBB core in an area where warm and cold currents converge (Kennett et al. 2007) to form complex eddie systems (Bassin et al. 2005), imply that SST values from intertidal mussels will differ significantly.

## Molluscs as Environmental Proxies

### Oxygen Isotopes in Molluscs

Urey (1947) first demonstrated that the stable oxygen isotopic composition of calcium carbonate deposited by marine mollusks was predominantly temperature dependent and thus of value as a paleothermometer. Subsequent studies of modern marine mollusks from known environments confirmed that oxygen isotopic analysis is an effective method for reconstructing SST (e.g., Craig 1969; Epstein 1953; Killingley 1981; Killingley and Berger 1979; Shackleton 1969, 1973). Since then, oxygen isotopic analysis of molluscan shell carbonate has become an established technique for determining SSTs and the season of prehistoric shellfish harvesting in archaeological specimens (see Leng and Lewis 2016).

The method was initially recognized as a powerful tool for paleo-environmental reconstruction because oxygen isotopic ratios in calcareous fossils contain information about the physical and chemical environment of their growth, specifically the temperature dependent ratio of $^{18}O$ to $^{16}O$ in sea water preserves in calcareous fossils, such as mollusks (Epstein et al. 1951, 1953; Wefer and Berger 1991). Two environmental factors contribute to the isotopic composition of shell carbonate in marine mollusks: the isotopic composition of seawater and water temperature. The isotopic composition of sea water is affected by salinity in coastal settings and Global Ice Volume in the open ocean (Sharp 2007). As San Miguel Island contains no substantial rivers or streams and is a fairly small island located at the north westernmost extent of the Southern California Bight, Global Ice Volume likely contributes most in this instance.

Equilibrium oxygen isotope precipitation of calcium carbonates decreases by about 0.24‰ for each 1ºC rise in water temperature (Craig 1969). The empirical relationship between water temperature and the oxygen isotope composition of various carbonate minerals (i.e., calcite, aragonite) have been explored in a number of studies along with fractionation behavior of inorganic and biogenic calcites (e.g., Epstein et al. 1953; Craig 1969; Grossman and Ku 1986; Kim and O’Neil 1997; Leng and Pearce 1999). As the isotopic fractionation factor between carbonate and water is temperature dependent, the oxygen isotopic composition of carbonate is a function of temperature. A paleotemperature equation was developed by Epstein et al. (1951, 1953) based on oxygen isotopic measurements of mollusk shell carbonate precipitated at known water temperatures. In the equation:

$$T(^{o}C) = a+b(\delta^{18}O_{cc}-\delta^{18}O_{sw}) + c(\delta^{18}O_{cc}-\delta^{18}O_{sw})^{2}$$

$\delta^{18}O_{cc}$ is the oxygen isotopic ratio of the carbonate, expressed as a deviation in ‰ (parts per mil) from a standard carbonate (PeeDee Belemite [PDB] or Vienna PeeDee Belemite [VPDB]) and $\delta^{18}O_{sw}$ represents the oxygen isotopic composition of the water expressed in a similar fashion, as a deviation from standard mean ocean water (smow). To solve the equation for temperature (T), the value of the water must be known. When the delta value for the water is constant, the oxygen isotopic ratio increases/ decreases by approximately 0.2‰ for every 1°C increase/decrease in water temperature. Thus, in the open ocean where the composition of seawater has been relatively stable since the middle Holocene (~6000 years to the present day; Fairbanks1989), oxygen isotopic measurements of calcium carbonate extracted from the sequential growth increments of mollusks reflect seasonal fluctuations in water temperature.

Paleotemperature equations for inferring SSTs have been refined for calcite and aragonite, two different mineral phases of calcium carbonate, which forms the structure of marine mollusks. Epstein et al. (1953) based their equation on organically precipitated calcium carbonate in mollusks of the genus *Haliotis*, a large gastropod with a complex mineral structure consisting of both aragonite and calcite. Horibe and Oba (1972) determined that the relationship between SST and $\delta^{18}O$ is different for aragonite and calcite based on two pelecypods from Mutsu Bay, Japan. A large body of research has subsequently been carried out to refine formulae and corrections when using the oxygen isotope ratio of calcite from marine mollusks to reconstruct paleoenvironmental conditions (see Pearson 2012 for comprehensive review).

The season of molluscan death can also be estimated from the final growth increment. The methods for extracting seasonal information from mollusk shells were initially worked out by Shackleton (1973) and have changed little since. Calcium carbonate samples are extracted along a shell's growth axis from the growth margin towards the hinge. Using specimens of the limpet, *Patella tabularis,* collected alive from Nelsons Bay Cove, South Africa, Shackleton determined that oxygen isotopic changes through the growth of mollusk shells paralleled seasonal fluctuations in temperature and that the shell margin samples accurately reflected the season of molluscan death. Based on this study, Shackleton (1973) outlined a number of criteria that should be met to make seasonal temperature determinations using oxygen isotopic analysis. First, shell growth must take place under conditions of isotopic equilibrium with the surrounding water. Second, the isotopic composition of the water in which the shellfish lives must remain constant (in relation to salinity) throughout the year. Third, the shell must precipitate carbonate throughout the year at a relatively fast rate. Finally, the seasonal temperature range must be greater than week-to-week variations in water temperature.

Additional research has focused on establishing the precision of the oxygen isotopic method for determining seasonality. Based on a study of modern and archaeological *Mytilus californianus* specimens from the California Coast, Killingley (1981) proposed that the month of prehistoric shellfish collection can be determined by statistical treatment of oxygen isotopic data. Bailey et al. (1983; also see Deith 1985) argued, in contrast, that determining the season of molluscan death to the month was unrealistic because of known oxygen isotopic differences between species and regional climatic variation through time. Numerous studies have utilized isotopic signatures from archaeological California mussel shells to infer season of harvest data in Channel Island middens (e.g., Glassow et al. 2012; Jew et al. 2013a, b, 2014; Kennett 2005; Rick et al. 2006; Robbins and Rick 2006). I am conducting additional stable isotope analyses on marine mollusk shells from Bay Point sites and will include a season of harvest study in future research.

## Carbon Isotopes in Molluscs

Carbon isotope ratios ($^{13}$C/$^{12}$C, used to derive $\delta^{13}$C) are collected from molluscan shell carbonate along with oxygen isotope ratios ($^{18}$O/$^{16}$O, used to derive $\delta^{18}$O) and in spite of complexities involved in determining the source(s) of all represented shell carbon, shell $\delta^{13}C$ has also been shown to reflect environmental conditions (Leng and Lewis 2016; McConnaughey and Gilliken 2008; Spero et al. 1997). $^{13}C/^{12}C$ ratios are driven by the relative proportions of dissolved inorganic carbon (DIC) in sea water and physiological processes like respiration and symbiont photosynthesis (Spero et al. 1991). Ambient and respired $CO_2$ contribute to the formation of mollusk shells and the importance of each determines which contributes more, and therefore which is more reflected in the shell $\delta^{13}C$ record. It is generally accepted that terrestrial (air-breathing) organisms construct shell carbonates mainly from respired $CO_2$, and that aquatic organisms build their shells predominantly from ambient inorganic carbon (McConnaughey et al. 1997). Thus, ambient DIC is the main source of carbon in aquatic shells, with shell $\delta^{13}C$ usually being a few ‰ lower than ambient $\delta^{13}C$ DIC, likely reflecting shifts in salinity in some instances (McConnaughey and Gilliken 2008). However, the source of shell carbon remains uncertain to some extent as some studies have shown that it does not necessarily precipitate in isotopic equilibrium with DIC for unknown reasons (i.e., may respond to additional environmental variables such as $CO_2/O_2$ ratio, DIC content, the organisms physiology, etc.), requiring context specific interpretations of shell $\delta^{13}C$ records (see McConnaughey and Gilliken 2008). In addition, some studies suggest that higher calcification rates, elevated sea water $[CO_3^{-2}]$ and higher water pH may also be associated with anomalous lower $\delta^{13}C$ values in foraminifera (Bemis et al. 2000; Pak et al. 2004; Spero et al. 1997), suggesting that higher water pH (in addition to lower surface water temperatures) during the Terminal Pleistocene and Early Holocene could be contributing to low $\delta^{13}C$ values.

As $\delta^{13}C$ values of DIC in upwelled water are normally lower than those in surface water, it is often used as a tracer of upwelling strength (Sheu et al. 1996). However, $\delta^{13}C$ values from one Southern California (Newport Beach) study reveal complex patterns of variability with no clear decrease during upwelling periods as expected (Santos et al. 2011). The authors posit that the local upwelling signal may be complicated by oceanic circulation patterns in the area and that a clearer signal may be observable at sites with simpler circulation patterns and stronger upwelling. For instance, this study documented periods of particularly high $\delta^{13}C$ variability following unusually wet periods that could not be linked to lower salinity values, suggesting the increase in rainfall had further complicated local oceanic circulation patterns and highlighting the need for localized context-specific interpretations. Such issues are less likely to be problematic on San Miguel Island as it is a semiarid environment and located at the north and westernmost edge of the southern California Bight, in an area of stronger upwelling than the southern California mainland coast (as in Santos et al. 2011). Nevertheless, the complex mixing of major oceanographic currents, coastal eddies, island wakes, and wave direction in the region (see Adams et al. 2008; Bassin et al. 2005; Caldeira et al. 2005; Dong and McWilliams 2007; Fewings et al. 2015; Hickey et al. 2003) could affect these values in unforeseen ways at various points in time.

## Mollusc Samples and Archaeological Sites

This study includes archaeological California mussel shell samples from Daisy Cave and Cave of the Chimneys and two mussel shells that were collected live at Bay Point by Christopher Jazwa in August 2017. The two archaeological sites are located within ~100 meters of each other on the northeast coast of San Miguel Island near Bay Point. Archaeological background and radiocarbon chronologies are discussed in Chapter I of this dissertation. Figure 2.1 provides a visual representation of the over 80 $^{14}$C dates for these sites, organized by stratigraphic component. Sample details and precise $^{14}$C ages are presented in Tables 1.1 and 1.2, of this dissertation along with calibrations and localized delta R corrections.

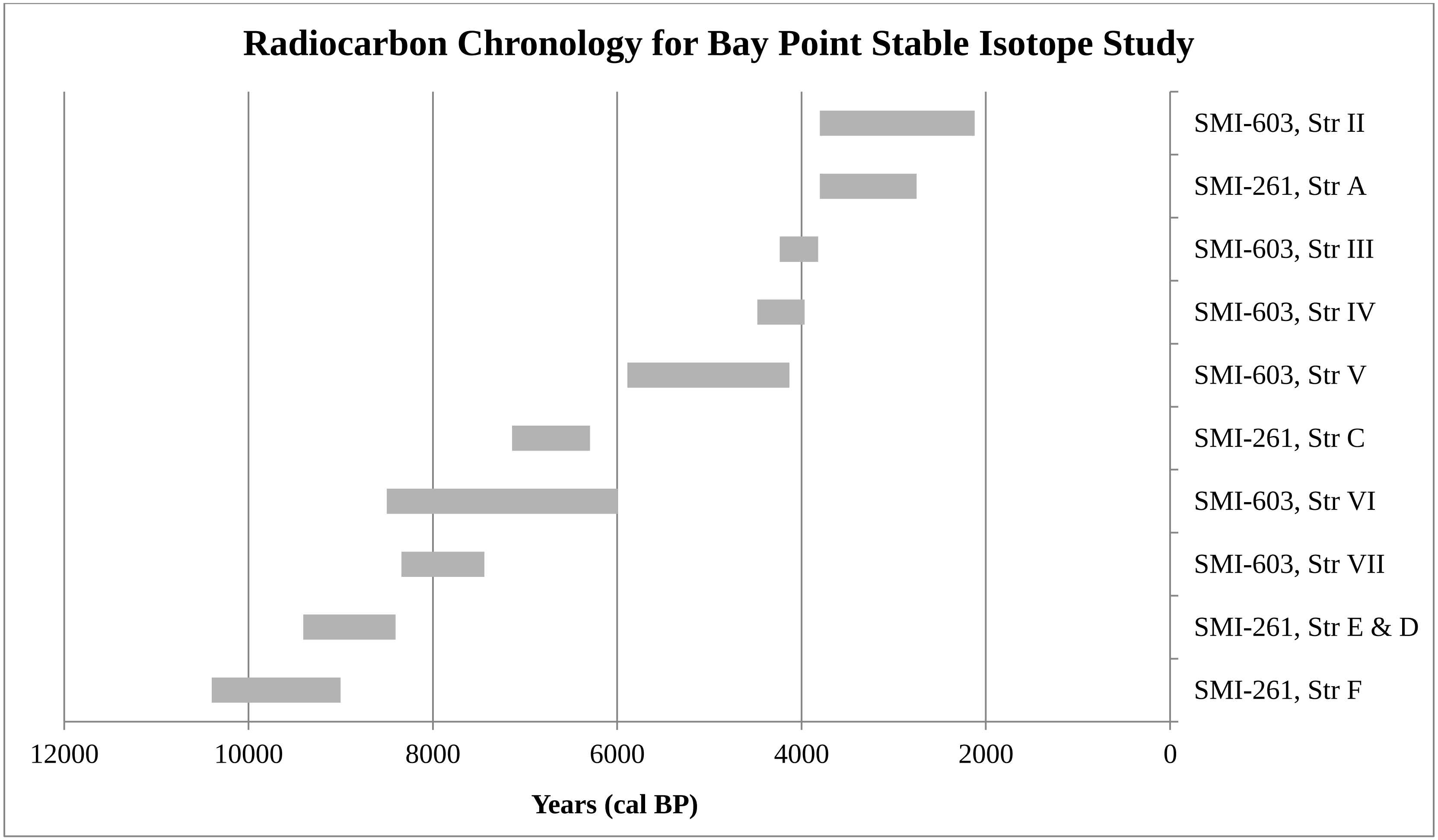

**Figure 2.1.** Visual representation of traditional and AMS $^{14}$C date ranges for charcoal, twig, and marine shell samples from Daisy Cave (CA-SMI-261) and Cave of the Chimneys (CA-SMI-603). Data compiled from Tables 1.1 and 1.2.

## **Biology and Ecology of *Mytilus californianus***

California mussels are relatively large, fast-growing, and edible marine bivalves. Unlike most types of bivalves (i.e., clams and scallops), California mussels do not live in sandy or muddy substrates, but rather attach themselves to rocks and boulders in the intertidal or subtidal zones. They extrude strong hairs, called byssal threads, which anchor them to large boulders, where they congregate in extensive masses called "mussel beds" (Brandon and Rokop 1985). California mussels are competitively dominant species in open-coast rocky intertidal communities along much of the Pacific Coast of North America, inhabiting a large geographic range that extends from the Aleutian Islands to the tip of the Baja California peninsula (Blanchette et al. 2006; Blanchette and Gaines 2007; Broitman et al. 2005; Coe and Fox 1942, 1944). They are an important food source for animals, including humans, in higher trophic levels and a dominant competitor for space on intertidal boulders, where they will often out-compete other plant and animal species (Paine 1974; Petersen 1984). As a foundation species, California mussels support considerable biodiversity in the rocky intertidal ecosystems they inhabit (Suchanek 1992), where their ability to overgrow competitors allows them to create habitat-forming beds that harbor a wide array or organisms (Dayton 1971).

Growth rates for California mussels are highly variable (2 to 6 mm/month) and contingent on a variety of factors including water temperature, available nutrition (i.e., drift algae, phytoplankton, dinoflagellates, diatoms, detritus, bacteria, etc.), currents and wave action (Coe and Fox 1942, 1944; Fox and Coe 1943). Optimum ocean water temperatures for California mussel growth are between 17º and 20º C, but studies have documented biological function (i.e., fecal discharge) in water temperatures as low as 7 to 8ºC and as high as 24 to 26ºC, suggesting the species is well adapted to shifts in a wide range of water temperatures (Coe and Fox 1944; Phillips 2005). Nuances in the relationship between mussel growth and water temperature illustrate a wide range of variation for this species. An early study by Rao (1953) revealed a linear relationship between shell and tissue weights in *M. californianus*; demonstrating that shell weight increased relative to tissue weight in populations with decreasing average annual temperatures. In the Southern California Bight, mussels show a positive scope for growth with increasing temperatures within their range (Blanchette and Gaines 2007; Blanchette et al. 2007), however, in an annual cycle the highest rates of mussel growth correspond with months containing the lowest water temperatures (Tegner et al. 2001; Vilchis et al. 2005). In addition to favoring growth rate, warm SST and weak seasonal upwelling also contribute to larger overall individuals (increased biomass), the proliferation of more extensive mussel beds (abundance) and recruitment (Coe and Fox 1942; Phillips 2005; Blanchette et al. 2006; Blanchette and Gaines 2007).

## Methods: Stable Oxygen and Carbon Isotope Analysis

Whole shells or large fragments with intact terminal edges (see Schweikhardt et al. 2011; Jew et al. 2014) were selected for stable isotope analysis. It is preferable to only use valves of the same side (i.e. all right-sided or all left-sided valves) to negate the possibility of sampling the same organism twice, but the reality of archaeological research is that we need to work with the limited samples we have available. The collections from which these mussel valves were selected were excavated ~20 years ago and have since been washed, sorted, stored, and moved repeatedly so that finding intact valves of the same side would have severely limited the sample size for my study. Acknowledging the importance of not sampling the same individual twice, I selected whole and fragmented valves of the same side when possible and carefully examined all specimens to ensure that when opposite valves were selected, they could not possibly represent the same individual. For instance, when right and left valves were selected from the same stratum they were placed alongside all sampled valves of the opposite side and only used if size (length and/or width) and other physical characteristics (i.e. shell thickness, color, growth band patterning, etc.) confirmed that they represented different individuals.

Here, I present stable isotope results from 55 mussel valves selected from 10 archaeological components at Daisy Cave and Cave of the Chimneys, and two modern mussel shells collected live from Bay Point, totaling 867 powdered samples. All shells were cleaned and rinsed to remove adhering midden soil and visible organic material. The outer surfaces of the shells were etched using a dilute solution of HCl (0.5 molar) to remove any diagenetically altered carbonate (Bailey et al. 1983). Shells were then rinsed in deionized water and left to dry before powdered samples were drilled. Each mussel valve was inspected for an intact terminal growth band and calcite samples were extracted from the exterior prismatic layer of the shell longitudinally across the shell's growth axis using a microdrill (0.5 mm carbide drill bit) in 1-3 mm increments depending on growth band thickness and shell size in attempts to follow visible growth bands on each shell. Attention was paid to sample only the outer calcite part of the shell, as mixing carbonate phases (i.e., inner aragonite and outer calcite layers are secreted by mussels) may skew isotopic results (Keith et al. 1964), and to drill at low speeds (~550-650 RPM) to avoid reaching high temperatures, which may alter minerals such as calcite.

Isotopic sampling consisted of extended profiles performed on several shells from each component for paleo-SST reconstructions. Extended profiles sampled multiple growth bands (12-30) on several mussel valves from each component to provide SST changes for at least one full annual cycle and in some instances sampled several annual cycles (e.g., Figure 2.2). The terminal growth band documents the most recent deposition of calcium carbonate, the approximate season of harvest, and estimated SST at the time the shell was collected. The adjacent growth intervals represent the growth phase directly preceding the terminal growth band, providing an indication of upward or downward trends in isotopic values and estimated SST. Regional studies of archaeological mussel shells have used a variety of sampling strategies including the terminal growth band (TGB) plus 1-5 samples to determine season of harvest (Culleton 2009; Jew et al. 2013a, b, 2014; Eerkens et al. 2013).

Calcite samples were analyzed at Oregon State University, College of Earth, Ocean, and Atmospheric Sciences Stable Isotope Laboratory under the supervision of Dr. Jennifer McKay. Samples were analyzed by dual inlet isotope ratio mass spectrometry using a MAT252 isotope ratio mass spectrometer connected to a Kiel III carbonate prep system in which samples were reacted at 70°C with 103% orthophosphoric acid. Data were calibrated using the in-house carbonate standard Wiley and the international standard NBS-19, which were analyzed with each batch of samples as a check standard.

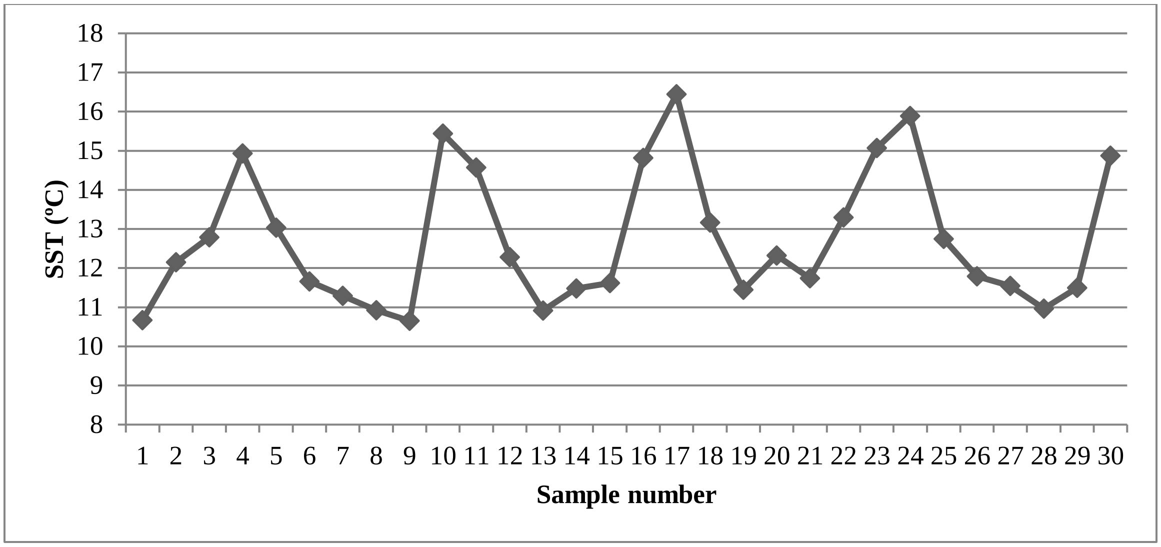

**Figure 2.2.** Example of extended profile shell (CH.6.2) showing multiple year (4+) SST sequence. CH.6.2 is a large broken right valve measuring >52.74 mm in width and was likely ≥150 mm in length. Sampling including 30 powdered samples representing ~54 mm of shell growth extending up from the terminal growth band, which is represented as sample #1 on the left side of the horizontal axis.

All values were reported in δ-notation in per mil (‰) units relative to the Vienna PeeDee Belemnite (VPDB) standard using the formula:

$$\delta^{18}O = ((R\ sample – R\ standard)/R\ standard)\ X\ 1000$$

where *R* represents heavy/light ratio for the abundance of any two isotopes. A positive δ value represents a more enriched heavy isotope in comparison to the standard, in other words there are higher proportions of the lighter $^{16}$O isotope compared with the heavier $^{18}$O isotope, and negative δ values are associated with the depletion of heavy isotopes (Wefer and Berger 1991). When the error involved with this type of analysis is considered, a minor (oxygen) to negligible (carbon) offset is present but not significant as the precision of the oxygen isotopic ratios is +/-0.1. Like other regional studies (Glassow et al. 1994; Jew et al. 2013a, b, 2014; Kennett 2005), I used Epstein et al.'s (1951, 1953) formula for converting δ$^{18}$O values to SST estimates as adapted for California mussel by Killingley (1981; Killingley and Berger 1979):

$$T\,(°C) = 16.4 - 4.2\,(\delta^{18}Occ(PDB) - \delta^{18}O\ water(smow)\,) + 0.13\,(\delta 18O\ cc(VPDB) - \delta 18Owater(smow))^2$$

Modern shells were profiled (12 samples per shell) and isotopic signatures and recorded SST were compared to isotope values to accurately pair isotope-to-SST conversion equations which were then applied to archaeological samples. The selected $\delta^{18}O_{sw(‰)}$ for the Early, Middle, and Late Holocene time periods was calibrated using LaGrande and Schmidts' (2009:20) SST averages for the Pacific Ocean. I used two adjustments for ice volume corrections ($\delta^{18}O_{water(smow)}$). Adjustments provided by Fairbanks (1989) include shifting values throughout the Holocene, and a local adjustment based on an ocean water sample of -0.32°C from Santa Rosa Island (Robbins and Rick 2007:30) was also used. Reconstructed SST values using both ice volume corrections were compared with an analysis of variance using one profile shell from each component. Results of the ANOVA analysis indicates that SST values are relatively homogenous throughout the Holocene regardless of which ice volume correction is employed, except during the earliest component I sampled, Stratum F at Daisy Cave (see ANOVA results in Table 2.2). Two profiled shell samples from Stratum F showed significant differences in estimated SST values using the two corrections, suggesting that either correction is suitable for samples dating within the past ~9300 years, but an adjusted correction may be required for Terminal Pleistocene and earlier Holocene samples when increased flow of subpolar waters was more prominent. The Fairbanks (1989) model allows for shifts through time, whereas the Robbins and Rick (2007) correction is more localized. By including both I am providing a limited range of potential SST values, however, ice volume corrections are extremely complex and constantly being revised (see Duplessey et al. 2002; Pearson 2012) suggesting proxy SST values may be refined in the future.

## **Salinity**

Although water temperature and salinity regulate seasonal $\delta^{18}O$ values of shell carbonate, the analysis of mussel shells from an island environment allows their categorization under the generalized marine model of carbonate $\delta^{18}O$, which assumes constant salinity. In marine environments, water $\delta^{18}$O and salinity are assumed to be relatively constant during the short lifespans of mollusks (~10-20 years), so shifts in $\delta^{18}$O values in marine shells primarily record changes in water temperature where increased values correspond to cooler water temperatures and vice versa (Culleton et al. 2009:1355). As shell $\delta^{13}$C reflects the mixture of fresh and ocean water DIC (dissolved inorganic carbon), it has the potential to correct paleo-SST estimates derived from $\delta^{18}$O when salinity is a primary factor and may provide an indication of changes in water $\delta^{18}$O (McConnaughey and Gilliken 2008). Data collected by Engle (2010:201) from 2000 to 2006 reported near constant salinity throughout the year (~33 ppt) with only slight fluctuations (>1 ppt) around the Northern Channel Islands, suggesting salinity is not highly variable in the study area. Correlation analysis reveals a wide degree of variation in the relationship between $\delta^{13}$C and $\delta^{18}$O in the past (see below). There does not appear to be a consistent correlation between $\delta^{13}$C and $\delta^{18}$O in each of the profiled shells, though there is an overall trend towards inverse correlations between these values. Although some profiled shells show strong inverse correlations between $\delta^{13}$C and $\delta^{18}$O, others show weak inverse correlations, and a few show weak positive correlations between these isotopic values. Although this issue should be addressed in future research, interpreting this variation is beyond the scope of this study.

### Reconstructing Paleo-SST

Descriptive and multivariate statistics were used to evaluate data generated by this study. I compared the mean, range, standard deviation, and variance for isotopic values and inferred SST between each component and used analysis of variance (ANOVA; Sokal and Rohlf 2012:319-372) tests to compare isotopic values and inferred SST between components. Modern SST data were used to calculate general patterns of annual temperature distributions (see Figure 2.3) and produce a trajectory of expected shifts in water temperature between seasons. Correlation analysis was applied to each sequence to identify and compare patterns in enriched and/or depleted isotopic values and estimated SST. The midpoint (median) and average (mean) values of the temperature range represented in each isotopic oxygen profile will be used as principal summary statistics, and variability in temperature ranges will be examined to determine the degree of

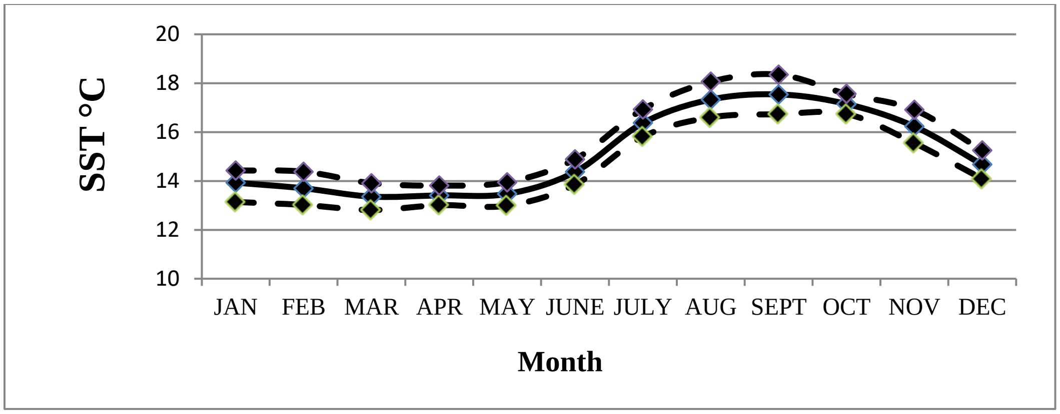

**Figure 2.3.** Modern SST averages for 1981-1991 (see Kennett 2005:56) from nearshore environments off the coast of San Miguel Island, including 95% confidence intervals (adapted from Jew et al. 2013a:5).

variation in the past and to determine whether they result primarily from variable temperatures at the maximum or minimum ranges (i.e., Robbins et al. 2013).

## Results

Stable isotope ($\delta^{13}C$ and $\delta^{18}O$) results from 867 Samples extracted from 55 archaeological and two modern California mussel shells are presented in Table 2.1, and paleo and modern SST values using these isotopic data along with two methods of ice volume corrections are presented in Table 2.2. Combined paleo-SST ranges, including all shell samples from each component, are presented in Table II.3 along with a variety of summary statistics to evaluate differences. Using a regional ice volume correction of -0.7 as per Schmidt et al. (1999; see also LeGrande and Schmidt 2006), modern mussel shells collected live at Bay Point show average SST of 14.9 °C, with a ~7.4$^{o}$ range from 11.68 to 19.11 °C (Figure 2.4). Sampling on one of the modern mussel shells captured a multi-year sequence including a known El Niño event in 2015, which was recorded in higher than average winter and summer ranges (Figure 2.5).

Estimated SSTs recorded in the calcite of archaeological mussel shells from Daisy Cave and Cave of the Chimneys were found to be between 8.05 and 17.91 °C, suggesting that SSTs were 1-3$^{o}$ cooler than present between ~10,200 and 2,200 cal BP. Archaeological samples also show a slightly wider range than is present today in the

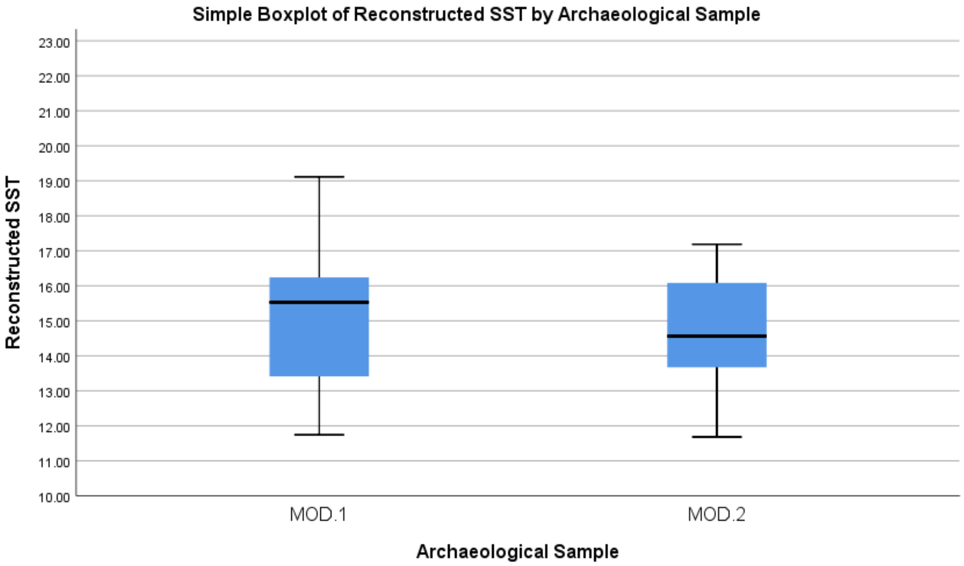

**Figure 2.4.** Boxplot graphs showing SST ranges from annual cycles recorded in two modern mussel shells from Bay Point, San Miguel Island. The heavy line represents the median values for each sample, the blue box contains the interquartile range (i.e., half the data falls within the blue box and the location of the box notes skewness in the overall distribution), and the extreme values represent the maximum and minimum values.

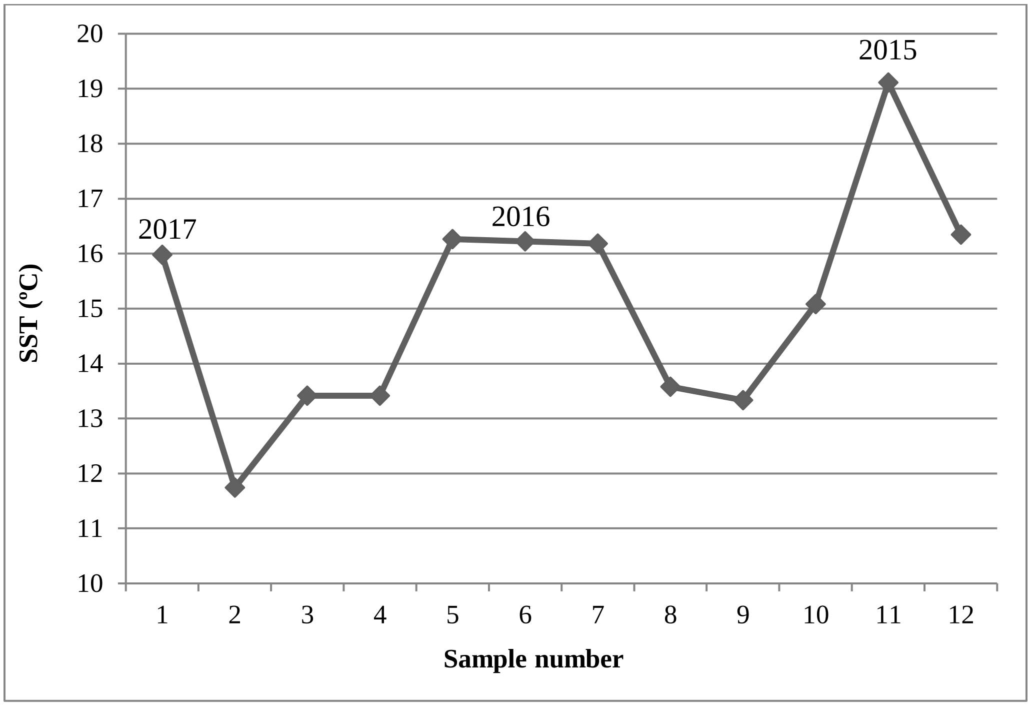

**Figure 2.5.** Line graph of reconstructed SST based on $\delta^{18}$O values for a mussel shell (MOD.1) that was collected live at Bay Point in August 2017 (collected by Chris Jazwa).

**Table 2.1.** Summary statistics of $\delta^{13}C$ and $\delta^{18}O$ for each sampled shell

| Sample # | Value | n | Min | Max | Mean | Median | SD | $\sigma^2$ | r |
|---|---|---|---|---|---|---|---|---|---|
| MOD.1 | $\delta^{13}C$ | 12 | -0.56 | 0.49 | -0.04 | -0.05 | 0.33 | 0.11 | -0.93124 |
| | $\delta^{18}O$ | | -0.65 | 1.16 | 0.35 | 0.23 | 0.5 | 0.25 | |
| MOD.2 | $\delta^{13}C$ | 12 | -0.36 | 0.41 | -0.004 | -0.01 | 0.26 | 0.07 | -0.71365 |
| | $\delta^{18}O$ | | -0.18 | 1.18 | 0.42 | 0.47 | 0.38 | 0.15 | |
| CH.2.1 | $\delta^{13}C$ | 12 | 0.05 | 0.96 | 0.62 | 0.63 | 0.3 | 0.09 | -0.8 |
| | $\delta^{18}O$ | | 0.09 | 1.34 | 0.66 | 0.63 | 0.39 | 0.15 | |
| CH.2.2 | $\delta^{13}C$ | 12 | 0.34 | 1.06 | 0.55 | 0.44 | 0.23 | 0.06 | -0.47286 |
| | $\delta^{18}O$ | | 0.4 | 1.23 | 0.79 | 0.77 | 0.29 | 0.08 | |
| CH.2.1.1 | $\delta^{13}C$ | 12 | 0.31 | 0.87 | 0.66 | 0.66 | 0.14 | 0.02 | -0.38 |
| | $\delta^{18}O$ | | 0.29 | 1.28 | 0.87 | 0.97 | 0.3 | 0.09 | |
| CH.2.2.1 | $\delta^{13}C$ | 19 | -0.46 | 0.98 | 0.23 | 0.1 | 0.37 | 0.14 | -0.76 |
| | $\delta^{18}O$ | | 0.35 | 1.24 | 0.8 | 0.78 | 0.31 | 0.1 | |
| CH.2.2.2 | $\delta^{13}C$ | 12 | 0.85 | 1.48 | 1.2 | 1.25 | 0.18 | 0.03 | -0.35 |
| | $\delta^{18}O$ | | 0.2 | 1.33 | 0.78 | 0.77 | 0.37 | 0.14 | |
| CH.2.3.1 | $\delta^{13}C$ | 15 | 0.49 | 1.29 | 1.02 | 1.05 | 0.2 | 0.04 | 0.28 |
| | $\delta^{18}O$ | | 0.09 | 1.1 | 0.58 | 0.63 | 0.33 | 0.11 | |
| CH.2.3.2 | $\delta^{13}C$ | 12 | -0.24 | 0.75 | 0.34 | 0.37 | 0.3 | 0.09 | -0.51588 |
| | $\delta^{18}O$ | | 0.71 | 1.47 | 0.66 | 1.27 | 0.25 | 0.06 | |
| CH.2.4.1 | $\delta^{13}C$ | 23 | -0.31 | 0.3 | 0.03 | 0.02 | 0.17 | 0.03 | -0.32803 |
| | $\delta^{18}O$ | | 0.6 | 1.48 | 1.16 | 1.16 | 0.21 | 0.04 | |
| CH.2.4.2 | $\delta^{13}C$ | 12 | -0.06 | 1.06 | 0.5 | 0.47 | 0.4 | 0.16 | -0.04832 |
| | $\delta^{18}O$ | | 0.32 | 1.31 | 0.8 | 0.86 | 0.31 | 0.1 | |
| DC.D6.A.1 | $\delta^{18}O$ | 12 | 0.2 | 1.03 | 0.64 | 0.66 | 0.23 | 0.05 | -0.59 |
| | $\delta^{13}C$ | | 0.06 | 1.15 | 0.83 | 0.98 | 0.32 | 0.1 | |
| DC.D6.A.6 | $\delta^{18}O$ | 20 | 0.84 | 1.43 | 1.1 | 1.11 | 0.19 | 0.04 | -0.73 |
| | $\delta^{13}C$ | | 0.17 | 1.13 | 0.69 | 0.69 | 0.29 | 0.09 | |
| DC.D6.A3.1 | $\delta^{18}O$ | 12 | 0.16 | 0.92 | 0.45 | 0.44 | 0.22 | 0.05 | -0.79 |
| | $\delta^{13}C$ | | 0.29 | 1.38 | 0.99 | 1.12 | 0.32 | 0.1 | |
| CH.3.1 | $\delta^{13}C$ | 12 | 0.66 | 1.43 | 1.19 | 1.23 | 0.24 | 0.06 | -0.45835 |
| | $\delta^{18}O$ | | 0.34 | 1.48 | 0.79 | 0.7 | 0.4 | 0.16 | |

SD = standard deviation, $\sigma^2$ = variance, r = correlation coefficient between $\delta^{13}C$ and $\delta^{18}O$.

**Table 2.1.** (continued)

| Sample # | Value | n | Min | Max | Mean | Median | SD | $\sigma^2$ | r |
|---|---|---|---|---|---|---|---|---|---|
| CH.3.2 | $\delta^{13}C$ | 12 | 0.17 | 0.9 | 0.61 | 0.62 | 0.19 | 0.03 | -0.37482 |
| | $\delta^{18}O$ | | 0.49 | 1.5 | 0.04 | 1.22 | 0.34 | 0.12 | |
| CH.3.3 | $\delta^{13}C$ | 12 | 0.39 | 0.99 | 0.77 | 0.77 | 0.19 | 0.04 | -0.15706 |
| | $\delta^{18}O$ | | 0.13 | 1.09 | 0.74 | 0.86 | 0.37 | 0.14 | |
| CH.4.1.1 | $\delta^{13}C$ | 12 | 0.7 | 1.63 | 1.09 | 1.02 | 0.25 | 0.06 | -0.57198 |
| | $\delta^{18}O$ | | -0.07 | 1.34 | 0.78 | 0.79 | 0.43 | 0.18 | |
| CH.4.1.2 | $\delta^{13}C$ | 20 | -0.28 | 1.01 | 0.5 | 0.64 | 0.43 | 0.19 | -0.43449 |
| | $\delta^{18}O$ | | 0.33 | 1.25 | 0.9 | 0.91 | 0.28 | 0.08 | |
| CH.4.2.1 | $\delta^{13}C$ | 12 | 0.18 | 1.06 | 0.51 | 0.43 | 0.27 | 0.07 | -0.78547 |
| | $\delta^{18}O$ | | 0.24 | 1.03 | 0.71 | 0.76 | 0.28 | 0.08 | |
| CH.4.2.2 | $\delta^{13}C$ | 12 | 0.38 | 1.32 | 0.89 | 0.91 | 0.32 | 0.1 | -0.52419 |
| | $\delta^{18}O$ | | 0.33 | 1.18 | 0.82 | 0.87 | 0.29 | 0.09 | |
| CH.4.2.3 | $\delta^{13}C$ | 12 | 0.25 | 1.45 | 0.92 | 0.98 | 0.32 | 0.1 | -0.2439 |
| | $\delta^{18}O$ | | -0.39 | 0.97 | 0.46 | 0.51 | 0.44 | 0.19 | |
| CH.5.1 | $\delta^{13}C$ | 12 | 0.6 | 1.57 | 1.21 | 1.23 | 0.28 | 0.08 | -0.61182 |
| | $\delta^{18}O$ | | 0.18 | 1.24 | 0.77 | 0.86 | 0.39 | 0.6 | |
| CH.5.2 | $\delta^{13}C$ | 22 | -0.03 | 1.32 | 0.85 | 0.91 | 0.31 | 0.09 | -0.0984 |
| | $\delta^{18}O$ | | 0.44 | 1.41 | 0.86 | 0.93 | 0.32 | 0.1 | |
| CH.5B.1 | $\delta^{13}C$ | 18 | 0.36 | 0.98 | 0.73 | 0.77 | 0.17 | 0.03 | -0.06729 |
| | $\delta^{18}O$ | | 0.34 | 1.41 | 1.02 | 1.08 | 0.32 | 0.1 | |
| CH.5B.2 | $\delta^{13}C$ | 12 | 0.08 | 0.96 | 0.55 | 0.54 | 0.26 | 0.07 | -0.234 |
| | $\delta^{18}O$ | | 0.42 | 1.32 | 0.87 | 0.87 | 0.28 | 0.08 | |
| CH.5C.1 | $\delta^{13}C$ | 12 | 0.63 | 1.34 | 0.95 | 0.98 | 0.23 | 0.05 | -0.62339 |
| | $\delta^{18}O$ | | 0.18 | 1.56 | 1.09 | 1.13 | 0.38 | 0.14 | |
| CH.5C.2 | $\delta^{13}C$ | 12 | 0.98 | 1.87 | 1.42 | 1.44 | 0.27 | 0.07 | 0.28548 |
| | $\delta^{18}O$ | | 0.23 | 1.16 | 0.74 | 0.78 | 0.35 | 0.13 | |
| CH.6.1 | $\delta^{13}C$ | 12 | 0.27 | 1.15 | 0.66 | 0.62 | 0.27 | 0.07 | -0.14 |
| | $\delta^{18}O$ | | 0.56 | 1.79 | 1.1 | 1.11 | 0.42 | 0.18 | |
| CH.6.2 | $\delta^{13}C$ | 30 | 0.08 | 1 | 0.58 | 0.57 | 0.28 | 0.08 | -0.19484 |
| | $\delta^{18}O$ | | -0.06 | 1.36 | 0.85 | 0.98 | 0.42 | 0.18 | |

SD = standard deviation, $\sigma^2$ = variance, r = correlation coefficient between $\delta^{13}C$ and $\delta^{18}O$

**Table 2.1.** (continued)

| **Sample #** | **Value** | **n** | **Min** | **Max** | **Mean** | **Median** | **SD** | **$\sigma^2$** | **r** |
|---|---|---|---|---|---|---|---|---|---|
| CH.6.6 | $\delta^{13}C$ | 12 | 0.71 | 1.55 | 1.09 | 1.01 | 0.26 | 0.07 | -0.88739 |
| | $\delta^{18}O$ | | 0.25 | 1.24 | 0.93 | 1 | 0.28 | 0.08 | |
| CH.6.7 | $\delta^{13}C$ | 20 | -0.45 | 1.06 | 0.48 | 0.61 | 0.43 | 0.19 | -0.0167 |
| | $\delta^{18}O$ | | 0.29 | 1.55 | 0.95 | 1.04 | 0.4 | 0.16 | |
| CH.6.8 | $\delta^{13}C$ | 20 | -0.04 | 1.38 | 0.55 | 0.5 | 0.38 | 0.15 | -0.76464 |
| | $\delta^{13}C$ | | 0.31 | 1.56 | 0.93 | 1 | 0.36 | 0.13 | |
| CH.7.1 | $\delta^{18}O$ | 12 | -0.39 | 1.09 | 0.55 | 0.64 | 0.43 | 0.19 | 0.12 |
| | $\delta^{13}C$ | | 0.5 | 1.72 | 1.05 | 1.02 | 0.41 | 0.17 | |
| CH.7.2 | $\delta^{18}O$ | 12 | -1.17 | 0.91 | -0.04 | 0.02 | 0.62 | 0.38 | -0.7 |
| | $\delta^{13}C$ | | 0.37 | 1.49 | 0.93 | 0.83 | 0.36 | 0.13 | |
| CH.7.6 | $\delta^{18}O$ | 12 | 0.15 | 1.12 | 0.52 | 0.41 | 0.32 | 0.1 | -0.76542 |
| | $\delta^{13}C$ | | 0.28 | 1.55 | 1.09 | 1.14 | 0.37 | 0.14 | |
| CH.7.7 | $\delta^{18}O$ | 20 | -0.2 | 0.97 | 0.43 | 0.56 | 0.35 | 0.12 | -0.59109 |
| | $\delta^{13}C$ | | 0.08 | 1.44 | 0.91 | 0.98 | 0.37 | 0.14 | |
| CH.7.8 | $\delta^{18}O$ | 20 | -1.19 | 0.86 | 0.22 | 0.36 | 0.47 | 0.22 | -0.28894 |
| | $\delta^{13}C$ | | 0.47 | 1.53 | 1.13 | 1.17 | 0.3 | 0.09 | |
| CH.7.9 | $\delta^{18}O$ | 20 | -0.32 | 0.86 | 0.32 | 0.44 | 0.32 | 0.1 | -0.38231 |
| | $\delta^{13}C$ | | 0.16 | 1.62 | 1.08 | 1.12 | 0.4 | 0.16 | |
| DC.D6.A.1 | $\delta^{18}O$ | 12 | 0.2 | 1.03 | 0.64 | 0.66 | 0.23 | 0.05 | -0.59 |
| | $\delta^{13}C$ | | 0.06 | 1.15 | 0.83 | 0.98 | 0.32 | 0.1 | |
| DC.D6.A.6 | $\delta^{18}O$ | 20 | 0.84 | 1.43 | 1.1 | 1.11 | 0.19 | 0.04 | -0.73 |
| | $\delta^{13}C$ | | 0.17 | 1.13 | 0.69 | 0.69 | 0.29 | 0.09 | |
| DC.D6.A3.1 | $\delta^{18}O$ | 12 | 0.16 | 0.92 | 0.45 | 0.44 | 0.22 | 0.05 | -0.79 |
| | $\delta^{13}C$ | | 0.29 | 1.38 | 0.99 | 1.12 | 0.32 | 0.1 | |
| DC.D6.C.1 | $\delta^{18}O$ | 12 | -0.38 | 0.52 | 0.11 | 0.04 | 0.3 | 0.09 | -0.54 |
| | $\delta^{13}C$ | | 0.01 | 1.07 | 0.61 | 0.67 | 0.32 | 0.1 | |
| DC.D6.C.2 | $\delta^{18}O$ | 12 | -0.65 | 1.15 | 0.58 | 0.74 | 0.48 | 0.23 | -0.1 |
| | $\delta^{13}C$ | | 0.55 | 1.52 | 1.09 | 1.13 | 0.29 | 0.08 | |
| DC.D6.C.7 | $\delta^{18}O$ | 12 | 0.56 | 1.39 | 0.86 | 0.84 | 0.23 | 0.06 | 0.26989 |
| | $\delta^{13}C$ | | 0.57 | 1.46 | 1.15 | 1.26 | 0.29 | 0.08 | |

SD = standard deviation, $\sigma^2$ = variance, r = correlation coefficient between $\delta^{13}C$ and $\delta^{18}O$

**Table 2.1.** (continued)

| **Sample #** | **Value** | **n** | **Min** | **Max** | **Mean** | **Median** | **SD** | **$\sigma^2$** | **r** |
|---|---|---|---|---|---|---|---|---|---|
| DC.D6.C.8 | $\delta^{18}O$ | 12 | -0.29 | 1.58 | 0.74 | 0.94 | 0.56 | 0.32 | -0.67517 |
| | $\delta^{13}C$ | | 0.02 | 1.45 | 1.03 | 1.15 | 0.42 | 0.18 | |
| DC.D6.C.9 | $\delta^{18}O$ | 20 | -0.59 | 0.92 | 0.51 | 0.56 | 0.36 | 0.13 | 0.174885 |
| | $\delta^{13}C$ | | -0.28 | 0.95 | 0.38 | 0.38 | 0.42 | 0.18 | |
| DC.D6.C.10 | $\delta^{13}C$ | 12 | -1.11 | 1.35 | 0.44 | 0.57 | 0.64 | 0.41 | -0.53029 |
| | $\delta^{18}O$ | | 0.18 | 1.42 | 0.93 | 1.09 | 0.42 | 0.18 | |
| DC.D6.D.1 | $\delta^{13}C$ | 20 | 0.12 | 1.31 | 0.75 | 0.63 | 0.37 | 14 | -0.07473 |
| | $\delta^{18}O$ | | 0.23 | 1.38 | 0.87 | 0.97 | 0.39 | 0.16 | |
| DC.D6.E2.1 | $\delta^{13}C$ | 23 | -1.15 | 0.63 | 0.08 | 0.87 | 0.56 | 0.31 | -0.14041 |
| | $\delta^{18}O$ | | 0.5 | 1.74 | 1.17 | 1.66 | 0.38 | 0.14 | |
| DC.D6.E2.2 | $\delta^{13}C$ | 19 | -0.07 | 1.24 | 0.68 | 0.61 | 0.36 | 0.13 | -0.41885 |
| | $\delta^{18}O$ | | -0.01 | 1.09 | 0.66 | 0.73 | 0.36 | 0.13 | |
| DC.D6.E3.1 | $\delta^{13}C$ | 12 | -0.04 | 1.18 | 0.81 | 0.94 | 0.34 | 0.11 | -0.03 |
| | $\delta^{18}O$ | | 0.77 | 1.71 | 1.22 | 1.26 | 0.26 | 0.07 | |
| DC.D6.E3.2 | $\delta^{13}C$ | 20 | 0.05 | 1.1 | 0.69 | 0.81 | 0.36 | 0.13 | -0.24286 |
| | $\delta^{18}O$ | | 0.39 | 1.48 | 1 | 1.06 | 0.31 | 0.1 | |
| DC.D6.E4.1 | $\delta^{13}C$ | 12 | -0.78 | 0.91 | -0.08 | -0.14 | 0.47 | 0.22 | 0.01 |
| | $\delta^{18}O$ | | 0.39 | 1.67 | 1.16 | 1.2 | 0.37 | 0.14 | |
| DC.D6.E4.2 | $\delta^{13}C$ | 12 | 0.15 | 1.23 | 0.59 | 0.49 | 0.36 | 0.13 | 0.051993 |
| | $\delta^{18}O$ | | 0.43 | 1.36 | 0.83 | 0.76 | 0.35 | 0.12 | |
| DC.D6.F1.1 | $\delta^{13}C$ | 12 | 0.38 | 1.3 | 0.89 | 0.92 | 0.27 | 0.07 | -0.73154 |
| | $\delta^{18}O$ | | 0.32 | 1.42 | 0.88 | 0.81 | 0.36 | 0.13 | |
| DC.D6.F1.5 | $\delta^{13}C$ | 24 | 0.12 | 1.23 | 0.65 | 0.6 | 0.26 | 0.07 | -0.3411 |
| | $\delta^{18}O$ | | 0.08 | 1.42 | 0.9 | 0.94 | 0.35 | 0.13 | |
| DC.D6.F1.6 | $\delta^{13}C$ | 22 | -0.39 | 1.12 | 0.35 | 0.46 | 0.48 | 0.23 | -0.15429 |
| | $\delta^{18}O$ | | 0.1 | 1.32 | 0.8 | 0.95 | 0.36 | 0.13 | |
| DC.D6.F2.1 | $\delta^{13}C$ | 12 | 0.17 | 1.18 | 0.63 | 0.61 | 0.29 | 0.08 | -0.25 |
| | $\delta^{18}O$ | | 0.14 | 1.79 | 0.96 | 0.97 | 0.47 | 0.22 | |
| DC.D6.F2.5 | $\delta^{13}C$ | 20 | -0.53 | 1.3 | 0.45 | 0.34 | 0.57 | 0.32 | -0.41634 |
| | $\delta^{18}O$ | | -0.24 | 1.17 | 0.59 | 0.64 | 0.43 | 0.19 | |

SD = standard deviation, $\sigma^2$ = variance, r = correlation coefficient between $\delta^{13}C$ and $\delta^{18}O$

**Table 2.2.** Summary statistics of estimated SST for each sampled shell

| Sample # | Ice volume correction* | N | Min | Max | Mean | Median | SD | σ$^2$ | ANOVA** |
|---|---|---|---|---|---|---|---|---|---|
| MOD.1 | -0.7 | 12 | 11.17 | 15.18 | 12.83 | 12.43 | 1.21 | 1.47 | F(1, 32)=0.03, p =0.8545 |
| | -0.32 | | 11.42 | 15.43 | 13.08 | 12.68 | | | |
| MOD.2 | -0.7 | 12 | 11.68 | 17.19 | 14.74 | 14.56 | 1.56 | 2.44 | |
| | -0.32 | | 11.84 | 17.34 | 14.9 | 14.72 | | | |
| CH.2.1 | 0.03 | 12 | 10.93 | 16.02 | 13.69 | 13.79 | 1.6 | 2.56 | |
| | -0.32 | | 11.17 | 16.27 | 13.94 | 14.04 | | | |
| CH.2.2 | 0.03 | 12 | 11.35 | 14.76 | 13.14 | 13.25 | 1.18 | 1.4 | |
| | -0.32 | | 11.6 | 15.01 | 13.39 | 13.5 | | | |
| CH.2.1.1 | 0.03 | 12 | 11.17 | 15.18 | 12.83 | 12.43 | 1.21 | 1.47 | |
| | -0.32 | | 11.42 | 15.43 | 13.08 | 12.68 | | | |
| CH.2.2.1 | 0.03 | 19 | 11.34 | 14.96 | 13.11 | 13.18 | 1.27 | 1.62 | |
| | -0.32 | | 11.59 | 15.21 | 13.36 | 13.43 | | | |
| CH.2.2.2 | 0.03 | 12 | 10.95 | 15.54 | 13.2 | 13.23 | 1.52 | 2.31 | |
| | -0.32 | | 11.2 | 15.79 | 13.45 | 13.48 | | | |
| CH.2.3.1 | 0.03 | 15 | 11.91 | 16.01 | 14 | 13.79 | 1.35 | 1.81 | |
| | -0.32 | | 12.16 | 16.25 | 14.25 | 14.04 | | | |
| CH.2.4.1 | 0.03 | 23 | 10.36 | 13.91 | 11.67 | 11.67 | 0.86 | 0.73 | |
| | -0.32 | | 10.61 | 14.16 | 11.91 | 11.91 | | | |
| CH.2.4.2 | 0.03 | 12 | 11.04 | 15.06 | 13.1 | 12.86 | 1.26 | 1.59 | F(1,22)=0.23, p=0.6345 |
| | -0.32 | | 11.28 | 15.31 | 13.35 | 13.1 | | | |
| DC.D6.A.1 | 0.05 | 12 | 11.68 | 16.09 | 12.98 | 12.35 | 1.31 | 1.71 | F(1, 22)=0.26, p=0.6179 |
| | -0.32 | | 11.95 | 16.36 | 13.25 | 12.62 | | | |
| DC.D6.A.6 | 0.05 | 20 | 11.73 | 15.65 | 13.56 | 13.53 | 1.19 | 1.41 | |
| | -0.32 | | 12 | 15.92 | 13.83 | 13.8 | | | |

SD = standard deviation, σ$^2$ = variance

* Two versions of ice volume corrections were used in this analysis: the first correction for each sample is based on Fairbanks (1989) and the second is a localized correction from Santa Rosa Island (Rick et al. 2006).

**ANOVA tests compared SST values derived from both equations using the two different ice volume corrections. All ANOVA tests were performed using SAS 9.4 software.

**Table 2.2**. (continued)

| Sample # | Ice volume correction* | N | Min | Max | Mean | Median | SD | $\sigma^2$ | ANOVA** |
|---|---|---|---|---|---|---|---|---|---|
| DC.D6.A3.1 | 0.05 | 12 | 10.73 | 15.18 | 12.32 | 11.8 | 1.29 | 1.67 | |
| | -0.32 | | 10.99 | 15.45 | 12.59 | 12.07 | | | |
| CH.3.1 | 0.05 | 12 | 10.33 | 14.95 | 13.12 | 13.49 | 1.65 | 2.71 | F(1,22)=0.16, p=0.06917 |
| | -0.32 | | 10.6 | 15.22 | 13.39 | 13.76 | | | |
| CH.3.2 | 0.05 | 12 | 10.24 | 14.35 | 12.09 | 11.4 | 1.38 | 1.9 | |
| | -0.32 | | 10.51 | 14.62 | 12.36 | 11.67 | | | |
| CH.3.3 | 0.05 | 12 | 11.92 | 15.82 | 13.33 | 12.83 | 1.51 | 2.27 | |
| | -0.32 | | 12.19 | 16.09 | 13.6 | 13.1 | | | |
| CH.4.1.1 | 0.05 | 12 | 10.88 | 16.65 | 13.17 | 13.12 | 1.75 | 3.06 | |
| | -0.32 | | 11.15 | 16.92 | 13.44 | 13.39 | | | |
| CH.4.1.2 | 0.05 | 20 | 11.28 | 15.02 | 12.68 | 12.66 | 1.13 | 1.27 | F(1,38)=0.57, p=0.4534 |
| | -0.32 | | 11.55 | 15.29 | 12.95 | 12.93 | | | |
| CH.4.2.1 | 0.05 | 12 | 12.17 | 15.39 | 13.48 | 13.26 | 1.15 | 1.31 | |
| | -0.32 | | 12.44 | 15.66 | 13.75 | 13.53 | | | |
| CH.4.2.2 | 0.05 | 12 | 11.55 | 14.99 | 12.99 | 12.8 | 1.19 | 1.42 | |
| | -0.32 | | 11.82 | 15.26 | 13.26 | 13.07 | | | |
| CH.4.2.3 | 0.05 | 12 | 12.41 | 17.91 | 14.48 | 14.28 | 1.79 | 3.21 | |
| | -0.32 | | 12.68 | 18.18 | 14.75 | 14.55 | | | |
| CH.5.1 | 0.07 | 12 | 11.27 | 15.59 | 13.2 | 12.84 | 1.6 | 2.56 | |
| | -0.32 | | 11.56 | 15.88 | 13.49 | 13.13 | | | |
| CH.5.2 | 0.07 | 22 | 10.59 | 14.53 | 12.81 | 12.53 | 1.28 | 1.64 | F(1,42)=0.57, p=0.4534 |
| | -0.32 | | 10.88 | 14.82 | 13.1 | 12.82 | | | |
| CH.5B.1 | 0.07 | 18 | 10.6 | 14.95 | 12.16 | 11.92 | 1.3 | 1.69 | |
| | -0.32 | | 10.9 | 15.24 | 12.45 | 12.21 | | | |

SD = standard deviation, $\sigma^2$ = variance

* Two versions of ice volume corrections were used in this analysis: the first correction for each sample is based on Fairbanks (1989) and the second is a localized correction from Santa Rosa Island (Rick et al. 2006).

**ANOVA tests compared SST values derived from both equations using the two different ice volume corrections. All ANOVA tests were performed using SAS 9.4 software.

**Table 2.2.** (continued)

| Sample # | Ice volume correction* | N | Min | Max | Mean | Median | SD | $\sigma^2$ | ANOVA** |
|---|---|---|---|---|---|---|---|---|---|
| CH.5B.2 | 0.07 | 12 | 10.95 | 14.62 | 12.79 | 12.81 | 1.12 | 1.25 | |
| | -0.32 | | 11.25 | 14.91 | 13.08 | 13.1 | | | |
| CH.5C.1 | 0.07 | 12 | 9.98 | 15.59 | 11.9 | 11.75 | 1.54 | 2.38 | |
| | -0.32 | | 10.27 | 15.89 | 12.2 | 12.04 | | | |
| CH.5C.2 | 0.07 | 12 | 11.6 | 15.39 | 13.32 | 13.17 | 1.44 | 2.07 | |
| | -0.32 | | 11.9 | 15.68 | 13.61 | 13.46 | | | |
| DC.D6.C.1 | 0.1 | 12 | 11.92 | 16.26 | 13.81 | 13.55 | 1.32 | 1.73 | F(1,22)=0.37, p=0.5483 |
| | -0.32 | | 12.25 | 16.58 | 14.14 | 13.88 | | | |
| DC.D6.C.2 | 0.1 | 12 | 10.11 | 14.05 | 11.86 | 11.7 | 1.16 | 1.35 | |
| | -0.32 | | 10.43 | 14.38 | 12.19 | 12.03 | | | |
| DC.D6.C.7 | 0.1 | 12 | 10.35 | 13.98 | 11.58 | 11.18 | 1.17 | 1.38 | |
| | -0.32 | | 10.68 | 14.31 | 11.91 | 11.5 | | | |
| DC.D6.C.8 | 0.1 | 12 | 10.4 | 16.22 | 12.11 | 11.59 | 1.72 | 2.94 | |
| | -0.32 | | 10.73 | 16.55 | 12.43 | 11.92 | | | |
| DC.D6.C.9 | 0.1 | 20 | 12.43 | 17.42 | 14.74 | 14.76 | 1.72 | 2.97 | |
| | -0.32 | | 12.76 | 17.74 | 15.07 | 15.09 | | | |
| DC.D6.C.10 | 0.1 | 12 | 10.45 | 15.57 | 12.52 | 11.85 | 1.71 | 2.91 | |
| | -0.32 | | 10.82 | 15.9 | 12.85 | 12.18 | | | |
| CH.6.1 | 0.18 | 12 | 8.91 | 13.91 | 11.71 | 11.66 | 1.72 | 2.94 | |
| | -0.32 | | 9.34 | 14.34 | 12.14 | 12.09 | | | |
| CH.6.2 | 0.18 | 30 | 10.65 | 16.44 | 12.73 | 12.21 | 1.72 | 2.96 | |
| | -0.32 | | 11.08 | 16.87 | 13.16 | 12.64 | | | |
| CH.6.6 | 0.18 | 12 | 11.15 | 15.18 | 12.39 | 12.12 | 1.13 | 1.27 | |
| | -0.32 | | 11.58 | 15.61 | 12.82 | 12.55 | | | |

SD = standard deviation, $\sigma^2$ = variance

* Two versions of ice volume corrections were used in this analysis: the first correction for each sample is based on Fairbanks (1989) and the second is a localized correction from Santa Rosa Island (Rick et al. 2006).

**ANOVA tests compared SST values derived from both equations using the two different ice volume corrections. All ANOVA tests were performed using SAS 9.4 software.

**Table 2.2.** (continued)

| Sample # | Ice volume correction* | N | Min | Max | Mean | Median | SD | $\sigma^2$ | ANOVA** |
|---|---|---|---|---|---|---|---|---|---|
| CH.6.7 | 0.18 | 20 | 9.89 | 15.01 | 12.31 | 11.94 | 1.64 | 2.69 | |
| | -0.32 | | 10.32 | 15.44 | 12.74 | 12.37 | | | |
| CH.6.8 | 0.18 | 20 | 9.85 | 14.92 | 12.39 | 12.12 | 1.46 | 2.12 | F(1,38)=0.87, p=0.3563 |
| | -0.32 | | 10.28 | 15.35 | 12.82 | 12.55 | | | |
| CH.7.1 | 0.25 | 12 | 9.1 | 14.05 | 11.82 | 11.92 | 1.69 | 2.85 | |
| | -0.32 | | 9.63 | 14.58 | 12.35 | 12.45 | | | |
| CH.7.2 | 0.25 | 12 | 10.02 | 14.58 | 12.32 | 12.71 | 1.48 | 2.2 | |
| | -0.32 | | 10.55 | 15.11 | 12.85 | 13.24 | | | |
| CH.7.6 | 0.25 | 12 | 9.76 | 14.94 | 11.66 | 11.45 | 1.5 | 2.64 | |
| | -0.32 | | 10.29 | 15.47 | 12.19 | 11.98 | | | |
| CH.7.7 | 0.25 | 20 | 10.23 | 15.76 | 12.38 | 12.08 | 1.52 | 2.31 | |
| | -0.32 | | 10.76 | 16.29 | 12.91 | 12.61 | | | |
| CH.7.8 | 0.25 | 20 | 9.85 | 14.18 | 11.5 | 11.31 | 1.2 | 1.45 | F(1,38)=1.94, p=0.1719 |
| | -0.32 | | 10.38 | 14.71 | 12.03 | 11.84 | | | |
| CH.7.9 | 0.25 | 20 | 9.48 | 15.43 | 11.7 | 11.53 | 1.64 | 2.67 | |
| | -0.32 | | 10.01 | 15.96 | 12.23 | 12.06 | | | |
| DC.D6.D.1 | 0.32 | 20 | 10.35 | 15.05 | 12.46 | 12.05 | 1.6 | 2.56 | |
| | -0.32 | | 10.99 | 15.69 | 13.1 | 12.69 | | | |
| DC.D6.E2.1 | 0.32 | 23 | 8.92 | 13.93 | 11.21 | 12.26 | 1.53 | 2.33 | |
| | -0.32 | | 9.56 | 14.57 | 11.84 | 12.9 | | | |
| DC.D6.E2.2 | 0.32 | 19 | 11.52 | 16.02 | 13.3 | 13 | 1.45 | 2.1 | |
| | -0.32 | | 12.16 | 16.66 | 13.94 | 13.64 | | | |
| DC.D6.E3.1 | 0.32 | 12 | 9.04 | 12.84 | 11 | 10.86 | 1.08 | 1.16 | |
| | -0.32 | | 9.68 | 13.49 | 11.64 | 11.5 | | | |

SD = standard deviation, $\sigma^2$ = variance

* Two versions of ice volume corrections were used in this analysis: the first correction for each sample is based on Fairbanks (1989) and the second is a localized correction from Santa Rosa Island (Rick et al. 2006).

**ANOVA tests compared SST values derived from both equations using the two different ice volume corrections. All ANOVA tests were performed using SAS 9.4 software.

**Table 2.2.** (continued)

| Sample # | Ice volume correction* | N | Min | Max | Mean | Median | SD | $\sigma^2$ | ANOVA** |
|---|---|---|---|---|---|---|---|---|---|
| DC.D6.E3.2 | 0.32 | 20 | 9.94 | 14.39 | 11.89 | 11.65 | 1.28 | 1.63 | |
| | -0.32 | | 10.58 | 15.03 | 12.53 | 12.29 | | | |
| DC.D6.E4.1 | 0.32 | 12 | 9.19 | 14.4 | 11.25 | 11.1 | 1.5 | 2.26 | F(1,22)=1.09, p=0.3081 |
| | -0.32 | | 9.83 | 15.04 | 11.89 | 11.74 | | | |
| DC.D6.E4.2 | 0.32 | 12 | 10.44 | 14.24 | 12.58 | 12.88 | 1.41 | 1.98 | |
| | -0.32 | | 11.08 | 14.88 | 13.22 | 13.52 | | | |
| DC.D6.F1.1 | 0.65 | 12 | 9.53 | 14.01 | 11.76 | 12.01 | 1.48 | 2.19 | F(1,22)=4.56, p=0.0442 |
| | -0.32 | | 10.82 | 15.3 | 13.05 | 13.3 | | | |
| DC.D6.F1.5 | 0.65 | 24 | 9.57 | 14.99 | 11.68 | 11.51 | 1.44 | 2.08 | |
| | -0.32 | | 10.86 | 16.28 | 12.97 | 12.8 | | | |
| DC.D6.F1.6 | 0.65 | 22 | 9.96 | 14.9 | 12.07 | 11.48 | 1.45 | 2.11 | |
| | -0.32 | | 11.25 | 16.19 | 13.36 | 12.77 | | | |
| DC.D6.F2.1 | 0.65 | 12 | 8.05 | 14.74 | 11.44 | 11.36 | 1.9 | 3.6 | |
| | -0.32 | | 9.34 | 16.03 | 12.73 | 12.66 | | | |
| DC.D6.F2.5 | 0.65 | 20 | 10.58 | 16.28 | 12.93 | 12.72 | 1.77 | 3.12 | F(1,38)=5.33, p=0.0264 |
| | -0.32 | | 11.87 | 17.57 | 14.22 | 14.01 | | | |

SD = standard deviation, $\sigma^2$ = variance

* Two versions of ice volume corrections were used in this analysis: the first correction for each sample is based on Fairbanks (1989) and the second is a localized correction from Santa Rosa Island (Rick et al. 2006).

**ANOVA tests compared SST values derived from both equations using the two different ice volume corrections. All ANOVA tests were performed using SAS 9.4 software.

**Table 2.3.** Summary statistics of estimated Paleo-SST* values for each component

| Site (CA-) | Stratum | N | Mean | SE of Mean | Standard deviation | Variance | Skewness | Kurtosis | Range | Min | Max |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bay Point | Modern | 24 | 14.9 | .36 | 1.77 | 3.13 | .17 | .02 | 7.43 | 11.68 | 19.11 |
| SMI-603 | II | 129 | 12.86 | 0.13 | 1.45 | 2.09 | 0.33 | -0.86 | 5.66 | 10.36 | 16.02 |
| SMI-261 | A | 44 | 13.06 | 0.2 | 1.33 | 1.76 | 0.51 | -0.68 | 5.36 | 10.73 | 16.09 |
| SMI-603 | III | 36 | 12.85 | 0.26 | 1.57 | 2.46 | 0.23 | -1.18 | 5.58 | 10.24 | 15.82 |
| SMI-603 | IV | 68 | 13.28 | .18 | 1.49 | 2.23 | .8 | .45 | 7.04 | 10.88 | 17.91 |
| SMI-603 | V | 88 | 12.67 | 0.15 | 1.42 | 2.01 | 0.3 | -0.87 | 5.62 | 9.98 | 15.59 |
| SMI-261 | C | 80 | 12.97 | 0.21 | 1.92 | 3.68 | 0.62 | -0.52 | 7.31 | 10.1 | 17.41 |
| SMI-603 | VI | 94 | 12.4 | 0.16 | 1.58 | 2.5 | 0.38 | -0.48 | 7.53 | 8.91 | 16.44 |
| SMI-603 | VII | 92 | 11.85 | 0.15 | 1.46 | 2.14 | 0.46 | -0.42 | 6.33 | 9.1 | 15.43 |
| SMI-261 | E | 118 | 12 | 0.15 | 1.61 | 2.59 | 0.29 | -0.71 | 7.11 | 8.92 | 16.02 |
| SMI-261 | F | 90 | 12.03 | 0.17 | 1.64 | 2.69 | 0.41 | -0.1 | 8.23 | 8.05 | 16.28 |

* Ice volume corrections based on Fairbanks (1989).

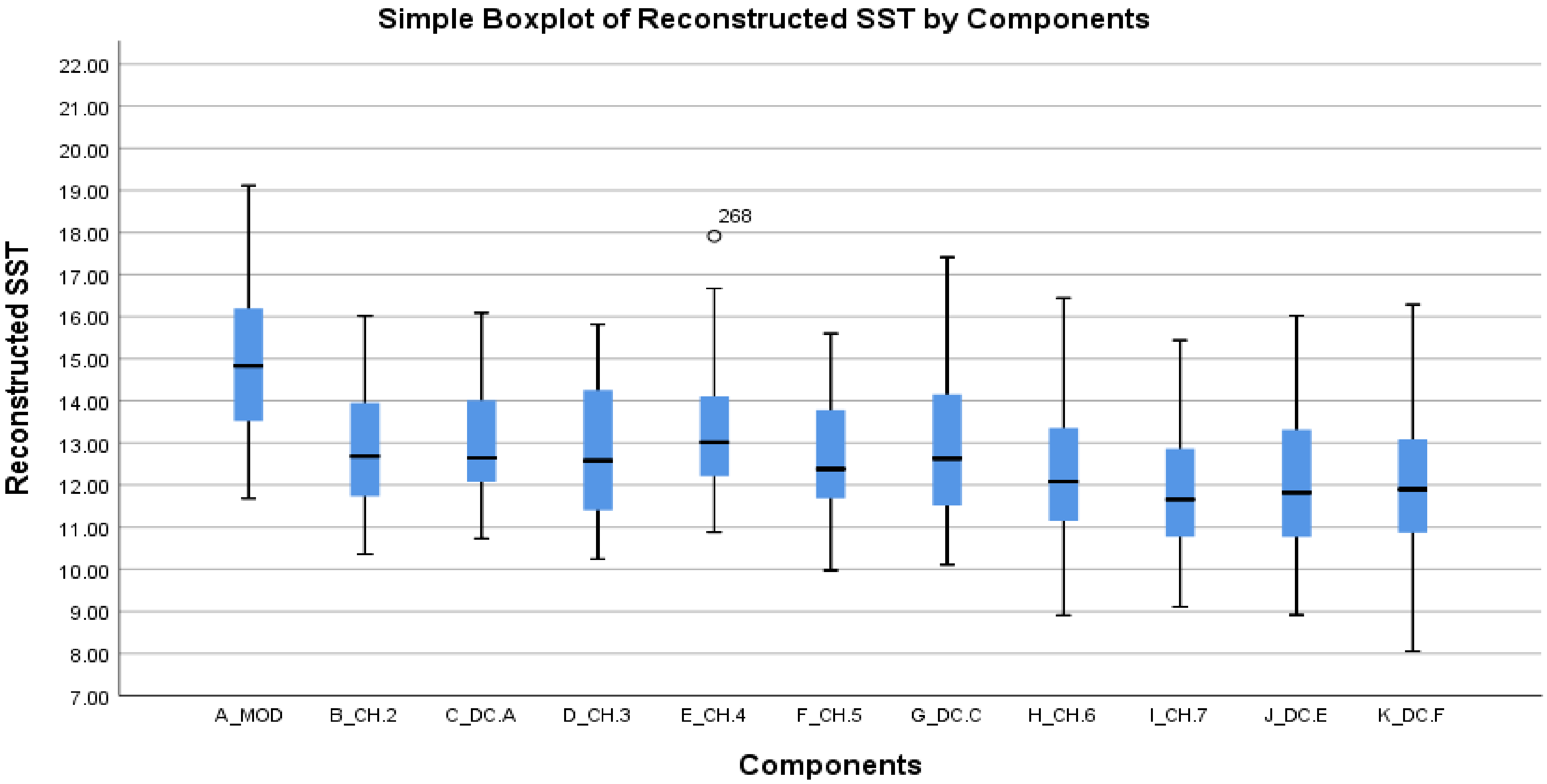

**Figure 2.6.** Boxplot graphs depicting combined SST values from all shell samples within each stratum to represent the component as a whole. For instance, “A_MOD” contains all SST data from both modern shell samples combined in a single boxplot to represent this time period.

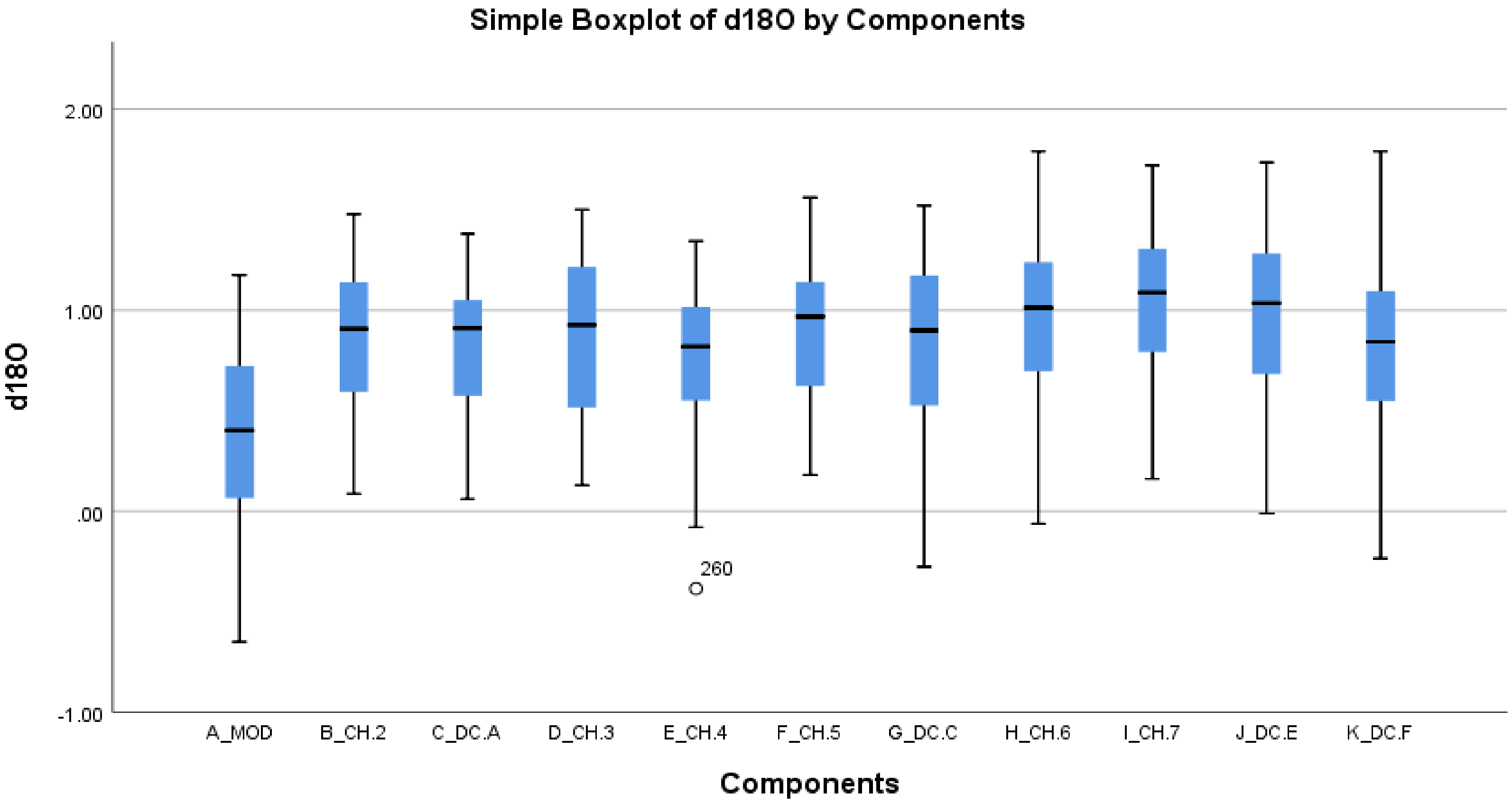

**Figure 2.7.** Boxplot graphs depicting combined $\delta^{18}O$ values from all shell samples within each stratum to represent the component as a whole. For instance, "A_MOD" contains all $\delta^{18}O$ data from both modern shell samples combined in a single boxplot to represent this time period.

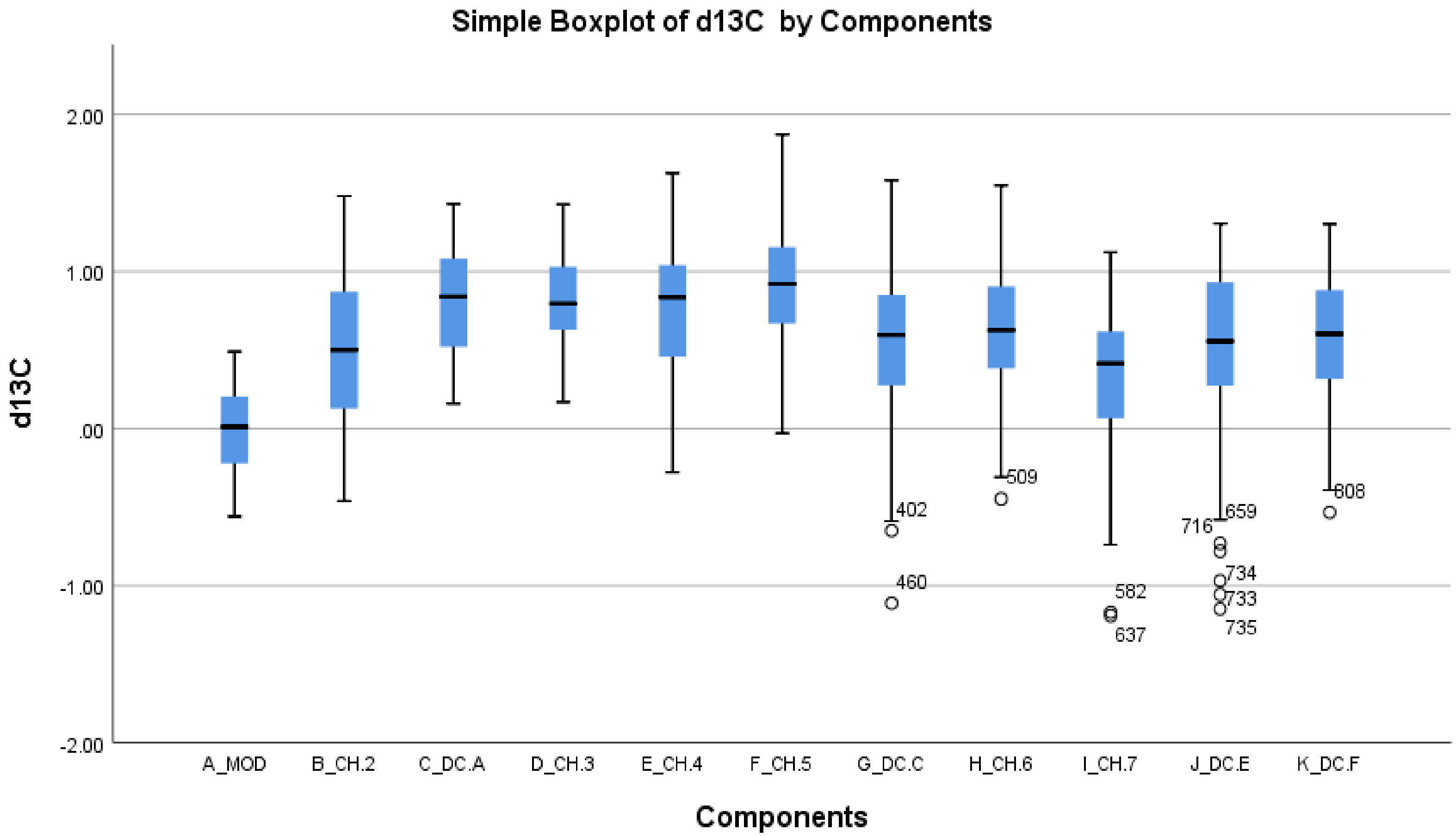

**Figure 2.8.** Boxplot graphs depicting combined $\delta^{13}$C values from all shell samples within each stratum to represent the component as a whole. Outlier values are depicted by small open circles of which the numerical values are arbitrary (they represent the sample number within the larger dataset).

Southern California Bight, particularly between ~9,200 and 10,200 cal BP (Stratum F at Daisy Cave). Mean SST and annual ranges in water temperature variation show oscillating patterning through time, with an general warming trend from the Early Holocene (~10,200 cal BP) to the Middle Holocene peak between ~3900 and 4300 cal BP, after which there is a slight decrease in the average and annual range of nearshore water temperatures for the remaining paleo-sequence presented here (Figure 2.5). Standard deviations and variance in SST also reveal the highest values (standard deviation up to 1.9 with variance of up to 3.6) in the earliest temporal phase represented here (Stratum F at Daisy Cave; see Table 2.2) further confirming increased variation at this time.

The $\delta^{18}$O values in the Bay Point sequence range from -0.65‰ to 1.79‰ with a mean value of 0.87‰, showing a range of 2.44‰ over the past 10,000 years (see Table 2.1 and Figure 2.7). The distribution is negatively skewed as the mean (0.87) and median (0.93) are both lower than the mode (1.13), but only moderately so (-0.46), as confirmed by a low kurtosis value (-0.22). As explained earlier, $\delta^{18}$O values are largely driven by temperature, though salinity may have contributed to some degree, particularly in the earlier temporal periods included in this study.

The $\delta^{13}$C values in the Bay point sequence have a range of 3.06‰, including a minimum recorded value of -1.19‰ to a maximum of 1.87‰ with a mean of 0.59‰ (see Table 2.1 and Figure 2.8). The distribution is also negatively skewed (-0.52), but only moderately so, with a relatively low kurtosis value (.56). $\delta^{13}$C values are driven by salinity, upwelling and associated nutrients in ocean water, with higher values usually being indicative of surface water and lower values (especially extreme low values) usually being associated with upwelling events, which bring deep ocean waters containing more depleted/lower values up to the surface. $\delta^{13}$C values from mussel shells from these sites oscillate through time, but not always in conjunction with $\delta^{18}$O. The overall patterning shows oscillations including extreme low values during the Early Holocene with the highest values in the Middle Holocene and then somewhat lower values in the early Late Holocene (Stratum II at Cave of the Chimneys) and modern samples. In addition to increases and decreases in mean $\delta^{13}$C values, ranges within each component also shift through time, with the widest ranges in the Early Holocene and the smallest ranges in the Late Middle Holocene and early Late Holocene components represented by Stratum III at Cave of the Chimneys and Stratum A at Daisy Cave. The $\delta^{13}C$ range represented in the modern shells, however, is the lowest of all. The highest mean and maximum $\delta^{13}C$ values were recorded in shells from Stratum V at Cave of the Chimneys and all Middle Holocene components contain very similar mean values (see Figure 2.8), suggesting less upwelling along with relative stability in nearshore habitats on the northeast coast of San Miguel Island after sea level stabilization (~6,000 cal BP).

Examining the Early Holocene dataset in more detail suggests more fluctuations (enriched and depleted values) and less stable conditions in addition to increased upwelling events during this climatically dynamic time period. Stratum F contains higher overall values, suggestive of less upwelling events, when compared to Stratum E, which contains several extremely low (outlier) $\delta^{13}C$ values, as does Stratum VII at Cave of the Chimneys. This implies there were fewer upwelling events around San Miguel Island between ~10,200 and 9200 cal BP, followed by an increase in upwelling events between 9600 and 7500 cal BP, potentially accompanied by higher surface water pH. Stratum C, at Daisy Cave contains relatively high values, but also shows extreme low (outlier) values and has the largest range of values overall, suggesting oscillating conditions continued during the late Early Holocene before sea levels stabilized. The stark contrast between the Early and Middle Holocene components suggests that after sea levels stabilized, so too did nearshore upwelling patterns in the outer Southern California Bight. The very low $\delta^{13}C$ mean value in modern samples is likely a result of the much smaller sample size in this component (only two modern shells were tested), though it might be indicative of increased upwelling events in the region today as compared to the Middle Holocene. Additional sampling is required to further address this pattern.

Correlation analysis (Pearson's r) was conducted between $\delta^{18}O$ and $\delta^{13}C$ in each sampled shell resulting in a wide range of results (see correlation [r] values on Table 2.1), suggesting the relationship between $\delta^{18}O$ and $\delta^{13}C$ is complex and driven by multiple variables. There are, however, a few overall patterns that are worth mentioning. For the most part correlations are negative, showing an inverse relationship between $\delta^{18}O$ and $\delta^{13}C$, with r values ranging from strong inverse correlations (-0.93) to weak inverse correlations (-0.03) and everything in between. Out of the 55 sampled shells, only seven reveal a positive correlation between $\delta^{18}O$ and $\delta^{13}C$ values and they are all low, ranging from +0.01 to +0.29. Most of the shells containing a positive correlation between $\delta^{18}O$ and $\delta^{13}C$ are from Early Holocene components, with one from the Middle Holocene (Stratum V at Cave of the Chimneys) and one from the early Late Holocene (Stratum II, Level 3, at Cave of the Chimneys).

## Discussion

### Trans-Holocene Paleo-SST Reconstructions

Comparison of the oxygen isotopic results from full profiles of archaeological mussel shells with historic temperature records provides insights into paleo-SST trends. The highest resolution SST curve for the SBB shows fluctuating temperatures throughout the Holocene (Figure 2.9; Kennett and Kennett 2000; Kennett 2005). This curve, based on the oxygen isotopic composition of *G. bulloides* from varved sediments, indicates alternating warm and cool millennial scale periods. Warmer water intervals were inferred to have occurred between ~11,000 and 9,600 BP, ~8,200 and 6,300 BP, ~5,800 and 3,800 BP and ~2,900 to 1,500 BP, with a general warming trend from ~500 BP to the present (Kennett 2005). Colder water intervals occurred between ~9,600 and 8,200 BP, ~6,300 and 5,800 BP, ~3,800 and 2,900 BP and ~1,500 and 500 BP (Kennett 2005).

Moving backwards through time: in Stratum II (~2165-3725 cal BP) at Cave of the Chimneys, SST estimates are between 10.36 and 16.27 °C with an average of 12.86 °C, indicating cooler water temperatures than present. In addition, average values are fairly consistent except for two shells from the lower (older; see Table I.2) levels of this stratum (levels 3 and 4), which likely drive the significant differences in mean values for profile shells in this component ($F(8, 120)=6.73$, $p<.0001$; Figure 2.10A). Occupations represented by Stratum A at Daisy Cave (~2840-3680 cal BP) overlap somewhat with dated samples from Stratum II at Chimneys. SST values for Stratum A range from 10.73 to 16.09 °C with an average of 13.06 °C. ANOVA analysis also reveals significant differences in mean SST values of profiled shells in this component (F(2,

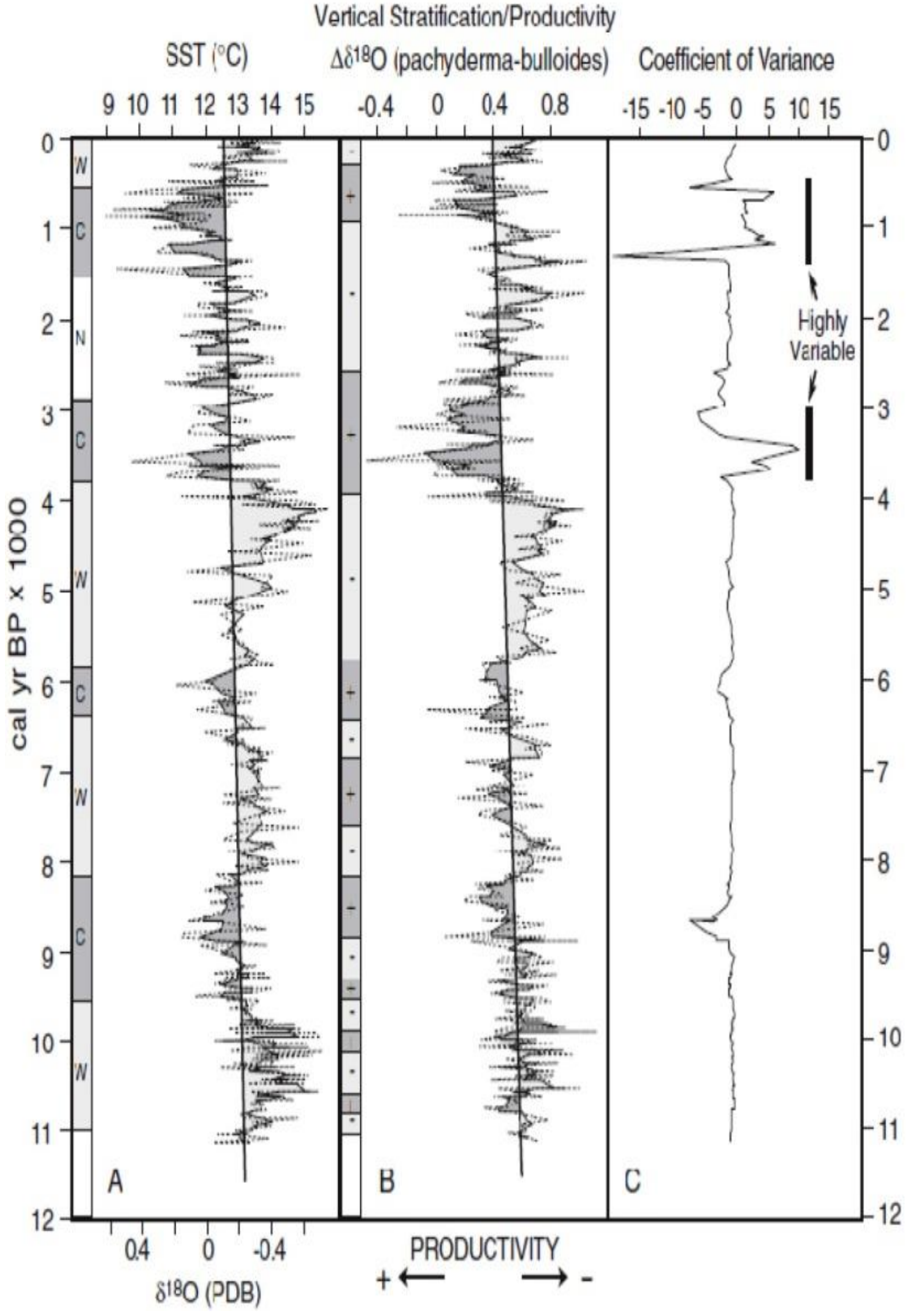

**Figure 2.9.** Holocene climate record for the Santa Barbara Basin (Kennett 2005:66,67). (A) SST curve based on oxygen isotopic composition of surface-dwelling foraminifera (*Globigerina bulloides*) from varved sediments. Bar on left side represents warm (w) and cold (c) water cycles. (B) Vertical stratification/productivity record based on differing isotopic composition of surface-dwelling (*G. bulloides*) and deeper-dwelling (*Neogloboquadrina pachyderma*) foraminifera. Bar on left shows intervals inferred as high (=+) or low (-) productivity. (C) Water cycles through the Holocene.

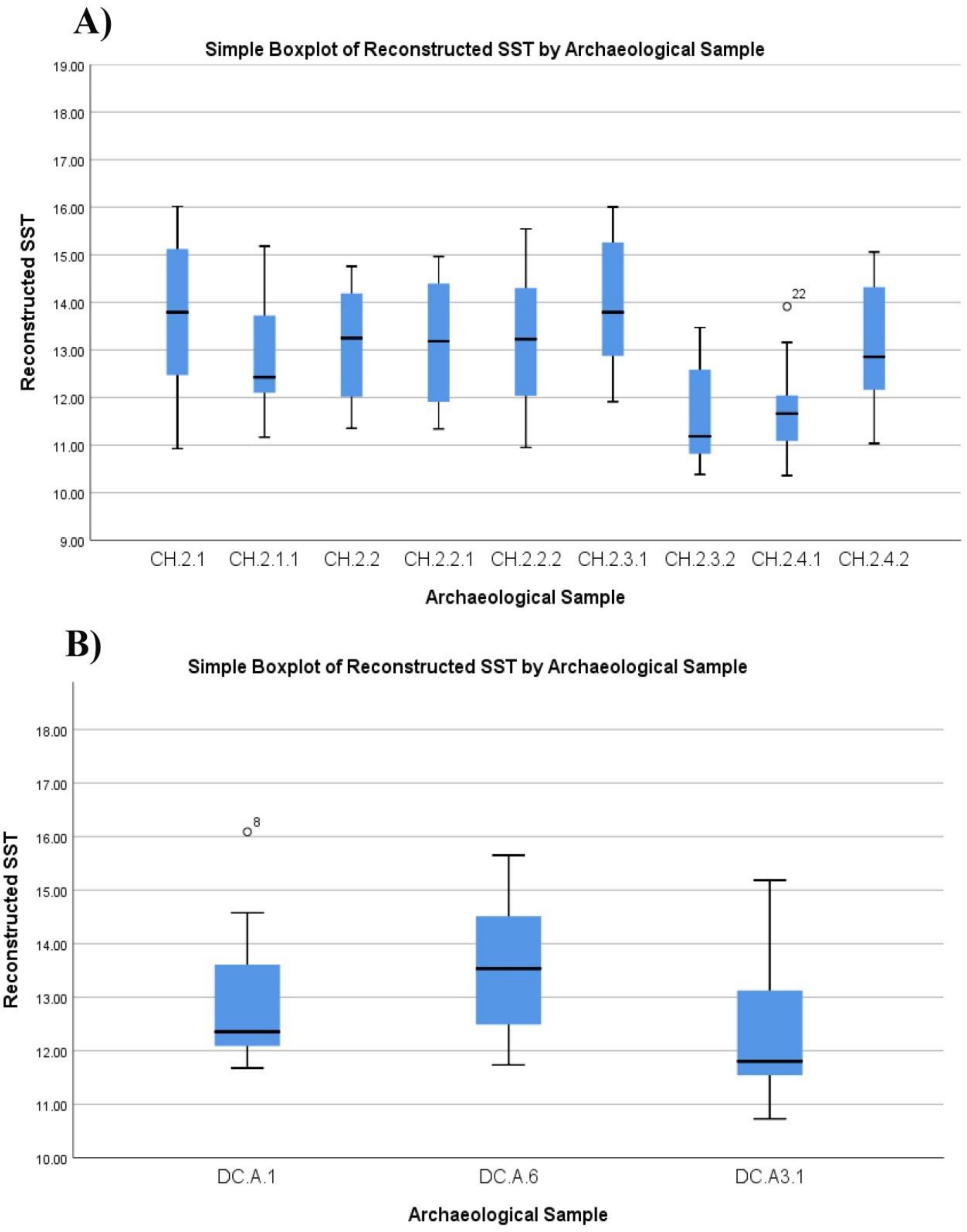

**Figure 2.10.** Boxplots depicting full range of SST variation from individual shell samples within each archaeological component: (A) Depicts SST ranges and means for all profiled and extended profiled shells from Stratum II at Cave of the Chimneys, and (B) Depicts all ranges and means for profiled and extended profiled shells from Stratum A at Daisy Cave.

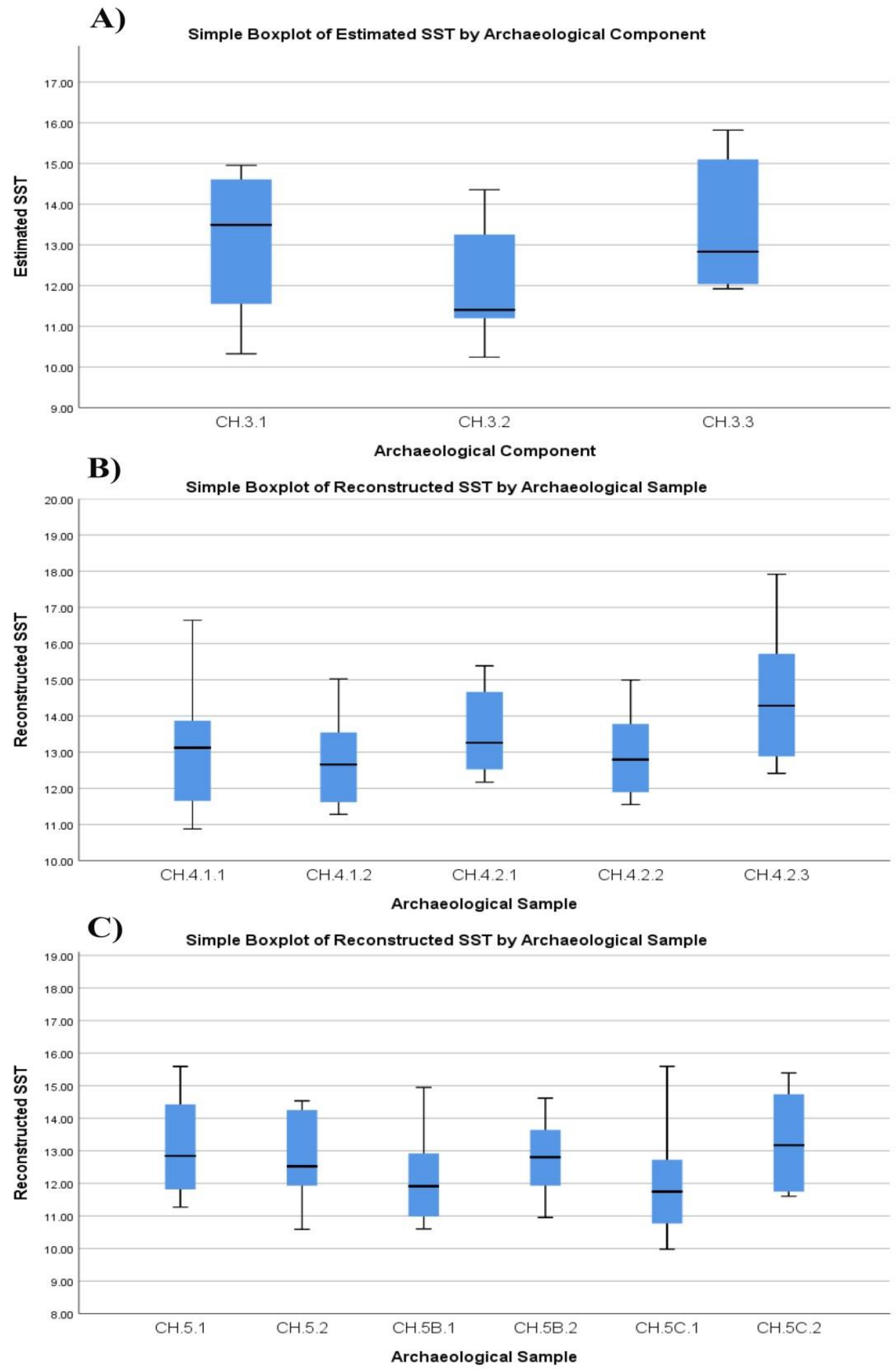

**Figure 2.11.** Boxplots depicting full range of SST variation from individual shell samples within each archaeological component: (A) Depicts SST ranges and means for all profiled and extended profiled shells from Stratum III, and (B) Depicts all ranges and means for profiled and extended profiled shells from Stratum IV, and (C) Depicts all ranges and means for profiled and extended profiled shells from Stratum V, at Cave of the Chimneys.

41)=3.7, p=.0332; Figure 2.10B) suggesting significant oscillations in water temperature in this time period, much like Stratum II. Kennett's (2005) SBB curve implies variable/warmer water temperatures between ~2900 and 1500 BP, preceded by cooler temperatures between ~3800 and 2900 BP. Though both of these strata contain dated samples straddling this warmer/variable and cooler period, making it difficult to confirm or deny this pattern, the fact that the warmer temperatures were recorded in shells from the lower (older) levels of both strata (most likely within thetime frame represented by a cooler phase in SBB core) suggests significant differences between the SBB and Bay Point sequences that show finer-grained temporal patterning at the localized scale (see below).

Samples from Stratum III (~3920-4130 cal BP), contain similar SST values ranging from 10.24 to 16.09 ° C, with an average of 12.85°C and show homogeneity between mean values (F(2, 33)=2.29, p=0.1168; Figure 2.11A) suggesting relative stability at this more narrowly defined point in time. Profiled mussel shells from Stratum IV (~3900 to 4400 cal BP) at Cave of the Chimneys contain the warmest recorded SST values in this study (10.88 to 18.18 ° C, mean = 13.5 ° C) and correspond with a sea urchin lens (see Chapter V of this dissertation) accumulated sometime between ~3965 and 4380 cal BP. In spite of the relatively short time period represented in this deposit, analysis of variance reveals significant differences between mean values of profiled shells from this stratum (F(4, 63)=3.31, p=.0158; Figure 2.11B) suggesting short-term oscillations possibly suggestive of increased ENSO events (Carré et al 2005). In addition, this component corroborates the SBB core data as it falls within a temporal phase defined by warmer SST. Although Stratum V also falls within this warmer phase (~4230-4540 cal BP), however, it is slightly cooler than all of the above components with an average SST of 12.67 ° C, showing localized divergence from the SBB core sequence. SST values in this component range from 9.98 to 15.59 ° C and analysis of variance shows relative homogeneity between mean values of sampled mussel shells (F(5,8 2)=2.21, p=.0612; Figure 2.11C) suggesting this pattern was relatively stable in the few hundred years potentially represented in this deposit. Patterning in nearshore SST as described above allows us to further fine-tune the larger regional trends represented in the SBB sequence.

The preceding three components contain dated samples that fall within the Middle to Early Holocene transition. Stratum C (~6400-6800 cal BP), at Daisy Cave contains deposits dated between 6410 and 6930 cal BP, which should fall within a warmer water interval according to the SBB curve. Estimated SST in this component ranges from 10.1 to 17.41 with an average of 12.97 ° C. This component dates just before a cool period in the SBB curve at ~6300 to 5800 cal BP, and is slightly warmer than Stratum V, which falls within this time period. Analysis of variance reveals highly significant differences in mean SST values within this stratum (F(5, 74)=10.49, p<.0001; Figure 2.12A), implying significant oscillations in SST during this time period. This large range in values could be indicative of the temperature shift as it occurs. For instance, some of the profiled shell samples (DC.C.2, DC.C.7 and DC.C.8) contain much lower values and may represent the beginning of this cold phase slightly earlier than estimated in the SBB core. Direct dating of these shell samples should allow a more nuanced interpretation of the SST shifts occurring at this time. Stratum VI (~3900 to 4400 cal BP) at Cave of the Chimneys overlaps somewhat with Stratum C, at Daisy Cave, but contains dated samples spanning a much longer time frame (~5800 to 8400 cal BP). SST values for this stratum range from 8.91 to 16.44 ° C, with an average of 12.4 ° C. This stratum potentially contains samples from both warmer and cooler intervals in the SBB core complicating interpretations. An analysis of variance, however, shows a high degree of homogeneity in mean SST values of sampled mussel shells (F(4, 89)=0.92, p=0.458; Figure 2.12B) in spite of the long time frame potentially included in this sample, suggesting that sampled shells do not encompass the full temporal range encompassed in $^{14}$C date ranges. Stratum VII at Cave of the Chimneys includes samples dated within a narrower potential time range of ~7480-8300 cal BP, which falls mostly within a warm water interval on the Kennett's SBB curve, although it precedes it slightly. Nearshore SSTs on the northeast coast of San Miguel Island do not appear to mirror the SBB core in this instance as values fall within a similar range as those from Stratum VI (~6000 to 8400 cal BP) (9.1 to 15.43 ° C), and the average and maximum water temperatures are even lower (11.85 ° C). An ANOVA test also shows high homogeneity between mean values in this stratum (F(5, 86)=0.82, p=0.5402; Figure 2.12C). These data might indicate a short-term cooler phase within the larger regional warming trend.

Dated samples from the following components fall well within the Early Holocene time period. Stratum E at Daisy Cave contains 13 dated shells, which span ~8480 to 9280 cal BP. Radiocarbon dating of twigs and marine shells suggest intact ordered layers spanning sometime between ~8480 and 8900 cal BP for level E1, between ~8925 and 9050 cal BP for level E3, and between 8970 and 9280 cal BP for level E4. SST values for Stratum E range from 8.92 to 16.02 ° C, with an average of 12 ° C. This includes a shell from the bottom of Stratum D that was dated between ~8470 and 8590 cal BP. This time frame is solidly within a cooler water interval on the SBB core, and although the mean and maximum values are slightly lower, the minimum value is warmer than the minimum value in Stratum F, which falls within a warmer phase on the SBB curve. An analysis of variance test suggests extreme oscillations in mean water temperature values during this time period (F(6, 112)=5.48, p<.0001; Figure 2.13A). Stratum F at Daisy Cave contains charcoal and shell samples dated between ~9200 and 10,200 cal BP, which overlaps warmer and cooler water intervals on the SBB curve, blurring our ability to confirm patterning between SBB and nearshore trends. This component shows mean SST at 12.03 ° C and contains the coldest recorded SST value in this study. Estimated SST values range from a record low of 8.05 to a near record high of 16.28 ° C, suggesting extreme oscillations in SST ranges during this time period and overall warmer conditions (higher mean and max values) than later on in Stratum E. An analysis of variance, however, shows a low degree of homogeneity between mean values (F(4, 85)=2.38, p=0.0576; Figure 2.13B) in spite of larger overall ranges of values.

## Trans-Holocene Oceanographic Conditions

A nearshore trans-Holocene paleo-climate record depicting localized variation for Bay Point is presented in Figure 2.13. Paleo-SSTs were estimated using established conversions and corrections for marine shell carbonate (calcite phase) in the study area and show a general trend toward warmer waters from ~10,200 years ago to the present. Comparisons with the SBB cores taken from the Santa Barbara Channel north and east of San Miguel Island reveal some similarities in broad-scale patterning along with localized variation, confirming the need to establish site-specific nearshore sequences when

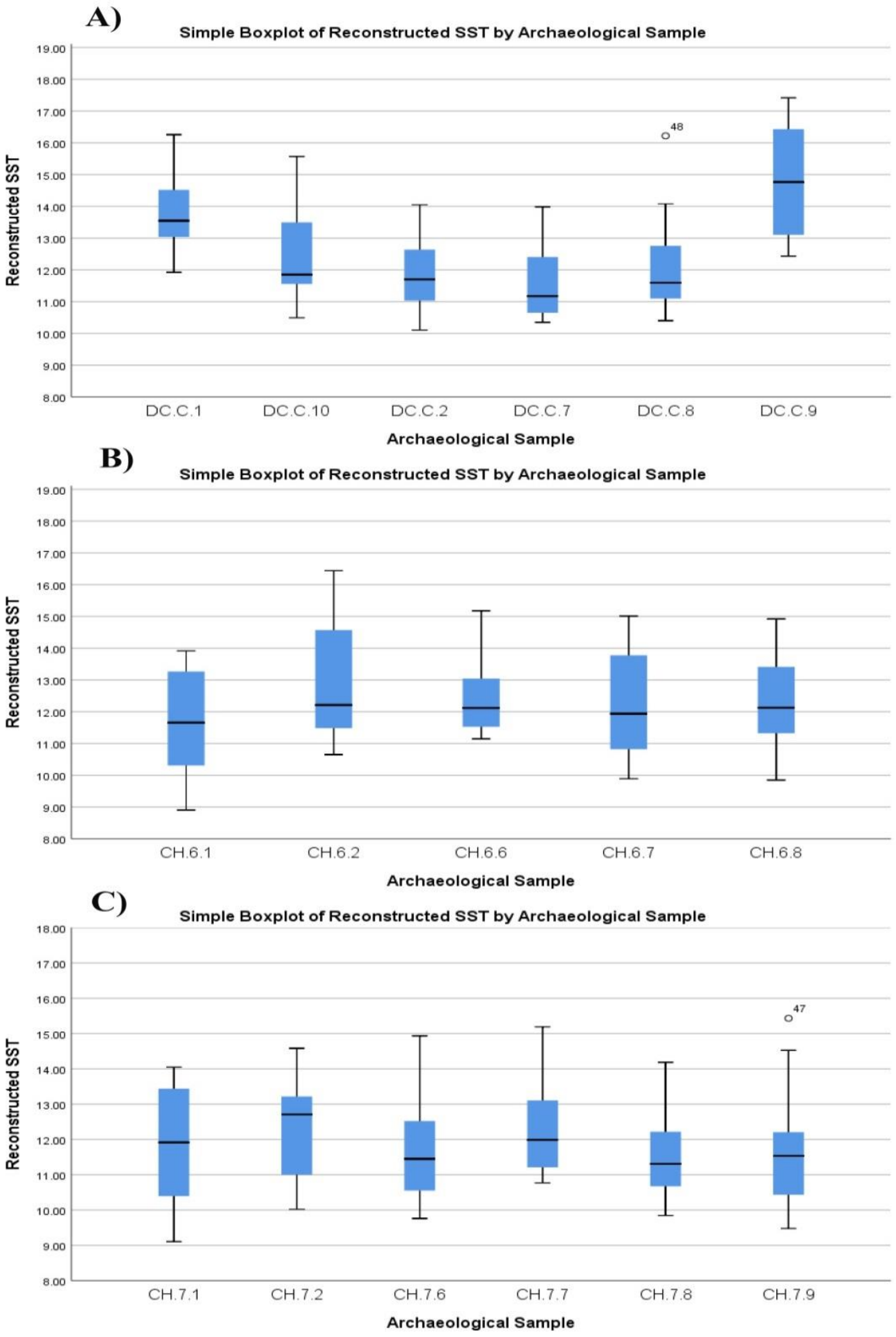

**Figure 2.12.** Boxplots depicting full range of SST variation from individual shell samples within each archaeological component: (A) Depicts SST ranges and means for all profiled and extended profiled shells from Stratum C, at Daisy Cave, and (B) Depicts all ranges and means for profiled and extended profiled shells from Stratum VI, and (C) Depicts all ranges and means for profiled and extended profiled shells from Stratum VII, at Cave of the Chimneys.

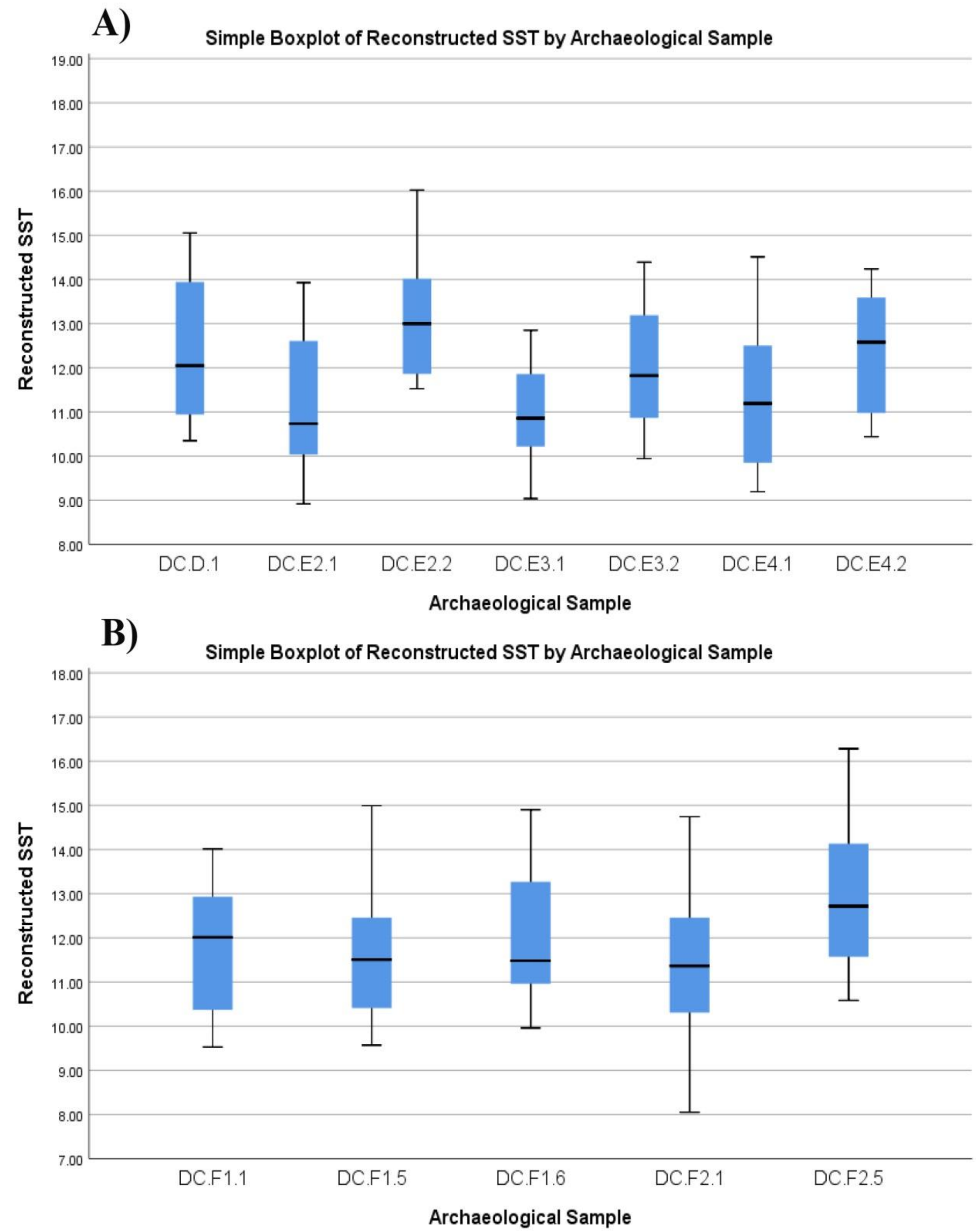

**Figure 2.13.** Boxplots depicting full range of SST variation from individual shell samples within each archaeological component: (A) Depicts SST ranges and means for all profiled and extended profiled shells from Stratum E, at Daisy Cave, and (B) Depicts all ranges and means for profiled and extended profiled shells from Stratum F, at Daisy Cave.

investigating the nature and effects of human interactions with intertidal marine resources. The complex pattern of oceanographic currents, gyres and eddies moving through and mixing in the Southern California Bight (see Figure 1.2) implies significant variation exists in nearshore SST between islands and even along coastlines of the same island (i.e., north shore vs. south shore, etc.). In addition, water temperatures differ at different depths in the water column implying we should see variations in SST when sampling different organisms collected at the same location depending on their primary intertidal depth habitats. For instance, SST derived from stable isotope signatures in shells of red abalone (who inhabit low intertidal to subtidal zones) should be lower overall than SST derived from stable isotope signatures in California mussel shells, which primarily inhabit the middle intertidal zone (though these can be subtidal as well), or owl limpets (*Lottia gigantea*) that inhabit the upper intertidal. The primary concern this data addresses is whether the overall trends observed in deep-ocean cores mirror nearshore habitats and how useful various regional sequences are when interpreting archaeological datasets. As indicated above, some of the patterning from the Bay Point sequence mirrors warm and cool phases seen in the SBB core, suggesting that broad, long-term (millennial) trends are consistently represented in a regional scale. However, the Bay Point sequence also shows opposing patterns in localized nearshore trends that are directly relevant to human harvesting and subsistence adaptations, highlighting the need for localized SST reconstructions.

A detailed comparison of the Bay Point nearshore sequence to Kennett's (2005) SBB core generated sequence (see Figure 2.8) requires numerical values to test against the dataset I generated, and I hope to be able to access and evaluate this data in the future. For now, I compared the Bay Point sequence against the graphed version of the SBB core dataset (Figure 2.14). The first primary difference between sequences is the range of $\delta^{18}$O values, which appears to be ~0.6 to -0.7 on the Kennett's (2005) SBB curve and -0.65 to 1.79 in the Bay Point sequence. Although minimum values are similar, the range and maximum values are much higher in the nearshore Bay Point sequence, showing more enriched/cooler overall temperatures than the SBB core data. This might be due to the complex patterns of oceanographic currents and mixing in the Southern California Bight (see Figure 1.2) and the location of the core in an area that receives inflow from the

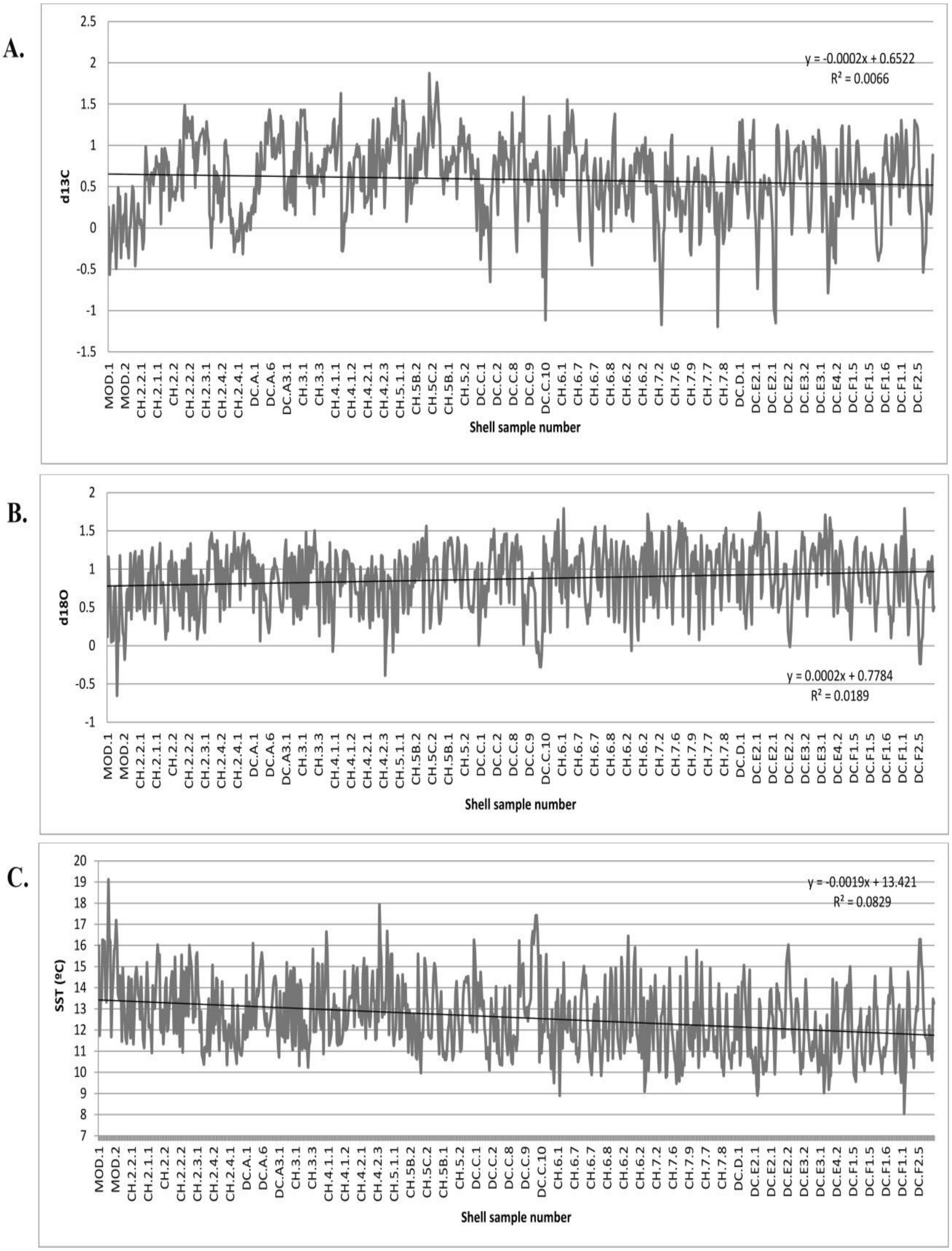

**Figure 2.14.** Holocene climate record for the nearshore environment of Bay Point, San Miguel Island. (A) Depicts $\delta^{13}$C PDB values, (B) depicts $\delta^{18}$O PDB values, and (C) depicts SST curve based on oxygen isotopic composition of mussel shells from archaeological sites at Bay Point. A linear regression was fit to each graph, with formula and $R^2$ vlaues depicted.

warmer California Countercurrent that moves northward from Baja California Mexico along the southern California coastline. San Miguel Island in contrast is in the direct path of the cooler California Current (moves southward into the bight) and is minimally influenced by the California Countercurrent, as it is further out at the edge (western extent) of the bight. Additionally, wave effects (Adams et al. 2008), island wakes (Caldeira et al. 2005; Dong and Williams 2007), shifts in cross-shelf water flow in the Bight (Fewings et al. 2015) and multiple-scale variability (see Dong et al. 2009) in nearly all of these factors further complicate oceanographic circulation patterns in this area. Specifically, the Santa Barbara Basin (north and east of San Miguel Island) where the cores were taken, contains complex patterning of sub-mesoscale coastal eddies (Bassin et al. 2005) making this a less than ideal location for a regionally representative sample.

As different conversions and corrections were used in the establishment of SST data for Kennett's (2005) SBB curve, I compared the Bay Point sequence using the raw $\delta^{18}$O values rather than SST derived from conversions with corrections, as approximated from the graph. There are several obvious issues with this comparison, but I believe it shows some key differences: 1) the overall range of $\delta^{18}$O values (vertical axes in Figure 2.14) between both sequences differ considerably; and 2) additional short-term peaks are evident in the Bay Point sequence. For instance Kennett's (2005) SBB curve shows a warm phase between ~5,800 and 3,400 BP, which the Bay Point sequence further refines by showing cooler (more enriched values) during the beginning of this almost two thousand year phase (Stratum V) and confining the warm peak within this phase to between 3,900 to 4,400 cal BP (strata III and IV). Similarly, although three strata fall within the SBB curve warmer phase between 6,300 and 8,200 BP, distinctions within this roughly two-thousand-year time span are distinguishable in the Bay Point sequence. Specifically, Stratum C shows a warm peak between ~6,400 to 6,900 cal BP, and Strata VI and VII show overall cooler temperatures in the larger time span of ~6,000 to 8,400 cal BP. Although these variations are somewhat vague due to the differing levels of data available for comparison, I believe that this shows the value and utility of using finer-grained nearshore archaeologically derived stable isotope studies in conjunction with larger-scaled regional trends to examine oceanographic conditions in localized nearshore intertidal habitats that coastal forager-fishers were interacting with on a daily basis.

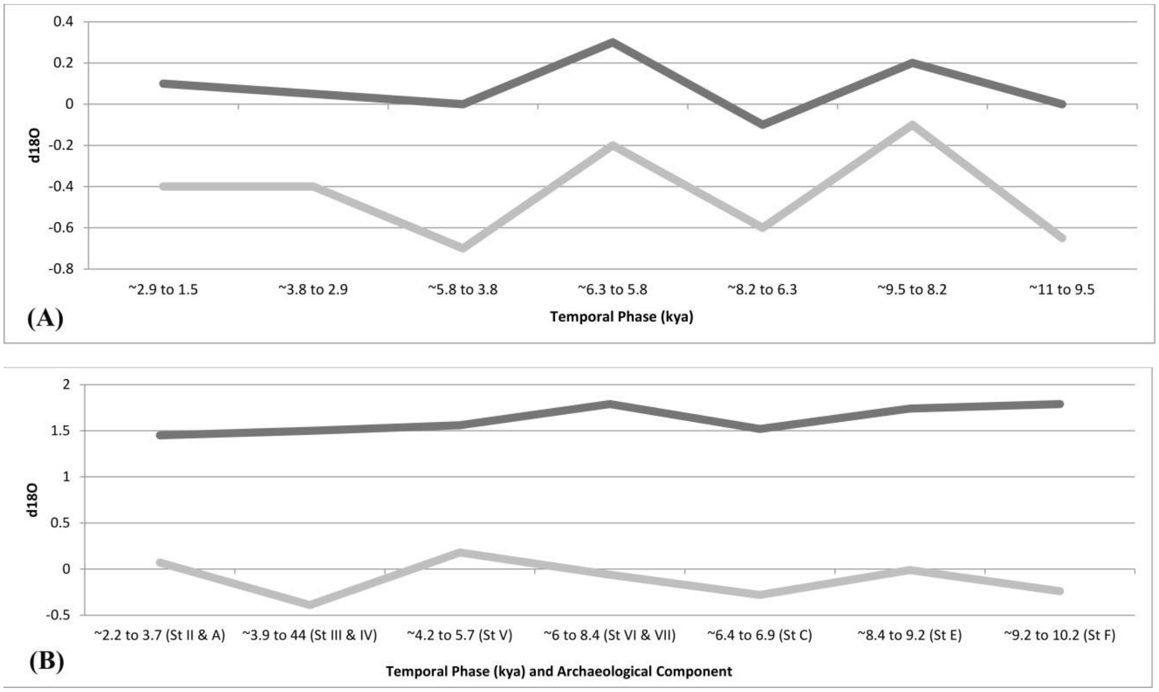

**Figure 2.15.** Line graphs depicting generalized Holocene trends in $\delta^{18}$O values: (A) represents data derived from the Kennett's (2005) SBB curve and (B) represents data derived from the Bay Point nearshore sequence. The lighter line below represents minimum $\delta^{18}$O values and the darker line above represents maximum values.

Previous isotopic analysis suggested that warmer water temperatures around 4300 cal BP may have led to an increase in sea urchin abundance on the northeast coast of Santa Rosa Island as documented in an archaeological midden (CA-SRI-191) that contained unusually high densities (~21% by weight) of this echinoderm (Robbins and Rick 2006; Rick et al. 2006). The Bay Point sequence suggests this may indeed be a wider, regional trend as Stratum IV contained high densities of sea urchin tests and the warmest recorded water temperatures in my study. These data also suggest that this warm water event was not long-lived and did not result in a "barrens" environment as described in modern studies. Kennett et al. (2007) highlight differences between terrestrial (precipitation) and marine paleo-environmental records saying that proposed increases of ENSO events indicated by higher SSTs during the Middle Holocene (as proposed by Friddell et al. 2003) are unlikely, and positing that warmer SSTs indicated at the millennial-scale may not necessarily correlate with more intense or frequent ENSO activity. Although that is one possible interpretation and remains a viable scenario, the combination of the Bay Point SST sequence and faunal data from these sites (see Chapter V) suggest that in this instance there may have been increased ENSO events during the late Middle Holocene when water temperatures were warmest. On the other hand, my study also documents significant climatic variability and oscillations during the Early Holocene, although on an overall cooler scale.

Differences in nearshore habitats between the Channel Islands and around a single island can also be quantified with these datasets. The California mussel shell sampled for isotopic analysis by Rick et al. (2006: Table 4) showed an average water temperature of 14ºC, with a range of 10.5 to 17ºC. The mussel shells sampled from Stratum IV at Cave of the Chimneys, which falls into a similar time frame based on $^{14}$C dates, contain mean values ranging from 12.95 to 14.55ºC (using the same ice volume correction as Rick et al. 2006, see Table 2.2) with ranges between 10.88 and 18.18 ºC. This comparison shows relative similarity between the paleo-SST data for these two sites along with slight localized variation between islands. The Bay Point sites are located on the northeast of San Miguel Island and CA-SRI-191 is located on the northeast coast of neighboring Santa Rosa Island. The northern shores of both these islands are in the direct path of the cooler water brought in by the California Current extending south into the Southern California Bight. Isotopic analyses by Jew et al. (2013) showed variation around the coast of San Miguel Island, although the $^{14}$C age ranges of the tested sites differed somewhat. Isotopic date from another site on northeast Santa Rosa Island (CA-SRI-666) suggests warmer waters in the Early Holocene when compared to the Bay Point sequence (Jew et al. 2014). Although the methods in this study varied in that it was focused primarily on establishing season of harvest data and thus utilized limited profiles when compared to my study, the mussel shell that was profiled fully (11 samples, Jew et al. 2014:Figure 4) shows a range of ~12 to 17ºC, which is higher than contemporaneous assemblages at Bay Point (Stratum E, at Daisy Cave) where the range is 8.05 to 16.02ºC with a mean value of 12ºC. Clearly sample size necessitates caution as the Bay Point sample is larger, but the differences are quite stark and suggest significant localized variation between sections of the northeast coast of San Miguel and Santa Rosa islands at roughly the same time period.

## Implications for Human Impact Studies on the Northern Channel Islands

A number of studies have documented shifts in size ranges and mean values through time for harvested shellfish taxa on the Northern Channel Islands (e.g., Braje et al. 2012; Erlandson et al. 2008d, 2011b, 2015a) in attempts to decipher whether decreasing sizes resulted from climatic shifts (i.e., SST) or human harvesting pressure. Localized nearshore trends for each site or island area (northeast Santa Rosa Island, etc.) are required to examine the cause of shifts in sizes and relative abundances of key shellfish through time in a site-specific context, but trends from Bay Point sites can be examined in the context of my nearshore SST sequence. Overall, the Bay Point sequence does not suggest that surface water temperature was responsible for shifts in relative abundances and sizes of abalone and mussel, implying that human harvesting and not climatic shifts was impacting the sizes and distributions of nearshore shellfish.

The SBB curve produced by Kennett (2005) shows a cool phase between ~5800 and 6200 cal BP, which Glassow et al (2012) argue is the cause for increased red abalone densities during this time at the Punta Arena site on Santa Cruz Island. Stable isotope analysis of archaeological mussel shells from the red abalone component at the Punta Arena site show lower values when compared to modern samples from the site vicinity, however, this study does not examine paleo-SST values for other components within the site either before or after the red abalone lens. The Bay Point sequence also shows lower values in all archaeological components when compared to modern samples, suggesting this is not an accurate comparison, and that shifts in paleo-SST need to be examined in the context of earlier and later paleo-components, not just against modern samples.

Although this time period is not clearly represented in the Bay Point sequence it is safe to assume that if cooler water temperatures were responsible for increased abundance of red abalone in island middens, later time periods (i.e., the Middle Holocene) should show a decrease in red abalone remains as compared to Early Holocene components at Bay Point, which are definitely cooler. The pattern is clearly reversed, however, at least on San Miguel Island. Red abalone is scarce in the Early Holocene components represented at these sites and is far more abundant during the warmer Middle Holocene occupations (see below). Mussel and black turban snail shells are the primary constituents in all Early Holocene strata at Bay Point, with red abalone becoming increasingly important during the Middle Holocene (see Ainis 2012; Forgeng 1992), when water temperatures were significantly warmer. The suitable SST range for red abalone is between 11 and 16ºC, with larvae not surviving above 18ºC (Hobday and Tegner 2002; Leighton 1974). As surface water temperatures stayed mostly within this range even during the warm peak during the late Middle Holocene, it is unlikely that SST shifts were responsible for changes in types of collected shellfish through time. Although the Bay Point sequence does not represent nearshore SST conditions throughout the region, my study suggests that in this case at least, shifts in SST were not driving changes in the relative abundance and sizes of harvested red abalone at these sites.

## Interpretation of Carbon Isotopes ($\delta^{13}C$)

Deciphering the precise nature and mechanism of carbon accumulation in marine shells is complex and not fully resolved by chemists (e.g., Duplessy et al. 2002; McConnaughey and Gilliken 2008; Santos et al. 2011. Nonetheless, it is being used to infer general productivity in marine environments (e.g., Flores et al. 2018; Kawahata et al. 2009). It is generally agreed that depleted $\delta^{13}C$ values are suggestive of increased upwelling events bringing deeper carbon (DIC) depleted water to the surface, but the factors contributing to oscillations in this ratio are complex and varied. The Bay Point sequence reveals trans-Holocene patterning in generalized upwelling and associated marine productivity that can be examined in conjunction with SST values for a more holistic view of productivity in nearshore marine habitats.

When examining the trends presented in Figure 2.13A a few general patterns are discernable. First, there is an increase in enriched $\delta^{13}C$ values through time from the Early to the Middle Holocene, after which $\delta^{13}C$ values are generally more depleted, particularly in the modern samples. Second, the relative range of $\delta^{13}C$ values is greatest during the Early Holocene and narrows significantly in the Middle and Late Holocene. As discussed previously in this chapter, correlations between $\delta^{13}C$ and $\delta^{18}O$ values in this study are not straight-forward implying that water temperature alone is not driving marine productivity (see Table 2.1 for Pearson's r values in each shell sample). However, it seems likely that increased upwelling, potentially driven by the influx of cooler water from melting polar ice caps during the Terminal Pleistocene is driving the depleted values and wider ranges seen in the Early Holocene. Subsequently as sea level stabilized, the lack of fresher water from melting ice caps allowed ẟ$^{13}$C values to rise somewhat and stabilize.

In addition to warmer surface and thermocline temperatures during the Middle Holocene, increased thermal stratification during this time period has been suggested (Friddell et al 2003) and may be confirmed by the shorter range and enriched ẟ$^{13}$C values seen in this sequence. The lack of depleted ẟ$^{13}$C values (indicative of deeper ocean water) during the Middle Holocene warming phase could be due to increased stratification in the water column during this time period, keeping enriched surface values above and depleted values lower down in the water column. Overall, this implies less mixing during this time and fits with interpretations of less upwelling.

Although sea level stabilization occurred closer to 6000 years ago, this time period is not well represented at the Bay Point sites. Rather, shell samples beginning in Stratum V at Cave of the Chimneys (~4400-5600 cal BP) show a stark contrast to all previous and older samples, marking this point in time where the stabilization of nearshore conditions is visible in this dataset. The ẟ$^{13}$C data from my study suggests that upwelling and/or marine productivity may be somewhat reduced and that this may coincide with increased stratification in the water column during warm water periods and potential El Niño events (i.e., strata IV and V have warmest SST and enriched ẟ$^{13}$C values). Other studies have documented complex trends indicating the dynamics of nearshore resources do not always coincide with the presence of El Niño warm water events (Elbert et al. 1994; Navarrete et al. 2002) and showing there is not necessarily a direct relationship between coastal upwelling and variability in oceanographic phenomena like ENSO events (Vargas et al. 2007; see Flores et al. 2018). Interpretation of this dataset is ongoing, and I hope to tease out more detailed patterning in these trends in the future.

In Chapter III, I summarize the extent of human use of seaweeds over the past several thousand years and highlight the nutritional characteristics of some of the most common taxa in the region to ague that Native people actively harvested this plentiful resource in spite of sparse archaeological and ethnographic evidence. I also review ethnographic and ethnohistoric accounts from the Pacific Coast of the Americas that document the dietary and technological use of seaweeds by indigenous peoples, supporting the idea that the Island Chumash also used such resources in the past.

# CHAPTER III

## THE POTENTIAL USE OF MARINE MACROPHYTES BY NATIVE PEOPLES OF THE PACIFIC COAST OF ALTA AND BAJA CALIFORNIA

Excerpts of this chapter were included in a co-authored book chapter:

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### Introduction

Human harvesting, utilization, and cultivation of seaweeds is undoubtedly extensive on a global scale (i.e., Chapman 1970; Evans 1986; McManus 1988; Mouritsen 2013; Ono 2010; Pereira 2016; Ryther 1981; Thi Thanh Vinh 2006; Vasey 1996; Wang and Chang 1994; Xia and Abbott 1987; Zaneveld 1959). A wide variety of uses foster an extensive aquaculture resulting in the harvest of ~16 million tons of seaweed annually, a staggering amount that was worth $7.4 billion in 2008 (Bostock et al. 2010). The value for edible marine algae alone accounts for billions of dollars, with China producing 2.5 billion tons of *konbu* (*Saccharina japonica*) per year and Japanese aquaculture of *nori* (*Porphyra*) said to be worth an annual sum of $2 billion (Mouritsen 2013:42). In addition to dietary uses, seaweeds maintain widespread use as fertilizer and animal feed, and for the extraction of potash, agar, alginic acid, cellulose, and iodine, amongst other chemical compounds (Chapman 1970; Evans 1986; Hoppe and Schmid 1969; McManus 1988; Mouritsen 2013; Smith 1905a, b; Tseng 1944a, b; Wang and Chiang 1994). Although the earliest known written record of seaweed use appears to be a Chinese herbal guide dated to 2700 B.C. (see Bell 1981:117), they were likely used for human consumption and medicinal purposes far earlier. Nutritional research shows that edible seaweeds provide a variety of nutrients essential to human health, including high levels of amino acids, essential fatty acids, vitamins, trace minerals, and hold many medicinal benefits (i.e., Dawczynski et al. 2007; Pereira 2011; Fleurence 1999; Gupta and Abu-Ghannam 2011;

Mautner 1954; Schmid 1969; Shalaby 2011; Silva et al. 2013; Wang and Chang 1994). Loaded with vitamins and minerals and often high in protein, seaweeds rival the nutritive quality of many edible terrestrial plants (Ryther 1981); prompting the use of the term "sea vegetables" rather than "sea weeds" (Tseng 1944b).

Seaweed cultivation has been practiced in many coastal areas for several hundred years, though the antiquity of seaweed and kelp management is uncertain (Bell 1981:117; Chapman 1970; Fleurence 2016:149; Mouritsen 2013:94; Thi Thanh Vinh 2006). An Icelandic saga dated to AD 961 refers to laws concerning the right to collect dulse (*Rhodymenia palmata*), or *sol*, recorded in the early 12th Century when it was reportedly transported over long distances as a prized trade item (Bell 1981:118; Chapman 1970:88). Regardless of when it began, global use and farming of marine macroalgae is clearly on the rise; seaweeds are now among the most important cultivated marine organisms in terms of biomass (Barsanti and Gualtieri 2014) relieving the pressure on naturally occurring and endemic populations (Critchley and Ohno 1998). Future uses of marine macroalgae will undoubtedly be discovered in our global state of resource depletion. For instance, new research is promoting the use of seaweeds as an untapped resource for biofuel production (Mansilla et al. 2012; Renita and Amarnath 2011; Wei et al. 2013). Biomass from large-scale commercial farming of seaweeds is being transformed into economically viable products (e.g., Hafting et al. 2015) and providing contributions to efforts for mitigation and adaptation to climate change (Camus et al. 2018; Duarte et al. 2017).

More than 150 species of edible seaweed have been reported worldwide (Kumar et al. 2008; see also Chapman 1970; Mouritsen 2013), with other counts exceeding 170 species (Evans 1986), and a recent book detailing 665 species of edible red, green, and brown algae (Pereira 2016). China, Hawaii, and Taiwan maintain the highest numbers of edible seaweed with between 74 and 76 species respectively (MacGaughey 1916, 1918; Wang and Chiang 1994; Xia and Abbott 1987), followed by other southeast Asian cultures (see Zanefield 1959), including 45 species consumed in the Philippines (McManus 1988, see also Trono 1999), and 35 species harvested in Japan (MacGaughey 1916:476) to name a few. Though hundreds of species are edible, however, less than 20 account for ~90% of harvested biomass (Pereira 2016:vii) and several species belonging to only four genera represent ~93% of cultivated marine macroalgae worldwide (Fleurence 2016:150, Table 5.1). In addition to having formed pivotal components of human subsistence for thousands of years, some seaweeds were recognized as containing medicinal properties by aboriginal populations around the globe (Chapman 1970:224-228; Mouritsen 2013:216-220). The bioactive substances and chemical constituents of marine algae are now being shown to contain immunomodulating and antitumor properties, explaining the intricacies of exactly how they contribute to the healing of disease and maintenance of good health (e.g., Sithranga-Boopathy and Kathiresan 2010; Mouritsen 2013:108-109; Smit 2004; Wijesekara et al. 2010) as long acknowledged by ancient peoples.

In addition to dietary uses, the high salt and agar content of seaweeds make them an excellent temporary preservative in the form of alginate (Smith 1905a:165; Tseng 1944a), a salt derived from alginic acid (a constituent of brown algae) that is commonly used in various forms to give fish, meat and sausage products a longer shelf life (Hoppe and Schmid 1969:309; Tseng 1944b). Salt was a prized commodity in many ancient societies, when salting meats and fish was the only mode of preservation. Also called "white gold," salt was used as a religious offering and medium of exchange and payment by the Vikings, Romans, Egyptians, Phoenicians, and other historic empires (Pereira 2016a:21; Mouritsen 2013:98) as well as considered a prized trade item by Native People of the western coast of North America (Turner and Bell 1993). Wrapping meats or other perishable food items in moist and salty seaweed might have been an efficient means for Native Islanders to temporarily preserve fresh shellfish, fish, and slabs of butchered marine mammal for up to several days, especially if they were able to keep these kelp-wrapped meat bundles cool.

In recent times and in the U.S. in particular, the term 'kelp' has come to be associated with large brown marine algae mostly in the order Laminariales (Chapman 1970:24; Hoppe and Schmid 1969:346; Tseng 1947). The term 'kelp,' however, has its origins in northern Europe during the 17th century, where it was used to denote 'seaweed ash,' a pivotal component of an extensive industry that harvested tens of thousands of tons of kelp annually for the production of soda ash, or potash. Kelp kilns on the British, Scottish, Irish, and French coasts used seaweed ash, or kelp, in the production of potassium and sodium salts used to manufacture soaps and glass, and later in the early 19th century for the extraction of iodine (Chapman 1970:24-47; Dawes 1998:400; Hoppe and Schmid 1969). In the years preceding and during World War I, the American Pacific Coast kelp industry, based in Alta and Baja California, produced large quantities of potash, iodine, and kelpchar; then during World War II, the focus of the California kelp industry shifted to the production of agar (see Cameron 1915; Chapman 1970:48-62; Crandall 1915; Tseng 1944a, b, 1947). The first use of the term 'kelp' to denote the seaweeds themselves rather than their ash product seems to originate in New Zealand, where the term 'bull kelp' was first applied to *Macrocystis pyrifera* (Tseng 1947:72).

Although it is abundantly clear that seaweeds play a pivotal role in the diets of coastal people around the world, archaeologists rarely discuss the potential that they were harvested in the past and perhaps more extensively exploited than we are aware. This is unsurprising on some level as seaweeds rarely preserve in archaeological contexts. Finding evidence of macrophytes in the past is a challenge for paleontologists as well as archaeologists, the lack of skeletal structure and strengthening tissue of any sort make fleshy algae extremely unlikely to preserve in any but the most exceptional of circumstances (Bell 1981; Dimbleby 1967:40). In contrast, coralline algae contain a calcified thallus allowing them to preserve and are indeed found in many Channel Island midden deposits (e.g., Ainis 2012:187, Table A-7). However, the paucity of direct evidence for seaweed harvesting does not negate the likelihood that people utilized and consumed them to a significant degree in the past, and even when not directly quantifiable, seaweeds should be included in our discussions of subsistence practices in coastal environments. For instance, Biagi and Nisbet (2006) highlight the importance of including seaweeds in discussions of prehistoric subsistence economies focused on nearshore habitats (i.e., mangroves) and Bell (1981) offers extensive discussion on the topic and means for potentially identifying these resources in archaeological deposits. Ainis et al. (2014) demonstrated a means for identifying seaweed use indirectly through the identification of associated molluscs in shellmidden sites on the Channel Islands – a topic also addressed briefly by coastal archaeologists in Europe and Australia (see Bell 1981; Colonese and Wilkens 2005; Rowland 1977).

Significant climatic change and shifts in oceanographic conditions (i.e., lowered sea levels and subsequent effects on the flows of various currents), including sea surface temperatures, towards the end of the Pleistocene and through the early part of the Holocene likely facilitated the distribution or restriction of more sensitive macrophyte taxa. For these reasons, researchers have suggested that species densities and distributions may have varied along the Pacific coast of the America's in the past (e.g., Dayton 1985; Graham et al. 2003, 2010; Lüning 1990), specifically during the time of early human colonization of the New World. *Sargassum* remains in Terminal Pleistocene deposits at the Monte Verde site in Chile are a primary example of this phenomenon. This genus is currently scarce along the western coast of South America but appears to have been more abundant roughly 12,000 years ago (Dillehay et al. 2008; Ugent and Tindall 1997). In addition, the translocation of introduced and invasive macrophyte species during the past few hundred years has altered community compositions around the world (i.e., Williams and Smith 2007), necessitating caution when interpreting the geographic extent of community compositions and populations in the past based on modern macrophyte distributions.

In this chapter, I summarize the biology, diversity, ecology, and productivity of marine macroalgae and angiosperms in the California Bight. A brief overview of the pivotal kelp forest ecosystems surrounding the Channel Islands demonstrates the inherent diversity and abundance of related resources to Indigenous island populations. I discuss nutritional information for seaweeds from the Pacific Rim with a focus on the specific taxa that inhabit nearshore and offshore environments in the region and would have been available to Native Channel Islanders, supporting the likely consumption of seaweeds in the past. Ethnographic and ethnohistoric information for the western coast of North America is reviewed to demonstrate the extensive use of these resources by Native people inhabiting coastal environments in the greater region and to make a case for the potential use of marine algal resources in the absence of direct reference. The paucity of explicit ethnographic and ethnohistoric accounts for island inhabitants in general is caution against discounting their use offhand, as there are few ethnographic accounts of any kind for the Indigenous people of the Channel Islands. I discuss the inherent challenges of uncovering macroalgal remains in archaeological contexts, along with suggestions for uncovering the likely use of these highly perishable resources in the past. As evidence for the use of endemic plants mounts on the Channel Islands (Gill 2013; Gill and Hoppa 2016; Gill et al. 2019a), I suggest that "sea vegetables" were harvested by native inhabitants as well, further negating the concept of marginality for the islands. I close this chapter with suggestions for future research intent on uncovering hints of seaweed use in the past, with hopes of encouraging scholarship on this topic.

## Biological Background

Marine vegetation consists of marine algae and marine angiosperms, with marine algae including benthic (i.e., attached to the sea floor) and planktonic forms (i.e., free floating and mostly unicellular) (Levring 1969a); as this chapter is focused on the human use of marine vegetation, I am predominantly focused on the benthic forms. Key differences in their organization and construction separate marine algae (seaweeds and kelps) from marine angiosperms (seagrasses), which are true flowering plants – being algae, rather than true plants, seaweeds have no root system, buds, flowers, or seeds (Chapman 1970; Mouritsen 2013; Thomas 2002). Algae are single or multi-celled organisms that live in water and contain chlorophyll, allowing them to perform photosynthesis; as primary producers, they are pivotal to food chains in all aquatic ecosystems (Pereira 2016).

Seaweeds are the common term for marine macroalgae or macrophytes, which are aquatic photosynthetic organisms in the Eukaryota Domain and include a wide variety of forms (Chapman 1970; Little et al. 2009). As photosynthetic protists, they are distinguishable by various structural and chemical attributes, and are defined by their larger size, multi-cellular construction, and attachment to substrata (Dawes 1998; Little et al. 2009; Lobban and Wynne 1981). For the most part, carbohydrates (alginate, carrageenan, and agar) assume the role of structural support for seaweed stipes and blades, a function which pectin undertakes in terrestrial plants (Mouritsen 2013:59). Specific molecular structures vary by seaweed species, though all these forms of carbohydrates bond with water to create the gel-like substances that are widely utilized in the production of various food items, medications, and other products. Generally, brown algae contain alginates, and red algae contain carrageenans and agars.

Broad characteristics of seaweeds include holdfasts for attachment to the substratum, branches or blades for photosynthesis, and a stem-like structure called a stipe that allows the blade to rise to the water surface rather than rest on the ocean floor, though some species consist simply of a flat plate of tissue (e.g. *Ulva*) (Chapman 1970; Little et al. 2009:77; Thomas 2002). Root systems are not needed for nutrient absorption, which is the case with terrestrial plants, as nitrogen, phosphorus, and trace elements are dissolved in the surrounding sea water and exchanged by diffusion across the surfaces of the algae (Thomas 2002). Carbon dioxide is also exchanged in this way and is one of the requirements, along with light and water, for photosynthesis. Chloroplasts are present in most surface tissues to maximize photosynthetic growth and larger species have a gas-filled bladder, or pneumatocyst, to keep their blades floating as close to the surface as possible for ultimate light absorption. Holdfasts perform the mechanical features of a root system, with various morphologies designed to anchor the seaweed to different substrata and withstand the effects of turbulent waters. Rocky bottom dwellers often have large holdfasts that resemble either a root-like mass or a disk, which attach to boulders, rocks, and gravel to firmly anchor the algae. Species inhabiting sandy or silty ocean floor environments develop holdfasts made from delicate root-like rhizoids, some even forming extensive horizontal mats. Seaweeds are constructed of branched threads, or filaments, that are composed of mucilaginous and gelifying substances; this architecture allows flexibility along with elasticity (e.g., *Himanthalia*) or tensile resistance (e.g., *Fucus*), depending on which is the better adaptation (Delf 1943:508).

Growth rates vary drastically for different types of seaweeds, which include annual and perennial species. Some annuals are short-lived, including the commonly eaten sheet-like lavers (*Porphyra*) and sea lettuce (*Ulva*), which only live for a few weeks. The larger annuals tend to have very high growth rates; with significant water depths giant kelp (*Macrocystis*) can grow up to 45 cm per day (Chapman 1970:11) and bull kelp (*Nereocystis*) is said to achieve lengths that exceed the height of “mature trees” within a season (Thomas 2002:30). Many seaweeds are perennial, living for up to several decades, though for some species the fronds are produced annually and only the basal structure is perennial. Seaweed life cycles are complicated and tremendously varied with multiple exceptions and alternatives to every rule, though generally speaking most have an asexual phase in which they are sporophytes with diploid cells, followed by a sexual phase in which they are gametophytes with haploid cells. Further biological details are beyond the scope of this chapter, but additional information can be found in Dawes (1998), Lobban and Wynne (1981), and Dixon (1973) amongst other sources.

Seaweeds are partitioned into three main algal divisions, or phyla: Chlorophyta (green algae), Rhodophyta (red algae), and class Phaeophyceae in phylum Ochrophyta (brown algae), all of which contain a high degree of variation (Chapman 1970; Dawes 1998; Lobban and Wynne 1981; Thomas 2002). Primary distinctions between the three divisions include mostly unicellular and microscopic filamentous forms within Chlorophyta, and a broader range of forms extending from smaller filamentous varieties to large thalloid plants comprising the Phaeophyta and Rhodophyta divisions. Fossil evidence suggests that seaweeds evolved roughly 600-900 million years ago (late Precambrian) with seagrasses evolving only 100 million years ago (Cretaceous) (Dawes 1998). Although primitive in terms of physiology, seaweeds have continued as the dominate form of marine vegetation despite the subsequent evolution of more complex marine plants (i.e., vascular seagrasses), proving their evolutionary superiority.

## Macroalgae

### *Chlorophyta*

Green algae are found primarily in freshwater environments; only ~10% occupy marine environments, most of which are macroalgae, and many of which are edible and widely used as food. Green algae contain the most similarity with vascular plants, including identical pigments and the production of starch as the final product of photosynthesis, leading researchers to suggest that the evolution of higher plants proceeded from this division (Levring 1969b). Chemical similarities include the storage of reserve-polysaccharide as starch (amylose and amylopectin), which is formed within the chloroplast, in much the same way as flowering plants (van den Hoek 1981).

Chloroplasts are not masked (as in brown and red algae), but contain chlorophyll (*a* and *b*), which provide the green coloration, and *ß* carotene and the xanthophylls (carotenoid plant pigments, i.e., lutein and zeaxanthin), as in vascular plants.

Taxonomic classifications are somewhat debated, but most recognize three classes of green alage: Chlorophyceae, containing four orders with some marine genera; Prasinophyceae, containing one order with no marine taxa; and Charophyceae, containing 15 orders and many marine taxa. The widely eaten *Ulvales* (sea lettuce) are members of the class Chlorophyceae. Roughly, 16,800 species of green algae have been identified (Dawes 1998:114), with estimates of 1,800 species inhabiting marine environments (Mouritsen 2013:22; Thomas 2002:11). At least 25 (Evans 1986:288) and up to 127 species (Pereira 2016) are edible and widely used as sea vegetables by people around the world.

### *Phaeophyceae (phylum Ochrophyta)*

The brown algae consist of multicellular organisms and are almost exclusively found in marine environments. They are allocated to a single class, Phaeophyceae, with debates concerning the number of taxonomic orders, which varies between 14 and 16 (see Dawes 1998:134). The various orders of Phaeophyceae encompass more than 250 genera and close to 2000 species (Dawes 1998; Mouritsen 2013:22; Thomas 2002:11; Wynne 1981), of which at least 54 (Evans 1986:288) and up to 191 species (Pereira 2016) are eaten. Most of the larger brown algae require hard substrate for attachment (i.e., lithophytes), though many of the smaller filamentous species float freely (i.e., epiphytes). The widely utilized kelps (*Macrocystis* and *Laminaria*) and rockweeds (*Ascophyllum* and *Fucus*) are members of this phylum.

Thallus organization of brown algae displays broad morphological variations that are likely a result of differences in degree of exposure and salinity (Wynne 1981). Morphologies range from simple creeping branched filamentous forms to the highly complex organization of the kelps (Laminariales), which contain sieve tubes for photosynthesis. Basic thallus types include tufts of uniseriate filaments, discs or crusts, and erect axes. These generalized thallus types include further variation as they may be simple or branched, terete or ligulate, sacate or foliose, or any combination of these forms. Growth occurs through diffused or generalized cell division (i.e., occurring in almost any cell) or through localized cell division within a region (i.e., an intercalary meristem).

Brown algae contain chlorophylls *a* and *c*, and high concentrations of carotenoids, such as yellow-brown fucoxanthin, that mask chloroplasts and dictate the colors of the algae, which range from dark brown, to yellow, and olive green (Dawes 1998; Levring 1969b; Mautner 1954; Thomas 2002). Nutrients are reserved as carbohydrates and stored as glucose (laminarin or chrysolaminarin), accounting for 2-34% of the plants dry weight. Many species in this order accumulate and store iodine from seawater in their cells, with some even secreting iodine from their own thallus (Levring 1969b:73). The vast majorities of brown algae inhabit the intertidal and the upper sublittoral zones, where they are easily harvested, and achieve optimal growth and development in colder waters.

### *Rhodophyta*

The red algae are the most morphologically complex of the three phyla and their life cycles and reproductive strategies contain greater intricacies (Dixon 1973; Kraft 1981). Various characteristics divide red algae amongst 10 to 18 orders with the number of species in this phylum ranging from 2,500 to 20,000 with only ~3% residing in freshwater habitats (Dawes 1998:144; Dixon 1973:xii). Roughly 6,000 red algal species inhabit marine environments (Mouritsen 2013:22; Thomas 2002:11) and over 300 species are commercially important, including at least 81 (Evans 1986:288) and up to 338 (Pereira 2016) species that are widely consumed.

Red algae contain eukaryotic cells and lack any flagellar structures; the photosynthetic product, or food, is a carbohydrate stored as glucogen in the form of floridan starch (Dawes 1998; Dixon 1973; Levring 1969b). Chloroplasts are masked by red and blue pigments (i.e., phycoerythrin, phycocyanin, and allophycocyanin) within the cells, resulting in algal colors ranging from whitish-pink to purplish-black (Thomas 2002). Red algae contain chlorophyll *a*, $\alpha$ and $\beta$ carotenes, and xanthophylls (pigments). The red algae are capable of occupying greater depths than any other marine algae with a close correlation between color and ocean depth – the deeper dwelling species, which are never exposed, exhibit bright pink and red colors and those inhabiting the partially exposed intertidal zones usually display a wider range of duller colors (Levring 1969b). Red algae grow predominantly on rocks or as epiphytes on seagrasses and other algae, extending to the lower limits of sea vegetation at a depth of 30-70 m, or 200 m in extremely clear waters (Levring 1969b).

## Angiosperms

Contrary to what their common name implies, seagrasses are angiosperms or flowering plants rather than true "grasses" (Poaceae). Less than 0.01%, or roughly 58 species, of flowering plants inhabit submerged marine habitats worldwide (Dawes 1998). Seagrasses primarily inhabit sheltered bays and estuaries with sandy substrate (i.e., eelgrass, *Zostera marina*), and several species of surfgrass (*Phyllospadix* spp.) form extensive meadows in rocky nearshore habitats (Little et al. 2009:76), the primary intertidal habitat on the Channel Islands. Like kelp forests, seagrass meadows are highly productive marine ecosystems and primary producers in coastal environments. Forming critical nursery habitats for many fish taxa, they are often linked with productive fisheries (Jackson et al. 2001).

Seagrasses display morphological and anatomical similarities to freshwater hydrophytes, though separate evolutionary trends are indicated from reproductive and structural variation (Dawes 1998:303-337; Tomlinson 1982). Contrary to their terrestrial cousins, seagrasses evolved a variety of physiological adaptations that allow them to flourish in submerged aquatic environments (Dawes 1998: 317-324; Little et al. 2009:76). For instance, they are anchored to the rocks with stolons and absorptive roots that allow the absorption of nutrients from the surrounding water and $CO_2$ is absorbed across the entire leaf surface. Seagrasses also display the presence of lacunae (air spaces); these air chambers are continuous in larger species, extending through the roots, rhizomes, blades, and shoots, allowing for gas exchange throughout the plant (Dawes 1998:310-311). Although seagrasses are known to reproduce sexually, vegetative growth can replace sexual reproduction when it is truncated by the challenges of an aquatic habitat, or when seeds are eaten by predators; in such instance their rhizome and apical meristem produces adventitious roots that erect short shoots at the nodes (Dawes 1998:315).

## **Biogeography of Seaweeds and Seagrasses in the Southern California Bight**

The marine algal flora found along the west coast of North America is tantamount to the rich communities found around the Japanese archipelago and the South African coastline and is second only to the marine flora of Australia and New Zealand. Early accounts describe the supreme abundance of seaweeds and kelps off the coast of Alta and Baja California (Crandall 1915; Frye et al. 1915; Smith 1905b), including kelp forests so thick in San Diego Bay during the mid-1800s that they were mistaken for a low island (Anderson 2005:25). Smith (1905b) suggests that the seaweed resources off the coast of North America are equal, if not superior to, those of the Japanese archipelago. Abbott and Hollenberg (1976:7) also note high similarity between suites of marine algal populations in California and the Japanese Archipelago, as some of the most diverse and dense in the Pacific region.

The California Channel Islands are located in the Southern California Bight, the marine bioregion spanning roughly 32,000 square km, extending from Point Sal in central California, to Punta Banda in Baja California, Mexico (Daily et al. 1993; McGinnis 2006). The high biodiversity in the Southern California Bight stems, in part, from the mixing of marine currents in this region (M. Graham et al. 2008). The warmer northbound waters of the Southern California Countercurrent collide with the cooler southbound waters from the California Current, fostering a wide array of both warm and cold-water marine organisms that were pivotal to islander subsistence. Native people hunted sea mammals and sea birds, fished, and collected crustaceans, echinoderms, and mollusks from kelp forest and intertidal habitats in the region for more than 12,000 years (Braje et al. 2012; Erlandson et al. 2009).

The eight Channel Islands and the east-west orientation of the mainland coast within the bight culminate in nearly 1000 km of coastline with significant variation in nearshore habitats, substrata, wave action, currents, and thermal regimes, resulting in considerable diversity in macrophyte assemblages (Abbott and Hollenberg 1976; Foster and Schiel 1985; Littler 1978; Murray et al. 1980; Murray and Bray 1993; Schiel and Foster 2015). Giant kelp (*Macrocystis*) forests are extensive in the Southern California Bight, contributing to high marine productivity by forming extensive and diverse nearshore habitats (M. Graham 2004; M. Graham et al. 2010; McGinnis 2006). Northward of Point Conception marine flora encompass greater biomass but contain less taxonomic diversity, with surface temperatures below 18°C fostering the proliferation of Laminariales and larger, fleshy red algae (Abbott and Hollenberg 1976:6). Taxonomic diversity is markedly higher south of Point Conception, though biomass is reduced; Fucales become the most common large brown algae, as surface temperatures above 18°C promote more subtropical taxa akin to the Pacific coast of Baja California, Mexico. Modern water temperatures in the area south of Point Conception foster the proliferation of benthic filter-feeder invertebrates (i.e., mussels and barnacles) in nearshore rocky intertidal habits, however, cooler waters promote the dominance of marine macroalgae in otherwise similar habitats to the north (Blanchette et al. 2007, 2009).

Kelp forests are dynamic ecosystems, encompassing considerable variation through time and are particularly susceptible to climatic and weather shifts such as El Niño events and other severe storms that cause changes in water temperatures, nutrient levels, and canopy cover (i.e., Dayton and Tegner 1984; M. Graham et al. 2007; Tegner and Dayton 1987; Wilson and North 1983). As the composition and extent of kelp canopies vary through space and time, ecological and oceanographic processes and their associated organisms change and adjust accordingly (M. Graham 2004; Steneck et al. 2002). Rising post-glacial seas have dramatically changed the coastal configuration of Alta and Baja California since humans initially colonized the islands, altering the distribution and abundance of kelp forests, other seaweeds, and seagrass meadows (M. Graham et al. 2010; Kinlan et al. 2005). For instance, rising ocean levels during the Early Holocene likely inundated shallow water seagrass meadows (i.e., *Zostera* inhabits ~2-5 m depths; Meling López and Ibarra-Obando 1999) resulting in destruction or translocation of these habitats and their associated fauna. Such changes may explain the near disappearance of sea turtle remains in archaeological sites on Cedros Island after ~8,000 years ago (DesLauriers 2010:113-114).

## Floristics

Murray et al. (1980) quantified seaweed floral diversity along the California coast, determining that the highest degree of floral richness occurs within the Southern California Bight (between 33° and 34° N latitude). The bight contains more than 73% of California's marine macrophytes, represented by close to 500 seaweed species. Fifty-nine species of green algae (Chlorophyta) make up 12% of the marine flora in the region, 86 species of brown algae (Phaeophyta) compose 18% of regional marine flora, and 347 species of red algae (Rhodophyta) comprise 71% of the marine flora in the Southern California Bight (Murray and Bray 1993:306). Four species of seagrasses are also found in the bight, including ditch-grass (Ruppia maritima), which is a salt-water tolerant freshwater species, eelgrass (*Zostera marina*), and two species of surfgrass (*Phyllospadix scouleri* and *P. torreyi*) that form extensive meadows in shallow subtidal to sublittoral zones of intertidal areas (Mondragon and Mondragon 2003; Murray and Bray 1993). Over a hundred genera of edible seaweeds, many containing multiple species, inhabit California Island waters and were available to island peoples for millennia (see Abbott and Hollenberg 1976 for extensive taxonomic list of southern California species).

Marine plants and algae are subject to intertidal zonation as much as other marine organisms that contain differing levels of endurance for substrata, wave action, tidal amplitude and frequency, temperature, and exposure (Chapman 1970; Dawes 1998; Stephenson and Stephenson 1972; Thomas 2002). The high degree of variation in intertidal and substrate conditions in the region leads to the predominance of site-specific and localized conditions over seasonal, temporal, and regional patterns (Emerson and Zedler 1978; Gunnill 1980; Littler et al. 1991; Seapy and Littler 1982). General patterns associated with macrophyte seasonality have been identified for the region by Littler (1978, 1980a, b) and Littler et al. (1991) including minor reductions in standing stocks and diversity after periods of tidal emersion during daylight (Fall/Winter), and expansion of large stocks during the summer months when daylight hours are longer and surface water temperatures are higher.

In the Southern California Bight, the intertidal distinctions between warm and cold-water taxa are observed primarily in the middle and lower intertidal zones (Table

3.1; Murray and Bray 1993:322-327; see also Abbott and Hollenberg 1976; Foster and Schiel 1985; Littler 1978). Upper intertidal zones in nearshore environments surrounding the Channel Islands are often dominated by wracks (i.e., *Pelvetia fastigiata* and *P. gracilis*) and morphologically simple marine algae such as sea lettuce and lavers (i.e., *Ulva* spp. and *Porphyra* spp.). The middle intertidal of warmer sites tend to contain species of fleshy red algae and seasonal patches of large leafy brown algae like *Endarachne* in the winter, as opposed to summer patches of red algae like pepper dulse (*Laurencia* spp.) and brown algae like *Sargassum*. In comparison, cold-water middle intertidal habitats are dominated by red algae (i.e., *Endocladia muricata*) including larger fleshy species (i.e., *Mastocarpus papillatus*), and acorn barnacles (*Balanus glandula*), which are often found in archaeological middens on the islands and mainland coast in significant amounts. Intertidal habitats located in the path of steady exposure to cold water currents are often dominated by the "cold-water indicator species" found along the central coast of California, such as rockweed (i.e., *Fucus gardneri*) and iridescent blade red algae (*Iridaea cordata*). Sites bathed in warmer waters tend to be dominated by feather-boa kelp (*Egregia menziesii*), sea palm (*Eisenia arborea*), and rockweed (i.e., *Halidrys dioica*). In general, lower intertidal zones in the region are dominated by large brown algae that flourish in the deeper, colder waters and are often monopolized by various species of kelp (*Laminaria* spp.) and chainbladder kelp (*Cystoseira osmundacea*).

Structural patterning of macrophyte communities and inherent seasonal and interannual variation follow vertical and horizontal gradients, differing according to substrate and community type (i.e., embayments, rocky intertidal zones, and offshore kelp forests). The highly dynamic nature of these nearshore environments imply that extensive modification of tidal and current flow and landscape are continuously reshaping and altering these ecosystems to the point where community profiles and extent were likely different at various points in the past. Nevertheless, tidal characteristics and salinity do not appear to vary greatly between sites in the Southern California Bight where substratum, water temperature regimes, and wave action are the primary parameters dictating macrophyte community structure (Murray and Bray 1993).

**Table 3.1.** Intertidal zonation of seaweed distribution in the Southern California Bight*

| **Cold-Water Habitats:** | **Warm-Water Habitats:** |
|---|---|
| ***High Intertidal Zone*** | |
| Tendency for morphologically simple seaweeds (e.g., *P. perforata*, *Ulv*a spp., *Scytosiphon dotyi*) to occur in patches. Olive-colored morphologies of *Pelvetia* spp. | Characterized by upper shore band of *Hesperophycus harveyanus* (scarce on mainland). Yellow-brown morphologies of *Pelvetia* spp. |
| ***Middle Intertidal Zone*** | |
| Predominance of larger, fleshy, saxicolous seaweeds, often associated with barnacles. Occasional occurrence of *Fucus* spp. | Predominance of smaller, fleshy, surf-associated algae. In less disturbed habitats larger seaweeds (e.g., *Pterocladia*, *Gigartina*, *Colpomenia*, *Gelidium*) are more common.<br>*Endarachne* in winter and *Laurencia* in summer and fall. On the islands *L. snyderiae* and *Sargassum* are common in summer and early fall. |
| ***Low Intertidal Zone*** | |
| Lower brown algal zone dominated by *Laminaria* and *Egregia*, increased abundance of *Cystoseira*. High abundance of fleshy, saxicolous red seaweeds (e.g., *Laurencia*, *Cryptopleur*a, *Iridaea*, and others) | Lower brown algal zone dominated by *Halidrys*, *Egregia*, and *Eisenia*. Complete absence of *Laminaria dentigera*. Lower abundance of fleshy, saxicolous red algae. Prominent taxa include *Pterocladia*, *Gelidium*, *Rhodoglossum*, and *Gigartina*. Absence of *Iridaea*. |

* Table adapted from Murray and Bray1993:325 (Table 7.1).

Climatic and water temperature shifts throughout the Holocene almost certainly influenced species richness and distribution (Graham et al. 2003, 2010), though physical parameters are likely responsible for short-term or seasonal variation in intertidal macrophyte communities (Dawson 1965; Littler et al. 1991; Murray and Littler 1977). In addition, the effects of exponentially increasing anthropogenic activities have certainly altered the distribution and composition of seaweed communities in more recent years. The pace of biogeographic changes increased historically as dam building, stream channelization, overgrazing, overfishing, soil erosion, pollution, and now accelerating sea-level rise have all affected local beach and nearshore habitats. Comparing survey data from the late 1950s to herbarium records from the early 20th century, for instance, Dawson (1959, 1965) documented a 50-70% reduction in species richness at sites with high sewage outfall into the ocean. Later studies confirmed anthropogenic effects on seaweed communities of the Southern California Bight (Thom and Widdowson 1978; Widdowson 1971), though Harris (1983) reported an increase in macrophyte diversity after improvements in sewage treatment. Studies elsewhere along North America’s west coast have also documented a dramatic decline in species richness and density due to eutrophication caused by a variety of human driven impacts induced by commercial fisheries since European colonization (Lotze and Milewski 2004).

## Kelp Forest Ecosystems

California kelp forests are among the most productive ecosystems on earth, providing habitat, nutrients, and shelter for marine birds and mammals, fish, molluscs, crustaceans, echinoderms, and other invertebrates (Dayton 1985; Foster and Schiel 1985; M. Graham et al. 2007; North 1971). Dense kelp forests are beneficial to coastal inhabitants as they reduce turbulent wave action with their bulk, subsidize terrestrial productivity with a wide range of marine organisms, and provide beneficial holdfasts to anchor boats, allowing people to more easily fish and hunt in these offshore forests (Erlandson et al. 2007, 2015; Figure 3.1). Giant kelp (*Macrocystis*), bull kelp (*Nereocystis luetkeana*), sea palm (*Eisenia arborea*), oarweed (*Laminaria farlowii*), feather boa kelp (*Egregia menziesii*), and elk kelp (*Pterygophora californica*) constitute the vast majority of macroalgal communities that form vertically structured habitats extending from the ocean floor to the sea surface (Chapman 1970:10-14; Crandall 1915; Foster and Schiel 1985; Hoppe 1969:163). *Macrocystis,* a perennial that grows best on rocky substrate in areas with continuous swell, is by far the dominant genus in kelp forests surrounding the Channel Islands (M. Graham et al. 2007); lengths are believed to reach 150 feet with beds extending for hundreds of yards to several miles across (Abbott and Hollenberg 1976; Chapman 1970: 11; Dayton 1985; Frye et al. 1915; North 1971). Regardless of debates concerning the number of species of *Macrocystis* in the region (see Murray and Bray 1993:332) it is clear that this genus dominates kelp beds and occupies extensive subtidal areas between Cedros Island (Baja California) and Point Conception (Alta California); though it is a less dominant constituent of seaweed colonies northward of this region, which contain higher densities of bull kelp (*Nereocystis luetkeana*) and winged kelp (*Alaria fistulosa*) (Cameron 1915; Crandall 1915; North 1971; Tseng 1947).

In his summary of flora inhabiting the kelp beds of southern California and the Pacific coast of northern Baja California, North (1971) lists a total of 127 species from 80 genera of macroalgae and one species of angiosperm; more recent work has documented 492 species of macroalgae and four species of angiosperms in the Southern California Bight (Murray and Beal 1993:306). Although Baja California is not mentioned in this study, biogeographic similarities with southern California coastal environments (see Edwards 2004) indicate that most of the same taxa are found along the northern part of the western coast of the peninsula, with species composition declining further south (see North 1971:51, Figure 21; see also Beas-Luna and Ladah 2014; Beas-Luna et al. 2014; Crandall 1915). Naturally, kelp forests in the bight display structural differences in dominant genera within and between kelp beds due to variations in the types of substratum, degree of wave action and exposure, the amount of light seeping through breaks in the canopy, and nutrient availability (Dayton et al. 1984, 1999; Dean et al. 1984; Graham 1997; Harold and Reed 1985; Murray and Bray 1993; North 1971). These factors also affect the nature of recruitment and growth, which vary seasonally and

**Figure 3.1.** Kelp forests and seagrass meadows surrounding the California Channel Islands. A) Giant kelp off the California Channel Islands (*Macrocystis pyrifera*) (NOAA Photo Library: sanc0061); B) Giant kelp off the California Channel Islands (NOAA Photo Library: sanc0063); C) A giant kelp holdfast that had become dislodged from the ocean floor by a storm (NOAA Photo Library: sanc0058); D) seagrass meadow from the northern Channel Islands (NOAA Photo Library: sanc0067).

are strongly correlated with shifts in environmental conditions (Graham1997; Tegner et al. 1997).

Kelp forests are divided into three morphological groups which are distinguished by the height of their fronds and their subsequent location in the marine forest: canopy kelps, stipitate kelps, and prostrate kelps (Dayton 1985). Kelps that produce surface canopies include the largest species, such as the regionally ubiquitous giant kelp (*Macrocystis* spp.), and smaller species such as bull kelp (*Nereocystis leutkeana*). The stipitate kelps are composed of species containing rigid stipes that support and hold their fronds above the ocean floor such as stalked kelp (*Pterygophora*), sea palm (*Eisenia*), broad-ribbed kelp (*Pleurophycus*), and others. The guild of prostrate kelps includes smaller species containing fronds that rest on the ocean floor, such as some species of oarweed (*Laminaria*). Kelp forests are often composed of all three types of canopy with the tiering of various kelp morphologies providing diverse habitat niches for specialized associated fauna; resulting in the high degree of structural, taxonomic, and ecological diversity.

These highly dynamic ecosystems undergo oscillations over short and long temporal scales dictated by a variety of oceanographic factors such as available nutrients, ocean temperature (SST), the amount of light (i.e., seasonal differences in the length of day), and storm events (i.e., ENSO; Dayton et al. 1992, 1999; Tegner and Dayton 1987), in addition to predator/prey interactions such as the presence or absence of sea otters and the intensity of sea urchin grazing (Dayton et al. 1998; Estes et al. 1989; Steneck et al. 2002) or grazing by other associated herbivores (e.g., Dethier et al. 2005; Lubchenco and Gaines 1982; Williams et al. 2013). Though the extent of kelp canopy coverage varies through time, kelp cover surveys from the early 1900s indicate that the area between Point Conception and Cedros Island (Baja California) contains the most extensive kelp forests along the western coast of North America (see Tseng 1947). Surveys in the 1970s estimated that an area of ~88 $km^2$ was encompassed by kelp forests in the Southern California Bight (Table 3.2). Roughly, half of seaweed biomass for the region is adjacent to the mainland coast, with the other half found in Channel Islands waters. In spite of being one of the smaller islands, San Nicolas contains the highest density of kelp canopy, accounting for over 14% of the total coverage for the bight (Figure 3.2; Murray and Bray 1993).

**Table 3.2.** Kelp Canopy Coverage in the Southern California Bight (1975-1977)*

| Location | Average Area (km$^2$) |
|---|---|
| Point Dume to Mexico border | 46.0 |
| **Southern California mainland Total:** | 46.0 = 52% of total SCB kelp |
| San Clemente Island | 9.0 |
| Santa Catalina Island | 0.7 |
| Santa Barbara Island | 2.3 |
| San Nicolas Island | 12.6 |
| **Southern Islands Total:** | 24.6 = 28% of total SCB kelp |
| Anacapa Island | 0.9 |
| Santa Cruz Island | 4.8 |
| Santa Rosa Island | 8.0 |
| San Miguel Island | 3.6 |
| **Northern Islands Total:** | 17.4 = 20% of total SCB kelp |

*Average area of kelp canopy cover was computed from eight aerial surveys in 50 beds throughout the Southern California Bight. Table modified from Murray and Bray (1993), with original data from Hodder and Mel (1978).

**Figure 3.2.** Extensive kelp forests off the coast of San Nicolas Island demonstrating the prevalence of this abundant resource for Indigenous Channel Islanders (Photos by René L. Vellanoweth, image modifications and composite by A. Ainis).

## **Nutritional Content of Seaweeds**

Virtually all seaweeds are edible, although they are not all ideally suited for human consumption. The high nutritional quality of seaweeds makes “sea vegetables” a favored food in many parts of the world. In coastal and island environments, where sea mammals, fish, and shellfish provide ample protein, seaweeds can balance the diet by supplying sugars, dietary fibers, calories, essential vitamins and trace minerals, and in case of green algae, carbohydrates. The nutritive qualities of seaweeds are often equal to, or in excess of, many commonly consumed fruits and vegetables (Pereira 2016:10; Madlener 1977; Ryhter 1981). For instance, the content of water-soluble vitamins, like B-complex and C, is often higher in marine algae than in commonly eaten vegetables (Nisizawa et al. 1987). In addition, many types of widely consumed seaweed (i.e., *Porphyra* spp. and *Ulva* spp.) contain significant amounts of $B_{12}$, which plays an important role in DNA synthesis but is completely lacking in most terrestrial plant foods (Pereira 2016:15). Though relative percentages of nutritional properties vary, a general overview suggests that by dry weight seaweeds contain roughly 3-47% protein, 7-38% ash, 10-66% dietary fiber, 30-66% carbohydrates, and 1-10% lipids (Pereira 2016:12-13, Table 2). Table 3.3 provides relative percentages of primary nutritional classes by dry weight for some of the seaweed taxa found in the waters surrounding the Channel Islands to demonstrate the nutritional composition of local flora and the utility of including these resources in islander diet.

Nutritional content varies between seaweed species, with some commonalities among general types (Chapman 1970; Mouritsen 2013). For instance, hollow green weed (*Enteromorpha*) is lower in sodium and higher in calcium and iron than both sea lettuce (*Ulva*) and wittrock (*Monostroma*), though all are green marine algae are relatively high in Niacin (Nisizawa et al. 1987). Red laver (*Porphyra* spp.) is comparable to spinach in the high amount of vitamin A it contains and exceeds the levels of vitamin C in oranges. Quantities of several B vitamins are very high in red lavers (Hoppe and Schmid 1969:361; Nisizawa et al. 1987:11), making it extremely beneficial to a diet lacking in fresh fruits and vegetables. Fat-soluble vitamins (i.e., A, D, E, and K) play important roles in bone growth and maintenance, reproduction, antioxidant activity, blood clotting, and cell division amongst others (Pereira 2016:15; Kim 2011). Table 3.4 provides examples of water- and fat-soluble vitamin content for some seaweed that are endemic to the Southern California Bight to demonstrate their potential nutritional value to Native peoples of the region.

In addition to being excellent sources of vitamins, seaweeds are generally good sources of many trace elements that are likewise essential to human health (e.g., Rao et al. 2007; Rupérez 2002). Although other marine resources like fish and shellfish also fulfill this dietary requirement, comparisons of trace element content between types of marine organisms demonstrates the utility of including marine macrophytes in the diet, as they often contain equal or higher amounts of elements essential to comprehensive nutrition (Table 3.5). Many species of brown and red marine macroalgae can absorb iodine from the seawater (where it occurs in small traces) and accumulate it in very high concentrations (Delf 1943:509). Members of the genus *Laminari*a can store 30 times the iodine content of surrounding ocean water, with seasonal fluctuations occurring primarily in sublittoral taxa, and younger plants generally containing higher concentrations than older plants (Hoppe and Schmid 1969:347-8). Table 3.6 depicts the trace element composition of several seaweeds currently inhabiting the region that would have likely been available and potentially consumed by islanders in the past.

The proteins in seaweeds vary from animal proteins in that they contain all, or most, of the amino acids, including those that cannot be synthesized by our bodies (i.e., essential amino acids; Pereira 2016: 15; Mouritsen 2013:54). Red lavers (*Porphyra*) have high protein content and contain all amino acids though the in vitro digestibility of all proteins is not equivalent. One experiment measured a 42% digestibility of proteins for *Gracilaria verrucosa*, but only 5% for *P. palmata* (Marrion et al. 2005). Taurine, an amino acid often found in red marine algae, is important to metabolic function and contributes to the elimination of excess cholesterol from the body, lowering cholesterol levels in the bloodstream. It has been suggested that Taurine might be a key factor contributing to the relatively low instances of high cholesterol amongst Asian populations who eat copious amounts of seaweed (Mouritsen 2013:55). Table 3.7 provides amino acid profiles for several genera of edible seaweeds found along the Pacific coast of Alta and Baja California to demonstrate their value in this respect.

Seaweeds contain three groups of carbohydrates (polysaccharides), many of which differ from those found in terrestrial plants. Seaweed carbohydrates include sugar, soluble dietary fiber, and insoluble dietary fiber, which form gelatinous substances that aid in the digestive process (Mouritsen 2013:54). Though indigestible to the human gastrointestinal tract, carbohydrates in the form of fiber are an essential component of human diet. The algal fibers that compose significant percentages of carbohydrates in many types of seaweed promote the proliferation of beneficial intestinal flora and acts as a hypoglycemic, amongst other healthful functions (Dawczynski et al. 2007:892). Various types of brown and red marine macroalgae are particularly rich sources of dietary fiber, containing higher amounts than most fruits and vegetables (33-50 g/100 g dry weight; Dawczynski et al. 2007; Pereira 2016:11), yet do not produce starch or the alpha-linked glucans digestible by most human populations (Hehemann et al. 2010). Laminarin, a reserve carbohydrate composed of glucose and found in certain brown marine algae, functions in a similar way as starch in terrestrial plants, making the inclusion of brown algae to a diet rich in marine protein highly beneficial. For Channel Islanders, carbohydrate and fiber-rich foods were critical to creating nutritionally balanced meals that complimented protein and lipid-rich shellfish, fish, marine mammals, and birds. Recent research has shown that Channel Islanders relied more heavily on blue dick corms and other terrestrial plant foods than previously realized, providing a significant terrestrial source of carbohydrates and calories (Gill 2015; Gill and Hoppa 2016; Reddy and Erlandson 2012). The abundant seaweeds in island waters would have provided another major carbohydrate and dietary fiber source that was also readily available year-round.

**Table 3.3.** Proximate composition (% dry weight) of select seaweeds*

| | **Ash** | **Protein** | **Lipid** | **Carbohydrate undifferentiated** | **Carbohydrate Fiber** | **Carbohydrate Non-fibrous** |
|---|---|---|---|---|---|---|
| **Chlorophyta** | | | | | | |
| *Enteromorpha* spp. | 15.2 | 19.5 | 0.3 | - | 6.8 | 46.1 |
| *Gelidium* sp. | 14 | 11.8 | 0.9 | 43.1 | - | - |
| *Ulva* spp. | 11.3 - 22.6 | 24.4 - 26.1 | 0.7 – 1.8 | 61.8 | 46.1 | 5.1 |
| *Monostroma* spp. | 14.9 | 20.0 | 1.2 | - | 57.2 | 6.7 |
| **Phaeophyta** | | | | | | |
| *Laminaria* sp. | 29.5 ± 1.1 | 7.5 ± 0.1 | 0.9 ± 0.01 | - | - | - |
| *Laminaria* sp. | 19.6 | 16.1 | 2.4 | 39.3 | - | - |
| *Laminaria* spp. | 17.2 – 27.3 | 4 – 6.7 | 0.7 – 1.7 | - | 4.6 – 10.2 | 31.9 – 47.5 |
| *Sargassum* sp. | 19.4 | 13.6 | 0.5 | 61.6 | - | - |
| **Rhodophyta** | | | | | | |
| *Alaria* spp. | 14.9 | 17.1 | 3.6 | 39.8 | - | - |
| *Gracilaria* sp. | 10.5 | 19.7 | 0.4 | 63.1 | - | - |
| *Palmaria* sp. | 34 ± 0.1 | 13.9 ± 0.3 | 1.8 ± 0.1 | - | - | - |
| *Porphyra* sp. | 8.7 | 33 - 47 | 0.7 | 40.7 | - | - |
| *Porphyra* sp. | 19.1 ± 0.6 | 24.1 ± 1 | 1 ± 0.1 | - | - | - |
| *Porphyra* spp. | 7.8 | 43.6 | 2.1 | - | 2.0 | 44.4 |

*Data compiled from data summarized in Kumar et al. 2008; Nisizawa et al. 1987; Sánchez-Machado et al. 2004; Fleurence 1999; Smith 1905

**Table 3.4.** Vitamin composition of some edible seaweed taxa

| | A (IU) | B complex | $B_1$ | $B_2$ | Niacin | C | $B_6$ | Biotin | Folic Acid | Choline | Lipoic acid | Inositol |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Chlorophyceae** | | | | | | | | | | | | |
| *Enteromorpha* spp. | 13000 | - | 6.0[2] | 20.5[2] | 65[2] | 432[2] | - | - | - | - | - | - |
| *Ulva lactuca* | | | | | | | | | | | | |
| *Ulva* sp. | - | 0.014[1] | - | - | - | - | - | .224[1] | .118[1] | .061[1] | .420[1] | .330[1] |
| *Ulva* spp. | 590 | - | 0.8[2] | 5.7[2] | 118[2] | 120[2] | - | - | - | - | - | - |
| *Monostroma* spp. | 2700 | 429[2] | 4.3[2] | 13.3[2] | 35[2] | 540[2] | - | .115[2] | .429[2] | .079[2] | .515[2] | .219[2] |
| **Phaeophyceae** | | | | | | | | | | | | |
| *Laminaria* sp. | 430-440 | 0.031[1] | 0.08[1] | 0.32[1] | 1.8[1] | 91[1] | 11.0[1] | - | - | - | - | - |
| *Fucus* sp. | | | | | | | | | | | | |
| **Rhodophyceae** | | | | | | | | | | | | |
| *Gelidium* sp. | - | .041[2] | - | - | - | - | - | .061[2] | .782[2] | 4.885[2] | .57[2] | .443[2] |
| *Gracilaria* sp. | 800 | .013[2] | - | - | - | - | - | .018[2] | .304[2] | 1.492[2] | .495[2] | .324[2] |
| *Palmaria palmata* | | | | | | | | | | | | |
| *Palmaria* sp. | | | | | | | | | | | | |
| *Porphyra tenera* | ≤44,500 | - | ≤0.25[1] | ≤1.24[1] | ≤10[1] | 831[1] | 20[1] | .294[1] | .088[1] | 2.92[1] | .790[1] | .062[1] |
| *Porphyra* sp. | 16000 | - | 12.9[2] | 38.2[2] | 110[2] | 1125[2] | 10.4[2] | - | - | 2920[2] | - | 62[2] |

*Data compiled from Kumar et al. 2008; Nisizawa et al. 1987; Xia and Abbott 1987.

[1] Value given in mg/g

[2] Value given in ppm

**Table 3.5.** Relative distribution of selected trace elements in marine organisms and seawater.

| Element | Seaweeds | Mollusks | Crustaceans | Fish | Seawater |
|---|---|---|---|---|---|
| Lithium (Li) | 5.7 | 6.0 | - | + | 7.0 |
| Boron (B) | 3.8 | 4.3 | 4.3 | 5.0 | 5.35 |
| Fluoride (F) | 5.0 | 5.3 | 5.3 | 5.3 | 5.85 |
| Aluminum (Al) | 4.2 | 4.3 | 4.7 | 5.3 | 8.5 |
| Silicon (Si) | 3.0 | (3.0) | (2.5) | 3.5 | 6.3 |
| Titanium (Ti) | 4.5 | 4.7 | 5.0 | 5.7 | 9.0 |
| Vanadium (V) | 5.7 | 6.0 | 6.3 | 6.7 | 9.5 |
| Chromium (Cr) | 6.0 | - | + | 6.7 | 10.3 |
| Manganese (Mn) | 4.3 | 4.5 | 4.5 | 4.7 | 9.5 |
| Iron (Fe) | 3.1 | 3.5 | 4.3 | 4.3 | 8.5 |
| Cobalt (Co) | 6.3 | 6.3 | 6.7 | 6.7 | 10.0 |
| Nickel (Ni) | 5.7 | 6.0 | 6.3 | 6.3 | 9.5 |
| Copper (Cu) | 5.1 | 4.3 | 4.5 | 5.3 | 9.0 |
| Zinc (Zn) | 4.3 | (3.5) | (3.3) | 4.0 | 8.5 |
| Arsenic (As) | 4.5 | 5.4 | 5.3 | 5.2 | 8.5 |
| Bromine (Br) | 3.2 | (3.5) | (4.0) | (5.3) | 4.2 |
| Rubidium (Rb) | 5.0 | 5.0 | - | - | 6.9 |
| Strontium (Sr) | 3.5 | 3.8 | (3.7) | 3.8 | 5.1 |
| Molybdenum (Mo) | 6.3 | 5.7 | 6.3 | 6.3 | (9.3) |
| Silver (Ag) | 6.5 | + | + | (5.0) | 9.7 |
| Cadmium (Cd) | 6.2 | 5.7 | 6.8 | (6.3) | 10.0 |
| Tin (Sn) | 6.0 | (4.7) | (4.7) | 5.5 | 8.5 |
| Iodine (I) | 3.8 | 5.7 | 6.0 | 5.7 | 7.3 |
| Barium (Ba) | 5.3 | 6.5 | (6.3) | + | 8.2 |
| Mercury (Hg) | 7.5 | - | - | (6.5) | 10.5 |
| Lead (Pb) | 5.3 | 5.7 | 6.0 | 6.5 | 8.3 |
| Radium (Ra) | 13.3 | - | 13.3 | 13.7 | 16.2 |

*Table compiled from Fukai and Meinke 1959:400; numerical values are the negative logs of abundance [element (g)/dry weight (g) at 105-110°].

**Table 3.6.** Mineral composition of some edible seaweed taxa*

| | Mineral | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Genus** | **Na** | **K** | **Ca** | **Mg** | **Fe** | **Zn** | **Mn** | **Cu** | **P** | **I** | **Se** |
| **Chlorophyta** | | | | | | | | | | | |
| *Entermorpha* | 0.57[1] | 3.5[1] | 0.91[1] | - | 350[1] | - | - | - | 0.80[1] | - | - |
| *Ulva* | 1,100 | 700 | 730 | 2,800 | 100 | - | 1-35 | - | - | 20 | - |
| *Ulva* | 3.183[1] | 0.731[1] | 1.12[1] | - | 62[1] | - | - | - | 0.094[1] | - | - |
| *Monostroma* | 1.8[1] | 0.81[1] | 0.69[1] | - | 25[1] | - | - | - | 0.2[1] | - | - |
| **Phaeophyta** | | | | | | | | | | | |
| *Alaria* | 4,200 | 7,500 | 1,000 | 900 | 18 | 3.4 | 1.0 | 0.17 | 500 | 17 | - |
| *Eisenia* | - | 4,000 | 1,200 | - | 12 | - | - | 0.3 | - | 50-500 | - |
| *Fucus* | 5469 ± 60 | 4323 ± 46 | 938 ± 7 | 994 ± 13 | 4.2 ± 0.17 | 3.71 ± 0.37 | 5.5 ± 0.11 | <0.5 | - | - | - |
| *Laminaria* | 3818 ± 43 | 11,579 ± 128 | 1005 ± 5 | 659 ± 6 | 3.29 ± 0.54 | 1.77 ± 0.44 | <0.5 | <0.5 | - | - | - |
| *Laminaria* | 31,110[2] | 67,780[2] | 7890[2] | 7570[2] | - | 4[2] | 4[2] | 2[2] | 2220[2] | 2500[2] | 4[2] |
| *Sargassum* | - | 15,000 | 1,400 | - | 30 | - | - | - | 60 | 40-60 | |
| **Rhodophyta** | | | | | | | | | | | |
| *Chondrus* | 4270 ± 62 | 3184 ± 0 | 420 ± 22 | 732 ± 6 | 3.97 ± 0.11 | 7.14 ± 0.13 | 1.32 ± 0 | <0.5 | - | - | - |
| *Palmaria* | 1,700 | 8,000 | 200 | 300 | 33 | 2.9 | 1.1 | 0.38 | 400 | 5 | - |
| *Porphyra* | 3627 ± 115 | 3500 ± 71 | 390 ± 17 | 565 ± 11 | 10.3 ± 0.41 | 2.21 ± 0.17 | 2.72 ± 0 | <0.5 | 500 | 0.5-1.5 | - |
| *Porphyra* | 5700[2] | 24,000[2] | 4400[2] | - | 130[2] | 100[2] | 20[2] | 14.7[2] | 6500[2] | - | 0.8[2] |

*Data compiled from Mouritsen 2013; Nisizawa et al. 1987; Rupérez 2002; amounts quantified as (mg)/(100g) dry weight unless otherwise noted

[1] amounts quantified as percent (%) dry weight

[2] amounts quantified as ppm (parts per mil)

**Table 3.7.** Amino acid composition (g amino acid/ 100 g protein) of some seaweeds*

| | **Chlorophyta** | **Phaeophyta** | | | **Rhodophyta** | | |
|---|---|---|---|---|---|---|---|
| | *Ulva* spp. | *Fucus* sp. | *Laminaria* sp. | *Undaria* sp. | *Gracilaria* sp. | *Palmaria* sp. | *Porphyra* sp. |
| Alanine | 5.5 – 7.0 | 5.4 | 5.7 | 4.7 | 65.3 | 6.3 – 6.7 | 6.2 - 7.4 |
| Arginine | 4.3 – 14.9 | 8.2 | 3.3 | 5.2 | 35.5 | 4.6 – 5.1 | 5.9 - 16.4 |
| Aspartic acid | 6.0 – 11.8 | 9.0 | 12.5 | 8.7 | 40.1 | 8.5 – 18.5 | 7.0 – 8.5 |
| Cysteine | NA | NA | 1.2 | 0.9 | 4.2 | NA | 1.2 |
| Glutamic acid | 6.9 – 23.4 | 11.0 | 23.8 | 14.5 | 63.6 | 6.7 – 9.9 | 7.2 – 10.2 |
| Glycine | 5.2 – 7.5 | 5.4 | 4.0 | 5.1 | NA | 4.9 – 13.3 | 5.1 - 7.2 |
| Histidine | 1.2 - 4 | 1.6 | 2.2 | 2.5 | 19.1 | 0.5 – 1.2 | 1.4 – 2.6 |
| Isoleucine | 2.3 – 3.6 | 3.0 | 2.7 | 3.3 | 29.4 | 3.5 – 3.7 | 3.1 - 4.0 |
| Leucine | 4.6 – 6.9 | 5.0 | 4.9 | 5.9 | 36.5 | 5.9 – 7.1 | 5.5 - 8.7 |
| Lysine | 3.5 – 4.5 | 6.0 | 3.9 | 5.6 | 16.6 | 2.7 – 5.0 | 4.5 – 4.9 |
| Methionine | 1.4 – 2.6 | 0.4 | 0.9 | 1.7 | 20.0 | 2.7 – 4.5 | 1.1 – 1.8 |
| Phenylalanine | 3.9 – 7.1 | 2.6 | 3.2 | 4.7 | 29.0 | 4.4 – 5.3 | 3.3 - 3.9 |
| Proline | 4.0 – 10.5 | 3.3 | 3.1 | 0.9 | 56.2 | 1.8 – 4.4 | 3.5 - 6.4 |
| Serine | 3.0 – 6.1 | 3.5 | 3.3 | 4.0 | NA | 4.0 – 6.2 | 2.9 – 4.0 |
| Threonine | 3.1 – 6.8 | 3.3 | 3.5 | 4.4 | 39.8 | 3.6 – 4.1 | 4.0 – 5.3 |
| Tryptophan | 0.3 | NA | 0.5 | 0.7 | NA | 3.0 | 0.7 - 1.3 |
| Tyrosine | 1.4 – 4.7 | 1.2 | 1.7 | 2.9 | 9.4 | 1.3 – 3.4 | 2.4 – 3.4 |
| Valine | 4.0 – 5.2 | 3.9 | 3.8 | 5.2 | 31.7 | 5.1 – 6.9 | 5.2 - 6.4 |

*Data compiled from Fleurence 1999; Schmid 1969; [not original sources]

Humans, being mammals, are incapable of synthesizing mono- and polyunsaturated fatty acids (MUFAs and PUFAs) on their own, necessitating the acquisition of this essential dietary component through ingestion. Marine resources generally are good sources of PUFAs and MUFAs, leading some scholars to connect aquatic adaptations to encephalization and brain development in human evolution (Cunnane and Stewart 2010; Will et al. 2016). Not only do seaweeds contain significant quantities of essential fatty acids, their fat composition contains almost perfectly balanced proportions of omega-3 and omega-6 for human requirements, making them ideal supplements to human diet (Mouritsen 2013:59-60). Though exact percentages vary between and within species depending on location and season of harvest, roughly 30-70% of fat content is composed of polyunsaturated fats, predominantly omega-3 and omega-6 fatty acids including arachidonic acid (AA), which is not found in terrestrial plants. Other marine resources that people often consume, like fish and shellfish, also contain significant amounts of omega-3 fatty acids, however, these are not produced by the organisms themselves but are acquired through their ingestion of marine algae.

Rhodophytes and phaeophytes contain significant amounts of digestible PUFAs, though chlorophytes contain significantly lower amounts with the exception of *Ulva* (Fleurence 1999; Pereira et al. 2012), which is arguably the most widely consumed green marine algae. The brown marine algae, *Sargassum*, which was likely consumed by the inhabitants of the Monte Verde site over 14,000 years ago, contains significant quantities of PUFAs (7.31 g/100g) and MUFAs (5.68 g/100g) making it an excellent addition to human diet (Renita and Amarnath 2011). Table 3.8 presents compiled data on the fatty acid content of seaweed taxa found in the southern California and northern Baja California region to demonstrate the benefit of consuming these resources.

Nutritional content and the bioavailability of nutrients fluctuate seasonally, making the nutritive qualities of various seaweeds more beneficial at particular times of the year (Fleurence 1999). For instance, in Japan, Hijiki (*Cystophyllum fusiforme*) is gathered in January and February when plants are small and tender, and Awo-nori (*Enteromorpha* spp.) is cropped during the winter and spring months between November and April, but Miru (*Codium* spp.) is only cropped in April and May (Smith 1905a:163-4). Iodine concentrations in seaweeds fluctuate throughout the year, in different parts of a single organism (i.e., stalk vs. leaf), and in algal stalks of different ages, with older specimens often containing higher concentrations (Smith 1905a:162). Early studies showed that the protein content of brown algae exhibited seasonal variation, with highest percentages in spring and the lowest amounts in fall (Black and Mitchell 1952; Mautner 1954:182). More recent work has confirmed that the protein content of *P. palmata* is ~25% of dry weight at the beginning of spring, but only 8% of dry weight at the end of summer (Galland-Irmouli et al. 1999). The composition of trace elements in Laminariacea vary seasonally, with higher concentrations found in the perennial stipe as compared to the fronds (Black and Mitchell 1952). For instance, the laminaran content of brown algae fluctuates seasonally (Nisizawa et al. 1987:14) and is often only present in certain parts of the kelp (i.e. fronds and blades), with some studies noting decreasing content with increasing water depth (see Hoppe and Schmid 1969:352-3).Similarly, the amounts of lipids in brown algae have been shown to have an inverse relationship with depth of immersion; lower quantities of lipids were found in plants inhabiting deeper waters, suggesting that lipids provided resistance to desiccation (Mautner 1954:183).

Hehemann et al. (2010) found that Japanese populations, who are known for their long history of extensive seaweed consumption (estimated at ~14 g/day; Fukuda et al. 2007), contain a gut bacterium, *Bacteroides plebeius,* that allows the human digestion of a normally indigestible compound, porphyran (Hehemann et al. 2010). This appears to be the first known instance of horizontal gene transfer from external bacteria consumed in food to human gut bacteria within the body. It is believed to have been transferred from microbes on marine red algae (*Porphyra* spp.) over the course of consuming copious amounts of seaweeds for hundreds, and likely thousands, of years. The porphyran-digesting enzyme was found to be common amongst Japanese individuals but absent in metagenomic data from modern North American populations. It is unknown whether Native Americans possessed gut microbiota like modern-day Japanese populations. Further genetic studies have the potential to reveal whether additional aboriginal populations in coastal environments acquired this or similar adaptations to seaweed consumption.

**Table 3.8.** Relative fatty acid contents of some edible seaweeds*

| | **Chlorophytes** | | | | | |
|---|---|---|---|---|---|---|
| | *Chaetomorpha* sp. | *Codium* sp. | *Codium fragile* | *Cladophora albida* | *Enteromorpha* sp. | *Ulva* sp. |
| SFAs | 60.59 ± 0.94 | 51.28 ± 1.44 | 62.37 ± 1.50 | 50.03 ± 0.56 | 64.85 ± 0.81 | 59.04 ± 0.85 |
| MUFAs | 11.84 ± 0.14 | 13.59 ± 0.45 | 15.29 ± 0.97 | 27.73 ± 0.11 | 17.52 ± 0.14 | 17.31 ± 0.15 |
| PUFAs | 27.57 ± 0.33 | 35.13 ± 0.91 | 22.34 ± 0.55 | 22.24 ± 0.24 | 17.64 ± 1.21 | 23.65 ± 0.26 |
| PUFAs (*n*-3) | 0.85 ± 0.04 | 9.52 ± 0.48 | 7.40 ± 0.34 | 2.88 ± 0.05 | 4.02 ± 0.06 | 18.00 ± 0.23 |
| PUFAs (*n*-6) | 26.72 ± 0.32 | 25.61 ± 0.78 | 14.93 ± 0.43 | 19.36 ± 0.23 | 13.62 ± 1.21 | 5.65 ± 0.11 |
| Ratio (*n*-6)/(*n*-3) | 31.25 | 2.69 | 2.02 | 6.73 | 3.39 | 0.31 |
| Ratio PUFA/SFA | 0.46 | 0.68 | 0.36 | 0.44 | 0.27 | 0.40 |

| | **Phaeophytes** | | | |
|---|---|---|---|---|
| | *Dictyota* spp. | *Laminaria* sp. | *Sargassum* sp. | *Taonia* sp. |
| SFAs | 45.98 ± 0.47<br>40.20 ± 0.31 | 33.82 ± 2.21 | 42.34 ± 0.28 | 35.47 ± 1.02 |
| MUFAs | 24.28 ± 0.13<br>29.34 ± 0.14 | 19.23 ± 1.99 | 19.03 ± 0.14 | 17.34 ± 0.61 |
| PUFAs | 29.74 ± 0.67<br>30.46 ± 0.28 | 46.94 ± 4.58 | 38.63 ± 0.32 | 47.19 ± 0.65 |
| PUFAs (*n*-3) | 6.57 ± 0.22 | 25.08 ± 3.21 | 10.10 ± 0.14 | 14.40 ± 0.55 |
| PUFAs (*n*-6) | 23.16 ± 0.63 | 20.99 ± 1.27 | 28.52 ± 0.29 | 32.79 ± 0.35 |
| Ratio (*n*-6)/(*n*-3) | 3.52 | 0.83 | 2.82 | 2.28 |
| Ratio PUFA/SFA | 0.65 | 1.39 | 0.91 | 1.33 |

| | **Rhodophytes** | | | | | |
|---|---|---|---|---|---|---|
| | *Bornetia secundiflora* | *Jania* sp. | *Palmaria* sp. | *Peyssonnelia* sp. | *Porphyra* sp. | *Pterocladiella capillacea* |
| SFAs | 46.14 ± 0.82 | 51.56 ± 0.31 | 60.48 ± 2.58 | 39.15 ± 0.46 | 64.95 ± 2.24 | 60.62 ± 0.65 |
| MUFAs | 18.66 ± 0.46 | 7.64 ± 0.08 | 10.67 ± 1.55 | 8.87 ± 0.11 | 18.91 ± 2.81 | 8.45 ± 0.10 |
| PUFAs | 35.20 ± 0.66 | 40.81 ± 0.69 | 28.86 ± 3.94 | 51.98 ± 0.53 | 16.10 ± 3.31 | 30.94 ± 0.40 |
| PUFAs (*n*-3) | 27.26 ± 0.64 | 25.46 ± 0.53 | 25.52 ± 3.34 | 51.98 ± 0.53 | 7.20 ± 1.48 | 16.19 ± 0.14 |
| PUFAs (*n*-6) | 7.94 ± 0.14 | 15.35 ± 0.44 | 2.14 ± 0.45 | 28.60 ± 0.25 | 7.97 ± 1.31 | 14.74 ± 0.37 |
| Ratio (*n*-6)/(*n*-3) | 0.29 | 0.60 | 0.13 | 1.92 | 1.21 | 0.91 |
| Ratio PUFA/SFA | 0.76 | 0.79 | 0.48 | 1.33 | 0.25 | 0.51 |

* Data compiled from Pereira et al. (2012); Sánchez-Machado et al. (2004).

## **A Deep History of Seaweed Use by Pacific Cultures**

Ethnographic, ethnohistoric, and modern accounts describe the varied ways that coastal people around the globe utilized seaweeds and seagrasses for dietary and other purposes. On the Japanese archipelago, fragments of *Eisenia* and *Sargassum* have been found in midden remains from the Jomon (6000 – 300 BC) and Yayoi (BC 300 – 400 AD) periods, and the written Law of Taiho (AD 701) includes several marine algae in a list of items paid to the Emperor's court as tax (see Nisizawa et al. 1987:5). Japanese written records from ~2000 years ago list fish and marine algae as highly important marine products and items of religious sacrifice offered in various rites (see Hoppe and Schmid 1969:361). Chinese written records of seaweed descriptions and uses extend back 4700 years (Bell 1981:117; Xia and Abbott 1987:341), though actual use in the region likely began much earlier. A written source from 600 BC demonstrates the great esteem held by the Chinese for seaweeds: "Some algae are a delicacy fit for the most honorable guest, even for the king himself" (Chapman 1970:94). The oldest Japanese-Chinese dictionary, the *Wamyosho*, contains a list of twenty-one species of brown, green, and red marine algae that were used as food during the Heiam era (AD 794-1185; Miyashita 1974). Extensive cultivation of seaweeds formed a pivotal part of local subsistence and regional economies in East Asia for hundreds of years. The traditional gathering of kelp was a seasonal endeavor facilitated by fishermen in open boats using hooks of various designs attached to long wooden handles, or tied to weighted ropes and dragged along the ocean floor to pull the weeds from the rocky sea floor (Chapman 1970:97; Smith 1905a). Smith also (1905a) mentions the inclusion of Ainu (aboriginal Japanese) anglers in his early description of Japanese kelp collection and describes women's roles as they participate in the various phases of drying and processing the algae.

Island cultures of Polynesia made extensive use of the bountiful marine resources surrounding their far-flung and relatively isolated island homes, though none seem to have used seaweeds as copiously as the Hawaiians who had specific names for the roughly 75 edible species they gathered. The general term *Limu* is used to denote marine algae in a broad sense followed by a descriptive term (MacGaughey 1916, 1918); for instance, *limu lo-loa* is the Hawaiian term for the red algae, *Gelidium*, meaning "the long and slender seaweed" (MacGaughey 1916:476). The nature of littoral and nearshore habitats dictated how various seaweeds were collected and by whom. Taxa growing in quiet nearshore waters were harvested by older women and children, while those growing in rougher waters were dived for by men and younger women using stone chisel tools, and the species inhabiting the outer reef were gathered by men from outrigger canoes (Abbott 2002:4; MacGaughey 1916). Indigenous people of the Marquesas archipelago (French Polynesia) also consumed seaweeds including two species of green seaweeds, *Enteromorpha flexusa* and *Caulerpa racemose*, which are still consumed by local populations today (Conte and Payri 2002).

On the islands of Austronesia, women and children appear to be the primary collectors of sea vegetables for subsistence purposes (Ono 2010:275). European immigrants and travelers in New Zealand during the early 1800s noted that the Maori used seaweeds as containers for oil and other fluids and recorded "the making of horn- or bone-like handles for knives from the hard bases of *Lessonia variegata*" (Brooker et al. 1989:87). The Maori were reportedly fond of Karengo (*Porphyra* spp.) (Dixon 1973:218-219), which they ate after steaming it in earth ovens, and drank after fermenting with juices (Brooker et al.1989:92-93). Several varieties of green and red seaweeds were also eaten by Maoris in salads and soups; and aboriginal Australians also ate at least two species of large brown seaweed (*Durvillea*) (Chapman 1970:93-94). Harvesting practices appear to have contributed to management of seaweed resources, which were "picked over annually without long-term damage" to kelp beds (Brooker 1989:88).

## Ethnographic and Ethnohistoric Accounts from the Pacific Coast of the Americas

Native people inhabiting the west coast of North America utilized seaweeds for dietary, medicinal, and other purposes to varying degrees and dried seaweeds were a valued trade commodity to inland groups who prized their high salt content and used them to treat iodine deficiency (Turner 1995:18, 22; Turner and Loewen 1998). Other accounts indicate seaweeds and seagrasses were harvested as preferred food sources, utilized in a wide variety of ways, and held deep roots in Native culture. Extensive linguistic references and special feasts and etiquette surrounding the consumption of seaweeds and seagrasses attest to their deep history of use in the region (Berlin 1973; Felger et al. 1980; Turner 1995; N.J. Turner 2003). Based on current distributions, at least four species of green seaweeds, 24 species of brown seaweeds, and 32 species of red seaweeds that inhabit the East Pacific are edible and widely consumed (Pereira 2016:346-373). Table 3.9 provides an extensive list of seaweed taxa inhabiting California coastlines that are known to be consumed and used as food, as potential candidates for Indigenous harvesting in the region.

### Dietary use of Seaweeds and Seagrasses North and South of the Channel Islands

In Alaska, Nunivak Islanders eagerly harvested seaweeds in early April with the first cracks of the winter ice, sending the children to look for them (Lantis 1946). Native inhabitants of Nelson Island, Alaska, gathered seaweed (*Fucus* spp.) in late May when herring eggs were attached, eating them together either raw or cooked, and collected kelp for food on various islands as well (Ager and Ager 1980:33). Translated accounts of Orthodox churchmen from the late 18th and early 19th centuries provide descriptions of Konyag islanders subsisting on shellfish and “sea cabbage (kelp)” while on hunting expeditions and during times when other foods were scarce (Black 1977:100).

Similar practices are described for Northwest Coast tribes such as the Kwakwaka’wakw, Haida, and Heiltsuk, who collected blades of giant kelp (*Macrocystis*), boa kelp (*Egregia men*ziesii) and eelgrass leaves (*Zostera marina*), submerging them with weights in advantageous locations (i.e., near river mouths) to increase the likelihood and amount of herring spawn (Turner 1995:20-21; Turner and Bell 1973). Green and purple lavers were eaten by the Haida and other Native groups of Queen Charlotte Islands and the surrounding area. Lavers were dried and compressed into blocks that could be sliced as needed, boiled and consumed. One account describes a “very palatable” meal of boiled dulse and halibut (Swan 1893). Turner (1995:22; 2003) lists red laver (*Porphyra abbottae*) as the most commonly consumed seaweed, describing how it was harvested from rocks at low tide in the early Spring, after which it was spread out to dry in the sun

**Table 3.9.** Edible seaweeds inhabiting California waters

| Taxa (Synonym/Formerly) | Common Name | Geographic Distribution** | Uses |
|---|---|---|---|
| **CHLOROPHYTA** | | | |
| *Codium dichotomum* | Japanese: Imose-miru, Yezu-miru | E Pacific (California, Mexico, Galápagos Is) | Used as food in Japan, Korea, Argentina |
| *Monostroma quaternarium* | none | NE Pacific (Alaska to Baja California, Costa Rica, Peru) | Used as food in Peru |
| *Ulva lactuca*<br>*(U. fenestrata)* | Sea lettuce, green laver | Ubiquitous – common to most shorelines of the world | Used as food and seasoning |
| **PHAEOPHYCEAE** | | | |
| *Costaria costata* | Ribbed kelp, seersucker kelp, short kelp | Pacific Coast of the Americas (Alaska to Mexico, Chile, Argentina) | Eaten when young and tender. Also used in medicine, cosmetics, fertilizer. |
| *Ecklonia arborea*<br>*(Eisenia arborea)* | Southern sea palm, striped kelp Japanese: Arame | E Pacific (British Columbia to Mexico) | Used as food in Asia and N Pacific. Used as folk medicine in Peru. |
| *Egregia menziesii* | Feather boa, boa kelp, feather boa kelp | NE Pacific (Alaska to Baja CA, Mexico) | Used as food in British Columbia |
| *Fucus evanescens*<br>*(F. distichus spp. evanescens)* | Popweed, rockweed, Arctic wrack | NE Pacific (Alaska to central California) | Used as food in Japan and Canada, younger plants are preferred |
| *Laminaria setchelli* | Southern stiff-stiped kelp, split blade kelp, split kelp, stiff-stiped kelp, oar weed | Aleutian Islands, Alaska to Baja California, Mexico | Eaten in many forms |
| *Lessoniopsis littoralis* | Short kelp, ocean ribbons, flat pompom kelp, strap kelp | Kodiak Island, Alaska to central California | Used as food |
| *Macrocystis pyrifera*<br>*(M. integrifolia)* | Giant Pacific kelp, sea ivy, giant kelp | Kodiak Archipelago, Alaska to northern Baja CA, Mexico | Used as food and commercially important for mineral extraction |
| *Nereocystis luetkeana* | Ribbon kelp, bull whip kelp, bull kelp, bladder kelp, sea whip, horsetail kelp, and others | NE Pacific (Alaska to central California) | Used as food, often pickled |

**Table 3.9** (continued)

| **Taxa (Synonym/Formerly)** | **Common Name** | **Geographic Distribution**** | **Uses** |
|---|---|---|---|
| **PHAEOPHYCEAE** (cont.) | | | |
| *Postelsia palmaeformis* | Sea palm, sea palm kelp | NE Pacific (Hope Island, British Columbia to central California) | Used as food |
| *Pterygophora californica* | Pompom kelp | NE Pacific (Alaska to Baja California, Mexico) | Eaten by the Inuit of Broughton Island |
| *Saccharina bongardiana (Laminaria bongardiana)* | Split kelp | NE Pacific (Alaska to California) | Used as food in Alaska |
| *Saccharina bongardiana (Laminaria bongardiana)* | Split kelp | NE Pacific (Alaska to California) | Used as food in Alaska |
| *Saccharina dentigera* | Mendocino coast kombu | NE Pacific (Alaska to California) | Used as food, contains medicinal qualities |
| *Saccharina groenlandica (Laminaria groenlandica)* | Short kelp, split kelp, sugar wrack | NE Pacific (Alaska to California) | Used as food, appetizing texture and flavor |
| *Saccharina sessilis (Hedophyllum sessile)* | Bubbly kelp, sea cabbage, sweet kombu | NE Pacific (Alaska to California) | Used as food by Indigenous and modern populations |
| *Stephanocystis osmundacea (Cystoseira osmundacea)* | Woody chain bladder, bladder chain kelp | Pacific (Northern Oregon to Northern Mexico) | Used as food, harvested by coastal communities |
| **RHODOPHYTA** | | | |
| *Chondracanthus exasperatus* | Turkish towel | NE Pacific (Alaska to Baja California, Mexico) | Used as food |
| *Gracilaria pacifica* | Red ogo seaweed, California limu, red spaghetti | NE Pacific (Alaska to California) | Used as food, source of agar |
| *Gracilariopsis andersonii (G. sjoestedtii)* | Sea spaghetti | NE Pacific (British Columbia to Mexico) | Used as food |
| *Halosaccion glandiforme* | Sea sac, dead man’s finger, salt sacs | NE Pacific (Alaska to California) | Used as food |

**Table 3.9** (continued)

| Taxa (Synonym/Formerly) | Common Name | Geographic Distribution** | Uses |
|---|---|---|---|
| *Iridaea cordata* | Rainbow kelp, rainbow seaweed | NE Pacific (Alaska to California) | Used as a nutritional supplement |
| *Polysiphonia mollis* | Hawaiian: Limu hawane, Limu pepe-iao | NE Pacific (Alaska to Baja California, Mexico) | Used as food in Hawaii |
| *Pyropia nereocystis (Porphyra nereocystis)* | Bull kelp laver, red laver, purple laver, rose nori, red nori | NE Pacific (Alaska to California) | Used as food |
| *Pyropia pseudolanceolata (Porphyra pseudolanceolata)* | Laver seaweed | NE Pacific (Alaska to California) | Used as food |
| *Sarcodiotheca gaudichaudii* | Red string seaweed | NE Pacific (Alaska to California) | Eaten fresh, salads |
| *Wildemania amplissima (Porphyra cuneiformis)* | Northern pink laver, red cellophane | NE Pacific (Alaska to California) | Used as food |
| *Wildemania miniata (Porphyra miniata)* | Red nori | NE Pacific (Alaska to California, Chile) | Used as food |

*This table is compiled from references and information provided in Pereira 2016:346-373.
**Listed geographic distribution is limited to the relevant region – Eastern Pacific near California. Additional geographic distributions for many of these taxa are listed in Pereira 2016:346-373.

then broken into small pieces and stored. The Haida and Kwakwak'wakw fermented red laver in a process that lasted several months before storing seaweed cakes in wooden boxes for winter consumption. Alternatively, blades were dried and browned over a fire then pounded into a powder that was boiled with water to make porridge. Seaweed was an intricate part of feasting etiquette in that one was expected to consume it prior to drinking water during a feast (Turner 1995:22). Ethnographic accounts describe seaweed harvesting as the work of women, who handled their own canoes and went out to seaweed beds to hand-gather in cooperative groups (Turner 2003).

Eelgrass rhizomes and leaf bases were consumed by the Straits Salish, Nuu-chah-nulth, Kwakwak'wakw, Haida, and other northwest coast peoples (Turner 1995:53-54; Turner and Bell 1973). The Kwakwak'wakw valued this resource as the "the food of their mythical ancestors," and celebrated with an Eelgrass feast (Turner 1995:54). Eelgrass rhizomes, stems, and leaf-bases were eaten raw as a feast food, steamed with meats, and made into cakes that were dried and stored for winter consumption. Surfgrass

(*Phyllospadix scouleri* and *P. torreyi*) was also eaten by some northwest coast groups, who formed cakes from the entire plant that could subsequently contribute to foods stored in preparation for winter.

To the south, the Seri Indians who inhabited the coast of the Gulf of California in what is now Sonora, Mexico, consumed two types of seagrass: eelgrass (*Zostera marina*) and ditch-grass (*Ruppia maritime*). Eelgrass was considered one of their primary traditional foods and the extensive linguistic terminology associated with this species has led researchers to suggest a considerable antiquity to this practice (Berlin 1973; Felger and Moser 1976: Felger et al. 1980; Sheridan and Felger 1977). It was harvested seasonally (late April – early May) in mass quantities by men and women then processed by the women and children who dried, threshed, and removed the fruits, which were toasted or eaten raw. Toasted fruits were also pounded with manos to open and remove the seeds, which were ground into flour using mano and metate and prepared as gruel of varying consistency.

Accounts from the early 1900s indicate that native people on islands off the coast of Chile consumed large amounts of sea lettuce (*Ulva* spp.) and bull kelp (*Durvillaea antarctica*), which they still call *cochayugo* (Chapman 1970:93). The traditional cuisine of Peru is also known to incorporate several varieties of red and green seaweed, with indications this practice extends back to the Indigenous founders of Peruvian empires thousands of years ago (i.e., the city of Caral ca. 2650 BCE; Bradley 2012).

Beyond dietary benefits acquired through the consumption of seaweeds, many species of marine algae contain medicinal qualities noted by aboriginal populations in many parts of the world (see Bell 1981:118; Chapman 1970; Hoppe 1969:126; Mouritsen 2013). In Peru, *mococho* (a term for edible seaweeds) is recognized as an excellent source of vitamins and chewed during the winter to ward off sickness (Bradley 2012) and on islands off the coast of Chile seaweed stems (likely *Phyllogigas*) are chewed to prevent goiter (Chapman 1970:93). Medicinal uses of seaweed have also been noted for Native Peoples of the Northwest coast of North America and the California coast, which are described below.

Although this chapter is focused on macroalgae as a viable food source, the use of blue-green microalgae (*Cyanophyta*, also known as Spirulina) by Native Americans is noteworthy. The protein content of Spirulina comprises over half of its dry weight and the inclusion of essential amino acids makes this microalga highly prized as a food supplement. Farrar (1966) describes several accounts written as far back as the mid-1500s detailing the gathering and consumption of a “very fine slime” that was collected from the surface of the brackish waters of Lake Tezcoco by the inhabitants of Tenochtitlán. The Aztecs called this “clear-blue” substance *tecuítlatl*, which they gathered with fine mesh nets seasonally when surface deposits were thickest. The microalga was then sun dried and made into cakes, or bricks, that kept well and reportedly resembled a salty flavored cheese.

## Dietary Use of Seaweeds along the California Coast

The diversity in marine biogeographic provinces bordering the California coastline fosters differing suites of marine algae along the northern, central, and southern coasts that were used to varying degrees by cultural groups inhabiting each area (Figure 3.3). Overall, marine macrophytes are abundant in the region and coastal people in what is now California easily gathered quantities of kelp and seaweeds off the shore and commonly dried them for winter use (Lightfoot and Parrish 2009:28, 31). Tseng (1947:69) mentions that Native peoples harvested seaweeds for food “for ages, before the advent of the white man….” Anderson (2005:45,131) notes that coastal tribes in California consumed marine algae like bull kelp, red lavers, and sea lettuce along with sustainable harvesting strategies like leaving algal holdfasts in place to support new growth. Lavers (*Porphyra* spp.) were harvested in early spring and dried before being eaten and sea lettuce (*Ulva lactuca*) was likely eaten as well by coastal tribes of northern California (Baker 1981:99).

Along the central California coast, seaweeds (*Porphyra* spp.), kelps (i.e., *Nereocystis luetkeanna* and *Pterygophora californica*), and sea palm (*Postelsia platforms*) were routinely harvested and consumed. Some inland groups undertook trips to the coast primarily for the purpose of collecting these resources (Lightfoot and Parrish 2009:216). The Kashaya Pomo and Coastal Yuki cooked the stalks of bull kelp (*Nereocystis luetkeanna*) and stalked kelp (*Pterygophora californica*) by placing them on hot ashes, hot coals, or in earthen ovens, before consuming them. Kelps were also cut into strips and dried for storage and later use. Sea palm was consumed by both groups, who ate it raw, or after cooking in hot ashes or on hot rocks.

Seaweeds were collected by some central coast peoples for their salt content, and others were routinely harvested as a food resource. The Kashaya Pomo favored *Porphyra lanceolata* and *P. perforata*, which were baked for immediate consumption, or sun-dried and stored in the form of large cakes (~ 20 cm in diameter) that would be baked or fried before being eaten (Lightfoot and Parrish 2009:216-217). Laver was gathered in the summer by the Coast Yuki, who sun-dried and heated it to soften the texture. Seaweeds

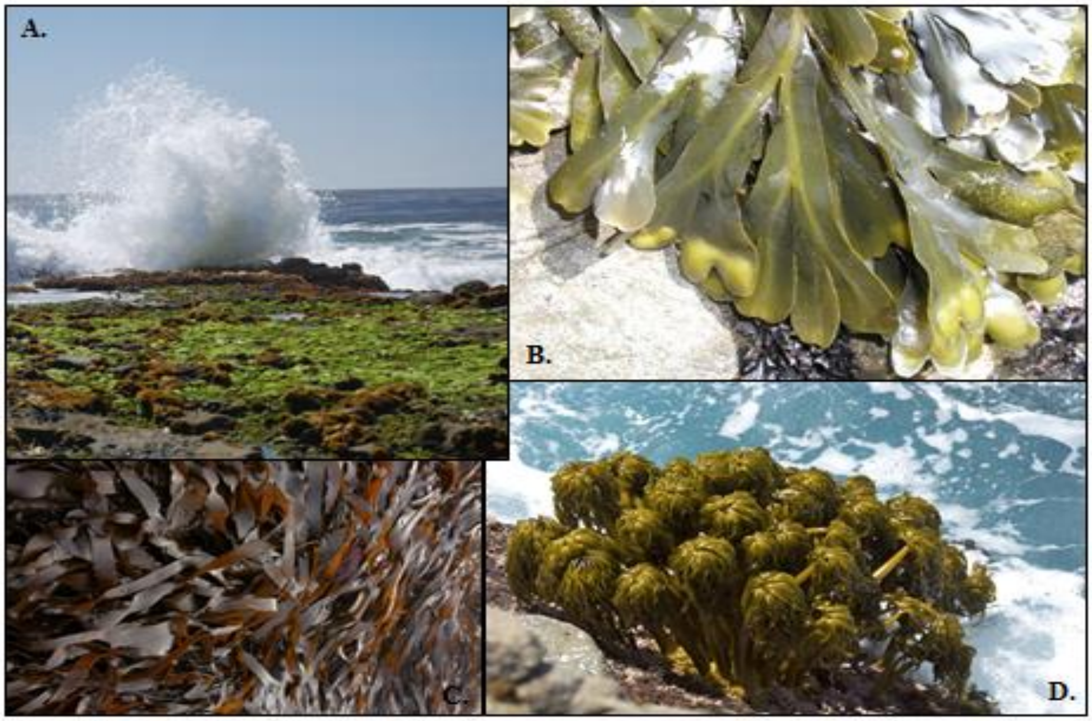

**Figure 3.3.** Some of the edible seaweed taxa noted in ethnographic accounts of Native Californians (image modifications and composite by Ainis). A) sea lettuce (*Ulva* spp.) on the north coast of San Nicolas Island (photo by Vellanoweth); B) rockweed (Fucus gardneri) (https://commons.wikimedia.org/wiki/File:Fucus_gardneri_rockweed.jpg); C) oarweed (Laminaria digitata) (https://commons.wikimedia.org/wiki/File:Oarweed_(6118562625).jpg); D) sea palm (*Postelsia palmaeformis*) (https://commons.wikimedia.org/wiki/Postelsia_palmaeformis#/media/File:Postelsia_palmaeformis_Salt_Point.jpg)

were also collected by the Coast Miwok during periods of low tide. Algae were dried in the sun or near a fire and eaten in that form or pounded and mixed with acorn mush. During the mid-1800s, Chinese migrants along the southern California coast made their living by gathering and selling seaweed, which they cultivated by preparing rocky littoral areas and "burning off" inedible varieties, creating more space for preferred species to grow (Wey 1988:111; see also Chapman 1970:90; Greenwood and Slawson 2008).

Timbrook (2011) summarizes information regarding Chumash names for a variety of kelp and seaweed, though she was unable to locate direct accounts of its consumption. Living Chumash descendants have described eating giant kelp, bull kelp, and other seaweeds in soups or stews (Q. Garcia pers. comm. with K. Gill, 2014), however, and the lack of ethnohistoric descriptions of seaweed consumption is likely due to the loss of traditional knowledge after more than two centuries of devastating rule by Spanish, Mexican, and American colonial regimes. The Island Chumash and Gabrielino/Tongva are poorly represented in the ethnographies of California Native peoples, which include only sparse accounts of islander ways and traditions.

Archaeological deposits testify to extensive kelp forest fishing by native islanders, but there has been little discussion of seaweed as a food source. Ethnographic and ethnohistoric accounts ranging from the Pacific Northwest to Chile demonstrate considerable use of seaweeds and seagrasses by native peoples, but accounts of Channel Islander foodways are limited on every account. Nevertheless, other cultural phenomena like songs and dances are often recorded in ethnographic accounts and these speak indirectly to the importance of kelps and seaweeds to indigenous peoples of California's islands. A Cruzeño (Santa Cruz Island) seaweed dance with accompanying paraphernalia is reported for the islands, though the songs were also in Barbareño Chumash, and one of them mentions the island of *Wi'ma* (Santa Rosa Island) (Hudson et al. 1977; Hudson and Blackburn 1985). In his accounts of Chumash ritual, Fernando Librado *Kitsepawit* describes several songs for the Seaweed Dance, which was performed by two people of any gender combination, or a single person, who would "imitate the movement of seaweed, any kind of seaweed" (Hudson et al. 1977:72-75). Dancers wore feather headdresses (*tsuh* and *tsiwin*), and feather skirts with feather wands in their hands. Faces were painted with black dots on one side and white dots on the other, over a background of red covering the face. Blackburn (1975:343) also notes the use of the term, *šutiwiʔyiš*, for the seaweed dance of Santa Cruz Island, which was performed on the mainland coast during historic times at Ventura, Santa Inés, and Santa Barbara (Hudson et al. 1977:72-75).

## Other Uses of Seaweeds and Seagrasses by Native Peoples Along the West Coast of North America

The Kwakiutl of British Columbia used the hollow, tubular stipes of *Nereocystis leutkeanna* to make ropes, harpoon lines, fishing lines and nets as well as for storage vessels to keep oil (Turner and Bell 1973). The Kashaya Pomo, inhabiting the central California coast, were also known to use fishing cordage manufactured from dried kelp strips (Goodrich et al. 1980:124-125). In his famous novel, *Island of the Blue Dolphins*, Scott O'Dell (1960) makes similar contentions that Native Nicoleño employed seaweed as fishing line, along with many other potential uses. Oral narratives by Fernando Librado *Kitsepawit*, record the Chumash use of kelp to anchor redwood plank boats (*tomols*) while fishing (Blackburn 1975:164; Hudson et al. 1978). Swan (1893) provides a detailed description of Native use of giant kelp (*Nereocystis lutkeana*) as fishing lines, stating "…when wet it is exceedingly strong, and equal to the best flax or cotton fishing lines of the white fisherman," further describing their use in deep-water fishing of black cod in depths of up to 200 fathoms. He also describes the use of the upper hollow portion of the stems as marine mammal and fish oil receptacles by northwest coast Indians, providing an in-depth description of the method as he observed it. Though not documented specifically with California Natives, ethnographic accounts from other maritime focused regions have shown that the hydroscopic properties of seaweeds function as a binder for caulking boats, with their mucilaginous nature preventing seams from drying out and cracking even when the boat is drying on shore between uses (Dimbley 1978 in Biagi and Nisbet 2006:222).

Archaeological evidence indicates that surfgrass was extensively utilized by coastal tribes of western North America (Scagel 1961), including the island Chumash and Gabrielino/Tongva, to manufacture cordage, water bottles, basketry, nets, skirts, roof thatching, storage containers, and other woven items (Connolly et al. 1995; Heye 1921:158e159, PL.CXXIII; Hudson and Blackburn 1983, 1985, 1986, 1987; Norris 1997; Olson 1971:221; Vellanoweth et al. 2003). Despite abundant archaeological evidence for the use of seagrass on the Channel Islands, however, no ethnographic accounts attest to this practice. Hudson and Blackburn (1987:160) lament that although seagrass cordage remains are often found on the islands, they were unable to locate ethnographic accounts referring to this tradition. Eelgrass remains have been found in archaeological contexts on Cedros Island, where their rhizomes may have been eaten, but the nature of native use of this resource is uncertain (Fauvelle et al. 2012). On the other side of the peninsula, however, the Seri Indians of Sonora harvested and relied on eelgrass seeds as one of their staple foods and used the grasses for a variety of purposes (Felger and Moser 1973).

In addition to being consumed directly, seaweeds are often used in food preparation to steam other dietary items, like the Polynesian practice of steaming foods wrapped in ti (*Cordyline fruticosa*) leaves in earthen or hot rock ovens. Rockweed (*Fucus gardneri*) fronds were used by the southern Kwakiutl of British Columbia to line steaming pits, within which they cooked clams, berries, and other foods (Turner and Bell 1973:260). The Tipai of northern Baja California were known to steam abalone by placing them shell down in the fire covered by wet kelp fronds (Hohenthal 2001:148).

Kelps and other seaweeds were also used as medicine by Native peoples of the Pacific Coast (Dillehay et al. 2008). In Chile, the stems of certain seaweeds (likely *Phyllogigas*) were called ‘goitre sticks’ and chewed by the indigenous people to ward off goiter (Chapman 1970:93). On the Northwest Coast, kelps (i.e., *Fucus gardneri* and *Nereocystis Leutkeanna*) were used as a heated poultice for aches and pains, particularly by pregnant women, as well as for scabs, burns, and swollen feet in conjunction with catfish oil and burnt ochre (Turner and Bell 1973). Turner (2003:289) also describes seaweed as “good for any kind of sickness in the stomach or body.” She lists indigenous medicinal uses of seaweed as a laxative and to relieve indigestion and heartburn among Northwest Coast peoples, and as an antiseptic poultice to deter infection and reduce swelling. The Kashaya Pomo sucked on dried pieces of stalked kelp to soothe sort throats and clear away mucus (Lightfoot and Parrish 2009:216). For the Chumash, a bath in hot seawater and boiled seaweed was used to treat paralysis and joint disorders (see Timbrook 2011).

## Identifying Seaweed Use in the Archaeological Record

Modern and historical uses of seaweed are well known around the globe, but their use is poorly understood archaeologically. Extensive evidence of indigenous seaweed use around the Pacific Rim provides a reasonable baseline for arguing that Native Channel Islanders and the coastal inhabitants of Alta and Baja California also utilized the rich and diverse seaweeds that surrounded them. The potential use of these abundant and nutritious resources by ancient coastal peoples has major implications for the perceived marginality of island environments. The nutritional properties of seaweeds from the Southern California Bight suggest they would have been an ideal addition to the diet of California island peoples, who intensively harvested a diverse array of other marine and terrestrial resources. The great diversity and biomass of seaweeds surrounding the islands off the coast of Alta and Baja California argues against their marginality, suggesting instead that seaweeds and seagrasses added significantly to the wealth of marine food, medicine, and technological resources available to island peoples. Once this possibility is recognized, new methods are needed for detecting the utilization of seaweeds in the archaeological record that can be used to test hypotheses about how significant seaweeds were in island economies. In addition, marine conservation efforts noting historic shifts in relative abundances of macroalgae are highlighting the need for baseline data on seaweed distributions in the past (e.g., Lotze and Milewski 2004) – a challenge that may be addressed through archaeological data sets.

The challenges posed by preservation biases of the archaeological record are well known. Although seagrasses are sometimes preserved, the identification of seaweeds in archaeological sites is extremely rare, even more so than terrestrial floral remains due to the lack of structural "hard parts" commonly found in wood and seeds. Wood charcoal is abundant in many island archaeological sites, as are carbonized macrobotanical remains, both of which are often identifiable to genus (see Reddy and Erlandson 2011; Gill 2013, 2014; Gill and Hoppa 2016). Yet carbonized remains of seaweeds have not yet been reported on the islands, likely due to their fragile nature and lower likelihood of surviving the carbonization process. Experimental studies of fresh seaweeds in New Zealand suggest that some large brown algae (e.g., *Macrocystis*) will naturally decompose within four months, while others (e.g., flapjack [*Carpophyllum*]) will take more than a year to fully decompose (Chapman 1950:253). A dearth of direct evidence for seaweed use does not mean they were not important to coastal foragers in the past, rather, we must explore new methods of detection for direct and indirect evidence.

Rare exceptions to such preservation problems include a saturated "wet-site" component at the ~14,000-year-old Monte Verde site in coastal Chile (Dillehay et al. 2008). Uncarbonized seaweed fragments were found at this pre-Clovis site, in hearth features and embedded in hut floors, indicating extensive use of seaweeds. Nine types of seaweed were identified—including microparticles from three genera found adhering to stone tools—testifying to their use by some of the earliest inhabitants of the Americas. This includes the earliest known human use of giant kelp and sargassum in the world. Some fragments were found in masticated "quids" mixed with terrestrial plant remains, suggesting medicinal uses; others were partially burned and may have been dried for storage, or cooked for consumption. Desiccated seaweeds have also been found in archaeological sites along Peru's hyper-arid Andean Coast. Seaweed remains were reportedly uncovered at Late Preceramic (~4450-3380 BP) sites in Peru (Raymond 1981; Bradley 2012:72) and a red alga (*Gigartina chauvinii*) widely consumed in the region today was found in another site dated to the 14th Century AD (see Bell 1981:119). The presence of seaweeds in Pacific Coast sites of South America demonstrates that New World peoples used these resources for 14,000 years or more, supporting the coastal migration theory and kelp highway hypothesis (Erlandson et al. 2007, 2015). If so, these early maritime peoples may have carried knowledge of seaweed use from homelands along the coastlines of northeast Asia and Beringia, implying that the earliest occupants of the California Islands also recognized the value of seaweeds, seagrasses, and their associated resources.

Along the Alta California Coast, kelp forest ecosystems and seaweeds have great antiquity (Steneck et al. 2002). However, in exploring the ancient human use of seaweeds, we should be cautious in extrapolating modern distributions, densities, and diversity into the deep past. Changes in climate and oceanographic conditions (sea surface temperatures, sea level changes, etc.) during the late Pleistocene and Holocene affected the densities and distributions of various seaweed taxa (e.g., Dayton 1985; Graham et al. 2003, 2010; Kinlan et al. 2005). *Sargassum* remains were relatively common at the ~14,000 year old Monte Verde site, for example, but the genus is relatively scarce along the west coast of South America today (Dillehay et al. 2008). Historically, the introduction of invasive species has also altered the composition of seaweed communities worldwide (i.e., Williams and Smith 2007). If we can learn to more effectively identify seaweed remains in archaeological sites, however, the resulting data can enrich our knowledge of changes in the distribution of various taxa through the millennia and aid in establishing regional baselines needed for kelp forest ecosystem management and conservation (i.e. Beas-Luna et al. 2014; Vilalta-Navas et al. 2018).

## Direct Evidence

### *Macrobotanical Remains: Carbonized and Desiccated Seaweeds*

For terrestrial plants, carbonization generally increases the likelihood that remains will preserve archaeologically, but it is not clear if that is true for seaweeds. Excavations in Scotland have uncovered carbonized “vitreous slag” identified as burnt seaweed through chemical analysis, suggesting that seaweed was used to wrap human bodies for cremation (Photo-Jones et al. 2007). This practice takes advantage of the gelatinous nature of seaweeds, which makes them a formidable binding agent that kept the bones and ash together during the cremation process. On the Scottish islands of Orkney and Shetland, carbonized materials from two Norse sites were also tentatively identified as burnt seaweeds, including specimens with characteristics typical of bladder wrack (*Fucus vesiculosus*) (see Bell 1981:119).

The use of dried seaweeds and seagrasses as fuel, roofing, and matting has been extensively documented around the world (McRoy and Helfferich 1980:298-299; Mouritsen 2013:5-12), a practice that may have occurred on islands given the abundance of seaweed and sometimes limited tree and scrub fuel sources. Descriptions of burnt seaweed fused with sand resemble small fragments of vitreous materials (see Photos-Jones et al. 2007) and may be confused with bitumen, or asphaltum, fragments imbedded with sand, which are commonly found in Channel Island middens. Preliminary comparative studies of burned Channel Islands seaweeds and samples of "vitreous slag" found in paleobotanical samples from island middens used electron microscope images to suggest that carbonized seaweeds may be common in some middens (K. Gill, pers. comm. 2016). Further microscopic and chemical analyses may help confirm whether these vitreous materials are seaweed residues, identify various types of seaweeds, and determine if they were used for food, fuel, or other purposes.

As this review has shown, uncarbonized seaweed remains can occasionally preserve in saturated or hyper-arid conditions such as Monte Verde and the Andean Coast of Peru. As archaeologists become more aware of seaweeds as potentially significant marine resources, I hope we will become more sensitive to identifying them in Channel Island shell middens. Recent excavations by Erlandson and Gill at a coastal cave site on Santa Cruz Island dated to ~AD 1400 revealed uncarbonized and desiccated fragments of several types of seaweed and kelp (Figures 3.4 and 3.5). These have yet to be identified to genus, but their presence suggests that desiccated seaweed remains may be recoverable in some contexts even where sediments are not fully saturated or completely dry. Uncarbonized and desiccated terrestrial plant remains (i.e., tobacco seeds) were also recovered from this site, pointing to the extraordinary preservation encountered (Gill et al. 2019a).

**Figure 3.4.** Fragments of marine algae from archaeological deposits in a sea cave on Santa Cruz Island (CA-SCRI-128) that has recently been dated to the Late Period (Excavations by J. Erlandson and K. Gill, image modification and composite by A. Ainis).

**Figure 3.5.** Fragments of desiccated kelp (magnified ×10) from archaeological deposits in a sea cave on Santa Cruz Island (CA-SCRI-128) that has recently been dated to the Late Period (Excavations by J. Erlandson and K. Gill, photo by K. Gill).

### *Microbotanical Remains: Phytoliths, Starches, and Isotopes*

Other promising approaches to documenting seaweed use by ancient coastal peoples involve the identification of various microbotanical remains, including phytoliths, starches, isotopes, and diatoms. Golokhvast et al. (2014) demonstrated that both red and brown algae from the Sea of Japan contain phytoliths. According to Synytsya et al. (2015), marine algae also contain cell wall polysaccharides (starches) that vary depending on taxon, anatomical part, life-cycle stage, and season/habitat. These polysaccharides can be good taxonomic markers, and the cell walls of red and brown algae also have specific structures composed of cellulose fibrils that could be identifiable archaeologically.

In Japan, Awo-nori (*Enteromorpha* spp.) is heated over a charcoal fire then ground and added to foods in powdered form (Smith 1905a:164). Along the Pacific Northwest coast of North America, the Kwakwak'wakw browned red laver (*Porphyra* spp.) blades by hanging them above the fire, then pounded the dried blades into powder which could be added to soups or "whipped into a froth" (Turner 1995:22). Such preparation techniques suggest that residue analysis (including chemical, phytolith, and/or polysaccharide residues) of ground stone tools, cooking vessels, dental calculus, hearths, and soils might be fruitful avenues of research for identifying seaweed consumption in the past. To my knowledge, no such analyses have been attempted in Pacific Coast shell middens, nor am I aware of existing comparative collections necessary to do so. It seems worth the effort, however, to document the nature of phytoliths in some abundant kelp and other seaweeds from the region and to check promising midden samples for their presence.

## **Indirect Evidence**

### *Associated Mollusks and Diatoms*

Several researchers have shown that indirect archaeological evidence for seaweed use can come from the identification of seaweed-associated mollusks. Rowland

(1977:230) suggested that small ‘uneconomic shells’ might have been brought to archaeological sites as attachments on purposely harvested marine plants. Mollusks known to be seaweed commensals were identified in Upper and Lower Paleolithic assemblages and used to imply the transportation and use of seaweeds in cave sites (Barrière 1969; Colonese and Wilkens 2005). Although no seaweed fragments were preserved, Bell (1981:122) used small marine mollusk commensals and bryozoans to argue for seaweed exploitation in a multi-component site dating from the early Iron Age to the pagan Saxon Period on Great Britain’s Sussex Coast. To indirectly demonstrate seaweed use in the past, Bell (1981) collected samples of several seaweed species off the beach and dissected the holdfasts, fronds, and stipes for materials that would potentially preserve in archaeological contexts. He identified five bivalves, six gastropods, barnacles, bryozoans, foraminifera, polychaetes, and gravels that may be associated with transportation of seaweeds to habitation sites.

Interactions between macroalgae and the herbivores that graze on them (e.g., Lubchenco and Gaines 1982) should be further explored in search of indirect evidence of seaweed harvesting in coastal shellmounds worldwide. For two shell middens from California’s Channel Islands, analysis of shellfish remains identified 18 types of small gastropods (n=1,082) associated with seaweeds and seagrasses (Ainis et al. 2014; Chapter IV of this Dissertation). Additional species of commensals inhabit Channel Island kelp forests (see Coyer 1987; Graham 2004; North 1971:52-67) and may be used to identify kelp or seaweed use. The analyzed Channel Island sites include multiple rock shelter and open-air components spanning much of the past 8600 years. Roughly 25 percent of the non-dietary mollusks at both sites were identified as seaweed and seagrass associates with various strata and features containing higher or lower densities. The number and diversity of these incidental gastropods associated with seaweeds and seagrasses points to the likely harvesting and use of these perishable resources by Native islanders throughout the Holocene. In the future, I hope archaeologists working on the California Islands and in coastal sites around the world will more closely examine small non-dietary shellfish taxa from archaeological shell middens for indirect evidence of seaweed and seagrass harvesting.

Another avenue for potentially identifying seaweed remains in archaeological deposits is through the identification of diatoms, some species of which are primarily associated with various seaweed taxa (Edgar 1979). This would potentially treat diatoms as indirect markers of seaweed gathering and use that may be detectable through SEM imaging or other high-powered microscopic analysis. Small otherwise unidentifiable fragments of seaweed may be recognized through the identification of certain diatom species adhering to them. Alternatively, the presence of specific diatoms in archaeological soil deposits could serve as indirect markers of seaweed at the site, in the absence of preserved fragments.

## Conclusion

In this chapter, I explored the biology, ecology, diversity, distribution, and nutritional content of seaweeds and marine plants along the Pacific Coast of North America, focusing on the Southern California Bight and islands of Alta and Baja California. I documented that seaweeds were used by coastal peoples throughout the Pacific region for food, medicine, and a variety of technological purposes. Historical accounts document the use of seaweeds as food for at least 4700 years in East Asia and archaeological records show both culinary and medicinal use of seaweeds along the Pacific Coast of South America for 14,000 years. Ethnohistoric accounts further demonstrate that Native peoples of the Pacific Northwest and California Coast used seaweeds for food and other purposes, practices that likely extend much earlier in time.

In contrast, ethnohistoric and archaeological evidence for the use of kelps and seaweeds by the Island Chumash, Gabrielino/Tongva, and Huamalgüeños is sparse. The lack of archaeological evidence for seaweed use in the Southern California Bight is likely due to preservation bias. The evidence may have been there all along; however, archaeologists seem either influenced by the dearth of ethnohistoric evidence or not yet ready to confront the challenges involved in finding archaeological evidence for seaweed use. Although archaeological evidence for the use of seagrasses is relatively abundant in the region, the ethnohistoric record is largely silent on this nearly ubiquitous technology and potential food source. A similar situation may apply to the lack of ethnohistoric records for seaweed use, reflecting the devastating effects of European contact on island peoples of the California Bight rather than an absence of use by maritime peoples with a deep history of intensive maritime adaptations.

With scores of edible seaweed species inhabiting the waters around California's Islands—rich in carbohydrates, essential fatty acids, and other key nutrients—it is increasingly difficult to characterize the islands as marginal habitats for human occupation. With an incredible wealth of marine mammals, fish, shellfish, and birds rich in protein and fats, abundant geophytes and other terrestrial plants rich in carbohydrates, and a plethora of edible seaweeds available as either staples or back up foods in times of stress, starvation seems nearly impossible, even with population increases later in time. As archaeological, genomic, and other support grows for a coastal dispersal from northeast Asia into the Americas following a Pacific Rim "kelp highway" route, it also seems likely the First Americans were maritime peoples who entered the New World with a detailed knowledge of coastal ecosystems and the seaweeds that were abundant in them.

Although the significance of seaweeds and marine plants to the earliest coastal peoples on the California Islands remains hypothetical for now, new scientific methods are emerging that allow archaeologists to evaluate the importance of seaweeds in the indigenous maritime economies of the Pacific Coast of the Americas. The challenge now is for archaeologists to search for the evidence needed to confirm or refute the idea presented here: that kelp forests, seaweeds and marine plants were important resources that helped attract maritime peoples to the islands of Alta and Baja California, and to sustained large populations of their descendants for millennia.

In Chapter IV, I explore the use of small non-dietary mollusks identified in coastal shell midden sites to infer seaweed and seagrass harvesting in the past. By examining these incidental constituents in two archaeological shell middens from the Channel Islands, I provide indirect evidence for the harvest and transportation of seaweeds and seagrasses to these sites in varying degrees and quantities throughout the past ~8500 years.

# CHAPTER IV

## USING NON-DIETARY GASTROPODS IN COASTAL SHELL MIDDENS TO INFER KELP AND SEAGRASS HARVESTING AND PALOENVIRONMENTAL CONDITIONS.

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## Introduction

Small, non-dietary shells are accidentally incorporated in archaeological middens through a variety of mechanisms (see Claassen 1998; Stiner 1999) and can provide significant information through their associations with purposely harvested perishable resources such as marine algae and plants. Marine benthic macrophytes, including seaweeds (multicellular marine macroalgae) and seagrasses (angiosperms, flowering sea plants), provide the foundation for healthy marine ecosystems and vibrant littoral habitats that have attracted human foragers for over 100,000 years (Avery et al. 2008; Erlandson 2001; Klein et al. 2004; Marean et al. 2007; Ramos et al. 2011) and other members of our genus for even longer (Cortéz-Sánchez et al. 2010; Cunane and Stewart 2010; Erlandson 2010; Stiner 1994; Szabó and Amesbury 2011). Roughly 150 species of seaweed are considered edible (Kumar et al. 2008) and used as food worldwide. These species contain various compositions of macro and micro-nutrients (Aaronson 1986; Chapman and Chapman 1980; Dawcyzynski et al. 2006; Druehl 2000; Fleurence 1999; Floreto and Teshima 1998; Guiry and Blunden 1991; Hong et al. 2007; MacArtain et al. 2007; Nisizawa et al. 1987; Turner 2003), with some species boasting mineral contents higher than many land plants (Indegaard and Minsaas 1991; Ito and Hari 1989; Rupérez 2002), making them a valuable food source. Seaweeds and seagrasses are also used for fuel, roofing and matting when dried (McRoy and Helfferich 1980:298-299; Mouritsen 2013:5-21), to underlay and wrap burials for cremation (Photos-Jones et al. 2007), as raw material for the production of cordage, nets, mats, and basketry (Connolly et al. 1995;

Hudson and Blackburn 1983, 1985, 1986, 1987; Olson 1971:221; Scagel 1961; Turner and Bell 1973; Vellanoweth et al. 2003), and to wrap and steam food (Turner and Bell 1973). Unfortunately, Seaweeds and seagrasses rarely survive in the archaeological record and only preserve under the most favorable conditions, for example caves and rockshelters (e.g., Connolly et al. 1996; Vellanoweth et al. 2003) and some open-air sites such as Monte Verde, Chile, where nine species of marine algae were identified from archaeological features and directly dated to roughly 14,000 years ago (Dillehay et al. 2008). Despite the fact that marine macrophytes are highly perishable, the small gastropods that live on them have been identified in archaeological contexts dated as far back as the Upper (Colonese and Wilkens 2005) and Lower Paleolithic (Barrière 1969), and hypothesized as indirect evidence that people brought seaweed to cave sites.

In the fossil record, the lack of evidence for kelp (large brown seaweeds in the family Laminariaceae that frequently form large underwater forests) requires researchers to use climatic models and historical distributions of kelp and their associates to infer their evolution and radiation across the world (Estes and Steinberg 1988). As related by Estes and Steinberg (1988:21); seaweed associates include kelp and seagrass limpets that possess unique morphologies and form close associations with particular marine algae and plants. Unlike kelps, seagrasses and associated limpets left evidence of their antiquity in fossil records of Eocene age; however, limpets bearing the unique morphological characteristics of associations with large brown algae only appear in the fossil record about 3 million years ago. The relatively sudden appearance of kelp associated limpets at this time has led researchers to suggest that this was when the widespread proliferation of kelps likely occurred (Estes and Steinberg 1988:21-22). We are proposing to use seaweed associates in a similar fashion, to signal, or infer, the harvesting of seaweeds and seagrasses that have not left direct evidence of their use in the archaeological record.

We present shellfish data from a trans-Holocene multi-component rockshelter on San Miguel Island (ca 8,500 – 1,000 cal BP) and a Middle Holocene open-air dune site on San Nicolas Island (ca 4,800 – 3,600 cal BP), located off the southern California coast (Figure 4.1). We identify several species of small gastropods that live predominantly (sometimes exclusively) on marine macrophytes (Figures 4.2 and 4.3), and we suggest that the presence of these shells in archaeological deposits serve as indirect evidence for human harvesting of these perishable resources. Varieties of other small gastropods are presented here with possible explanations for their presence in archaeological deposits. The aims of this study are to describe small gastropod assemblages from archaeological shell middens by: 1) quantifying non-dietary shells and placing them in habitat based categories; 2) employing heterogeneity measures and cross tabulation frequency distributions to investigate the significance of patterning; 3) examining inferred human harvesting of marine macrophytes through the presence of seaweed and seagrass associates; 4) presenting ethnographic and ethnohistoric accounts from the west coast of North America and Gulf of California as examples of marine macrophyte use by Native people in the greater region; and 5) exploring possible paleoecological and paleoenvironmental implications signaled by the presence of non-dietary shells, though this discussion remains exploratory.

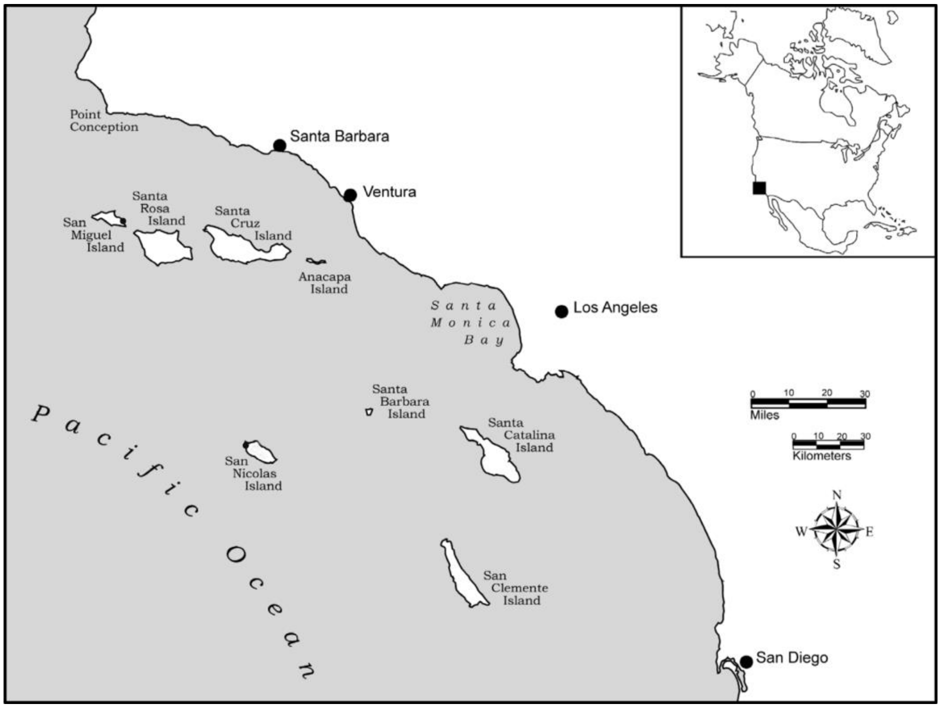


**Figure 4.1.** Map of the California Channel Islands with CA-SMI-603 demarcated on the northeast coast of San Miguel Island and CA-SNI-40 demarcated on the west end of San Nicolas Island.

**Figure 4.2.** Archaeological examples of seaweed associates identified in this study (top left to bottom right): *Callisotoma canaliculatum, Calliostoma ligatum*, *Acanthinucella punctulata*, *Lacuna marmorata*, *Lacuna unifasciata*, *Lirularia* sp., *Pleisiocystiscus jewettii*, *Alia carinata*, *Alia tuberosa*, *Stylidium eschrichtii*, *Clathurella canfieldi*, and *Odostomia nota*.

**Figure 4.3.** Archaeological examples of seaweed and seagrass limpets identified in this study (top left to bottom right): light and dark morphologies of *Lottia insessa*, *L. pelta* (seaweed morphology), *L. strigatella*. *L. instabilis*, *L. ochracea*, and *L. palacea*.

# Background

## Ethnohistoric Accounts of Seaweed and Seagrass Use from Western North America

Substantial and varied uses of seaweeds and seagrasses by Native people have been extensively documented for the west coast of North American and the Gulf of California. Multiple species of marine macroalgae and angiosperms were harvested, utilized and traded, forming a pivotal role in the lifeways of coastal peoples. Ethnographic accounts have documented a rich linguistic heritage associated with kelps and seagrasses including primary names differentiating stages of growth and aspects of use, suggesting considerable antiquity (Berlin 1973; Felger et al. 1980; Turner 1995, 2003).

Several marine macroalgae, including sea wrack (*Fucus gardneri*, *Fucus* sp.), giant kelp (*Macrocystis pyrifera*), bull kelp (*Nereocystis leutkeana*), and red lavers (*Porphyra* spp.) were (and in some cases still are) utilized by Native peoples of the Pacific Northwest Coast (Ager and Ager 1980; Turner 1995, 2003; Turner and Bell 1973). Several species of brown algal blades (*Egregia menziesii*, *Fucus* sp., *M. pyrifera*, and *N. leutkeana*) were used to catch herring eggs during spawning season. Herring spawn covered blades were dried then bundled and stored for winter use or traded as a valuable item through extensive coastal and inland networks (Ager and Ager 1980; Turner 1995; Turner and Bell 1973; Turner and Loewen 1998). Kelp blades were also used as heated poultices and the long hollow tubular stipes were used to store oil and grease and to make ropes, fishing nets and lines, and harpoon lines (Turner and Bell 1973). Ethnohistoric accounts also indicate that coastal tribes in central California harvested and ate brown (*Nereocystis leutkeana*), red (*Porphyra* spp.), and green (*Ulva lactuca*) algaes (Anderson 2005:45, 131-132).

To a lesser degree, marine seagrasses were also used for food. Surfgrass (*Phyllospadix scouleri* and *P. torreyi*) and eelgrass (*Zostera marina*) plants were dried and formed into cakes for winter consumption, and eelgrass roots and rhizomes were used to flavor meat (Turner 1995:53-54). The *Kwakwaka'wakw* participated in an Eelgrass Feast, in which uncooked rhizomes, stems, and bases were eaten as the food of their mythical ancestors (Turner 1995:54), suggesting antiquity to the practice of consuming eelgrass. In addition, ethnographic and archaeological evidence indicates that seagrass was utilized by coastal tribes along western North America (Scagel 1961), including the Channel Islands (Heye 1921:158-159, PL.CXX111; Hudson and Blackburn 1983, 1985, 1986, 1987; Olson 1971:221), to make cordage, mats, and basketry items.

The Seri (*Koŋkáak*) Indians of the Sonoran Desert, Mexico, are the only people known to have extensively harvested the seeds of a submerged marine angiosperm (Felger and Moser 1973, 1976, 1985; Felger et al. 1980). Not only were eelgrass seeds utilized, they were one of the most important traditional foods of the Seri (Sheridan and Felger 1977). Eelgrass flour was of particular importance as a storable food; it was placed in sealed pottery vessels and hidden in caves with other edible items for times of need (Felger and Moser 1970, 1971, 1976). In addition to its dietary value, eelgrass was also used to line baskets and sea turtle carapaces for the placement of meat and other foods, spread over the frame of shelters for shade and roofing, and in the construction of children's toys (Felger et al. 1980). In addition, eelgrass has been used to determine seasonality of an archaeological event. In one instance where eelgrass was found covering a group of burials, the lack of fruit, seeds or flowering structures suggested it was collected before its reproductive structures emerged, implying the burial event occurred in winter (Felger et al. 1980:272).

## California Channel Islands: Kelp Forests and Nearshore Environments

The California Channel Islands consist of eight islands located off the coast of southern California. They are divided into two geographical groupings, the northern Channel Islands, consisting of Anacapa, Santa Cruz, Santa Rosa, and San Miguel Islands, and the southern Channel Islands of Santa Catalina, Santa Barbara, San Clemente, and San Nicolas. Although the Channel Islands are located in relative proximity, a mixture of geographic, oceanographic, physical, and biological features produce unique nearshore communities on each island, dictating local marine productivity and contributing to the diversity and abundance of marine resources along their shores (Engle 1994; Schoenherr et al. 1999). The outer islands, San Miguel and San Nicolas, reap the benefits of the colder nutrient rich waters of the California Current that extends down the coast from northern California. Traveling northward and moving up from Baja California, the California Countercurrent (or Davidson Current) brings warmer waters that bathe Santa Catalina and San Clemente before moving out to the other islands. Fluctuations in water temperature associated with these currents produces varying sizes of offshore kelp beds, and different invertebrate compositions in intertidal environments on a single island, as well as among islands.

Californian kelp forests are composed primarily of large brown algae; the dominant subtidal species include the giant kelp *Macrocystis pyrifera* and the bull kelp *Nereocystis luetkeana* (Abbott and Hollenberg 1976; Mondragon and Mondragon 2003). Based on substantial differences in oceanic conditions among marine habitats along the coast of California, kelp forests surrounding the California Channel Islands have been placed within the "Southern California" biogeographic range extending from Point Conception, California to Punta Banda, Baja California, Mexico (Edwards 2004). These kelp forests are dominated by the canopy-forming giant kelp (*Macrocystis pyrifera*), along with stipitate subcanopy kelps (*Eisenia* and *Pterygophora*) and nonstipitate low-lying kelps (*Dictyoneuropsis* and *Laminaria*), with varying amounts of other kelps such as the surface canopy feather-boa kelp (*Egregia menziesii*) (Dayton 1985; Graham 2004; Graham et al. 2003; Mann 1973; North 1971; Rosenthal et al. 1974). Giant kelp forests sustain extremely varied and dynamic ecological communities, creating an extensive ecological web of interdependent species that benefit from the reduction in current intensity found in their immediate surroundings (Coyer 1986; Dayton 1985; Dayton et al. 1998; Foster and Schiel 1985; Graham 2004; Graham et al. 2003; Jones 1971; North 1971). Coastlines of the Channel Islands also harbor large surfgrass (*Phyllospadix* spp.) and eelgrass (*Zostera* spp.) meadows, anchored in shallow subtidal to sublittoral zones of rocky intertidal areas and exposed during low tides (Mondragon and Mondragon 2003). Primary intertidal environments on San Miguel and San Nicolas islands include protected outer coast habitats, semi-sheltered coastlines often with offshore kelp beds,

**Figure 4.4.** View of rocky shore and kelp patches looking out from Cave of the Chimneys (CA-SMI-603, above) and CA-SNI-40 (below).

and open coast habitats, characterized as unprotected surf pounded shores. Within varying habitat types a range of physical and biological factors influence the proliferation of associated biota (Brandon and Rokop 1985; Hinton 1987; Lewis 1964; Little et al. 2009; Ricketts et al. 1985; Stephenson and Stephenson 1972). The plethora of shell midden sites on the Channel Islands suggests that rocky intertidal communities were utilized extensively by humans. Rocky shores form relatively stable substrate, promoting high diversity and stable communities of the larger shellfish collected for consumption.

The archaeological sites discussed in this paper are located on the coast, overlooking rocky intertidal habitats with associated kelp beds (Figure 4.4). Midden constituents consist predominantly of black abalone (*Haliotis cracherodii*), California mussel (*Mytilus californianus*), and black turban snail (*Chlorostoma funebralis*), all of which are found in the upper to middle intertidal zone. Other common shellfish species include red abalone (*H. rufescens*) and wavy top shell (*Megastraea undosa*), found in the lower to subtidal zone, and sea urchin (*Strongylocentrotus* spp.), found in middle intertidal to subtidal zones, demonstrating that people collected from the full range of intertidal zones/habitats. Additional dietary species include brown turban snails (*C. brunnea*), several species of crab and chiton, and numerous limpet species.

## Channel Islands Archaeology

The Channel Islands have a long and continuous record of human occupation, with the northern islands containing archaeological sites dated to almost 13,000 years ago and representing some of the oldest evidence for coastal lifeways on the west coast of North America (Erlandson et al. 2011b; Johnson et al. 2002; Rick and Erlandson 2012). Numerous studies investigating trans-Holocene human-environmental dynamics on the Channel Islands demonstrate that people relied on a relatively consistent suite of key resources through time (Braje et al. 2012; Erlandson et al. 2005; Rick 2011), showing small-scale variable impacts on intertidal habitats (Braje et al. 2007; Erlandson et al. 2008, 2011a; Rick et al. 2005a, 2008). General subsistence trends for the region suggest that shellfish provided a dietary staple during the Early and Middle Holocene, with the use of near and offshore fisheries increasing through time, replacing shellfish as a dietary staple during the Late Holocene (Braje et al. 2012; Erlandson et al. 2009; Glassow 1993; Kennett 2005; Rick et al. 2005a). The importance of marine mammal and cetacean hunting varied through time depending on location and the productivity of island and offshore rookeries (Braje et al. 2011; Colten and Arnold 1998).

# Archaeological Sites and Methodology

## Cave of the Chimneys (CA-SMI-603)

Located on the northeast coast of San Miguel Island, Cave of the Chimneys is a multi-component site containing approximately 7,500 years of human occupation. The rockshelter currently sits on a steep cliff face roughly 12 meters above a rocky coastline and is accessible by a narrow ledge on the southeast side of the shelter (Figure 4.5). The cave consists of andesitic conglomerate in a sandy matrix and appears to have been formed by marine erosion during high interglacial sea levels of the Pleistocene. The rockshelter measures approximately 10 meters deep by 12 meters wide with a skylight measuring roughly 1.5 meters in diameter. The large east facing entrance provides adequate lighting and protection from the strong northwesterly winds that pummel San Miguel Island most of the year (Johnson 1973:63). Sediments fill the site to less than one meter toward the back of the rockshelter and gently slope downward forming an apron at its mouth. Deposits are intact, finely stratified, and extremely well-preserved.

Archaeological excavations revealed seven distinct, chronologically intact stratigraphic layers representing intermittent occupational phases that were radiocarbon dated to between about 8,600 and 1,000 cal BP (Table 4.1). A total of 1,588 liters was excavated between 1997 and 1999. The exceptional preservation at this site is evidenced by delicate strands of seagrass cordage found in the basal components and dated to the Early Holocene (Vellanoweth et al. 2003). Faunal constituents, including over 122 kg of shell and over 2 kg of bone (predominantly fish), demonstrate the importance of rocky intertidal and nearshore habitats to site inhabitants (Ainis 2012; Ainis et al. 2011; Ainis and Vellanoweth 2012; Rick et al. 2005b; Vellanoweth et al. 2002).

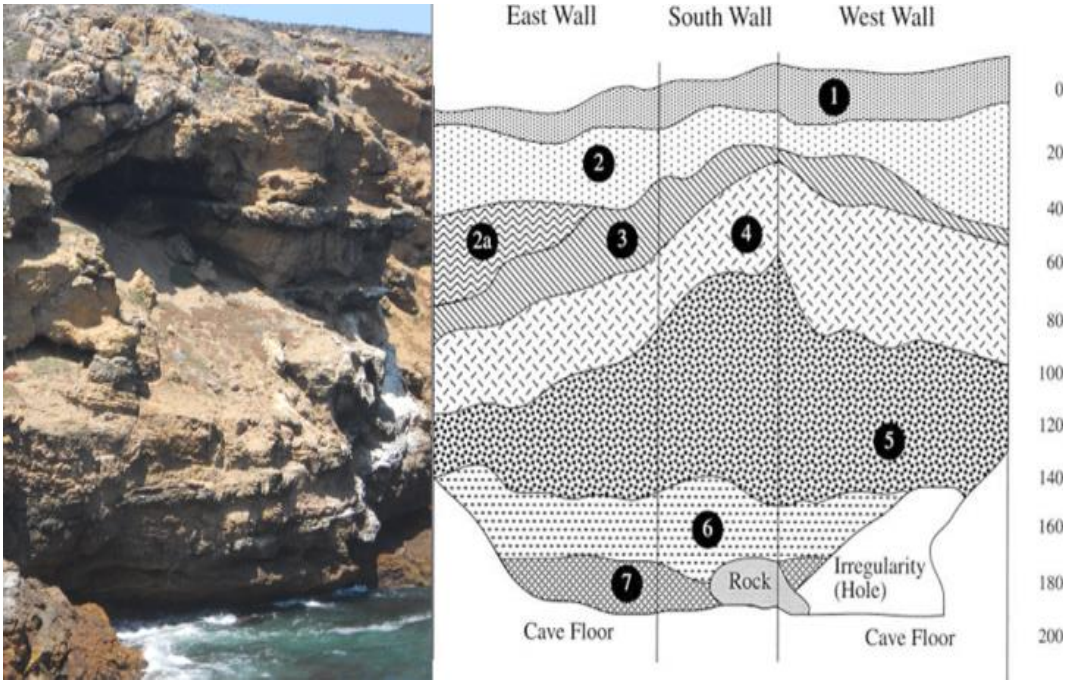


**Figure 4.5.** Entrance to Cave of the Chimneys (CA-SMI-603) and stratigraphic profile drawing of Unit 1 excavations.

**Table 4.1.** A radiocarbon chronology for Cave of the Chimneys (CA-SMI-603)*.

| Unit or Probe, Stratum/Level | Lab Number | Material Dated | Uncalibrated RCYBP | Adjusted Age Range (cal BP 1σ) |
|---|---|---|---|---|
| 1, I | OS-85199 | Marine Shell | 1700 ± 25 | 1067 : 956 |
| 1, II / 1 | OS-85200 | Marine Shell | 2800 ± 25 | 2311 : 2191 |
| 1, II / 2 | OS-85201 | Marine Shell | 2930 ± 25 | 2461 : 2331 |
| 1, II | Beta-115556 | Marine Shell | 2980 ± 60 | 2575 : 2352 |
| 1, II / 3 | OS-85202 | Marine Shell | 3560 ± 25 | 3268 : 3128 |
| 1, II / 4 | OS-85203 | Marine Shell | 4010 ± 25 | 3804 : 3672 |
| 1, III | Beta-115557 | Marine Shell | 4270 ± 70 | 4188 : 3955 |
| Probe B, 15-20 cm | Beta-12454 | Marine Shell | 4430 ± 60 | 4403 : 4207 |
| 1, IV/2 | Beta-115558 | Marine Shell | 4450 ± 70 | 4426 : 4208 |
| 1, V | Beta-115559 | Marine Shell | 4480 ± 60 | 4445 : 4245 |
| Probe B, 15-20 cm | Beta-14364A | Charcoal | 3930 ± 60 | 4497 : 4257 |
| Probe B, 35-40 cm | Beta-14367A | Charcoal | 3940 ± 60 | 4512 : 4292 |
| Probe B, 35-40 cm | Beta-12455A | Marine Shell | 4560 ± 60 | 4841 : 4683 |
| 1, VI | Beta-129099 | *Olivella* bead | 7300 ± 70 | 7623 : 7483 |
| 1, VI | Beta-136695 | Marine Shell | 7300 ± 60 | 8180 : 8019 |
| 1, VII | Beta-122713 | Marine Shell | 7650 ± 70 | 7963 : 7805 |
| 1, VII | Beta-136696 | Marine Shell | 7740 ± 80 | 8070 : 7876 |
| 1, VI | Beta-122712 | Marine Shell | 8120 ± 80 | 8456 : 8268 |

*Beta dates compiled from Kennett (1998), Vellanoweth et al. (2002), and Vellanoweth et al. (2003). OS dates compiled from Ainis and Vellanoweth (2012). Dates were calibrated via Stuiver and Reimer's (1993, 1999) Calib 6.0.1 using a ΔR of 225 ± 35 years and adjusted according to Hughen et al. (2004).

## CA-SNI-40

Situated on the northwest coast of San Nicolas Island, CA-SNI-40 is a large linear sand dune with paleosols and occupational middens, measuring approximately 1 km long (Figure 4.6). The surface of the site resembles a red abalone midden, though erosional exposures and controlled excavations revealed several discrete deposits within two main components dated to between 4200 and 3800 cal BP (Table 4.2). A Middle Holocene cemetery located on the east end of the dune was excavated in the late 1950s and dated to the same time period as the midden (Reinman and Townsend 1960). Many artifacts from the cemetery correspond directly with items uncovered in the midden, suggesting continuity between the cemetery and associated midden at this site. Recent excavations took place between 2010 and 2011. Five loci were sampled and 30 1×1-meter units were excavated, removing 8,185 liters of archaeological materials and soil matrix. The samples discussed here are from two 1×1-meter units (11 and 12A) in Locus E, located on the top of the dune. The components are primarily comprised of red (*H. rufescens*) and black abalone (*H. cracherodii*), wavy top shells (*Lithopoma undosa*), and other rocky intertidal shellfish and crustacean taxa along with the bones of teleost fishes, elasmobranches, sea mammals and marine birds. A wide variety of artifacts in various stages of production, including several types of Olivella (*Callianax biplicata*) beads, abalone nacre sequins, bone tools, and pendants made from imported soapstone was uncovered during excavations. The relatively large size of the midden deposit at this site and the short temporal chronology of radiocarbon dates suggest CA-SNI-40 was utilized extensively for a brief period of time.

**Table 4.2.** A radiocarbon chronology for CA-SNI-40.

| Locus | Unit | Stratum/ Level | Lab Number | Material Dated | Uncalibrated $^{14}$C Age Range (RYBP) | Calibrated Age Range (BP) One Sigma: |
|---|---|---|---|---|---|---|
| Auger | #4 | - | OS-105788 | *S. bifurcatus* | 4720±45 | 4788-4617 |
| A | 1 | IA/1 | OS-85189 | *H. cracherodii* | 4360±30 | 4280-4125 |
| A | 2 | I/1 | OS-85188 | *H. rufescens* | 4370±20 | 4282-4141 |
| A | 2 | IIA/1 | OS-85191 | *H. cracherodii* | 4380±35 | 4308-4142 |
| B | 3 | II/1 | OS-85195 | *H. cracherodii* | 4280±30 | 4147-3995 |
| B | 3A | Pit Feature | OS-85192 | *H. cracherodii* | 4390±30 | 4318-4157 |
| C | 5 | I/2 | OS-85197 | *H. cracherodii* | 4340±35 | 4242-4083 |
| C | 6 | Ochre Feature | OS-85196 | *H. cracherodii* | 4130±30 | 3953-3821 |
| C | 6 | IIIO/2 | OS-96261 | *H. cracherodii* | 4120±25 | 3941-3813 |
| C | 5/6A | IIHR/1 | OS-105787 | *H. rufescens* | 4440±40 | 4392-4238 |
| C | 5/6A | IIHC/1 | OS-105782 | *H. cracherodii* | 4440±30 | 4386-4247 |
| C | 5/6B | IU/1 | OS-96260 | *H. cracherodii* | 4120±25 | 3941-3813 |
| D | 7 | I/4 | OS-85190 | *H. cracherodii* | 4070±25 | 3861-3726 |
| E | 9 | IA/1 | OS-85194 | *H. cracherodii* | 4150±30 | 3969-3836 |
| E | 11 | IIHC/1 (Dark Feature) | OS-105783 | *M. californianus* | 4440±30 | 4341-4182 |
| E | 12 | IA/1 | OS-85193 | *H. cracherodii* | 4070±35 | 3867-3719 |
| E | 12 | II/1 | OS-85198 | *Diomedeidae* | 4480±30 | 4423-4286 |
| E | 12 | IIHC/trans | OS-105786 | *H. cracherodii* | 4370±40 | 4303-4128 |
| E | 12A | IIHC/SU/1 | OS-96262 | *H. cracherodii* | 4170±25 | 3982-3866 |
| E | 12A | IIHR | OS-105789 | *H. cracherodii* | 4180±25 | 4011-3871 |
| E | 10A/ 12A | Ash Feature | OS-105784 | *Chlorostoma* sp. | 4300±30 | 4206-4050 |
| E | 10A/ 12A | Ash Feature | OS-105785 | *M. californianus* | 4220±30 | 4072-3930 |
| E | 10A/ 12A | Ash Feature | OS-96263 | *H. cracherodii* | 4230±35 | 4085-3934 |

Dates were calibrated via Stuiver and Reimer (1993, 1999) Calib 6.0.1 using a ΔR of 225±35 years and adjusted according to Hughen et al. 2004.

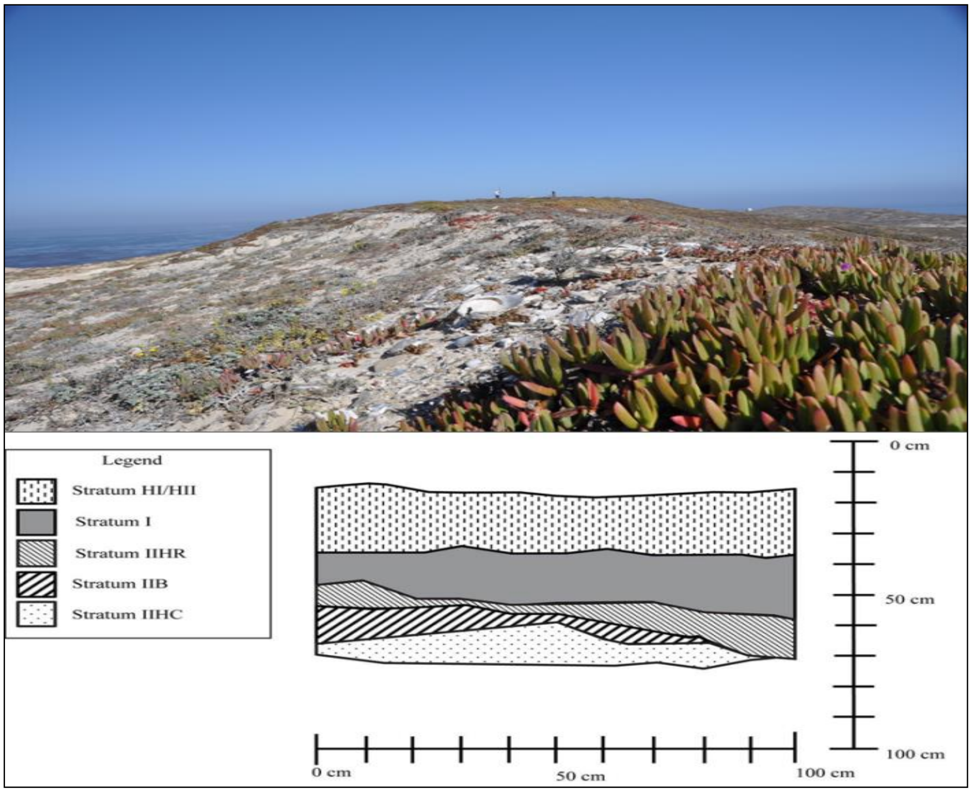


**Figure 4.6.** The large dune that comprises CA-SNI-40 (facing west) and stratigraphic profile drawing of Unit 12A.

## Analytical Methods

The small gastropods analyzed in this study were excavated from sites CA-SMI-603 and CA-SNI-40 using standard stratigraphic methods of recovery and recordation. The minimum number of individuals (MNI) was calculated for each taxonomic designation using apices (though most shells were whole due to their small size), and all shell remains were weighed using a digital scale to two decimal places. Identifications were made to the lowest taxonomic level possible using comparative collections at the Los Angeles County Natural History Museum, California State University, Los Angeles, and the University of Oregon, as well as multiple reference books (Allen 1969; Brandon and Rokop 1985; Carlton 2007; Hinton 1987; McLean 1978; Morris 1966; Morris et al. 1980; Rehder 1981).

Density measures were calculated by dividing the minimum number of individuals (MNI) for each taxonomic group over the excavated volume ($m^3$) for each stratum and feature. Because identifications of small gastropods were not always possible at the species level, we calculated taxonomic richness of each stratum by counting the total number of taxonomic categories identified therein. An analysis of covariance (ANCOVA) was used to investigate changes in taxonomic richness through time. Along with shifts in foundation species, changes in taxonomic richness have the potential to illuminate shifts in community composition of intertidal gastropods (e.g., Needles and Wendt 2013). Diversity and equitability measures, utilizing richness and abundance data from each taxonomic category, were used to describe the heterogeneity of analyzed samples. The Shannon-Weaver function (Reitz and Wing 2008) was used to calculate taxonomic diversity (H') measured as:

$$H' = - \Sigma(p_i)\ (\mathrm{Log}_e\ p_i)$$

where $H'$ is the heterogeneity measurement of the sample; $p_i$ is the relative abundance of each species or genus within the sample (calculated using MNI of all identified small gastropods); and $\mathrm{Log}_e\ p_i$ is the logarithm of $p_i$. Equitability (V': equivalent to Pielou's evenness index J') was measured as:

$$V' = H' / \mathrm{Log}_e\ S$$

where $H'$ is the Shannon-Weaver function and $S$ is the total number of taxa (using lowest possible taxonomic identifications) in each stratum or feature. Analyses of variance (ANOVA) were computed to determine if significant differences in species density among strata at each site were present. The use of density values rather than MNI allowed us to factor out sample size as a contributing variable. Non-parametric contingency tests (G-Test of Independence) were used to distinguish similarities or differences in community composition of seaweed associates, gravel dwellers, mollusk associates, and rock and boulder dwellers; and investigate changes in the relative proportions of shellfish from our four categories (Type 1-4, see Table 4.3) both within and between archaeological sites. ANCOVA and ANOVA tests were run in SAS 9.2 and G-Tests were run in BiomSTAT (Sokal and Rohlf 2012). All G-values are reported with Williams correction, degrees of freedom (df), and $p$ values expressed as $<0.05$ with $\alpha = 0.05$ unless otherwise noted.

## Results

Excavations of Unit 1 at CA-SMI-603 yielded a total of 122 kg of shell identified to 78 species, 16 genera, and seven higher taxonomic levels (Ainis 2012). A total of 42 kg of shellfish remains was recovered from Units 11 and 12A at CA-SNI-40 and identified to 42 species, 11 genera, and three higher taxonomic levels. A total of 4,568 individuals belonging to 34 genera and 61 species of small gastropods were identified in this study, excluding larger shellfish taxa known to be of dietary value. We grouped the small, non-dietary gastropod shells into four categories (Type 1-4) based on substrate, habitat, and associations with other shellfish. Our categories are defined in Table 4.3 and general ecological information for each species is presented in Table 4.4.

### Application and Interpretation

#### *Intrasite Analysis: CA-SMI-603*

Analysis of small gastropods from Cave of the Chimneys resulted in the identification of 3,305 individuals belonging to 28 genera and 49 species (Table 4.5), with seaweed and seagrass associates comprising close to 26% of the MNI of small gastropods. The assemblage is dominated by small limpets (*Lottia* spp.) and slipper snails (*Crepidula* spp., *Garnotia* spp.) (Figure 4.7). Diversity and equitability indices reveal a high diversity of taxa accompanied by relatively high equitability throughout the deposit (Figure 4.8), indicating a fairly even distribution of a large variety of taxa. An analysis of covariance demonstrated that there is no linear relationship between taxonomic richness and time (strata) at this site (ANCOVA; $F_{1,4} = 0.13$, $p = 0.7375$). Though richness oscillates through time (Table 4.6), densities follow a downward trend (Figure 4.9), indicating that although most taxa continue to be present through time their numbers decline

**Table 4.3.** Categorical definitions of non-dietary gastropods in archaeological shell middens.

| Category | Characterization | Habitat/ Substrate | Definition and Association | Inference | SMI-603 (MNI) | SNI-40 (MNI) |
|---|---|---|---|---|---|---|
| Type 1 | Seaweed and Seagrass Associates | Kelpbeds and seagrass meadows | Taxa that live on, or are closely associated with, marine macrophytes; some taxa are species specific to certain kelps and seagrasses. | Can be used to infer harvesting of marine macrophytes and transportation of marine vegetation back to the archaeological site. | 852<br>(27%) | 234<br>(22%) |
| Type 2 | Sand and Gravel Dwellers | Coarse sand and gravely substrate underlying kelpbeds and seagrass meadows | Taxa that live in the coarse sand and gravely substrate often underlying kelpbeds and seagrass meadows; some are also often found on the base and holdfasts of kelps and seagrasses. | Possible use as indicators of marine macrophyte harvesting by pulling up entire stocks including bases and holdfasts. | 32<br>(1%) | 23<br>(<2%) |
| Type 3 | Mollusk Commensals | Live on other larger shellfish in the intertidal zone | Taxa that are known associates of other mollusks in the intertidal zone; some are found on a variety of taxa and others are species specific. | Can be useful in instances where the host shell is no longer present because it was used to manufacture tools or ornaments. | 1,392<br>(44%) | 432<br>(40%) |
| Type 4 | Rock and Boulder Dwellers | Rocks and boulders in upper intertidal to sublittoral zones | Taxa that live on large rocks and boulders at various depths in the intertidal zone; possible associations with all species of shellfish gathered for subsistence purposes. | Possible explanations for the presence of these shells include scraping of rocks and boulders for mussels, turban snails, etc.; harvesting clusters of shells rather than individuals; accidental dislodging by strands of kelp and seagrasses that were dragged and collected in the intertidal zone. | 1,908<br>(60%) | 741<br>(69%) |

**Table 4.4.** Ecological profiles for mollusk taxa

| Scientific Name | Common Name | Category/Type (see Table 4.3) | Habitat Zone | Habitat Notes and Associations | Trophic Type and Food Preference |
|---|---|---|---|---|---|
| *Acanthinucella (Acanthina) punctulata* | Spotted thorn drupe | 1, 2 | intertidal and sublittoral | clean coarse sand among eelgrass (*Zostera*), coralline algae, and rocks | predators - primarily eats Littorines |
| *Acmaea mitra* | Whitecap limpet | 3, 4 | low intertidal, subtidal | low intertidal/pools | herbivore - eats encrusting algae *Lithothamnion*, *Lithophyllum* |
| *Acteocina civitella* | Pillow barrel-bubble, Western barrel-bubble | 2 | high intertidal to 46m | bays and lagoons in sand and mud | predator - eats foraminifera |
| *Alia carinata* | Carinate dove snail | 1 | low intertidal to 15m | kelp stipe/holdfast, abundant in surf grass (*Phyllospadix*) and eelgrass (*Zostera*) habitat and in shallow kelp forests | herbivore/detritivore |
| *Alia tuberosa* | Variegate dove snail | 1 | sublittoral zone | Kelp and eelgrass (*Zostera*), drift algae, sand and gravel under kelp | epifaunal predator |
| *Amphissa* spp. | Dove shells, Dove snails | 4 | low intertidal and subtidal | grazer on rocks | herbivore |
| *Amphissa versicolor* | Variegate Amphissa, | 4 | intertidal to 46m | rocky intertidal | carnivore |
| *Callianax biplicata* | Purple olive shell | 2 | low intertidal to 50m | sandy bottoms/beaches | omnivore/detritivore Kelp blades and detritus |
| *Calliostoma canaliculatum* | Channeled topsnail | 1 | low intertidal to 37m | lives on kelp (*Macrocystis* and *Cystoseira*) | herbivore/omnivore - kelp, diatoms, bryozoans, hydroids, detritus |
| *Calliostoma ligatum* | Blue topsnail | 1 | low intertidal to 54m | found in and around kelp beds (on *Macrocystis* and *Cystoseira*) and eelgrass (*Zostera*) | herbivore/omnivore - kelp, diatoms, bryozoans, hydroids, tunicates, detritus |
| *Calliostoma* spp. | Top snails | 1 | low intertidal to sublittoral | species specific to kelps, some species specific to portions of stipe/blades/holdfasts | herbivore/omnivore - kelp, diatoms, bryozoans, hydroids, detritus |

**Table 4.4.** (continued)

| Scientific Name | Common Name | Category/Type (see Table 4.3) | Habitat Zone | Habitat Notes and Associations | Trophic Type and Food Preference |
|---|---|---|---|---|---|
| *Cerithiopsis carpenteri* | Carpenter's miniature cerith | 4 | subtidal to 30m | common under rocks at low tide and in sublittoral | omnivore: primarily sponges |
| *Clathurella canfieldi* | unknown | 1, 2 | intertidal | in sand among surfgrass/eelgrass roots | predator - polychaete worms |
| *Conus californicus* | California cone | 2, 4 | low intertidal to subtidal | rock crevices, sand pockets | predator - worms, mollusks, crustaceans, buried in sand when not eating |
| *Crepidula aculeata* | Spiny slipper snail | 4 | low intertidal to 60 m | common on rocks and hard debris in shallow subtidal | ciliary feeder on detritus |
| *Crepidula coei* | unknown | 3, 4 | intertidal | common on gastropods - *Polinices* (moon snails) | ciliary feeder on detritus |
| *Crepidula nummaria* | Northern white slipper snail | 4 | intertidal to subtidal | attaches to rocks or dead shells | ciliary feeder on detritus |
| *Crepidula onyx* | Onyx slipper snail | 4 | intertidal to 90m | smaller males often stack on top of larger females | ciliary feeder on detritus |
| *Crepidula perforans* | Western white slipper snail | 4 | intertidal | under rocks, resides on interiors of dead shells | ciliary feeder on detritus |
| *Crepidula* spp. | Slipper snails | 4 | intertidal to subtidal | | ciliary feeder on detritus |
| *Crepipatella lingulata* | Wrinkled slipper snails | 4 | intertidal to 100m | on rocks/snail shells | ciliary feeder on detritus |
| *Diodora arnoldi* | Neat-rib keyhole limpet | 4 | low intertidal to 25m | undersides of rocks | herbivore |
| *Diodora aspera* | Rough keyhole limpet | 4 | low intertidal to subtidal | undersides of rocks | omnivore - prefers encrusting bryozoans but will eat algae |
| *Diodora* spp. | Keyhole limpets | 4 | intertidal to subtidal | undersides of rocks | omnivore |
| *Epitonium tinctum* | Tinted wentletrap, White wentletrap | 3 | low intertidal to subtidal | on sand, at base of sea anemones/feeds on tips of *Anthopleura* tentacles | predator - eats tips of *Anthopleura* |
| *Fissurella volcano* | Volcano limpet | 4 | intertidal, mostly middle intertidal | undersides of rocks | herbivore |

**Table 4.4.** (continued)

| Scientific Name | Common Name | Category/Type (see Table 4.3) | Habitat Zone | Habitat Notes and Associations | Trophic Type and Food Preference |
|---|---|---|---|---|---|
| *Fissurellidae* | Keyhole limpets,<br>Slit limpets | 4 | intertidal to subtidal | on and under rocks and boulders | omnivore - feed on algae and detritus; some are carnivores and feed on sponges |
| *Fusinu skobelti* | Kobelt's spindle-shell | 2 | intertidal | sandy bottoms | carnivorous scavengers |
| *Fusinus luteopictus* | Painted spindle-shell | 2 | low intertidal to 40m | rocks | carnivorous scavengers |
| *Garnotia adunca* | Hooked slipper-shell | 3 | mid to low intertidal | on intertidal snail shells including *Calliostoma*, *Chlorostoma*, *Lirabuccinum* | ciliary feeder on detritus |
| *Garnotia norrisiarum* | Norris slipper shell | 3 | subtidal | commonly and primarily on *Norrisianorrisi* (and sometimes *Promartyniapulligo* shells) | ciliary feeder on detritus |
| *Garnotia* spp. | Slipper shells | 3 | | attach to species specific host shells | ciliary feeder on detritus |
| *Hipponix panamensis* | Flat hoofsnail | 4 | intertidal to 46m | clings to rocks, algae | sedentary limpet, obtain food with extensible snout |
| *Hipponix tumens* | Ribbed hoofsnail | 4 | low intertidal | rock crevices | sedentary limpet, obtain food with extensible snout |
| *Homalopoma baculum* | Berry dwarf turban | 4 | mid intertidal | under rocks | epifaunal predator |
| *Homalopoma luridum* | Dall's dwarf turban | 4 | intertidal to sublittoral | rocks (shells are often used by hermit crabs) | epifaunal predator |
| *Homalopoma* spp. | Dwarf turbans | 4 | intertidal to sublittoral | rocks | epifaunal predator |
| *Lacuna marmorata* | Chink shell | 1, 4 | mid to high intertidal | rocks, seaweed and seagrasses (*Phyllospadix* and *Zostera*) | herbivore - algae -- is eaten by *Leptasterias* |
| *Lacuna* spp. | Chink shell | 1 | mid to high intertidal | species specific to kelps and sea grasses in moderately shallow water | herbivore |

**Table 4.4.** (continued)

| Scientific Name | Common Name | Category/Type (see Table 4.3) | Habitat Zone | Habitat Notes and Associations | Trophic Type and Food Preference |
|---|---|---|---|---|---|
| *Lirularia* spp. | Minute trochids | 1, 2 | intertidal to sublittoral but mostly sublittoral | on gravel/loose rocks/algae, common at the base of kelp and on eelgrass (*Zostera*) | herbivore |
| *Littorina keenae* | Flat periwinkle | 4 | In the splash zone | rocks in the high tide line | herbivore: diatoms, films |
| *Littorina plena* | Black periwinkle | 4 | high intertidal zone | rocks with algae, mussels and barnacles | herbivore |
| *Littorina scutulata* | Checkered periwinkle | 4 | common in upper intertidal zone, lower than L. planaxis | rocks | herbivore: diatoms, microscopic algae, lichens as well as macroalgae |
| *Littorina* spp. | Periwinkles | 4 | upper and high intertidal | on rocks in shallow water along shoreline | herbivore |
| *Lottia asmi* | Black limpet | 3 | mid to low intertidal | attaches to host shell or rock, can move from one to another, found on *Chlorostoma funebralis* (primarily) or *C. gallina*, but also *Mytilus* and rocks | herbivore: microscopic algae on host shell/rocks |
| *Lottia digitalis* | Ribbed limpet, Fingered limpet | 4 | upper intertidal and splash zone | vertical or overhanging rock faces, exposed rocky coasts, occasionally on gooseneck barnacles (these have lighter morph) | microscopic algae and newly settled barnacles |
| *Lottia fenestrata* | Fenestrate limpet, Chocolate limpet | 4 | mid to low intertidal | reef rocks and boulders adjacent to lose sand | herbivore |
| *Lottia insessa* | Seaweed limpet | 1 | low intertidal | common on stipes and holdfasts of *Egregia* (feather boa kelp) | herbivore: feed directly on the kelp, forming scars and eventually destroying it |
| *Lottia instabilis* | Unstable seaweed limpet | 1 | low intertidal, subtidal | kelp stipes (primarily *Laminaria setchelli* and *Pterygophora californica*) | herbivore: kelp stipes and other algae |

**Table 4.4.** (continued)

| Scientific Name | Common Name | Category/Type (see Table 4.3) | Habitat Zone | Habitat Notes and Associations | Trophic Type and Food Preference |
|---|---|---|---|---|---|
| *Lottia ochracea* | Yellow limpet | 1, 4 | one of few limpet species in sublittoral zone | in sublittoral depths under kelp and surfgrass (*Phyllospadix)* and the undersides of small rocks at low tide | herbivore |
| *Lottia palacea* | Surfgrass limpet | 1 | low intertidal | common on blades of surfgrass (*Phyllospadix*) along open coast, occasionally on eelgrass | herbivore: feeds on superficial algae |
| *Lottia paradigitalis* | unknown | 3, 4 | high and mid intertidal | rocks, shells of turban snails and mussel (*Mytilus*) | herbivore |
| *Lottia pelta* (rock morph) | Shield limpet | 4 | mid to low intertidal | rocky reef, rocks and boulders | herbivore |
| *Lottia pelta* (dark seaweed morphology) | Shield limpet | 1 | mid to low intertidal | stipes and holdfasts of kelps (*Egregia* and others) | herbivore: kelps |
| *Lottia persona* | Masked limpet, Speckled limpet | 4 | high to mid intertidal | rocks | herbivore |
| *Lottia rosacea* | Rose limpet | 2, 3 | common in subtidal | associated with coralline algae | herbivore |
| *Lottia scabra* | Rough limpet | 4, 3 | mid intertidal | rocky reefs and boulders, often found on Owl limpet (*L. gigantea*) | herbivore: algal films |
| *Lottia scutum* | Pacific plate limpet | 4 | mid to low intertidal | rocks | herbivore: algal films, crustose algae |
| *Lottia strigatella* | Checkered limpet | 1, 4 | middle intertidal to sublittoral under kelp | kelp beds, eelgrass (*Zostera*) roots, algae | herbivore: microscopic algae and diatoms |
| *Lucapinella callomarginata* | Hard-edged fleshy limpet | 4 | low intertidal to subtidal | underside of rocks | omnivore: primarily sponges (*Tetilla*), but will consume algal films |
| *Mitromorpha aspera* | Rough miter-form | 2 | intertidal | gravel at low tide and in sublittoral | epifaunal predator |
| *Nucella emarginata* | Emarginate dog winkle | 3, 4 | middle intertidal | rocks, mussel beds, often in association with *O. circumtexta* | predator: prey on *Mytilus*, barnacles (*Balanus*) |

**Table 4.4.** (continued)

| Scientific Name | Common Name | Category/Type (see Table 4.3) | Habitat Zone | Habitat Notes and Associations | Trophic Type and Food Preference |
|---|---|---|---|---|---|
| *Nucella* spp. | Dogwinkle | 4 | shallow intertidal | rocks | predator |
| *Nucella emarginata* | Emarginate dog winkle | 3, 4 | middle intertidal | rocks, mussel beds, often in association with *O. circumtexta* | predator: prey on *Mytilus*, barnacles (*Balanus*) |
| *Ocinebrina (Ocenebra) circumtexta* | Circled rock shell | 3, 4 | intertidal, common in rocky crevices at mid-tide | rocks in heavy surf areas, often associated with barnacles (*Balanus*) | predator |
| *Ocinebrina (Ocenebra) interfossa* | Sculptured rock shell | 4 | intertidal to 100m | under rocks | predator, can drill into mollusks and barnacles |
| *Ocinebrina (Ocenebra) lurida* | Lurid rock shell | 4 | intertidal to 200m, common at low tide | on/under rocks, common in low intertidal in northern CA, rare in sublittoral in southern CA | predator, eats *Cryptochiton stelleri* and *Mytilus* |
| *Ocinebrina (Ocenebra) minor* | Minor rock shell | 1, 2 | sublittoral zone | not uncommon in sublittoral zone, particularly under kelp | predator |
| *Ocinebrina (Ocenebra)* spp. | Rock shell | 4 | intertidal to sublittoral | rocks and crevices, rocky bottoms | predator |
| *Odostomia nota* | Odostome | 1 | intertidal, shallow water | common on eelgrass (Zostera) roots | may be parasitic on certain molluscs |
| *Pleisiocystiscus jewettii* | unknown | 1, 2 | low intertidal | gravel of tide pools, with coralline algae, in surfgrass (*Phyllospadix*) holdfasts | predatory snail |
| *Pseudomelatoma torosa* | Knobbed towershell | 4 | low intertidal to 30m | rocky areas | predatory snail - polychaete worms |
| *Stylidium (Bittium) eschrichtii* | Threaded cerith | 1, 2 | low intertidal and sublittoral | clean coarse sand among eelgrass (*Zostera*)/rocks/coralline algae | herbivore: algae/detritus |
| *Terebra* sp. | Auger shell | 2 | intertidal to 1000m | offshore sandy bottoms | predator |
| *Trimusculus reticulatus* | Reticulate gadinia | 4 | mid intertidal | rock overhangs | planktivore; primarily pelagic diatoms |
| *Volvarina taeniolata* | California marginella | 4 | intertidal and sublittoral | rocks | predator |

Sample size can be ruled out as a factor affecting the decline in density (from 3,367 MNI/m$^3$ in Stratum VII to 1,285 MNI/m$^3$ in Stratum II), as Strata II and IV contain the largest excavated volumes (see Table 4.6 and Figure 4.9 for excavated volumes and density values). Furthermore, we found that differences in species densities among strata are highly significant and not related to sample size (ANOVA; $F_{65, 300} = 6.72$, $p < 0.0001$). Overall, we found significant differences between strata and relative abundances of shells in the four categories were significant ($G = 155.868$, $df = 15$, $p = 0$). However, these data contained non-significant subsets that show similarities among some strata and the four shell types. These subsets include Strata VI and VII ($G = 23.5391$) and Strata II, III, and VI ($G = 22.6048$), suggesting that primary differences in frequency patterning occur between the basal deposits and the upper components.

Interestingly, these data coincide with reconstructions of post-glacial shifts in giant kelp forests off the coast of mainland California, which predict increased kelp forest biomass during the Terminal Pleistocene and Early Holocene before declining rapidly as sea surface temperatures rose in the Middle Holocene (Graham et al. 2010). Kelp forests surrounding the Channel Islands were proposed to have reached peak productivity during the Early Holocene followed by a significant decrease (50-80%) in kelp forest productivity and associated resources by the later part of the Middle Holocene as climatic conditions warmed (Graham et al. 2010:404). Though tentative, it is possible that data patterning for small gastropod assemblages at CA-SMI-603 reflect a decline in local kelp biomass between the time when Strata V and IV were deposited, coinciding with declining kelp productivity as proposed by Graham and colleagues (2010). On the other hand, changes in human settlement and land use patterns are equally valid cultural variables that could explain the distribution of small gastropods at this site.

**Table 4.5.** CA-SMI-603, Unit 1, MNI of small gastropods

| | **Stratum** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Taxa** | **II** | **III** | **IV** | **V** | **VI** | **VII** | **Total** | **%** |
| *Acanthinucella punctulata* | - | - | - | 1 | - | - | 1 | 0.0 |
| *Acmaea mitra* | 12 | 3 | 20 | 17 | 3 | 1 | 56 | 1.7 |
| *Alia carinata* | 10 | 6 | 38 | 12 | 4 | 12 | 82 | 2.5 |
| *Alia tuberosa* | 1 | - | 17 | 8 | - | 1 | 27 | 0.8 |
| *Amphissa* spp. | - | - | - | - | - | 4 | 4 | 0.1 |
| *Amphissa versicolor* | 19 | 2 | 21 | 15 | - | - | 57 | 1.7 |
| *Callianax biplicata* | 2 | - | 1 | 1 | 1 | - | 5 | 0.1 |
| *Calliostoma* spp. | 1 | - | - | 2 | - | - | 3 | 0.1 |
| *Clathurella canfieldi* | 1 | 1 | - | - | - | - | 2 | 0.1 |
| *Conus californicus* | - | - | 2 | - | - | 1 | 3 | 0.1 |
| *Crepidula coei* | 9 | 1 | 3 | 6 | 12 | - | 31 | 0.9 |
| *Crepidula nummaria* | - | - | - | - | - | 2 | 2 | 0.1 |
| *Crepidula perforans* | 1 | - | - | 1 | - | - | 2 | 0.1 |
| *Crepipatella lingulata* | - | 1 | - | - | - | - | 1 | 0.0 |
| *Diodora arnoldi* | - | - | 1 | - | - | - | 1 | 0.0 |
| *Diodora aspera* | - | - | 2 | - | - | - | 2 | 0.1 |
| *Diodora* spp. | - | 1 | - | - | - | - | 1 | 0.0 |
| *Epitonum tinctum* | - | - | 1 | 1 | - | - | 2 | 0.1 |
| *Fissurella volcano* | 22 | 3 | 28 | 29 | 6 | 10 | 98 | 3.0 |
| *Garnotiaadunca* | 57 | 5 | 11 | 175 | 166 | 16 | 430 | 13.0 |
| *Garnotia norrisiarum* | 6 | - | 10 | 3 | 12 | 7 | 38 | 1.1 |
| *Garnotia* spp. | - | - | - | 1 | 6 | 2 | 9 | 0.3 |
| *Hipponix panamensis* | 1 | - | 3 | - | - | 2 | 6 | 0.2 |
| *Hipponi xtumens* | 1 | - | 2 | 1 | 1 | - | 5 | 0.2 |
| *Homalopoma baculum* | - | - | 1 | 10 | - | 1 | 12 | 0.4 |
| *Homalopoma luridum* | 1 | 6 | 16 | 1 | - | 2 | 26 | 0.8 |
| *Lacuna marmorata* | 10 | 1 | - | - | - | 1 | 12 | 0.4 |
| *Lacuna* spp. | 1 | - | 1 | 10 | - | 1 | 13 | 0.4 |
| *Lirularia* spp. | - | - | 8 | 1 | - | - | 9 | 0.3 |
| *Littorina keenae* | 6 | 2 | 11 | 10 | 1 | 4 | 34 | 1.0 |
| *Littorina plena* | 9 | 4 | 14 | 12 | - | - | 39 | 1.2 |
| *Littorin ascutulata* | - | - | - | 2 | - | - | 2 | 0.1 |
| *Littorina* spp. | - | - | - | - | 1 | - | 1 | 0.0 |

**Table 4.5.** (continued)

| Taxa | II | III | IV | V | VI | VII | Total | % |
|---|---|---|---|---|---|---|---|---|
| | **Stratum** | | | | | | | |
| *Lottia digitalis* | 48 | 12 | 66 | 48 | 31 | 5 | 210 | 6.3 |
| *Lotti fenestrata* | 11 | 6 | 40 | 22 | 17 | - | 96 | 2.9 |
| *Lottia insessa* | 8 | - | 8 | 6 | 1 | 6 | 29 | 0.9 |
| *Lottia ochracea* | 1 | 3 | 4 | 9 | 11 | 6 | 34 | 1.0 |
| *Lottia palacea* | - | - | 2 | - | - | - | 2 | |
| *Lottia paradigitalis* | - | 6 | 4 | 7 | 38 | 23 | 78 | 2.4 |
| *Lottia pelta* (rock morph) | 21 | 14 | 60 | 69 | 14 | 28 | 206 | 6.3 |
| *Lottia pelta* (seaweed morph) | 52 | 10 | 92 | 110 | 111 | 51 | 426 | 12.8 |
| *Lottia persona* | 1 | 5 | 7 | 8 | 1 | - | 22 | 0.7 |
| *Lottia rosacea* | - | - | - | - | - | 2 | 2 | 0.1 |
| *Lottia scabra* | 79 | 28 | 156 | 192 | 88 | 47 | 590 | 17.8 |
| *Lottia scutum* | 7 | 3 | 13 | 44 | - | 3 | 70 | 2.1 |
| *Lottia strigatella* | 10 | 8 | 48 | 44 | 68 | 21 | 199 | 6.0 |
| *Lottia* spp. | 49 | 1 | 19 | 30 | 11 | 19 | 129 | 4.0 |
| *Nucella emarginata* | 2 | 1 | 3 | 4 | 1 | 2 | 13 | 0.4 |
| *Nucella* spp. | - | 1 | - | 2 | - | 4 | 7 | 0.2 |
| *Ocinebrin acircumtexta* | 1 | 3 | - | 3 | 2 | - | 9 | 0.3 |
| *Ocinebrina interfossa* | - | - | 1 | - | - | - | 1 | 0.0 |
| *Ocinebrina lurida* | - | - | - | 1 | - | - | 1 | 0.0 |
| *Ocinebrina minor* | - | - | - | 1 | - | - | 1 | 0.0 |
| *Ocinebrina* spp. | 1 | - | 3 | 3 | - | 1 | 8 | 0.2 |
| *Odostomia nota* | 1 | 1 | 2 | 3 | - | - | 7 | 0.2 |
| *Pleisiocystiscus jewettii* | - | - | 1 | - | - | 1 | 2 | 0.1 |
| *Stylidium eschrichtii* | - | - | 3 | - | - | - | 3 | 0.1 |
| *Terebra* sp. | 1 | - | - | 3 | - | - | 4 | 0.1 |
| *Trimusculus reticulatus* | - | - | - | 3 | - | 2 | 5 | 0.2 |
| *Volvarina taeniolata* | - | - | - | 1 | - | - | 1 | 0.0 |
| Total | 467 | 139 | 758 | 1003 | 632 | 303 | 3305 | 100 |

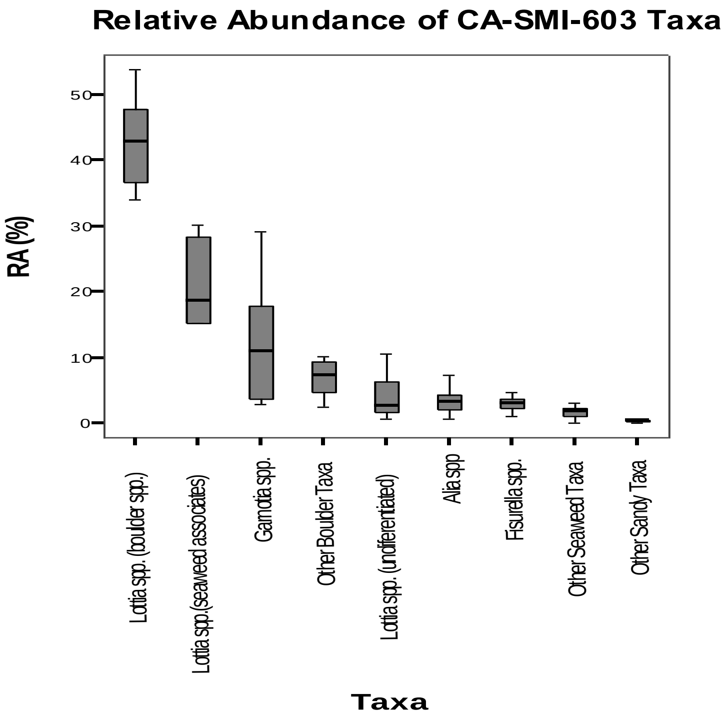


**Figure 4.7.** Composition of small gastropod taxa from CA-SMI-603. Boxplots include mean relative abundance and interquartile ranges. Error bars denote full ranges. N = number of analyzed strata (6), RA = relative abundance.

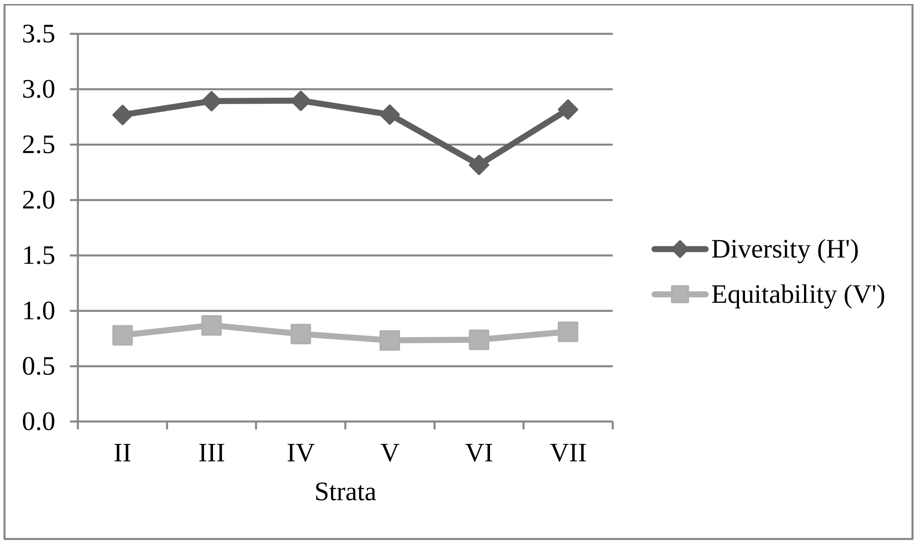


**Figure 4.8.** Heterogeneity measures for the small gastropod assemblage from CA-SMI-603. Changes in shellfish diversity and equitability through time are described by the Shannon-Weaver Diversity Function (H’) and Equitability Function (V’) (Reitz and Wing 2008).

**Table 4.6.** Quantitative measures

| Site (CA-) | Unit | Strata | Excavated Volume (m³) | Taxonomic Richness | Small Gastropod Density (MNI/m³) | Seaweed and Seagrass Density (MNI/m³) | Seaweed and Seagrass % MNI | Diversity (H') | Equitability (V') |
|---|---|---|---|---|---|---|---|---|---|
| SNI-40 | 11, 12 | IIHR | 0.138 | 30 | 2021.7 | 297.1 | 14.9 | 2.805 | 0.825 |
| SNI-40 | 11, 12 | IIB | 0.02 | 16 | 3000 | 500 | 16.7 | 2.382 | 0.86 |
| SNI-40 | 11, 12 | Dark Feat. | 0.016 | 14 | 4312.5 | 1562.5 | 36.1 | 2.343 | 0.865 |
| SNI-40 | 11, 12 | IIHC | 0.2765 | 35 | 3045.2 | 654.6 | 21.6 | 2.752 | 0.773 |
|  | **Totals:** |  | 0.4505 | 40 | 2772.5 | 572.7 |  |  |  |
| SMI-603 | 1 | II | 0.362 | 34 | 1284.5 | 265.2 | 20.7 | 2.768 | 0.778 |
| SMI-603 | 1 | III | 0.14 | 28 | 992.9 | 214.3 | 21.6 | 2.894 | 0.869 |
| SMI-603 | 1 | IV | 0.461 | 39 | 1644.3 | 485.9 | 29.5 | 2.897 | 0.792 |
| SMI-603 | 1 | V | 0.208 | 44 | 4822.1 | 995.2 | 20.7 | 2.771 | 0.733 |
| SMI-603 | 1 | VI | 0.127 | 23 | 4976.4 | 1535.4 | 30.9 | 2.318 | 0.738 |
| SMI-603 | 1 | VII | 0.09 | 32 | 3366.7 | 1111.1 | 32.9 | 2.818 | 0.812 |
|  | **Totals:** |  | 1.388 | 59 | 2377.5 | 612.4 |  |  |  |

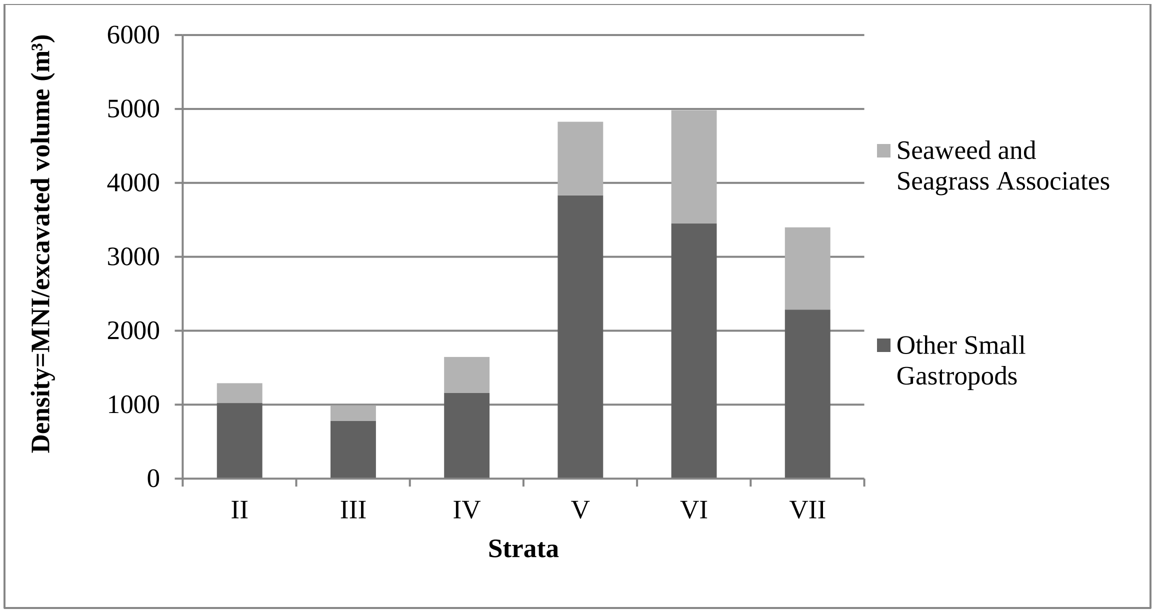


**Figure 4.9.** Density measures for small non-dietary gastropods from CA-SNI-603.

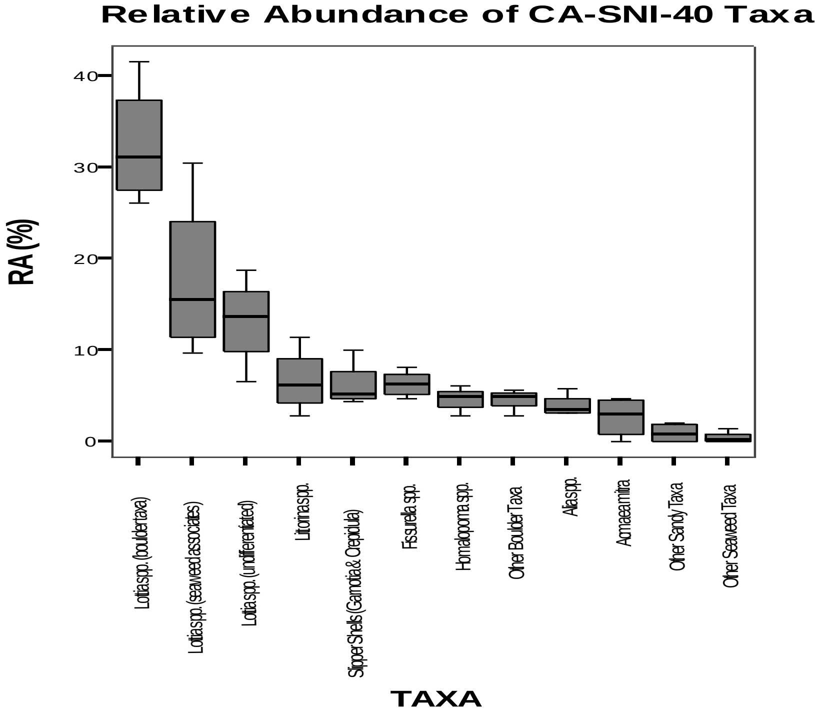


**Figure 4.10.** Composition of small gastropod taxa from CA-SNI-40. Boxplots include mean relative abundance and interquartile ranges. Error bars denote full ranges. N = number of analyzed deposits (4), RA = relative abundance.

### ***Intrasite Analysis: CA-SNI-40***

Analysis of small gastropods from two units at CA-SNI-40 revealed 1,263 identifiable individuals classified to 24 genera and 38 species (Table 4.7), with seaweed and seagrass associates making up roughly 22% of small gastropods. This assemblage is dominated by small limpets (*Lottia* spp.) that occupy boulders and rocks and species that live on seaweeds (Figure 4.10). Diversity and equitability measures show relatively high diversity, with slight drops in transitional strata (Stratum IIB) and discrete features, and consistently high equitability among taxa (Figure 4.11). We found no linear relationship between taxonomic richness and time (strata) at this site (ANCOVA; $F_{1,2} = 0.40$, $p = 0.5929$). Although richness is relatively consistent in the two main strata (IIHC and IIHR), it drops in the transitional layer (IIB) and in the distinct component designated as "dark feature" (Table 4.6). Density measures are highest in the "dark feature" and decrease slightly through time (Figure 4.12). Percentages of MNI for kelp and seagrass associates confirm density measures, following a similar pattern of lower percentages through time with a spike in the "dark feature" (Table 4.6). Differences in species densities among strata are significant (ANOVA; $F_{44,123} = 9.73$, $p = <0.0001$). Overall, differences between strata relative abundances of shells in the four categories are significant (G = 28.3468, df = 9, $p = 0.0008$). However, these data contained non-significant subsets that show similarities among some strata and the four shell types, including Strata IIHR and IIHC (G = 14.6331). This suggests that primary differences occur in the transitional layer and discrete feature.

The small gastropod assemblage from the "dark feature" reveals a drop in taxonomic richness along with an increase in density of seagrass and seaweed associates, which is 239% higher in this feature than in the surrounding midden (IIHC). The seaweed limpet (*Lottia insessa*) reaches its highest density in this component, where it makes up almost 22% of small gastropods, with combined seaweed and seagrass associates composing over 36% of small gastropod MNI, the highest in any deposit discussed here. This high concentration of seaweed associates marks the presence of a distinct activity area where kelp was likely processed in some way and potentially eaten. It is possible that this feature is the partial remains of a "shell bake," in which black abalone were

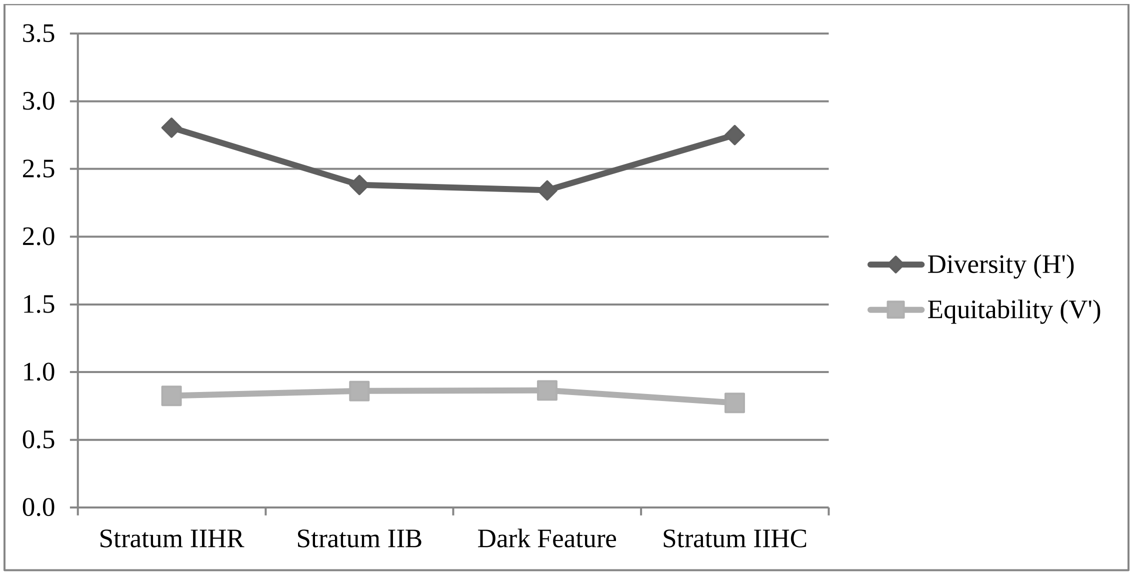


**Figure 4.11.** Heterogeneity measures for the small gastropod assemblage from CA-SNI-40. Changes in shellfish diversity and equitability through time are described by the Shannon-Weaver Diversity Function (H') and Equitability Function (V') (Reitz and Wing 2008).

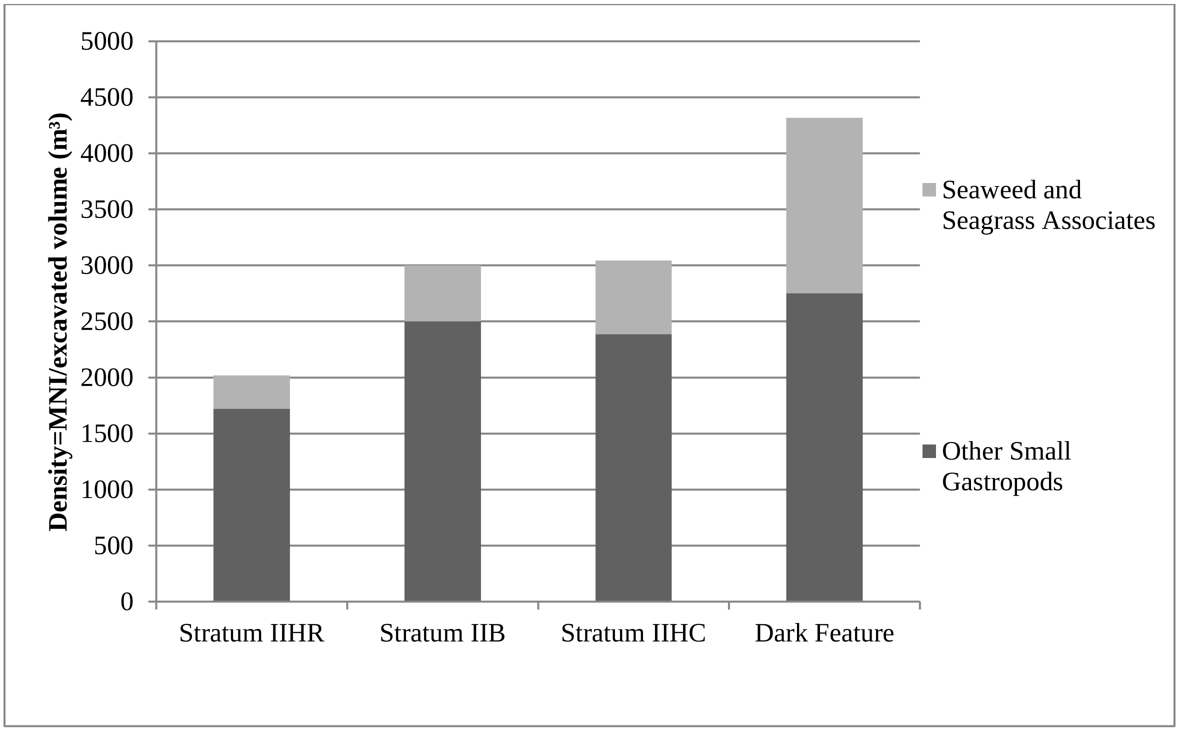


**Figure 4.12.** Density measures for small non-dietary gastropods from CA-SNI-40.

**Table 4.7.** CA-SNI-40, Units 11 and 12A, MNI of small gastropods

| **Taxa** | **Stratum IIHR** | **Stratum IIB** | **Stratum IIHC** | **Dark Feature** | **Total** | **%** |
|---|---|---|---|---|---|---|
| *Acanthinucella punctulata* | 1 | - | - | - | 1 | 0.1 |
| *Acmaea mitra* | 13 | 1 | 38 | - | 52 | 4.1 |
| *Acteocina culcitella* | - | - | 1 | - | 1 | 0.1 |
| *Alia carinata* | 10 | 2 | 27 | 4 | 43 | 3.4 |
| *Amphissa versicolor* | 9 | 3 | 29 | 2 | 43 | 3.4 |
| *Calliana xbiplicata* | - | - | 14 | - | 14 | 1.1 |
| *Calliostoma canaliculatum* | - | - | 2 | - | 2 | 0.2 |
| *Caliostoma ligatum* | - | - | 1 | - | 1 | 0.1 |
| *Cerithiopsis carpenteri* | 1 | - | 1 | - | 2 | 0.2 |
| *Conus californicus* | 1 | - | - | - | 1 | 0.1 |
| *Crepidula aculeata* | 3 | 2 | 8 | - | 13 | 1.0 |
| *Crepidula onyx* | - | - | 1 | - | 1 | 0.1 |
| *Crepidula perforans* | - | - | 3 | - | 3 | 0.2 |
| *Crepidula* spp. | 1 | - | 8 | 2 | 11 | 0.9 |
| *Crepipatella lingulata* | 5 | 1 | 10 | 1 | 17 | 1.3 |
| *Epitonium tinctum* | - | - | 1 | - | 1 | 0.1 |
| *Fissurella volcano* | 15 | 4 | 35 | 4 | 58 | 4.6 |
| *Fissurellidae* | 8 | - | 5 | - | 13 | 1.0 |
| *Fusinus kobelti* | - | - | 1 | - | 1 | 0.1 |
| *Fusinus luteopictus* | - | - | 1 | - | 1 | 0.1 |
| *Garnotia adunca* | 4 | 3 | 13 | - | 20 | 1.6 |
| *Garnotia norrisiarum* | 1 | - | 6 | - | 7 | 0.6 |
| *Homolopoma baculum* | 5 | - | 6 | - | 11 | 0.9 |
| *Homolopoma luridum* | 12 | 3 | 35 | 2 | 52 | 4.1 |
| *Littorina keenae* | 1 | - | 8 | - | 9 | 0.7 |
| *Littorina scutulata* | 31 | 4 | 41 | 2 | 78 | 6.2 |
| *Lottia asmi* | 14 | 2 | 55 | 4 | 75 | 5.9 |
| *Lottia digitalis* | 9 | 3 | 27 | 2 | 41 | 3.2 |
| *Lottia insessa* | 15 | 4 | 93 | 15 | 127 | 10.1 |
| *Lottiainstabilis* | - | - | 2 | - | 2 | 0.2 |
| *Lottia ochracea* | 3 | 3 | 15 | 3 | 24 | 1.9 |
| *Lottia pelta* (rock morph) | 2 | - | 17 | 1 | 20 | 1.6 |

**Table 4.7.** (continued)

| **Taxa** | **Stratum IIHR** | **Stratum IIB** | **Stratum IIHC** | **Dark Feature** | **Total** | **%** |
|---|---|---|---|---|---|---|
| *Lottia pelta* (seaweed morph) | 8 | 1 | 40 | 3 | 52 | 4.1 |
| *Lottia pelta* (uncategorized) | 1 | - | - | - | 1 | 0.1 |
| *Lottia scabra* | 56 | 20 | 184 | 11 | 271 | 21.5 |
| *Lottia strigatella* | 1 | - | 2 | - | 3 | 0.2 |
| *Lottia* spp. | 39 | 4 | 113 | 13 | 169 | 13.4 |
| *Lucapinella callomarginata* | 1 | - | - | - | 1 | 0.1 |
| *Mitromorpha aspera* | 1 | - | - | - | 1 | 0.1 |
| *Ocinebrina circumtexta* | 1 | - | 5 | - | 6 | 0.5 |
| *Pseudomelatoma torosa* | - | - | 1 | - | 1 | 0.1 |
| *Stylidium eschrichtii* | 3 | - | - | - | 3 | 0.2 |
| *Trimusculatus reticulatus* | 4 | - | 6 | - | 10 | 0.8 |
| **Total** | 278 | 60 | 855 | 69 | 1263 | 100 |

wrapped in seaweed and steamed, a hypothesis supported by the unusually high density of seaweed associates and ethnographic accounts of abalone being cooked in this fashion. Hohentahl (2001:148) describes how the Tipai of northwestern Baja, California, steamed abalone by placing them shell down on the fire and covering them with wet kelp.

### *Intersite Comparison*

Data from CA-SMI-603 and CA-SNI-40 are presented and compared to provide examples of inferred seaweed and seagrass harvesting through the identification and analysis of non-dietary shells, and to explore tentative interpretations signaled by the presence of ancillary shells. Our combined analysis of the shells recovered from two site on the California Channel Islands identified a total of 4,568 small gastropods belonging to 75 taxa. Diversity and equitability measures fall within very similar ranges and persist through time at both sites despite distinct differences in site type, location, and chronology. Consistently high diversity and evenness measures suggest that a wide variety of small gastropods was included in these deposits without dominance of any single taxon. Taxonomic richness fluctuates through time at both sites and is lower at CA-SNI-40 than at CA-SMI-603, possibly reflecting the distance of each site from the coast and/or differential preservation due to the relative protection afforded deposits in rockshelters vs. those left exposed to the elements at open-air dune sites. Alternatively, taxonomic richness could reflect small scale differences in the distribution and abundance of shellfish communities during particular times in the past, configurations controlled by the intensity of shellfish harvesting by humans and other predators, as well as by a variety of environmental factors.

Although richness measures are variable between sites, overall density measures are surprisingly similar (Table 4.6) as are relative percentages of shells belonging to each of the four categories (Table 4.3). Although decreasing trends in density are evident at both sites, the trend is more pronounced at CA-SMI-603, which contains a much longer occupational history. Decreasing trends in density could be reflective of a number of factors pertaining to human decision making and/or the environment, including variables such as changes in human harvesting practices and foraging locations, shifts in site function and settlement, regional or local environmental fluctuations, or decreasing kelp forest biomass as proposed by Graham et al. (2010); which in turn affects species recruitment, settlement, and productivity. Our primary goal for this paper, however, is to highlight the use of marine macrophytes as inferred by epifauna in archaeological contexts and to provide interpretive possibilities for future studies.

Comparing total MNI values for small gastropods at each site reveal differences in community composition (Type 1-4) between sites ($G = 20.8549$, $df = 3$, $p = .0001$). Differences in the composition of small gastropod assemblages for Early (CA-SMI-603, Strata VI and VII), Middle (CA-SMI-603, Strata III-V; CA-SNI-40, all components), and Late (CA-SMI-603, Stratum II) Holocene time periods reveal significant differences among temporal periods ($G = 78.6775$, $df = 9$, $p < .0001$). A separate G-test comparing Middle Holocene components at both sites (CA-SMI-603, Strata III-V; CA-SNI-40, all components) revealed no significant differences between samples ($G = 5.9531$, $df = 3$, $p = 0.1139$). This similarity in relative frequencies between Middle Holocene components at CA-SMI-603 and CA-SNI-40 indicate that statistically similar proportions of shells from each type were collected during roughly the same time period on two different islands, and that the Early Holocene components vary significantly from later components.

While there are changes in relative percentages and sizes of key shellfish taxa in these deposits, the primary suite of dietary shellfish is fairly consistent, suggesting a slight depression in intertidal productivity due to extensive harvesting during a relatively short time span. If this decrease in density reflects decreasing populations through time, it could be reflective of diminished offshore kelp beds exposing rocky intertidal taxa to increased wave action and disturbance, limiting settlement and survival. The overall trend of consistently high taxonomic diversity at both sites testifies to the relative stability of rocky shore communities (see Hockey and Bosman 1986; Moreno et al. 1986), and likely speaks to the knowledge of islanders who understood how to intensively harvest shellfish without causing primary species extinctions or severe ecosystem disruption.

## Behavioral Implications

Although non-dietary shells are likely riders/hitchhikers and thus incidental inclusions to archaeological middens, the question we wish to explore is, how were they included and what does their presence in an archaeological shell mound indicate? As some of these small species live directly on other larger shellfish their presence indicates the harvesting and use of their host species, while other small gastropods can be used to infer the harvesting of the marine vegetation they live on and consume.

### *Shellfish Harvesting Inferences*

Small rider species, such as *Garnotia norrisiarum*, can be useful in instances where the host shell may no longer be present because it was utilized in tool production or for ornamental purposes. This small slipper shell is known to live predominantly on *Norrisia norrisi*, as implied by its name. While excavated materials from CA-SMI-603 revealed only one identifiable fragment of *N. norrisi*, the presence of *G. norrisiarum* in several strata suggests that perhaps *N. norrisi* was collected and brought to the site but was not incorporated into the midden because the shell was utilized in the manufacturing of ornaments and fishhooks. Interestingly, these two species of shellfish appear together in both units sampled from CA-SNI-40; strata containing *N. norrisia* also contain *G. norrisiarum*, but neither is present in deposits without the other.

### *Indirect Evidence of Seaweed and Seagrass Harvesting*

Preservation biases often exclude perishable materials from being unearthed in archaeological contexts, however, this does not necessarily mean that they were not utilized, but only that their remains did not preserve. Although in most cases direct evidence of seaweed and seagrass harvesting has long disappeared from the archaeological record, either because of human consumption, processing, and/or site-specific taphonomic factors, indirect evidence in the form of seaweed associates is a veritable untapped reservoir of data. We suggest that the presence of Type 1 gastropods in archaeological contexts is the result of kelp and seagrass harvesting by humans in the past. The relative percentages of these shells in sites through time may be able to act as proxies for changes in harvesting intensity and potentially provide information regarding fluctuations in kelp and seagrass patches and regional or local environmental changes.

As described in ethnohistoric accounts from the west coast of North America (see section 2.1), the relative ease of drying and storing seaweeds makes them highly valuable as a storable non-meat food item and potential fuel source. Each family, genus, and species of macroalgae contains variable amounts of humanly digestible nutrients, with relative percentages also varying within species due to oceanographic, climatic, and seasonal differences (Floreto and Teshima, 1998; Kaehler and Kennish, 1996; Mabeau and Fleurence, 1993; Rupérez, 2002). The relatively lower protein content and higher dietary fiber content of brown algae (Laminariales and Fucales) in particular (Khotimchenko et al., 2002; Kumar et al., 2008) allows these “sea vegetables” to fulfill this human dietary requirement lacking in protein-rich marine diets. Marine macroalgae could thus serve as a valuable dietary alternative to terrestrial botanical resources, especially to islanders subsisting predominantly on marine resources. Though no firsthand accounts of Channel Islanders utilizing kelp for food survive, it is imperative to bear in mind that a lack of direct ethnographic information is anything but definitive. Furthermore, the rich record of coastal people using similar marine resources north and south of the Channel Islands (see section 2.1), where it is similarly plentiful, suggests their possible use by analogy. The bountiful resources provided by lush kelp forests along the Circum-Pacific Coast likely acted as a veritable ocean "highway" (Erlandson et al. 2007), dispensing similar suites of marine resources and coastal habitats as humans ventured further south into the Americas.

## Paleoenvironmental Implications

This study highlights the potential utility of identifying and analyzing all shells found in archaeological middens as a suite of species somewhat akin to a fossil assemblage, albeit an archaeologically biased assemblage. While clearly not equivalent to a naturally accumulated death assemblage, the addition of 75 taxa to the frequently analyzed suite of larger dietary mollusks provides the best data set possible for reconstructing the littoral paleoecology of coastal areas frequented by humans in the past, especially in the absence of naturally accumulated fossil records. Although we suggest this as a tentative hypothesis, it has been proposed by environmental scientists that the often ignored, small, non-dietary shells in archaeological middens are the most useful for paleoenvironmental reconstructions (Limondin-Lozouet et al. 2013:62).

Type 4 species can contribute to our understanding of intertidal paleoecology and in some cases the health of local kelp patches. Offshore kelp beds and *Macrocystis* in particular, can be a limiting factor to widespread larval dispersal of intertidal dwelling limpets, as they can decrease currents and wave action in its immediate surroundings (Turner 2003; Shanks et al. 2014). This links the presence of offshore kelp beds to higher local settlement for limpets living on rocks in the intertidal zone and suggests that diminishing kelp beds could result in reduced local populations for these boulder dwelling species and vice versa. Shanks et al. (2014) found a significant correlation between local recruitment of *Lottia scabra*, an intertidal rock dwelling limpet, and the presence of *Macrocystis* in the intertidal. In addition, Graham's (2004) study of associated taxa in southern California kelp forests found that several carnivorous mollusks (often found on rocks and boulders) were observed significantly more often in kelp forested habitats over deforested areas. While these species are not direct kelp or seagrass associates in the sense that they do not live directly on marine vegetation, they have a strong association with kelp forest habitats and their presence or absence through time could speak to the relative health of local kelp forest patches. Carnivorous species identified by Graham (2004) and found in the assemblages discussed here include *Fusinus kobelti*, *Homalopoma luridum*, and *Pseudomelatoma torosa*. In addition, the predatory *Conus californicus*, was found by North (1971) to be common in Southern California kelp beds even though it is not a direct kelp associate. Naturally, a wide range of biological, ecological, and environmental factors intersect and must be teased apart to reach a conclusive understanding of what is causing shifts in taxonomic richness and species density. Though this is beyond the scope of this paper, we believe it is an interesting possibility requiring further investigation.

### Methodological and Ecological Implications: Human Impacts

Although temporal scales for archaeological assemblages are often longer than ideal for ecological studies, shell middens around the globe contain substantial evidence that human harvesters impacted the size structure and relative abundances of exploited populations (Jerardino 1997, 2010; Langejans et al. 2012; Mannino and Thomas 2002; Parkington, 2008; Sealy and Galimberti 2011; Tonner 2005; and others). Nevertheless, factors such as species interactions and trophic level dynamics, and changes in oceanographic temperature and sea level complicate anthropogenic induced effects of predation and its clues in the archaeological record (see Bailey and Milner 2008; Dayton et al. 1998; Mannino and Thomas 2002).

Human harvesters in intertidal shellfish beds exert a disproportionate effect on rocky shore communities, significantly altering community dynamics as they collect much larger quantities with higher efficiency than other predators (Adessi 1994; Castilla and Durán 1985; Dye et al 1994; Hockey 1994; Moreno et al. 1984; Oliva and Castilla 1986; Ortega 1987). Although selective exploitation of shellfish in rocky intertidal areas can disrupt space mosaics causing significant changes in community structure, these disturbances are not permanent due to the dynamic nature of biological systems, and major changes may occur again when exploitation ceases or switches to another species (Durán and Castilla 1989; Dye 1992; Hockey and Bosman 1986; Lasiak 1991; Moreno et al. 1984, 1986; Oliva and Castilla 1986). In addition to impacts on exploited populations, non-targeted species can also experience indirect effects, such as altered size structures and alterations in species abundances (e.g., Roy et al. 2003). Lindberg et al. (1998) found that when the large and dietarily important limpet, *Lottia gigantea*, was removed from intertidal boulders, small limpets, such as *L. scabra*, often increased in density. Suggesting that increases in relative abundances of small, non-dietary limpets may also be indicative of intensive human harvesting of larger dietary species.

We suggest that small, non-dietary shells in coastal middens can contribute to a more complete (though not exhaustive) understanding of nearshore community composition and dynamics in the past. By identifying the full suite of represented species in archaeological assemblages, it is possible to infer the state of littoral ecosystems and how they shifted through time, allowing us to better reconstruct possible consequences of human predation in these heavily utilized primary resource habitats. Relative percentages of small gastropods can be used in conjunction with reduced abundances and shell size changes of purposefully harvested shellfish to support or negate perceived impacts. The presence of these species as well as their detailed analysis (e.g., stable isotope geochemistry, trace elemental analysis, etc.) can provide the environmental parameters against which anthropogenic impacts of marine resources can be compared. We believe that when all shells, including small, non-dietary mollusks, uncovered in coastal midden deposits are analyzed together as a suite of taxa, a more complete picture of the paleo-community is attainable. Adding ancillary mollusks can increase taxonomic richness counts from 10-20 dietary taxa to close to 100 total taxa as seen at CA-SMI-603 (Ainis 2012), thus greatly increasing the potential for nearshore reconstructions. Reconstructing the most representative population possible can contribute to our understanding of how these ecosystems were affected and potentially managed by humans in the past.

## **Conclusions**

This study demonstrates some of the types of data that can be gleaned from non-dietary shells accidentally incorporated in archaeological shell middens and suggests tentative implications for further investigation. The behavioral implications of this study suggest islanders from San Nicolas and San Miguel were utilizing very similar harvesting strategies despite typological, spatial, and temporal differences between sites, conforming to regional patterns and similar nearshore ecology on both islands. The methodological significance of this study lies in the discovery that small, non-dietary shells in coastal middens have stories to tell. Although they may not contain information on direct subsistence strategies, they can be used to infer harvesting of marine resources like kelps and seagrasses and potentially inform us on the community structure and relative health of local kelp forests and intertidal communities in the past. We have demonstrated that small gastropods can be used to infer kelp and seagrass harvesting; the presence of shellfish species whose shells were utilized and therefore no longer present in an archaeological assemblage; and tentatively support environmental data demonstrating shifts in kelp forest productivity. Furthermore, we suggest the possibility that ancillary shells may be used to signal paleoenvironmental factors such as changes in climate and sea surface temperature and nearshore ecology, though distinguishing between these interrelated factors is beyond the scope of this paper.

Whereas taxonomic identifications presented here are limited to the southern California region, the concept of identifying small shells and investigating the ecological implications they may contain is not limited to any one region or area. The identification of numerous seaweed and seagrass associates is a step towards better understanding the use of these highly perishable but extremely useful resources in the past. The application of these types of data has the potential to reveal new patterns and more in-depth understandings of coastal lifeways around the globe.

In Chapter V, I discuss methods for identifying and quantifying sea urchin remains in archaeological contexts. As primary consumers in kelp forest habitats, sea urchins are pivotal in structuring kelp forest communities and their relative abundances and size profiles in archaeological middens can inform us on the relative health of local kelp beds. I calculated a regression formula for estimating the sizes of harvested sea urchins by measuring hemipyramid length and demonstrate the utility of this method in reconstructing size frequency distributions throughout the several thousand-year sequence represented at Cave of the Chimneys.

# CHAPTER V:

## SEA URCHIN HISTORICAL ECOLOGY AND MORPHOMETRICS: ARCHAEOLOGICAL IDENTIFICATION AND INFERRING SIZE OF HARVESTED POPULATIONS THROUGH ALLOMETRY

### Introduction

Sea urchins play a pivotal role in shallow coastal habitats both as algal consumers and prey species, affecting the structure and functionality of many shallow marine ecosystems (Steneck 2013). Although sea urchins inhabit a wide range of depths, their ecological impacts are most notable in shallow nearshore marine habitats including kelp forests in temperate regions (Steneck et al. 2002) and sea grass beds in tropical and subtropical regions (Morrison 1988). As dominant herbivores in kelp forest ecosystems and primary consumers of marine algae, the health of sea urchin populations can be used as a proxy for the relative health of nearshore kelp forest ecosystems. Along with keystone predators like sea otters, spiny lobsters, and sheephead, sea urchins are prominent members of nearshore rocky ecosystems along the west coast of North America, dominating ecological interactions in these highly productive marine ecosystems (Dayton 1985; Graham 2004; Harrold and Reed 1985). Among the most well-studied echinoid species in the world, researchers are well aware of the multifaceted role red (*Mesocentrotus franciscanus,* formerly *Strongylocentrotus*) and purple (*Strongylocentrotus purpuratus*) sea urchins play as “ecosystem engineers” of nearshore and subtidal communities, where their grazing modulates the algal availability in their communities and creates cryptic microhabitats for other species (Tegner et al. 1995; Rogers-Bennett 2007; Rogers-Bennett and Pearse 2001).

Understanding the role of human fishers and shellfish collectors in dynamic nearshore habitats, particularly our interactions with kelp forest ecosystems, has long been of interest to researchers working along the Pacific Coast of North America (e.g., Erlandson et al. 2005b; Graham et al. 2003; Simenstad et al. 1978). Kelp forest ecosystems support complicated ecological webs of interaction and association between organisms as diverse as algae, invertebrates, mollusks, fish, marine mammals, and coastal birds (Steneck et al. 2002); but these are notoriously difficult to tease apart. Examining the nature of sea urchin harvesting in the past will contribute unique perspectives on the deep history of kelp forest ecosystems and human dependence on the plethora of resources they contain. In addition, archaeological data sets, such as those analyzed here, provide deep historical perspective on the relative state of kelp forests and intertidal ecosystems during climatic shifts in the past and can inform current management strategies faced with rising sea levels and water temperatures due to climate change.

Archaeomalacologists measure sizes of primarily harvested shellfish taxa to investigate changes in local faunal and foraging patterns through time (e.g., Ballbè 2005; Daniels 2014; Erlandson et al. 2008; Faulkner 2014; Jerardino 1997; Klein and Steele 2013; Prummel 2005). These datasets are used to reconstruct human harvesting patterns, infer predation pressure and degree of exploitation, and examine whether shifts in taxonomic abundance and/or average size are environmental or cultural in origin. Larger and thicker shelled mollusks, such as abalone, mussels, and clams have been used to investigate human use and impacts to intertidal habitats in coastal settings around the world (see references above). However, the poor preservation of sea urchin remains in archaeological contexts has largely precluded this echinoderm from being included in detailed studies of human exploitation and potential impacts to nearshore environments (but see Campbell 2008a, b; Gutiérrez-Zugasti 2011; Gutiérrez-Zugasti et al. 2016).

Researchers working on the California Channel Islands have used measurements of large gastropods (black and red abalone, *Haliotis cracherodii* and *H. rufescens*, wavy top shell, *Megastraea undosa*, owl limpet, *Lottia gigantea*) and bivalves (California mussel, *Mytilus californianus*) to examine the nature of nearshore shellfish harvesting throughout thousands of years of island occupation (Braje et al. 2012; Erlandson et al. 2004, 2008, 2011; Perry and Hoppa 2012; Raab and Yatsko 1992), but no studies of this nature have been conducted for echinoids, like sea urchin. Sea urchin fragments are common in archaeological shell middens on California's Channel Islands, sometimes forming dense "urchin lenses" comprised almost entirely of sea urchin fragments (Raab and Yatsko 1992; Salls 1991, 1992). Although they are nearly ubiquitous in Channel Island archaeological sites, the fragile nature of their test (outer shell) results in a high degree of fragmentation, hindering inferences on the harvested size of individuals in most cases.

This paper outlines methods for estimating the size of harvested sea urchin specimens through analysis of covariance (ANCOVA) studies and regression analysis performed on modern specimens. The resulting regression formula will allow archaeologists to reconstruct the nature of archaeological sea urchin populations in the past by configuring size/age estimates for harvested individuals. I demonstrate the application of these methods with archaeological data sets from Cave of the Chimneys (CA-SMI-603), quantifying the estimated size of more than 3740 sea urchins through measurements of >37,400 hemipyramids harvested by humans between ~8400 and 2200 cal BP. These data reveal oscillations in the average size, densities, and relative abundances of various size ranges of harvested specimens throughout the Holocene. These data show shifts in localized nearshore paleoenvironments and suggest human fishing and shellfish harvesting affected the demographics of intertidal urchin populations through time.

I examine the relationship between sea urchin test diameter (TD) and hemipyramid length (HL) for two species of sea urchin (*Mesocentrotus franciscanus* and *Strongylocentrotus purpuratus*) that are common along the west coast of North America, resulting in regression formulae that can be used to estimate the TD of crushed specimens in archaeological deposits. As it is nearly impossible to identify crushed urchin remains to the species level, I also examined the relationship between these two species in attempts to provide a comprehensive and methodologically feasible estimate when species level identifications are not possible.

## Identifying and "Ranking" Sea Urchin in Archaeological Deposits

The endoskeleton, or shell, of a sea urchin is comprised of calcareous plates called "tests." Although test surface patterns (i.e., pore-pair counts on ambulacral plates) can aid in genus level identifications at times, patterns often vary between plates on a single individual and overlap between taxa (Mortensen 1927). Since surface sculpture and pore-pair counts vary within a single specimen, test fragments cannot always be reliably identified to species or individual (Campbell 2008 a, b). Not only does this make species level identifications within a genus impossible, it also negates the ability to identify between genera in some instances. Sea urchins are rarely found whole in archaeological contexts and quantifying their remains is particularly challenging as the entire "shell" of the organism falls apart along the joints between test plates, resulting in dozens to hundreds of tiny fragments per individual. The spines and jaw separate from the test and the jaw elements disarticulate when the soft tissue that was holding them together decays, causing the whole organism to collapse along plate sutures (Smith 1984).

In this study I provide a method for inferring the sizes of harvested individuals in the past so these remains can be interpreted in terms of intensity of exploitation. By providing a means for achieving a measure of the distribution of sizes in an assemblage, archaeologists can compare sea urchin use between and within archaeological sites, and through time. As the size and age distributions of sea urchin will vary with habitat in relation to a variety of factors (i.e. available nutrition, SST, predator-prey dynamics, etc.), reconstructing sea urchin size and age frequency distributions can inform on the paleo-habitat from which they were harvested. For the genus *Strongylocentrotus* (of which *M. franciscanus* was recently a member, WORMS 2013), which includes all shallow water urchin off the Pacific Coast of North America, the features used to distinguish between species are lost through decay and weathering (Biermann et al. 2003:360) resulting in genus level identifications of *Strongylocentrotus* spp. at best.

Estimating the sizes of harvested sea urchin populations will allow archaeologists to better interpret potential causes of urchin lenses like those present in many Channel Island archaeological sites. A traditional Optimal Foraging hypothesis assumes that people would likely select larger individuals if it is for purely dietary reasons, though the ease of collecting hundreds of smaller individuals from the middle intertidal might negate the cost of diving or foraging deeper (i.e., subtidal) for larger specimens. One study demonstrated that shallow water urchin had thicker tests, shorter spines, and larger gonads (higher quality food) than those inhabiting deeper waters (Kramer and Nordin 1975). This suggests that people might have targeted medium sized individuals in the shallower intertidal waters knowing they contained higher quality food. Braje et al.

(2007: Table 1) rank sea urchin as sixth in the suite of intertidal mollusks often found in California Channel Island shell middens. At CA-SMI-603, however, it is the most abundant shellfish taxon by MNI (26%) and the third most abundant in terms of weight (21%), only slightly below abalone (24%), which is fairly significant considering that abalones have much stronger and heavier shells. I suggest that the exceptionally high nutritional value (see below) and ease of collection from the middle intertidal where they can grow in highly aggregated bands just below California mussel lenses, places them in a higher rank. Although larger individuals may be deeper in the low to subtidal zones and at the base of kelp holdfasts, I hypothesize that people were mostly focused on the collection of small to medium sized individuals, which are found highly aggregated in the higher intertidal.

Although sea urchins in general are thought to be a lower ranked resource among shellfish taxa that contain larger meat packages and are relatively easy to collect, ethnographic accounts indicate that sea urchin was highly valued and preferred by at least some of the Native cultures of western North America, which might suggest a higher ranking in some cases. In her synthesis of ethnographic annotations concerning the economic importance of shellfish among the Tlingit people of Alaska, Moss (1993:639) noted:

> Khlebnikov (1976:37) also mentions that sea urchins (*Strongylocentrotus* spp.) were in demand for their “delicious flavor” and “healing properties” [and people] regarded sea urchins as a “universal medicine for all illnesses.”

Sea urchin continues to be highly valued in certain parts of the world, fetching an incredibly high price relative to meat weight. The gonads are eaten raw and considered a delicacy in many Mediterranean cuisines as well as in Japan, South America, and the West Indies, and island cultures throughout the Pacific where Polynesians and Micronesians reportedly consume all of the internal organs (Brandon and Rokop 1985:182-183; Rahman et al. 2014; Ricketts et al. 1985:98). Prices of sea urchin have skyrocketed in recent years as supplies have dwindled due to high demand, and ocean temperatures have risen affecting the quality of some species (e.g., short-spined and northern sea urchin). Top quality roe can fetch AU$450 per kg in Japan, making it one of the most valuable sea foods in the world and leading to plans for farming the spiny echinoderms (see Rahman et al. 2014 and references therein).

## Sea Urchin Biology and Ecology

Sea urchins are regular (as opposed to irregular) echinoderms, meaning they have a globose shape that is flattened at the poles (Figure 1: A-C); the generally circular circumference of a sea urchin is referred to as the ambitus. Locomotion is achieved using hundreds of spines and podia. Many species of sea urchin have three types of spines, all of which are present on each individual; primary (also called radioles), secondary, and tertiary spines, which are usually apparent by the conspicuous size differences between them. However, species in the genus *Strongylocentrotus* have spines of various intermediate sizes and do not display a marked contrast between primary and secondary spines, further complicating identification of crushed remains in archaeological contexts. The Aristotle’s lantern (Figure 1:D) contains the organism’s mouth and jaw, including its five teeth, and is positioned underneath the sea urchins’ body to facilitate kelp grazing. Excretion organs are located at the opposite side and waste is omitted out the top of the urchin.

The sea urchin’s test is made of hexagonal calcareous (calcite) plates called ossicles, which are fenestrated (contain holes), increasing the relative strength of the organism. Fenestrated ossicles allow many echinoderms to fulfill strength requirements using minimum amounts of skeletal material (Weber et al. 1969), making their structure stronger than it appears. A sea urchin begins with 10 interambucular plates (five in each column), which increase in number as the individual grows and ages. As the organism’s skeleton, the test is a dynamic metabolic entity and its ossicles and rotula contain growth lines that reflect seasonal changes including available nutrition and reproductive stages (Bert 1985; Pearse and Pearse 1975) much like fish otoliths, though observing growth lines is only reliable in smaller/younger individuals (Shelton et al. 2006). Although growth rates vary depending on available nutrition and other factors, studies have shown that ~40% of the final test diameter can be attained during the first year, with growth rates slowing considerably after the first few years and as the individual ages (Ebert and

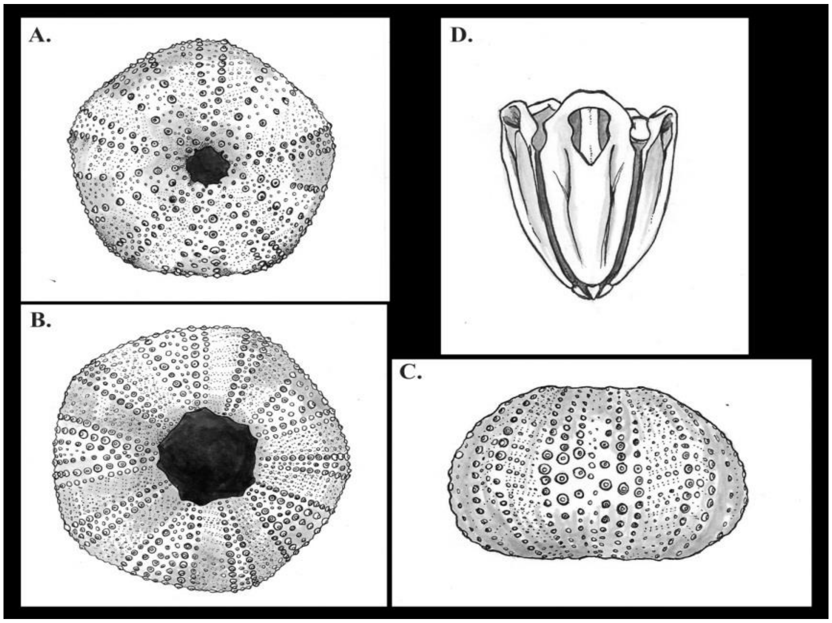


**Figure 5.1**. Sea urchin without spines: A) superior view, B) inferior view, C) side view, D) Aristotle’s lantern. Line drawings by Sonya Sobel.

Russell 1993; Ebert et al. 1999; Morgan et al. 2000a; Rogers-Bennett et al. 2003). Maximum lengths of spines differ between species, with purple sea urchin spines rarely exceeding 20 mm, and red sea urchin spines reaching up to 50+ mm in length (Tegner and Levin 1983). As an example of the developmental plasticity that is well documented in sea urchins, however, spine size can be affected by abiotic factors, and in areas with high wave action they are often shorter as a result of increased abrasion (Rogers-Bennett et al. 1995; Silver and Brierton 1974). The relative size of the Aristotle’s lantern is also somewhat plastic, with larger relative sizes documented in sea urchins residing in nutritionally poor conditions (Ebert 1980; Rogers-Bennett et al. 1995, 2003). Studies have shown, however, that changes in jaw size were not significant between adult and juvenile red sea urchins from shallow and deep habitats allowing researchers to pool these data sets (Rogers-Bennett et al. 2003).

Red and purple sea urchins are abundant in the intertidal zone of rocky shorelines along the Pacific coast of North America and are strongly associated with kelp forest ecosystems (Rogers-Bennett 2007). Red sea urchin inhabit subtidal zones to ~90 m and are common residents off the upper west coast of North America with a geographic range that extends from Kodiak, Alaska (58ºN) to the tip of the Baja California peninsula, although abundances decline rapidly south of the Vizcaino Peninsula (27ºN) (Kato and Schroeter 1985; Rahman et al. 2014). Purple sea urchins inhabit intertidal and subtidal habitats up to 160 m in depth, ranging from the Cook Inlet, Alaska, to Cedros Island, Baja California, Mexico (Tegner 2001; Morris et al. 1980). Although this species is generally described as herbivorous and indeed feeds on any algae and surfgrass in the wild, it is capable of an omnivorous diet under laboratory conditions (Lasker and Giese 1954). Once touted as the largest sea urchin in the world, the red sea urchin has been surpassed by a deep-sea species known as the giant heart sea urchin (*Spherosoma giganteum*) that measures ~380 mm (Kroh and Mooi 2010).

Recent genetic and morphological research has resulted in proposals to rename the red sea urchin, *Mesocentrotus franciscanus* (Tatarenko and Poltaraus 1993; Vinnikova and Drozdov 2011; Kober 2012; Kroh 2012). However, some marine ecologists continue to place it within the *Strongylocentrotus* genus based on biological and ecological similarity (Rogers-Bennett 2013). In addition, the large body of data conducted under the framework of both species being under the same genus remains relevant.

## Growth, Survival, and Reproduction

Sea urchins are very long-lived organisms, with growth continuing as the individual ages (Tanaka 1982). Growth rates are highly variable for both species (Morgan et al. 2000a; Pearse and Cameron 1991), occurring faster in kelp forests compared to urchin barrens (Rowley 1990), and at times showing more variation within than between sites (Russell 1987). Survival rates for red and purple sea urchin are lower in southern California locations when compared with northern sites, which may be due to higher predation rates and/or higher stress from warmer water temperatures (Russell 1987). Water temperature and food availability significantly affect growth and development of sea urchin (Miller and Emlet 1999; Vadas 1977) with the colder waters of the Pacific Northwest coast being most suitable to long lived (>50 years) individuals (Ebert et al. 1999).

Red and purple sea urchins follow annual cycles of reproduction, with spatial variation based on food abundance. Studies on red sea urchins have shown that individuals inhabiting shallower waters where drift algae is more abundant have larger gonads (Carney 1991). Basch and Tegner (2007) documented peak gonad indices at intermediate subtidal depth (~8 m) in kelp forests, with intermediate size indices higher in the intertidal, and the lowest recorded indices in the deep subtidal (~18 m). Another study showed more than four times larger gonads for red sea urchins living in shallow water with abundant drift algae when compared to those inhabiting intermediate and deep-water environments (Rogers-Bennett et al. 1995). However, in cases where tidal flow systems retain abundant drift algae in both shallow and deep habitats, gonad indices are comparable (Rogers-Bennett 2007:399), suggesting the primary factor is drift algae abundance and not water depth per se.

Fertilization occurs in the water column with male spawning preceding and stimulating female spawning (Christen et al. 1986; Levitan 2002). Adult population demographics constrain patterns of gamete release influencing sperm/egg availability and competition. Reduction of sea urchin populations by fishing could dramatically affect fertilization success, causing precipitous decreases akin to Allee effects rather than steady declines (Rogers-Bennett 2007:399). One study showed that purple sea urchins, which tend to be more aggregated, have greater reproductive success than red sea urchins, suggesting a correlation between reproductive success and population density (Levitan 2002, 2004), which has implications for interpreting long-term patterns in archaeological contexts where harvesting is ongoing.

Red sea urchins grow rapidly at the onset and exhibit remarkable longevity, capable of living >100 years and possibly up to 200 years (Ebert 1999; Tegner 2001). Sexual maturity is reached at approximately two years of age (~50 mm TD) and targeted size at recruitment for sea urchin fisheries is ~90 mm TD, which correlates to a lifespan of 6-10 years depending on which growth model estimate is used (Ebert and Russell 1992; Ebert et al. 1999; Morgan et al. 2000a; Rogers-Bennett et al. 2003). Although rarely reached in southern California waters, in the cooler waters of the Pacific Northwest this species can grow up to ~200 mm TD, estimated at more than 200 years old (Ebert and Southon 2003).

Sexual maturity is attained early in purple sea urchins, at one to two years of age (~25 mm), but growth is highly variable due to phenotypic plasticity and depends strongly on food availability (Davis and Coffman 2011; Hart and Strathmann 1994; Strathmann et al. 1992). Maximum size is ~100 mm TD, but this size is rarely attained in southern California waters, being more prevalent further north in colder waters (Ebert and Russell 1988). My sampling confirms this size bias, as most (98%) purple sea urchin we collected contained a test diameter of less than 65 mm, with only one individual measuring above 70 mm. Gonadal activity is cyclical resulting in monthly and/or seasonal variation in volume dependent to some extent on ecological habitat and available nutrition, but generally highest in December with several smaller peaks throughout the year (Lasker and Giese 1954).

The seasonality of spawning has been shown to vary according to location and through time within the same location. Spawning of red sea urchins has been documented between June and November off the Pacific Coast of Baja California (Pearse et al. 1970), with a slightly earlier spring-summer season in central California (Bennett and Giese 1955). Studies on the Northern Channel Islands documented spawning between December and February along with a similar winter-spring spawning period off the coast of northern California (Ebert et al. 1999; Kato and Schroeter 1985), suggesting they may be a strong indicator for seasonal harvesting in some areas (i.e., where spawning has been documented as consistently seasonal). Additional studies have documented spawning seasons ranging from spring to summer along the Northwest Coast of North America (Bernard 1977; Kramer and Nordin 1975, 1979), although research off the coast of southern California failed to document a standard season for red sea urchin spawning, suggesting the population spawned throughout the year as a consequence of their abundant food supply (Baker 1973; Kato and Schroeter 1985).

### Settlement and Recruitment

Sea urchin settlement is higher within the Southern California Bight, as compared to northern California, and highly seasonal, occurring from February to July (Ebert and Russell 1994). Settlement is also higher in northern Channel Island sites than along the adjacent mainland coast (Schroeter et al. 2009), which may explain why sea urchin lenses have been described for Channel Island sites, but not for mainland middens. The density of kelp forest patches does not appear to affect sea urchin settlement (Schroeter et al. 1996), although red sea urchins and larger purple sea urchins are often most abundant near the outer edges of kelp beds (Pearse et al. 1970; Tegner and Dayton 1981). Purple sea urchins have been shown to settle in more aggregated batches than red sea urchins (Ebert et al. 1994), but adult red sea urchins also tend to aggregate in patches, even within kelp beds, where they are comparatively rare (Rosenthal et al. 1974). This "clumping" behavior often results in groups of ~50 red sea urchins, with individuals and smaller groups merging until this average is reached (Low 1975). In addition, studies have shown that sea urchin settlement is favored following warm water events and in years when summer water temperatures are warm with increased salinity (Morgan et al. 2000b; Wing et al. 2003).

Size-frequency distributions vary significantly between habitats and through time, attesting to recruitment dynamics in that the number of juveniles mirrors recruitment success over the past few years. Factors determining settlement and recruitment also appear to play out differently on various spatial scales, although food availability and juvenile settlement and survival were important variables in the progression of distribution patterns over time (Ebert 1983; Pearse et al. 1970). Size-frequency distributions are strongly affected by predator interactions, and thus useful for archaeological interpretations. For example, bimodal size distributions were noted near the boundaries of kelp beds in southern California, where size-specific predation by spiny lobster and sheephead removed most individuals between 50 and 80 mm in diameter (Tegner and Dayton 1977, 1981; Tegner and Levin 1983).

Several studies (Ebert and Russell 1988; Rowley 1989; Wing et al. 1995) suggest that settlement processes are more important at large spatial scales (i.e., along a coastline), though post-settlement processes become more important at intermediate spatial scales (i.e., on a reef). Spatial distribution patterns at smaller scales appear to be driven by post-settlement processes as well, such as differential mortality, which likely explains the abundance of juveniles with adults in barrens habitats when compared to kelp forests (Rowley 1989). Another example includes juvenile sheltering under the spine canopy of adults (Tegner and Dayton 1977; Rogers-Bennett et al. 1995). Juvenile red sea urchins have been shown to actively move towards adults, demonstrating that this spatial association is not a result of larval settlement patterns but rather a process that occurs after larval settlement (Cameron and Schroeter 1980; Rogers-Bennett 1989). Although both species are known to exhibit this behavior, it is more frequent among red sea urchins, whose spines are longer. Adult red sea urchins have also been shown to emit a secondary chemical cue that signals the presence of predators, which juveniles respond to but larger individuals ignore (Nishizaki and Ackerman 2005).

## Population Regulation

Sea urchin populations are regulated by biotic factors such competition, predation, and disease; but abiotic factors such as small-scale hydrodynamics, water flow, storm events and substrate topography also influence distributions and survival (Ebeling et al. 1985; Tegner and Dayton 1991). Intraspecific competition has been inferred based on size-frequency distributions which show that the majority of purple sea urchins in high-density sites are mid-sized and small compared to low density sites within reserves where most individuals are much larger (Rogers-Bennett 2007:404). As red and purple sea urchin overlap in range and distribution, interspecific competition is also prevalent and plays an important role in determining species abundance (Kato and Schroeter 1985). Red sea urchins dominate in sheltered and benign habitats, such as low intertidal and subtidal areas. Purple sea urchins dominate the harsher habitats of the middle intertidal and subtidal areas exposed to increased wave action; but red sea urchins are dominant in a one-on-one conflict situation, often using their longer spines to keep purple sea urchins away from optimal habitats by actively fencing with them (Ebert 1977; Schroeter 1978).

Naturally, predation will also affect sea urchin population density and size-frequency distributions, although very large individuals may obtain refuge in size (Rogers-Bennett 2007). When sea otters (*Enhydra lutris*) are present, abalones and sea urchins will also compete for deep-crevice habitat, which can be very limited (Hines and Pearse 1982). Where sea otters are present, they have the largest known predatory effect on sea urchins, which dramatically decline in population and become restricted to cryptic microhabitats where they can hide (Bertness et al. 2001; Estes and Duggins 1995; Lowry and Pearse 1973). A "keystone" paradigm has been described based on studies from Alaska where distinct differences were noted between rich kelp forest habitats containing sea otters, and kelp-free barrens habitats dominated by sea urchin with little else surviving (Estes and Duggins 1995; Simenstad et al. 1978). This "alternate stable state" paradigm contains a trophic cascade with sea otters at the top, followed by invertebrate herbivores like sea urchins, and algae at the base. As primary predators of sea urchin, sea otter presence is considered a good indicator of whether a nearshore habitat is dominated by algae or urchins, but it is not a good indicator of species composition and abundance within the community (Watson and Estes 2011).

Although this scenario was originally noted for the Pacific Northwest coast of America, it is now being observed further south, including offshore of Santa Barbara, as sea otter populations return (Rogers-Bennett 2007; Vogel 2000). However, the contributing factors off the southern California coast are complicated by the presence of additional key predators like lobster and sheephead, resulting in more localized barren conditions (see below).

Outside the range of sea otters, however, there appears to be a variety of potential community types beyond the two extremes of kelp forest and barrens (Foster and Schiel 1988), suggesting that: 1) care must be taken in applying this paradigm to other regions as additional factors play important roles in driving sea-urchin induced deforestation; and 2) more work is needed in kelp forests in the southern range of these sea urchin species beyond the reach of sea otters to examine dynamics in the absence of these top predators (Rogers-Bennett 2007).

Interspecific competition between sea urchins and abalone (*Haliotis* spp.) are of interest in archaeological contexts as they were both abundantly harvested by Native peoples and being algal grazers and consumers of drift kelp, they compete directly for food and available space in rocky reefs (Karpov et al. 2001; Leighton 1968; Tegner and Levin 1982). On the Northern Channel Islands, urchin lenses are also often associated with dense accumulations of abalone shell. Ecological studies have shown that abalone will out-compete sea urchins for space, even though sea urchins may be more efficient feeders (Lowry and Pearse 1973; Tegner 1980) and can more effectively resist starvation by taking advantage of dissolved nutrients (Pearse et al. 1970). In one study, adult red sea urchin abundance was negatively correlated with adult red abalone abundance, although purple sea urchins were not (Karpov et al. 2001). On the other hand, juvenile red abalones are more abundant inside marine reserves with adult red sea urchin than in fished zones without sea urchin (Rogers-Bennett and Pearse 2001). It seems their spine canopy facilitates the survival of juvenile abalone in much the same way it fosters the distribution of juvenile sea urchins.

In the Southern California Bight, the California spiny lobster (*Panulirus interruptus*) and sheephead (*Semicossyphus pulcher*) are also primary predators regulating sea urchin populations (Lafferty 2004; Tegner and Dayton 1981) and can exert enormous pressure when both are abundant. Although spiny lobsters have been shown to prefer smaller specimens, selecting purple over red and juveniles over adults (Tegner and Levin 1983), sheephead consume juveniles and adults indiscriminately with their massive jaws, and have been shown to regulate red sea urchin populations even in the absence of lobster (Cowen 1983). One study on San Nicolas Island showed a 26 percent increase in sea urchin recruitment when sheephead were artificially removed (Cowen 1981), demonstrating the strong effect this predator has on the abundance, distribution, and behavior of sea urchins. On the other hand, the mere risk of predation by spiny lobster reduced purple sea urchin foraging by 44 percent in one study (Matassa 2010). Bi-modal size frequency distributions, where small sea urchins hid in the spine canopy of large adults, were documented in aquarium studies in which spiny lobster predominantly preyed on medium sized individuals (Tegner and Levin 1983).

Birds have also been shown to prey heavily on sea urchin, impacting up to one-third of the population of purple sea urchin in the intertidal. Western gulls in southern California reportedly prefer purple sea urchin over other prey due to their high caloric value and chose large sea urchins over small individuals when pecking at them in the intertidal, but preferred smaller ones when dropping them to crack open (Snellen et al. 2007).

Although physical factors like wave force, and water motion and temperature, clearly have significant direct and indirect effects on sea urchin populations, they are more detrimental to red sea urchins. Purple sea urchins are more resilient in their ability to withstand wave disturbance, warmer waters, low oxygen and high-silt concentrations, partly due to their smaller size and shorter spines (Schroeter 1978). This resiliency allows purple sea urchins to inhabit more exposed intertidal habitats where they were more easily harvested by Native peoples. As noted above, geographic range is more extensive for red sea urchins, but purple sea urchins span a greater distribution of depths.

Ocean warming increases sea urchin grazing (Burnell et al. 2013) and can produce a variety of indirect effects such as reducing nitrogen levels thereby negatively impacting kelp growth and quality, and creating conditions where disease proliferates (Ebert et al. 1999; Richards and Kushner 1994). Data from southern California also suggests that ocean warming events enhance urchin-predator abundances in that recruitment success of spiny lobsters and sheephead were increased during warm water events (Cowen 1985). Commercial sea urchin fishing intensity is also influenced by warm water events, creating a negative-feedback loop sustaining sea urchin barrens conditions. It has been suggested that warmer waters during El Niño events result in malnourished sea urchins with decreased gonad quantity and quality and subsequently decreased fishing effort (Hammann et al. 1995; Kato and Schroeter 1985). Decreased harvesting in turn maintains high sea urchin populations, facilitating barrens-like conditions and active foraging by sea urchins, leading to overgrazing of kelp. When drift algae is scarce (i.e., during El Niño events), red sea urchins will migrate from deeper to shallower waters and red abalone will climb kelp stipes to feed on blades (Rogers-Bennett 2007) making them easier to harvest from boats and intertidal habitats.

## Kelp Forest Dynamics

Sea urchins are primarily herbivorous inhabitants of kelp forest and rocky subtidal communities, significantly affecting the abundance and distribution of algal assemblages with their voracious grazing (Lawrence 1975). Playing an important role in algal community structure, sea urchin population and demography can be indicative of the health of local nearshore kelp forests and seagrass meadows. Like most organisms, sea urchins undergo natural fluctuations in abundance through time, and since they are major structuring forces within kelp forest communities their population density has major implications, often resulting in alternating ecological states of "kelp beds" vs. "urchin barrens" (Harrold and Pearse 1987; Tegner and Dayton 2000). When urchin populations are kept in check by natural predators, they are part of a healthy kelp forest ecosystem. But at high population densities they are thoroughly destructive, grazing away large tracts of kelp and creating a barren environment where not much survives until urchin populations are decimated by disease or environmental conditions, allowing the recolonization of kelps and seaweeds (Scheibling and Anthony 2001). Researchers have long emphasized the negative effects of urchin herbivory in creating "barrens," but positive associations between urchin, mollusks, and fish species that reside in nearshore habitats are less well understood (Rogers-Bennett 2007).

Alternate community states including productive kelp beds with high species diversity and echinoid dominated rocky shores with low species richness have been described. The popular paradigm of a trophic cascade, where the removal of natural predators (i.e., by commercial fisheries) leads to major increases in sea urchin populations and subsequent kelp deforestation, have led to the common description of these two primary states. Although commercial fisheries have removed most sea urchin predators, including sea otters and spiny lobsters, and competitors such as abalone (Dayton et al. 1998; Estes et al. 1998; Lafferty 2004; Rogers-Bennett et al. 2002), subsequent deforestation is not always as straight forward as the paradigm implies (Rogers-Bennett 2007:395). In contrast to the Aleutians, the richer biodiversity of kelp forests (and multiple predators on sea urchins) off the California Coast leads to greater resilience of kelp forests and greater resistance to wholesale deforestation, even in the absence of sea otters (Steneck et al. 2002). Additional factors like predator density and the abundance of drift algae, also contribute significantly to sea urchin induced deforestation. A shortage of drift algae can trigger a switch in sea urchin feeding modes, from sedentary drift feeders to active foragers decimating standing algae in kelp forests (Ebling et al. 1985; Harrold and Reed 1985). As drift algae decreases in availability, sea urchins induce even more damage by grazing pits in kelp holdfasts, causing structural failure and further kelp loss when stressed by waves or a storm event (Leighton 1971; Tegner et al. 1995). Sea urchin foraging behavior changes when they overgraze; they congregate to form dense feeding aggregations or "fronts" that eat through kelp stipes, killing the organism (Dean et al. 1984). Overgrazing seems to be related to population density, with a specific threshold (2 kg $m^{-2}$) above which grazing is highly destructive to kelp forests (Breen and Mann 1976; Lawrence 1975). In addition to oceanic factors contributing to a lack of drift algae, researchers have suggested that major recruitment events may also increase sea urchin densities to destructive levels (Watanabe and Harrold 1991).

In a global summary of kelp forests, Steneck et al. (2002) concluded that almost all studied regions experienced deforestation in the form of urchin barrens at some point in the past, though most are likely related to human fishing to some extent (Steneck 2013). As ecosystem drivers in kelp forest ecosystems, sea urchin abundance influences community diversity and structures subtidal kelp forests, potentially resulting in extreme barrens conditions when they are left unchecked by natural predators. However, species richness and the diversity of predators in the ecosystem are also key components to the equation, with barrens being more common in ecosystems containing low species diversity and only one primary predator of sea urchin (e.g. sea otters in the Pacific Northwest) as opposed to ecosystems with several predators (e.g. sea otters, lobster, and sheephead in southern California waters) and high species diversity (Steneck 2013).

### Fisheries: Conservation and Management

In spite of multiple declines in landings in recent decades, some of which were precipitated by strong El Niño events in the 1980s and 1990s (Kato and Schroeter 1985; Kalvass 2000), the California red sea urchin fishery continues to dominate along the west coast of North America (Rogers-Bennett 2013). The Baja California red sea urchin fishery also experienced a drastic decline (from 8,493 t in 1986 to 1,590 t in 1987) due to the 1987 El Niño event which affected roe quality and led to decreased fishing effort (Andrew et al. 2002). Recent analysis has estimated that a slight increase (10%) in fishing pressure could lead to a collapse of the population (Jurado-Molina et al. 2009).

Current management strategies rely on size limits and seasonal closures (Kalvass and Hendrix 1997), but size minimums may be more beneficial in maintaining adequate populations of large reproductive adults (Roger-Bennett et al. 1995; Birkland and Dayton

2005) which are extremely slow to recover from over fishing (Rogers-Bennett et al. 1998). Marine scientists have outlined a number of life history features that mirror some fish taxa and make red sea urchin in particular susceptible to overfishing. These include extreme long life (Ebert and Southon 2003), high densities required for fertilization success (Levitan et al. 1992), successful recruitment is patchy (Pearse and Hines 1987), fishery sized adults shelter juveniles (Tegner and Dayton 1977), and populations structured as metapopulations (Rogers-Bennett et al. 1995).

Aspects of long-term patterns in kelp forest ecosystem dynamics can be documented in archaeological faunal data sets from coastal middens and can contribute to discussions of relevant variables (i.e., predator dynamics) at various scales (i.e., regional or localized). For example, my study supports the notion that restricting harvest of the largest sized individuals by imposing a maximum size limit for capture may be more beneficial and productive than imposing a minimum size limit for harvest by showing that people consistently harvested medium sized sea urchin for millennia (in addition to a variety of mollusk, crustacean, and marine mammal resources) without causing an ecosystem collapse.

## Nutrition

Although the meat package provided by sea urchins is relatively small when compared to many other commonly harvested crustaceans, mollusks, and fish found in the same nearshore habitats, the high degree of nutrition available in these bite sized morsels is incomparable even among highly nutritious marine resources. The nutritional content (kcal) of sea urchin gonads, or roe, is higher than many mollusks, fish, and marine mammals (Table 5.1). Vitamin and mineral composition have also been shown to be relatively high. Sea urchin gonads are particularly high in Vitamin A (Table 5.2) and contain more potassium (P) than all tested marine organisms except kelp, and more zinc (Zn) than many mollusks and even some fish (Table 5.3). Nutritional requirements including macro- and micro-nutrients, vitamins, minerals, protein, carbohydrates, dietary fiber, and lipids require a balancing of available resources to form nutritionally sustainable menus. Even though marine resources are generally high in nutrition, the details of nutritional packages vary between organisms requiring people to consume a variety of foods for optimal health.

Marine resources in general are exceptional purveyors of natural bioactive compounds that are often not found in terrestrial plants and animal products. Like other marine resources, sea urchin roe is rich in beneficial bioactive compounds such as polyunsaturated fatty acids (PUFAs), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which have significant preventative effects on cardiovascular diseases and cancer (Rahman et al. 2014 and references therein). These compounds have also been identified as critical to the proper growth and function of large human brains and the prevention of maladies such as cretinism, hypothyroidism, and goiter (see Cunnane and Stewart 2010). In addition, recent research has shown that sea urchin roe contains a euphoria-causing chemical similar to what is found in cannabis. Specifically, sea urchin gonads contain a chemical neurotransmitter called an anandamide (also known as arachidonoylethanolamide or AEA; Susman 2012). Although there is no way to know for sure, detection of this property may have led to the prestige attributed to sea urchins by some Indigenous cultures and the lasting enjoyment of this food by many modern cultures.

## Materials and Methods

In 2011, 238 live urchin specimens (131 purple and 107 red sea urchins) were collected by colleagues and myself from two locations along the southwest coast of North America to test the efficacy of using urchin hemipyramids as a proxy for size (i.e., Test Diameter [TD]) of specimens harvested in the past. Thirty-nine purple sea urchins with TDs measuring ~26-50 mm were collected in December 2011 from intertidal rocks and boulders during low tide at Puerto Santo Tomas, south of the city of Ensenada, in Baja California, Mexico, and 52 red sea urchins with TDs measuring ~68-98 mm were purchased from local fishermen at the same location. Fifty-five red and 92 purple sea urchins measuring ~32 to 105 mm and ~45 to 77 mm respectively were collected at low tide along the rocky northwest coast of Alta California’s San Nicolas Island in June of

**Table 5.1.** Energy and macronutrient composition of sea urchin and some other key marine resources

| | | | **Macronutrients (per 100g portion)** | | | |
|---|---|---|---|---|---|---|
| **Common Name:** | **Scientific Name:** | **Energy (kcal):** | **Water:** | **Protein:** | **Lipid:** | **Carbohydrates:** |
| [1]Abalone | *Haliotis* spp. | 105 | 74.56 | 17.1 | 0.76 | 6.01 |
| [2]Sea urchin | *Strongylocentrotus* spp. | 120 | 73.8 | 16 | 4.8 | 3.3 |
| [1]Rockfish | *Sebastes* spp. | 90 | 79.08 | 18.36 | 1.34 | 0 |
| [1]Mackerel | *Scomber* spp. and *Trachurus* spp. | 158 | 70.15 | 20.07 | 7.89 | 0 |
| [1]Bearded seal (flesh) | *Erignathus barbatus* | 110 | 69.6 | 26.7 | 0.4 | 0 |
| [1]Bearded seal (liver) | *Erignathus barbatus* | 116 | 74.2 | 18.16 | 3.3 | 2.9 |
| [3]Sea lettuce | *Ulva* spp. (dried) | 361.4 | - | 24.4 | 1.8 | 61.8 |
| [3]Nori | *Porphyra* spp. (dried) | 305.9 | - | 34.2 | 0.7 | 40.7 |
| [3]Kelp | *Laminaria* spp. (dried) | 243.2 | - | 16.1 | 2.4 | 39.3 |

[1] USDA National Nutrient Database for Standard Reference, Release27

[2] Science and Technology Agency of Japan – Tables of Food Composition in Japan: Fishes and Shellfishes

[3] Kumar et al. 2008

**Table 5.2.** Vitamin composition of sea urchin and a sample of primary marine resources

| | | | | | | **Vitamins (mg)/100g edible meat** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Common Name:** | **Scientific Name:** | **A** | **$B_1$** | **$B_2$** | **$B_3$** | **$B_5$** | **$B_6$** | **$B_9$** | **$B_{12}$** | **C** | **E** | **K** |
| [1]Abalone | *Haliotis* spp. | 0.002 | 0.19 | 0.1 | 1.5 | 3 | 0.15 | 0.0005 | 0.00073 | 2 | 4 | 0.023 |
| [2]Sea urchin | *Strongylocentrotus* spp. | 0.58 | 0.1 | 0.44 | 1.1 | 0.72 | 0.15 | 0.0036 | 0.0013 | 3 | 3.6 | 0.027 |
| [1]Rockfish | *Sebastes* spp. | 0.004 | 0.023 | 0.187 | 2.393 | 0.333 | 0.21 | 0.009 | 0.00139 | - | 0.36 | - |
| [1]Mackerel | *Scomber* spp. and *Trachurus* spp. | 0.019 | 0.111 | 0.421 | 8.32 | 0.316 | 0.33 | 0.0151 | 0.0044 | 2 | 1 | 0.0001 |
| [1]Bearded seal (flesh) | *Erignathus barbatus* | - | 0.2 | 0.26 | 5.9 | - | - | - | - | - | - | - |
| [1]Bearded seal (liver) | *Erignathus barbatus* | 4.88 | - | - | 1.8 | - | - | - | - | - | - | - |
| [1]Kelp | *Laminaria* spp. | 0.006 | 0.05 | 0.15 | 0.47 | - | - | 0.18 | - | 3 | 0.87 | 0.066 |

**Table 5.3.** Mineral composition for sea urchin and other primary marine meat resources

| | | | | | | **Minerals (mg)/100g edible meat** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Common Name:** | **Scientific Name:** | **Ca** | **Fe** | **Mg** | **P** | **K** | **Na** | **Zn** | **Cu** | **Mn** |
| [1]Abalone | *Haliotis* spp. | 31 | 3.19 | 48 | 190 | 250 | 301 | 0.82 | 0.196 | 0.04 |
| [2]Sea urchin | *Strongylocentrotus* spp. | 12 | 0.9 | 27 | 390 | 340 | 220 | 2 | 0.05 | 0.05 |
| [1]Rockfish | *Sebastes* spp. | 14 | 0.3 | 27 | 205 | 386 | 74 | 0.36 | 0.034 | 0.011 |
| [1]Mackerel | *Scomber* spp. and *Trachurus* spp. | 23 | 1.16 | 28 | 125 | 406 | 86 | 0.67 | 0.093 | 0.015 |
| [1]Bearded seal (flesh) | *Erignathus barbatus* | 10 | 12.9 | - | 198 | - | - | - | - | - |

2011. Live collected sea urchins contained varying amounts of roe, which was not quantified for this study.

Although availability and quality of food influences the growth rate of sea urchins (Ebert 2001), the average size of an animal can be estimated from hemipyramid length because jaw size is proportional to test diameter (Rogers-Bennett et al. 2003). The distribution of harvested sizes (i.e., TD) can then be inferred from length measurements of hemipyramids, and the age distribution of harvested specimens can be inferred from the estimated sizes (Cerrato 1980), allowing for a reconstruction of population demographics for localized nearshore habitats. Biological studies have shown that change in jaw size is an appropriate indicator of growth and water depth does not affect growth significantly (Rogers-Bennett et al. 2003). Another study showed a linear relationship between test diameter and height with no seasonal variation in slope (Kramer and Nordin 1978). A comparison between the modern red sea urchin I sampled in this study and the equation developed by Rogers-Bennett et al. (2003) confirmed this conclusion, with the relationship between test diameter and jaw length for red sea urchin revealing relative homogeneity (ANOVA, F=0.02, n=212, p=0.8824). Even though individual values of measured and predicted test diameters were not identical, the sum of the differences between them reveals no strong directional bias.

Research by Campbell (2008b) demonstrated a linear allometric relationship between jaw size and TD using the means and standard deviations of several hemipyramid ratios for three species of *Strongylocentrotus* (including the two discussed here), although study sample size was relatively small (n=8 to 24). Several ratios calculated for hemipyramids demonstrated the efficacy of this relationship, but I chose a single measurement, hemipyramid length (HL), as a more feasible approach for archaeologists trying to quantify tens of thousands of hemipyramids. Attempting the construction of a useful and viable method for estimating sizes of large numbers of harvested urchins in archaeological assemblages, I measured hemipyramid length from the oral tip to the place where the dorsal tip of the projecting process and the base of the broad flat plate of the hemipyramid coincide on the calipers (Figure 5.2). This is somewhat modified from Campbell’s (2008b:22) length measurement, which extends from the oral

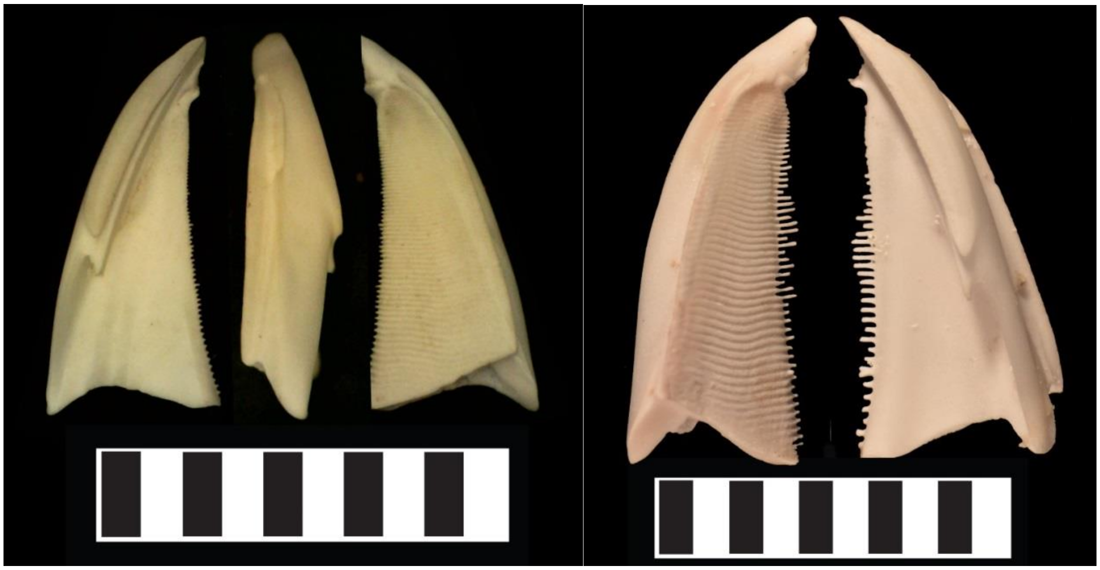


**Figure 5.2.** Left: red sea urchin hemipyramids. Right: purple sea urchin hemipyramids.

tip to the dorsal tip of the projecting process, as it is a more feasible measurement. My goal is to provide an estimate of size, by way of test diameter, for harvested sea urchin, which will contribute to our understanding and discussion of human interactions with sea urchins and kelp forest habitats in the past.

### Morphometrics Performed on Modern Sample of Sea Urchin

All live specimens were collected and processed within hours of being collected. Test diameters for all specimens were measured using electronic calipers to two decimal places before being crushed to remove the Artistotle's lanterns (mouth/jaw), which were bagged, labeled and frozen for return to the California Coastal Archaeology Lab (CCAL), California State University, Los Angeles (CSULA). Once at the CCAL, each specimen was boiled and cleaned using tweezers, toothpicks, and toothbrush, then left to air-dry. Once they were clean and dry, the length of each intact hemipyramid was measured using electronic calipers to two decimal places and entered into an Excel spreadsheet. I measured a total of 2124 whole hemipyramids (89%) for this analysis; broken elements (11%) were not included. All measured hemipyramids from an individual were averaged to determine the mean size of hemipyramid length for each individual, and standard deviations were calculated. Summary statistics for the modern sample of sea urchin used in this study are presented in Table 5.4.

### Morphometrics Performed on Archaeological Sea Urchin Samples

Hemipyramids were separated from other archaeological sea urchin remains (i.e., test fragments, spines, etc.) and lengths of intact specimens were measured using digital calipers and placed in bags representing .05 mm incremental size categories. Due to the exceptionally large number (>37,000) of specimens in this sample recording each individual measurement was not feasible, although it might be productive in studies with smaller sample sizes (i.e., Campbell 2008a, b; Gutiérrez-Zugasti et al. 2016). Examining the distribution of sizes at this small scale is clearly useful, but I also created a set of standardized size categories that can be used to examine age/size distributions more easily in extremely large assemblages like that presented here (Table 5.5).

The "Tiny" size category is based on the average size of purple sea urchins when they reach reproductive potential (~2 years, 25 mm). This size category includes individuals that are too small/young to reproduce and thus would not be viable food products for human foragers. It seems clear people understood this as there is only a handful (0.005%) of specimens in this size range out of the thousands that were quantified. These may have been collected by children, still learning what the desired size range was. The rest of the size categories are somewhat arbitrary in that they represent individuals within the reproductive stage of life and thus contain some degree of nutrition/food. The Small and Medium size ranges encompass purple urchin of reproductive age (26-51 mm) but are below the size of sexual reproduction for the juvenile red sea urchin (~50 mm), so likely consist of mostly purple urchin as well. As size ranges for purple and red sea urchin overlap extensively, all but the largest size category may potentially contain either species, though as red sea urchin reach sexual maturity at ~50 mm TD, anything in and below the Medium size category is most likely purple sea urchin. The Large and X-Large categories encompass adult purple and adult red sea urchin, so could be either species, but the X-Large category likely consists of red

**Table 5.4.** Summary statistics for sea urchin test and hemipyramid measurements on modern specimens from Alta (SNI*) and Baja (PST**) California.

| | Sea Urchin Test Measurements | | | | | Sea Urchin Hemipyramid Measurements | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Max D (mm) | Min D (mm) | Mean D (mm) | SD (mm) | N (whole) | % | Max L (mm) | Min L (mm) | Mean L (mm) | SD (mm) |
| SNI | | | | | | | | | | | |
| *S. purpuratus* | 92 | 76.64 | 45.31 | 57.81 | 4.2 | 777 | 85 | 15.07 | 9.53 | 12.04 | 0.09 |
| *M. franciscanus* | 55 | 105.21 | 31.79 | 84.65 | 15.32 | 507 | 92 | 19.8 | 7.58 | 16.36 | 0.09 |
| PST | | | | | | | | | | | |
| *S. purpuratus* | 39 | 50.3 | 26.3 | 39.38 | 6.94 | 373 | 96 | 11.2 | 5.6 | 8.81 | 0.06 |
| *M. franciscanus* | 52 | 98.24 | 67.1 | 77.97 | 5.67 | 467 | 90 | 19.11 | 13.77 | 16.26 | 0.07 |

*SNI = San Nicolas Island, Channel Islands, California, USA

**PST = Puerto Santo Tomas, Baja California, Mexico

**Table 5.5.** Sea urchin primary size categories used in this analysis

| **Size Category:** | **Test Diameter (mm):** | **Hemipyramid Length (mm):** |
|---|---|---|
| Tiny | ≤ 25 | 4 – 5.99 |
| Small | ~26 – 35 | 6 – 7.99 |
| Medium | ~36 – 51 | 8 – 10.99 |
| Large | ~52 – 65 | 11 – 13.49 |
| X-Large | ~66 - 99 | 13.5 – 18.99 |
| Red only | 100 + | 19 + |

sea urchin in southern California waters, where purple sea urchins are not known to grow to maximum size. The Red Only category defines the maximum size for purple urchin even though this size is not currently attained in southern California waters either (more prevalent in cooler waters to the north) but may be more useful when analyzing assemblages from the Northwest Coast of North America. A series of two-way analysis of variance (ANOVA, Sokal and Rohlf 2012) tests were then used to examine the relationship between hemipyramid count, hemipyramid density, and relative abundance of hemipyramids between archaeological components (stratum/level) using these primary size classes.

I wish to emphasize that these categories can be manipulated to address various datasets and might require the development of additional categories to better investigate finer-grained patterning in sizes of harvested specimens, or the combining of several categories to address larger scale patterns. As this data set consisted predominantly of smaller sized individuals, I defined this range more extensively, and as so few individuals were in the larger size categories they were collapsed. But the opposite might be true for other datasets, requiring further distinction within the larger size categories, etc. I encourage zooarchaeologists to use this formula to create meaningful categories for their specific datasets, which may or may not be the same as those used here.

## Allometry

Relationships between test diameter (TD) and hemipyramid length (HL) were tested between species and locations using log modified variables. All statistical analyses were performed using the SAS 9.4 statistical computing program. A series of analyses of covariance (ANCOVA, Sokal and Rohlf 2012) tests examined the linear relationships between modern specimens of red and purple sea urchins from San Nicolas Island, Alta California, and Puerto Santo Tomas, Baja California, revealing relative homogeneity of slope and intercept and resulting in a linear equation that can be used for specimens of both species as required by archaeologists. Following a series of ANCOVA tests, a regression analysis was also run using the same measurements from modern specimens to confirm accuracy. Lastly, an analysis of covariance was performed comparing the raw data to both linear formulas to confirm similarity of results.

## Results

### Modern Specimens: Allometric Results

My analysis revealed linear relationships between TD and HL for purple and red sea urchins from two locations along the southwest coast of North America. A series of analysis of covariance (ANCOVA, Sokal and Rohlf 2012) tests indicate that the slopes of the natural log of jaw size (HL) as a function of the natural log of test diameter (TD) are relatively homogenous between species and locations. Results from ANCOVA tests do not show a significant difference in the relationship between HL and TD for purple (F=2.23, n=131, p[slope]=0.1382, p[intercept]=0.1597) or red (F=1.7, n=107, p[slope]=0.1954, p[intercept]=0.2407) sea urchin from both locations. Analyses of covariance also show no significant difference between both species collected from San Nicolas Island (F=0.38, n=147, p[slope]=0.5409, p[intercept]=0.492) or at Puerto Santo Tomas (F=2.8, n=91, p[slope]=0.0979, p[intercept]=0.1309). The four samples were then combined and tested against each other, which also revealed no significant difference in linear relationship (F=2.14, n=238, p[slope]=0.0964, p[intercept]=0.1757). In addition, a regression analysis using data from both species and locations revealed a strong linear relationship (DF = 236, n=238, $r^2$ =0.9513). The original dataset was then tested against the expected outcomes using the ANCOVA and regression formulae and linear functions were shown to be homogenous (F=0.04, n=714, p[slope]=0.9646, p[intercept]=0.8229; Figure 3). These analyses indicate there is no significant difference in the allometric relationship between both species and locations, allowing us to estimate TD for archaeological assemblages in which purple and red urchins are indistinguishable. The large size of our sample robustly indicates that potential differences are not statistically significant and are strong enough to provide an estimate of sea urchin size from archaeological hemipyramids. The formulae derived from this analysis are as follows:

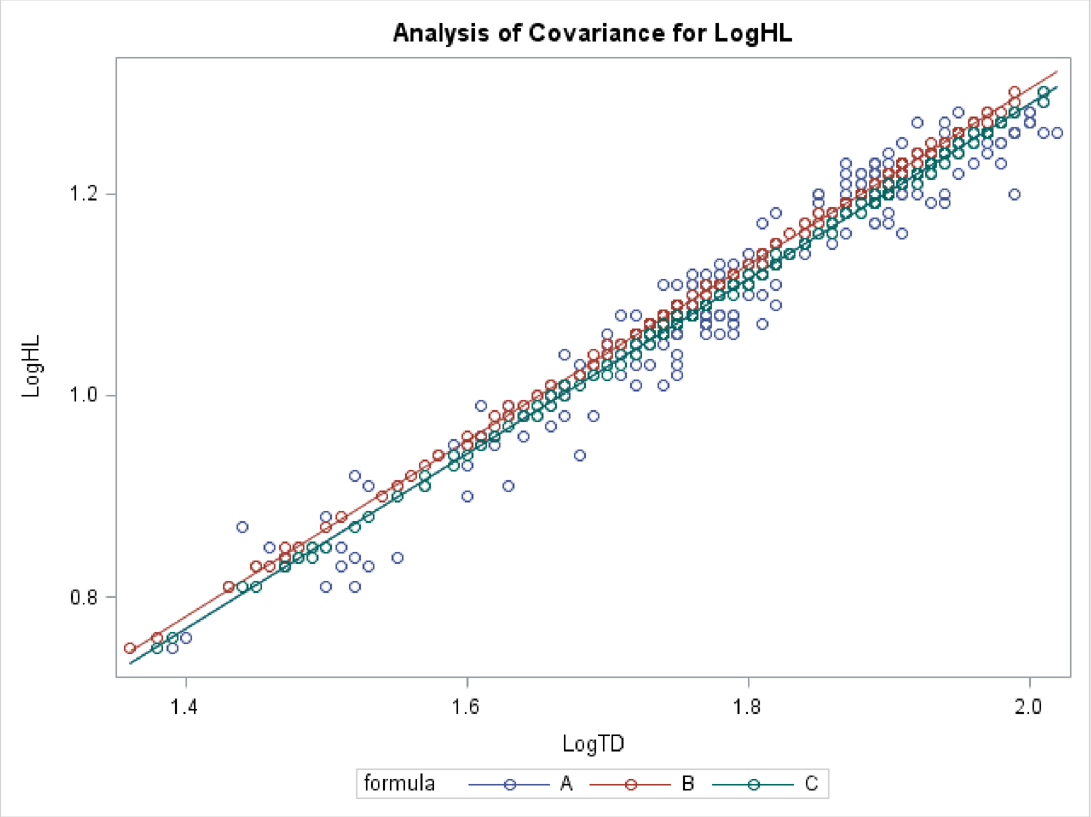


**Figure 5.3**. ANCOVA analysis depicting homogeneity between the linear functions (hemipyramid length and test diameter) of the modern sea urchin dataset (formula A, blue line) and the expected outcomes using the formulae developed through ANCOVA (formula B, red line) and regression (formula C, green line) analysis. Statistical analyses and graph were produced using SAS 9.4 software.

ANCOVA derived formula = logHL + 0.44276/0.86535

Linear regression derived formula = logHL + 0.43337/0.86818

where logHL is equivalent to the log transformed hemipyramid length in both equations.

## Archaeological Case Study: CA-SMI-603

Cave of the Chimneys (CA-SMI-603) is a multi-component rockshelter site located on a sea cliff near Bay Point on northeastern San Miguel Island (Ainis 2012; Ainis et al. 2011; Vellanoweth et al. 2003). Excavations were undertaken in the late 1990s by a team of archaeologists from the University of Oregon, with paleontological and archaeological materials being analyzed by a number of researchers over the years (see Chapter I). Radiocarbon dates reveal a near continuous occupational sequence spanning roughly 8400 to 2200 cal BP with ephemeral occupations until ~1000 cal BP. One of the Middle Holocene layers dated between ~3900 and 4400 cal BP, Stratum IV, contained an unusually high density of sea urchin remains (almost 10 kg representing over 2000 individuals, Figures 5.4 and 5.5), suggesting a similar pattern as observed at other "urchin lenses" on the Channel Islands. Stratum IV also contains slightly lower relative abundances by weight of mussel (28%) and abalone (26%) shells when compared to sea urchin (29%). Mussel and abalone are the primary shell types in all the other components at this site and most island middens; they have thick, heavy shells, making this proportion quite significant. Mussel and abalone produce much higher meat yields and seem to have been preferred for this reason, but we should be mindful of other factors affecting human collection choices, like taste and preference, food taboos, etc. Amazingly, several sea urchin tests excavated from this unit remained intact and field notes indicate that more were intact at the time of excavation. One possible reason for why intact sea urchins were deposited in this rockshelter includes boiling them whole, which may contribute flavor to a broth without crushing the test. Or, perhaps some of the collected specimens were tossed aside without being eaten because they were too small or were known not to contain significant gonad mass. This is suggested by a handful of measured specimens in the "tiny" category that are below the age/size of sexual maturity and thus likely devoid of gonads (the edible meat).

As part of this study, I developed a series of indices that can be used to evaluate the relative abundances of sea urchin compared to other primary shell taxa in archaeological middens. Table 6 demonstrates the relative abundance of urchin remains in the various cultural strata in relation to other primary shellfish taxa in the same components and provides index measures that are used to interpret the significance of these data.

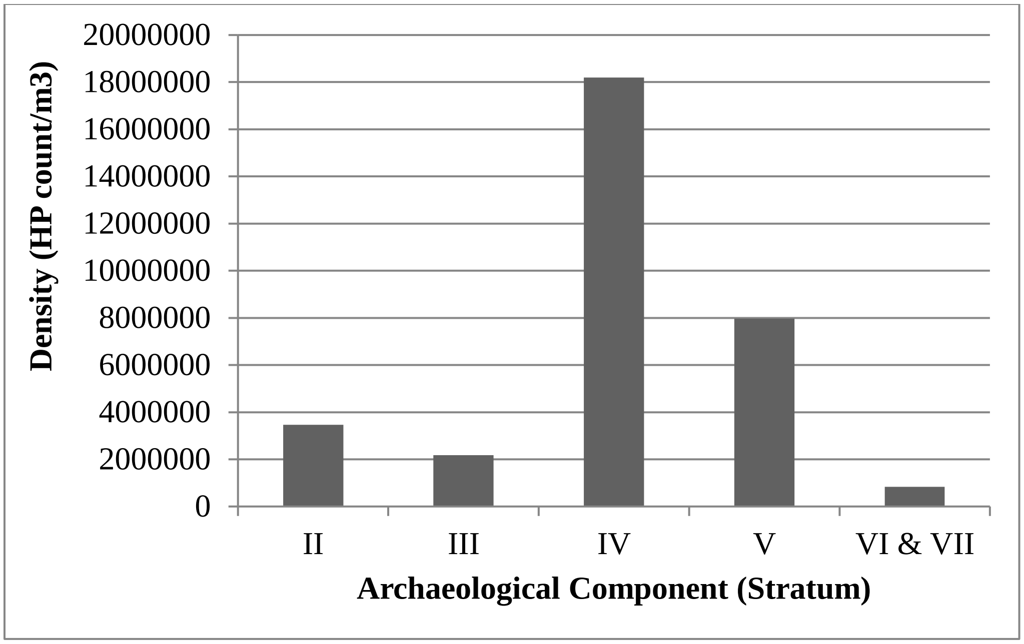


**Figure 5.4.** Density values for hemipyramid counts in all primary components at CA-SMI-603.

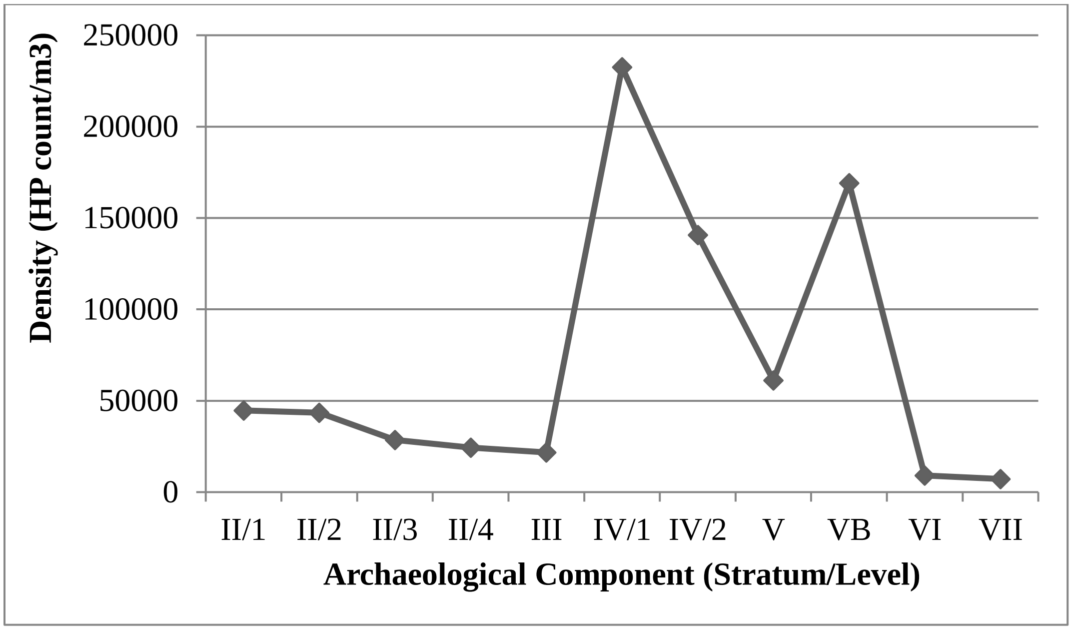


**Figure 5.5.** Hemipyramid density (HP count/m$^3$) spread out for each component (strata and levels) in Unit 1 at CA-SMI-603.

**Table 5.6.** Sea urchin distribution and indices for Cave of the Chimneys

| | Archaeological Component (Stratum) | | | | | |
|---|---|---|---|---|---|---|
| | **II** | **III** | **IV** | **V** | **VI** | **VII** |
| Urchin weight (g) | 4091 | 2520 | 9871 | 7753 | 1425 | 365 |
| Urchin MNI | 1161 | 338 | 2090 | 1211 | 319 | 114 |
| Urchin density (wt/m$^3$) | 12946 | 18000 | 54536 | 51007 | 11221 | 4294 |
| Urchin density (MNI/m$^3$) | 3674 | 2414 | 11547 | 7967 | 2512 | 1341 |
| Weight (g)/MNI (mean size index) | 3.52 | 7.46 | 4.72 | 6.4 | 4.47 | 3.2 |
| Urchin/shellfish Index | 0.25 | 0.26 | 0.29 | 0.22 | 0.08 | 0.04 |
| Urchin/abalone+mussel Index | 0.4 | 0.42 | 0.55 | 0.44 | 0.11 | 0.04 |
| Urchin/Red abalone Index | 1.21 | 1.28 | 1.58 | 2.01 | 2.77 | 3.23 |
| Urchin/Black abalone Index | 1.82 | 1.5 | 4.59 | 1.92 | 2.15 | 0.42 |
| Urchin/Mussel Index | 0.93 | 1.10 | 1.06 | 0.79 | 0.12 | 0.05 |
| Urchin/Turban snail Index | 3.66 | 7.22 | 3.09 | 1.1 | 0.79 | 0.53 |
| Estimated meat yield (g) | 2,385 | 1,469 | 5,755 | 4,520 | 831 | 213 |
| Estimated meat yield (% shellfish) | 21% | 21% | 26% | 22% | 13% | 6% |

* All “Index” values were calculated using weight (g) measures. Raw data and some values are from Ainis (2012).

### *Archaeological Sea Urchins: Morphometrics*

I sorted and identified all archaeological faunal materials and completed all length measurements of each intact hemipyramids from this archaeological assemblage. As there is not a conclusive way to differentiate test elements from red or purple urchins, all fragments were identified as *Strongylocentrotus* spp. Sorted fragments were weighed and quantified using the NRE method for determining the minimum number of individuals (MNI) with hemipyramids from the Aristotle's lantern portion of the urchin. Being hexagonal echinoderms, urchins possess five pyramids, or 10 hemipyramids. Although a number of elements can be used to establish sea urchin MNI (Campbell 2008b), hemipyramids were clearly the most frequent in this assemblage leading to their selection. A modification of this method for establishing MNI includes siding the hemipyramids and only tallying and measuring the side (left or right) with the highest counts (i.e., Zugasti et al. 2016). However, personal experience using this method resulted in significant differences in resulting trends depending on which side was examined so I chose to conduct the most comprehensive analysis possible using all intact hemipyramids of both left and right sides.

Over 26 kg of sea urchin remains were recovered from Unit 1, representing ~5,290 individuals. However, only ~4228 individuals were examined in this study. Of these, 37,412 hemipyramids were intact enough to permit the calculation of a hemipyramid length measurement, constituting the bulk of the assemblage (~78%) and the largest sample size I am aware of. Specimens intact enough to allow a length measurement accounted for between 64% and 89% of each tested component (i.e., stratum/level), providing robust sampling throughout the assemblage (Table 5.7 and Figure 5.6). Stratum IV contained the lowest percentages of broken hemipyramids by far (11-15% compared to 21-36% for all other components) suggesting taphonomic variables played out differently for this stratum. Potential reasons for this low percentage of broken hemipyramids could be: 1) rapid deposition covering sea urchin remains before they could be trampled and broken, and/or 2) this deposit was brushed or swept up against the wall of the rockshelter soon after deposition, also preventing trampling on the level of the other assemblages. The overall size distributions oscillate throughout the sequence, but

**Table 5.7.** Distribution of whole and broken hemipyramids for each archaeological component within Unit 1 at CA-SMI-603.

| Stratum/Level | Hemipyramid (count) | Measured (count) | % Measured | Unmeasured (count) | % Unmeasured |
|---|---|---|---|---|---|
| II/1 | 2,724 | 1,750 | 64% | 974 | 36% |
| II/2 | 2,088 | 1,352 | 65% | 736 | 35% |
| II/3 | 1,826 | 1,278 | 70% | 548 | 30% |
| II/4 | 1,562 | 1,058 | 68% | 504 | 32% |
| III | 3,234 | 2,562 | 79% | 672 | 21% |
| IV/1 | 13,258 | 11,824 | 89% | 1,434 | 11% |
| IV/2 | 9,847 | 8,368 | 85% | 1,479 | 15% |
| V | 7,708 | 5,313 | 69% | 2,395 | 31% |
| Vb | 4,399 | 2,803 | 64% | 1,596 | 36% |
| VI | 969 | 657 | 68% | 322 | 32% |
| VII | 612 | 445 | 73% | 167 | 27% |
| Total combined | 48,237 | 37,410 | 78% | 10,827 | 22% |

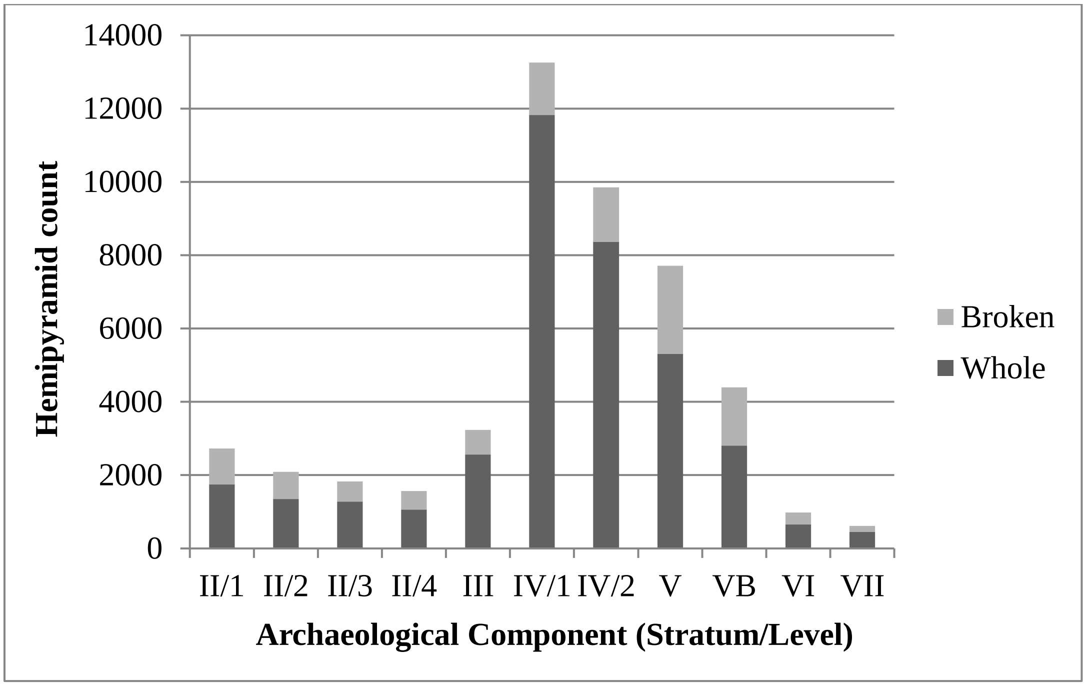


**Figure 5.6.** Distribution of broken and whole hemipyramids for each component at CA-SMI-603.

median and mode values are generally on the lower side of the range (Figure 5.7). As exact length of hemipyramids was not quantified (they were placed in 0.5 mm categories), mean values are not attainable, but examining the distribution of median and mode values allows similar inferences.

Overall, size estimates suggest that most specimens were in the Small (30%) and Medium (64%) sized categories, and thus likely represent a fishery focused on the harvesting of intertidal purple sea urchin as they are below the size of mature red sea urchin. When combined, the sea urchin hemipyramid assemblage for Cave of the Chimneys resembles a relatively normal bell curve, but it is positively skewed (1.01) with low kurtosis (-0.63) (Figure 5.8), likely driven by the low numbers in the larger sizes creating a light but spread out tail. When samples are broken down by component, distributions are all platykurtic and positively skewed (Figure 5.9). Size-frequency distributions are positively skewed in every component (range from 1.3 to 1.7), showing that higher amounts of larger individuals (right tail) are present; this is particularly apparent in Stratum III and Stratum IV, Level 2. All components also present a platykurtic distribution (range from 0.4 to 1.8), again showing thinner tails and overall shorter distributions. Skewdness and kurtosis values are likely driven by the fact that there are more categories of “larger” hemipyramids when compared to the number of categories for the smaller ones. This also confirms that the bulk of the distribution is in the small/medium size range as opposed to medium/large size range.

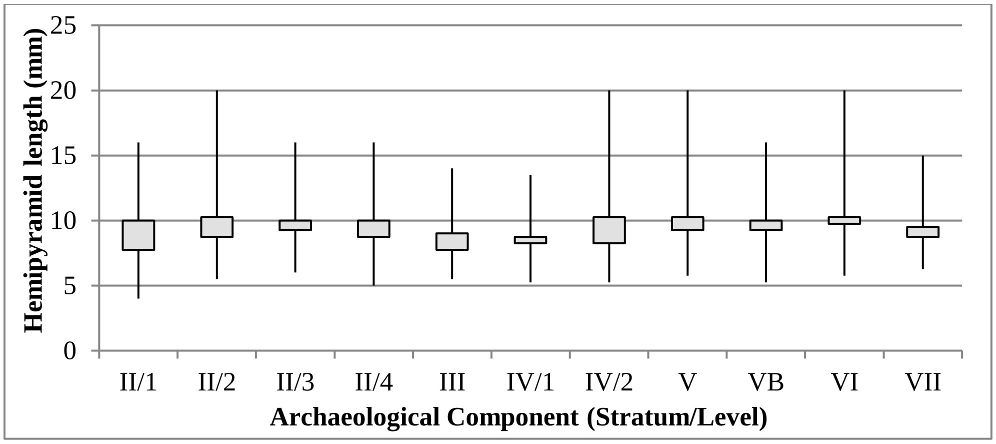


**Figure 5.7.** Summary statistics of hemipyramid size range by component at CA-SMI-603. Lines represent maximum and minimum measurements and boxes represent difference between the median and mode for each component.

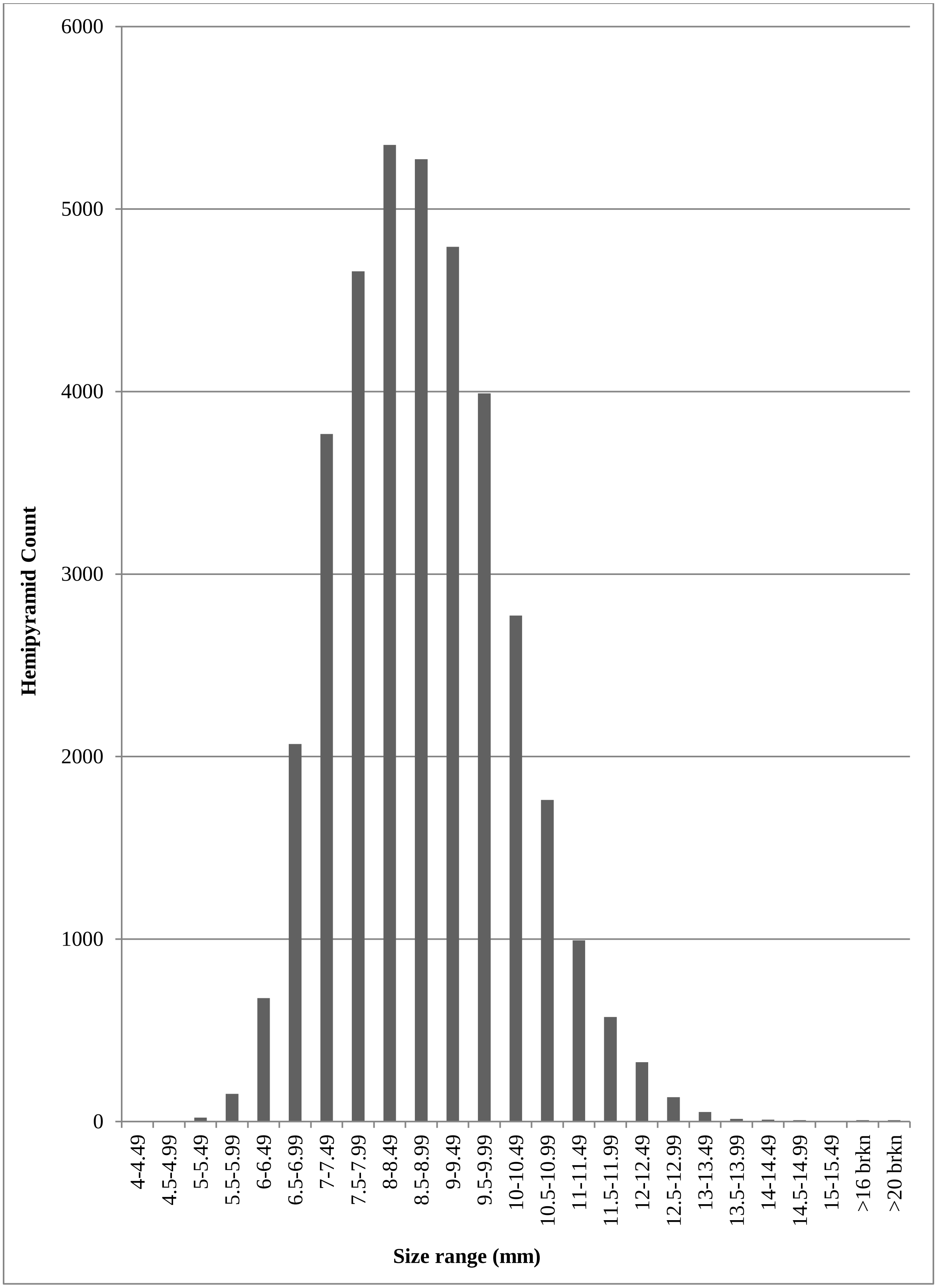
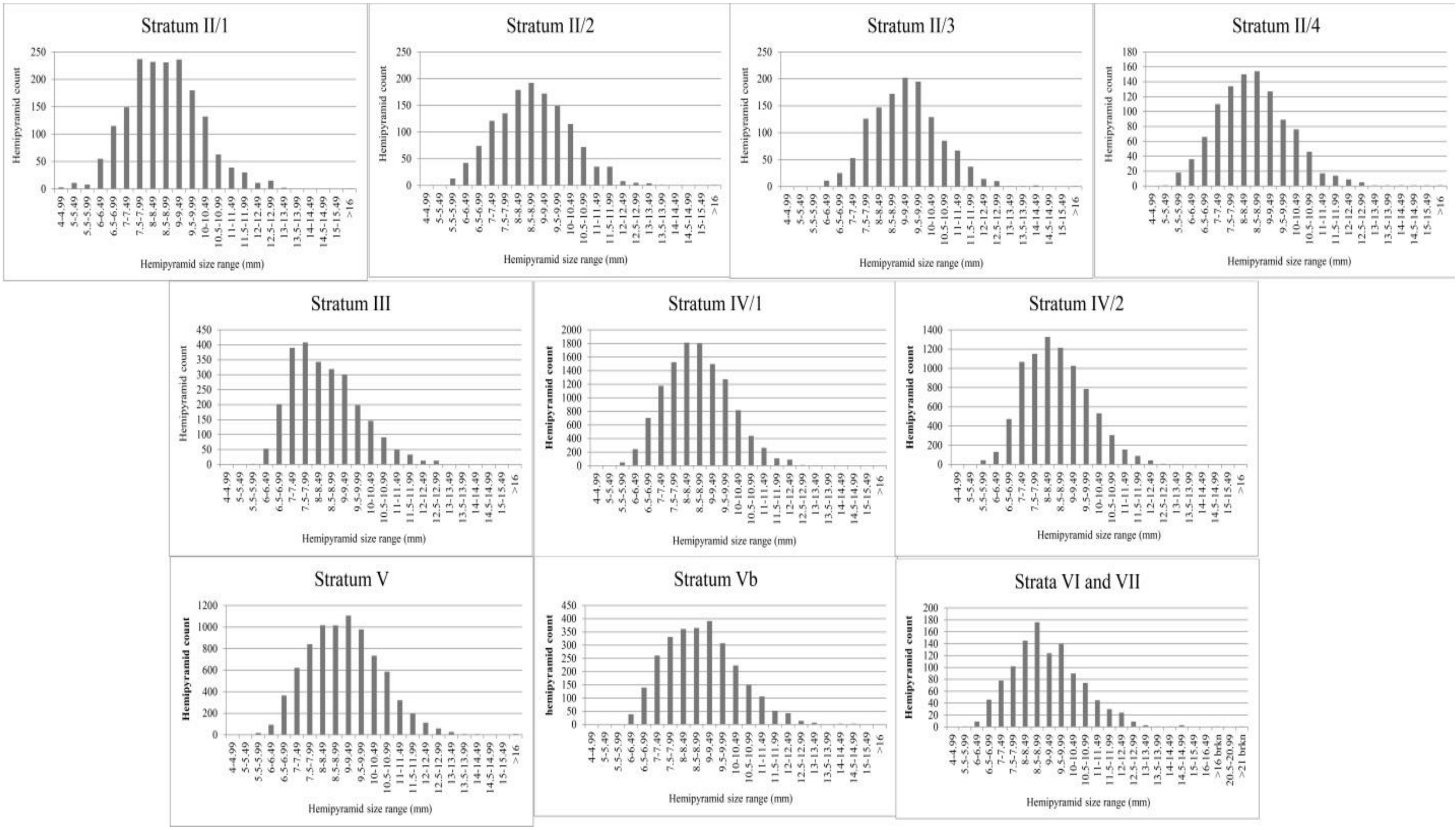


**Figure 5.8**. Size frequency distribution of the entire sea urchin sample from Unit 1, Cave of the Chimneys.



Stratum II/1

Stratum II/2

Stratum II/3

Stratum II/4

Stratum III

Stratum IV/1

Stratum IV/2

Stratum V

Stratum Vb

Strata VI and VII

**Figure 5.9**. Size frequency distributions for sea urchin hemipyramid sizes by Stratum and Level within Unit 1, CA-SMI-603.

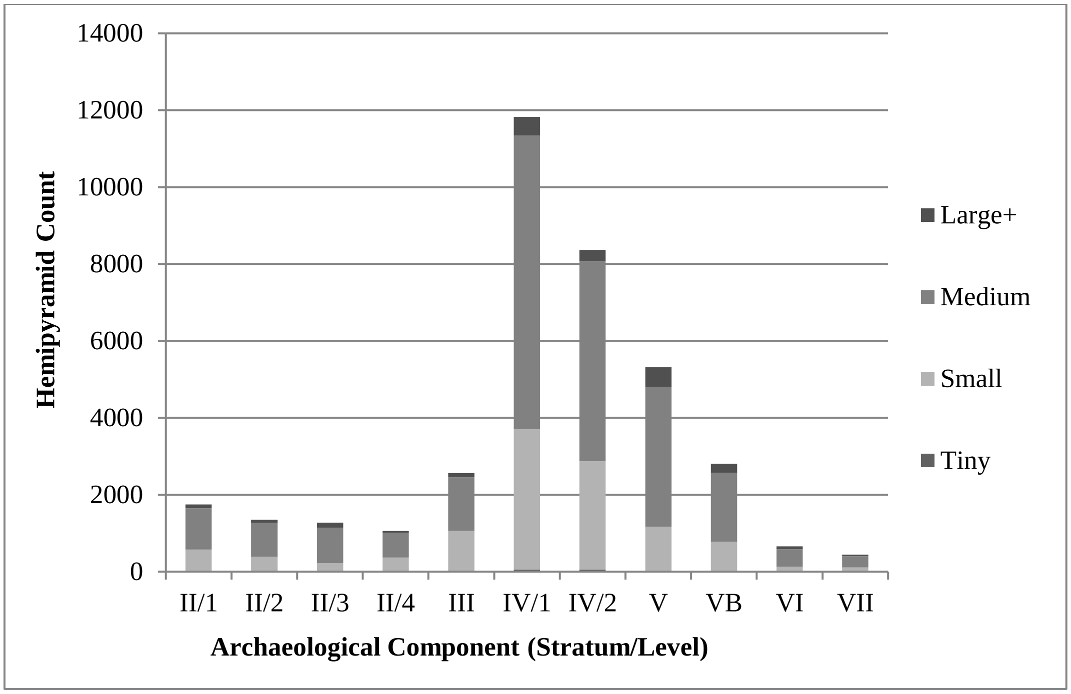


**Figure 5.10.** Sea urchin hemipyramid count by primary size classes by stratum and level in Unit 1, CA-SMI-603.

### *Hemipyramid Counts*

Examining raw counts of hemipyramids in each component at Cave of the Chimneys reveals a steady increase from Stratum VII to Stratum IV, beginning with low numbers in the basal Early Holocene components and increasing counts through several Middle Holocene occupations. After the extreme peak in Stratum IV, Level 1, there is a sharp drop in sea urchin numbers in Stratum III, and consistently low numbers in the upper components of the site (Figure 5.10). Two-way ANOVA results revealed significant differences between hemipyramid counts when analyzed by archaeological component (DF=10, $r^2$=61, p=0.0185) and primary size class (DF=4, $r^2$=61, p<0.0001). Differences were significant in Stratum IV, Levels 1 (p=0.0012) and Level 2 (p=0.0194), but not in other components where p values range from 0.1422 to 0.9481. Hemipyramid counts in the Small (p=0.0265) and Medium (p<0.0001) size classes were significant, but not in the Tiny (p=0.9791), Large (p=0.6766), or X-Large (p=0.2813) size classes.This confirms that both levels of Stratum IV contain significantly larger amounts of sea urchin remains and that primary difference in harvested size classes through time are within the most heavily harvested categories (i.e., Small and Medium).

### *Hemipyramid Relative Abundances*

When examining the assemblage by size category and primary strata designation through time (Figure 5.11), we see a similar distribution of sizes during the earlier occupations of the rockshelter (Strata V, VI and VII). The lowest components show distributions of 20-25 percent small, 65-70 percent medium, and ~10 percent large specimens. Stratum IV shows an increase in small individuals (~33%) along with similar proportion of medium (~65%) sized individuals and a decrease in larger sizes (~3%). This is also the component with the highest density of urchin remains. Stratum III reveals a continued increase in relative proportions of small sized individuals beyond that of Stratum IV (~40%), but with a slightly higher proportion of large sized individuals (~5%) as well. In Stratum II, relative abundances of the various size categories reverse trends as the percentage of small individual’s decreases and that of medium and large individuals increase. This stratum appears to be on a trend to once again resemble the earliest components, which were composed of roughly 50 percent small, 45percent medium, and 5 percent large individuals.

If the assemblage is further broken down to show differences within primary strata (i.e., levels), oscillations through time are even more evident (Figure 5.12). The rise in relative proportions of small individuals between strata V and IV are more extreme when compared to the relative stability between strata VII, VI, Vb, and V. Stratum V, which precedes Stratum IV, contains fairly dense urchin remains as well (51007 g/m$^3$) although the size/age profiles differ considerably from Stratum IV, containing higher proportions of medium and large sized individuals. Similarly, the large number of small individuals continues fairly steadily throughout strata IV/2, IV/1, III, and II/4. Not evident in the previous graph, highs of >30 percent small individuals are shown to continue through the lowest level of Stratum II (level 4) before drastically dropping in level 3 and then rising again incrementally through time between levels 3 and 1. The $^{14}$C dates for these components are very close and even overlap slightly; covering the

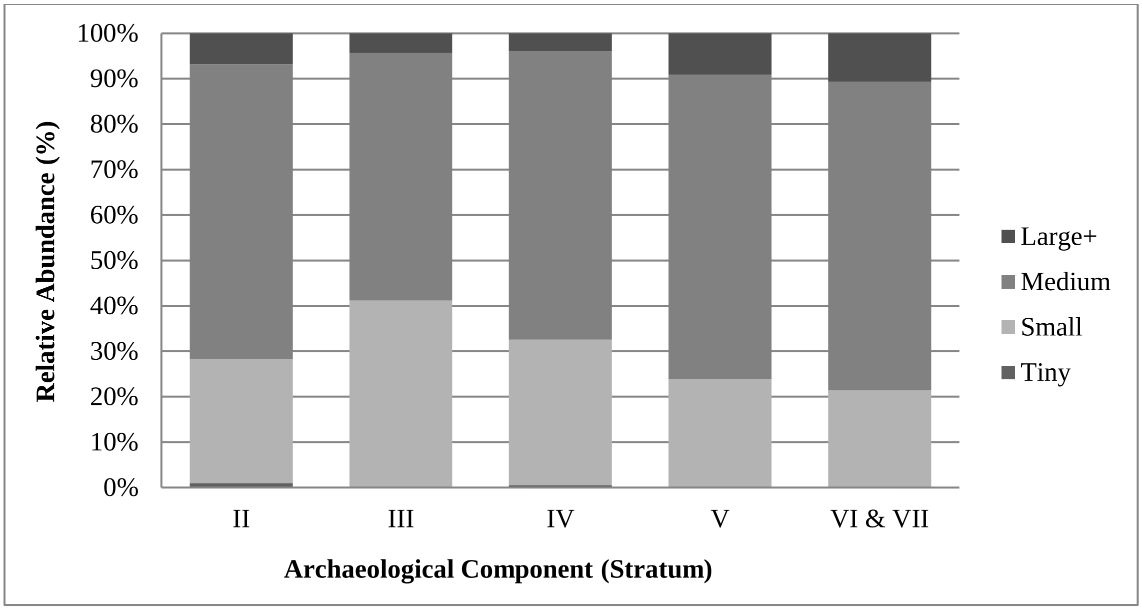


**Figure 5.11.** Relative abundances of primary size categories by Stratum in Unit 1, CA-SMI-603.

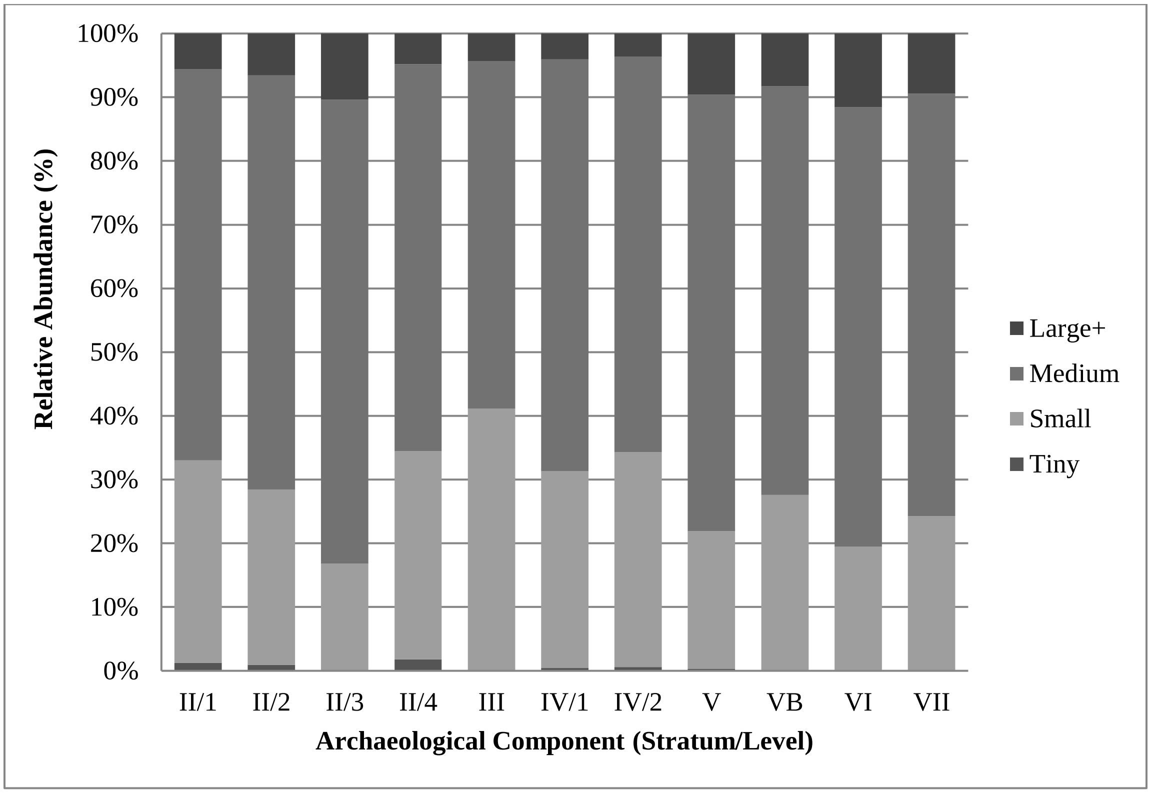


**Figure 5.12.** Relative abundances of primary size categories by Stratum/level in Unit 1, CA-SMI-603.

timespan between ~4300 and 3600 cal BP, suggesting this is not a short-lived situation. Although differences are apparent, an analysis of variance showed that the percentages of each size class were not significantly different between archaeological components (DF=10, $r^2$=98, p=1.0), but differences in proportions within the various size classes were significant (DF=4, $r^2$=98, p<0.0001). Relative abundances of Small (p<0.0001), Medium (p<0.0001), and Large (p=0.0015) size classes differed considerably, but relative abundances of hemipyramids in the Tiny (p=0.9015) and X-Large (p=0.9084) size categories did not, suggesting people were harvesting roughly similar proportions of very small and very large (likely red) sea urchin throughout the several thousand years Cave of the Chimneys was occupied.

### *Sea Urchin Density*

Urchin density is highest in Stratum IV (54,536 g/$m^3$), and even though size/age profiles stay fairly consistent between IV, III, and the base of Stratum II, the density of urchin remains drops significantly (18,000 g/$m^3$) in Stratum III. Hemipyramid density values showed significant differences between archaeological component (DF=10, $r^2$=59, p=0.0171) and primary size classes (DF=4, $r^2$=59, p<0.0001). Densities differed significantly in Stratum IV, Level 1 (p=0.0009), but only slightly in Level 2 (p=0.0493), with no significant differences noted in the other strata, where p values range from 0.0764 to 0.9863. Hemipyramid densities were similar for the Tiny (p=0.9814), Large (p=0.7002) and X-Large (p=0.2995) size classes, though they were significantly different for the Small (p=0.0396) and Medium (p<0.0001) size classes. This confirms the observation that people were harvesting small but relatively steady proportions (~3-5 percent) of the larger sized sea urchin (likely reds) throughout the occupations represented in these deposits.

Although distinct differences are noted in the Small and Medium size classes, which were selected most extensively, and in Stratum IV, which is the urchin lens. Overall, these data suggest people were harvesting relatively similar proportions of various sized sea urchins through time except during the Stratum IV occupations when urchin harvesting appears to have intensified significantly. This implies that fairly stable nearshore ecosystems were in place in the site vicinity in spite of intensified human foraging through time. However, even though differences are significant, the inclusion of additional nearshore resources like abalone and mussel in this stratum suggests a fairly healthy ecosystem, even if a bit heavy with sea urchin. For this reason, I propose that local kelp forests may have been on a trajectory towards urchin barrens, but people were able to forestall this outcome by harvesting large numbers of urchins, helping prevent a complete barrens environment from developing. This interpretation implies human management of kelp forest and nearshore resources and suggests that people were actively maintaining their food base, which is logical but hard to prove definitively in the absence of human witnesses to confirm.

## Discussion

It is clear that the community ecology of purple and red sea urchins is affected by human fishing pressure (see Steneck 2013), making them excellent species to focus on in reconstructing nearshore habitats in the past and examining evidence of impacts from human foraging. The assumption was that if archaeological urchin remains could be accurately identified to species within the genus *Strongylocentrotus*, temporal shifts in geographic ranges along the Pacific Coast of North America might be observable. However, my study has shown how examining age/size distributions also provides a wealth of information on harvesting location and effort even though species level identifications are not always possible. For instance, very large specimens are almost certainly red sea urchins and small and medium sized specimens are likely purple sea urchins, since red sea urchins would not be reproductively viable and thus void of roe at that age/size. When harvesting sea urchins, the focus must be on ripe gonads, not just meat/flesh as with commonly harvested molluscan taxa, requiring a more nuanced understanding of species biology and life cycle patterns to harvest effectively. This is a key difference with sea urchin that allows species identifications based on size to be more predictable than it would otherwise be with many molluscan taxa, which contain flesh that can be consumed regardless of age and reproductive capacity. It also suggests that in some areas where sea urchin spawning cycles are highly seasonal, archaeologists may use their presence in shell middens as seasonal indicators of harvesting and/or site use.

## Localized Temporal Trends

At Cave of the Chimneys, there are distinct differences between the two Early Holocene layers and the Middle and Late Holocene components regarding relative abundances of shellfish taxa (Ainis 2012; Ainis et al. 2011). These likely reflect the state of nearshore ecosystems in flux due to human harvesting, climate change, and sea levels rising at different rates during the Early Holocene versus stabilization during later time periods. Mussels grow relatively rapidly and appear to have been the primary focus of foraging by early inhabitants of this site. However, beginning with Stratum Vb (~4500 cal BP), when sea level rise had slowed dramatically, foraging patterns shift. The addition of more abalone, sea urchin, and turban snails to the diet appears to mirror healthy, productive nearshore communities and intertidal habitats. My preliminary analysis of fish bone from this site suggests a decrease in sheephead (a primary predator of sea urchin) remains between strata V and IV, although fish bone identifications are ongoing. If sheephead populations had been diminished as a result of increased fishing pressure, however, this may have contributed to proliferation of sea urchin during this time.

The predominance of small-medium sized sea urchins suggests relatively dense populations in localized nearshore habitats at Bay Point throughout the Holocene, even when people were harvesting relatively low quantities of them. This is based on studies that reveal most purple sea urchins in high-density sites are medium sized and small as compared to low density sites (i.e., within reserves) where most individuals are much larger (Rogers-Bennett 2007:404). In addition, the complete lack of any bimodal distribution in size frequency (see Figure 5.8) suggests that sea otters, sheephead, and crustaceans like spiny lobsters and crabs were not severely impacting sea urchin populations during this time. Studies have shown that crustaceans prefer mussels to urchins when available, and that they have a strong tendency to create bimodal distributions in sea urchin populations when they target them intensively (Steneck 2013). These crustacean predators make tasty meals for humans as well and were likely being harvested in conjunction with sea urchin and other resources, keeping predatory populations at bay. There is significant evidence of crab harvesting at the site (Ainis 2012), but lobster remains are more ephemeral in archaeological deposits in general due to their lack of hard parts other than their small mandible, making their presence difficult to quantify. It is possible that human harvesting of lobsters was one of the variables that allowed sea urchin populations to increase to destructive levels based on modern studies (Breen and Mann 1976; Lafferty 2004).

Basic quantification comparing sea urchin remains to primary shellfish taxa clearly demonstrate the dramatic increase in sea urchin in Stratum IV, where sea urchin has the highest weight, MNI, and density values (by weight and MNI) at this multi-component site (Table 5.6). A weight/MNI index is often used to estimate sizes of harvested mollusks in highly fragmented assemblages (e.g., Glassow 2000; Erlandson et al. 2015a) and is worth examining in this instance. According to this index, average estimated sea urchin sizes are largest in Strata III (7.22) and V (6.4). However, measured hemipyramids suggest higher amounts of smaller specimens in Stratum III, suggesting that this index value may blur finer-grained analyses like size-frequency patterns by averaging out the complexity of relative abundances in numerous size classes and thus should be avoided when possible.

I further explored the relationships between sea urchin and other primary shellfish taxa at the site using a variety of index measures (see Table 5.6). Stratum IV also shows the highest amounts of sea urchin in relation to other shellfish (urchin/shellfish index), and shellfish that are normally dominant in Channel Island middens combined (urchin/abalone+mussel index) and individually (e.g., urchin/red abalone index, etc.), further emphasizing the uncommonly dominant role sea urchin played in the diet during these occupations. Examining the relationship of sea urchin with red and black abalone reveals differences in how people were harvesting these species of abalone. The urchin/red abalone index shows more sea urchin in relation to red abalone in the earliest component (Stratum VII) with steadily decreasing index values through time, suggesting that more sea urchin in relation to red abalone was being harvested consistently through time at this site. The lack of oscillations in index values is noteworthy as all other examined relationships show reversals at some point. For instance, index values representing the relationship between harvested sea urchin and black abalone oscillate through time, with extreme low values in Stratum VII (0.42) and extreme high values in Stratum IV (4.59), that are interspersed with more moderate values in all other components (1.5 to 2.15). This pattern suggests more diachronic variation in harvesting trends for black abalone along with potential short-term localized impacts to this species (i.e., decreases due to intensive harvesting followed by rebounds, etc.). Index values show fairly similar relationships between sea urchin and California mussel in Middle and early Late Holocene strata (II, III and IV, index = 0.93, 1.1, and 1.06 respectively), with much lower amounts of sea urchin in relation to mussel in both Early Holocene components (VI and VII, index = 0.12 and 0.05 respectively), implying mussel played a significantly more dominant role in shellfish collection during the Early Holocene occupations. The sea urchin/turban snail index shows lower amounts of sea urchin in relation to this genus (includes brown and black turban snails) before the "urchin lens" (Strata V-VII) and higher values after the urchin lens in Stratum IV (Strata III and II), suggesting that sea urchin becomes increasingly important in relation to this relatively small but dietarily important shellfish taxa through time. Collectively, these data do not reveal an ecosystem collapse akin to modern "barrens" in Stratum IV, though they do show significantly increased harvesting and consumption of sea urchin during the time represented by the Stratum IV accumulation.

Demonstrating that medium-sized purple sea urchin was the focus of human collectors suggests that most sea urchin harvesting was occurring in intertidal areas (along with the collection of other shellfish resources), rather than in the subtidal zone. The presence of red abalone suggests people may have been diving for this large and meaty gastropod, which is often subtidal, but the sea urchin data do not suggest they were diving with a focus on large red sea urchin. Rather it suggests they may have collected some large red sea urchin "along the way" when they went after red abalone, or while diving and spearfishing in kelp beds. It should also be noted that red abalones can be found in the low intertidal zone at some locations on San Miguel Island today (Erlandson, pers. comm. 2019), so diving may not have been necessary to harvest them.

Though imperfect, estimated meat yield conversions can be useful in quantifying general trends in relative importance of dietary resources (see discussions in Erlandson

1994; Ainis 2012). Based on established meat multipliers for all of the primary shellfish taxa recorded at this site, sea urchin show relative prominence, comprising 6-13 percent of estimated meat yields from shellfish in the Early Holocene levels and 21-26 percent of estimated meat yield in all of the Middle and early Late Holocene strata (see Ainis 2012, Table A-10 for conversions and references).

### *Broader San Miguel Island Trends*

Preliminary identifications of a sample of faunal remains from nearby Daisy Cave show sea urchin comprising ~10 percent of shellfish weight in Stratum A, which dates between ~3600 and 2800 cal BP, with relative abundances ranging from <1 to 5 percent for all earlier archaeological components (Forgeng 1992). There do not appear to have been substantial occupations of Daisy Cave during the ~4500 to 4000 cal BP timeframe (see Chapter I) when the sea urchin lens was deposited at Cave of the Chimneys. However, the somewhat higher relative abundance of sea urchin at the base of Stratum A dates towards the end of the unusually high sea urchin densities at Cave of the Chimneys, suggesting this may document the tail end of the event.

Faunal analysis from other shell midden sites on San Miguel Island show similar patterns of high sea urchin density between ~4000 and 4500 cal BP with much lower densities in Late Holocene components (Erlandson et al. 2004). Faunal remains from Late Holocene (~2600 to 500 cal BP) occupations at Cuyler Harbor (CA-SMI-87) show sea urchin making up ~3-5 percent of shellfish weight, and faunal samples from a Late Holocene (~1250-900 cal BP) occupation at Otter Point (CA-SMI-481) on the north-central coast of the island show a similar pattern with sea urchin remains constituting ~7 percent of shellfish weight (Rick 2007). At CA-SMI-628, a moderately dense shell midden site located near Forney's Canyon on the south coast of the island (Braje 2010:70), sea urchin remains in Middle Holocene levels range from 11-14 percent of shellfish weight and 13-30 percent of shellfish MNI, but drop to between ~5 and 7 percent of weight and MNI respectively in levels dated to the Late Holocene (~1400 cal BP). Archaeological sites in the same area dated to the earlier Middle Holocene (~7000 to 6000 cal BP) and Early Holocene (~9800 to 8500 cal BP) contain much lower densities of sea urchin as well (~1-6% and <1% respectively), showing similar patterns to Cave of the Chimneys and suggesting we are observing an island-wide pattern. In a larger synthesis of data from San Miguel Island, Braje et al. (2012: Figure 2) show a spike in sea urchin density in archaeological sites on the island dated between ~4500 and 4000 cal BP, with sea urchin composing up to 40 percent of the shellfish weight in some components (see also Erlandson et al. 2005b).

I believe that a similar sea urchin lens may be present at CA-SMI-161, on the northeastern extent of Cuyler Harbor, which is just west of Bay Point, however, associated radiocarbon dates for this component are very limited. Rick et al. (2013) sampled three locations at CA-SMI-161, including one (Unit 3) where sea urchin comprised ~44 percent of shellfish remains by weight as opposed to <1 percent in the other two sampled units. Although the one red abalone shell dated from Unit 3 returned a $^{14}$C age range of ~5860-5740 cal BP, three other dated shells from the site returned $^{14}$C age ranges of ~4500-4280 cal BP (Rick et al. 2013:Table 1), which is directly comparable to stratum VI at Cave of the Chimneys. As CA-SMI-161 is an extensive open-air site encompassing several loci some of which are located on a ridge of a large partially vegetated sand dune, it is likely that deposits have undergone some degree of post-depositional movement and the one dated shell may or may not reflect the time of deposition for the sea urchin lens. It is possible that the sea urchin component at CA-SMI-161 also corresponds to $^{14}$C date ranges of later occupations (i.e., ~4500-4200 cal BP) and may be associated with the warm SST phase and sea urchin lens at Cave of the Chimneys (Stratum IV, ~4400-4000 cal BP), or it may be the remains of an earlier (~5700 cal BP) sea urchin feast or harvesting event that resulted in a high density sea urchin feature relatively close to shore at Cuyler Harbor. Rick et al (2013) imply that the sea urchin tests appeared to represent larger individuals, suggesting they may have been red sea urchins, though sizes were not quantified.

## Is There Archaeological Evidence for Urchin Barrens in the Southern California Bight in the Past?

In addition to those described above for San Miguel Island, dense sea urchin lenses have also been reported on San Clemente (Salls 1991, 1992) and San Nicolas islands. Some components at the Punta Arena site (CA-SCRI-109) on Santa Cruz Island and CA-SRI-191 on Santa Rosa Island could also be defined as sea urchin lenses as several layers dated between ~5300 and 5900 BP are composed of ~20% sea urchin remains by weight, with estimated meat yields of up to 24% (Sharp 2000). The occupational sequence at CA-SRI-191 on the northeast coast of Santa Rosa Island shows increased sea urchin abundance (~21% of shell weight) in faunal deposits at ~4300 cal BP along with warmer SST values (Rick et al. 2006).

A dense sea urchin lens (~1050 BP) in midden deposits at the Eel Point site on San Clemente Island led Salls to suggest that Indigenous fishing of sheephead may have resulted in the creation of urchin barrens and subsequent heavy human predation of the echinoderms, saying “the sea urchin then became dominant, creating a single resource base for the occupants of the site” (Salls 1991:79). He posited that this then led to deforestation of algal resources and a population crash for sea urchin, after which localized habitats recovered and the process began again. This interpretation is questionable, however, as the poor gonadal quality of sea urchins in barrens environments is well documented (see previous sections), making this an extremely poor food source and suggesting that people may have harvested urchins in earnest before the complete development of a “barrens” environment. Furthermore, without detailed faunal analysis it is difficult to determine whether people really were dependent on a “single resource base” of sea urchin as proposed by Salls (1991). It seems unlikely that mollusk, fish, mammal, and bird remains are entirely lacking from the assemblage. It is easy to note extreme differences in primary shell types between strata in archaeological shell middens during excavations but quantifying how significant those differences are requires detailed analysis. The sea urchin lens at Eel Point may have appeared to be composed entirely of sea urchin, much like Stratum IV at Cave of the Chimneys, but it seems unlikely that it truly was devoid of any other faunal remains.

Although the sea urchin lens at Eel Point on San Clemente Island dates much later than similar lenses on San Miguel and Santa Rosa islands, the complex nature of oceanographic currents and processes in the Southern California Bight create significantly different nearshore habitats on the various islands. San Miguel, Santa Rosa, and San Nicolas islands are in the direct path of the cooler California Current, which sweeps southward into the outer California Bight, and appear to have urchin lenses at similar dates. San Clemente and the other islands are primarily affected by the warmer California Countercurrent that extends northward from Baja California, Mexico, along with a complex swirl of wave-wind effects, cross-shelf nutrient transport, gyres and eddies (see Chapter I), however, and might have experienced similar conditions at different times in the past. The intensity of localized human harvesting and population demographics would also have affected the level of impacts to nearshore habitats on different islands through time. Although we know that human populations generally increased on the islands through time, with relatively high densities by the Middle Holocene, little is known about specific oscillations in population demographics for each island through time.

Erlandson et al. (2005b:17) suggested that Channel Island sea urchin lenses might represent “archaeological evidence for localized phase shifts in Channel Island kelp forests caused by humans” (see also Erlandson et al. 2004, 2008d). This suggestion is supported by my study, which shows a localized pattern (potentially evident across San Miguel Island) of very high densities of sea urchin that spiked during the latter part of the Middle Holocene. I propose that these urchin lenses do not represent complete urchin barrens as described in modern examples for two reasons. First, modern barrens are characterized by the near absence of anything but sea urchin, whereas this urchin lens clearly contains other marine animal resources, albeit in lower than average proportions. Second, if Indigenous islanders were faced with true urchin barrens as described by modern examples, why would they collect and carry virtually empty sea urchins up to Cave of the Chimneys and other sites? As explained earlier in this chapter, gonadal quantity and quality drastically falls in a barrens situation as the sea urchin are literally starving. Modern fishers do not harvest sea urchin from barrens, knowing the tests are virtually empty. It stands to reason that Native islanders figured this out pretty quickly as well.

For these reasons I propose that Indigenous islanders may have been able to help forestall the creation of urchin barrens by harvesting sea urchin in larger than normal quantities before nearshore kelp forests collapsed. Whether they did this knowingly, or not, is impossible to say, but the faunal data from the urchin lens (Stratum IV) at this site does not reflect a true barrens environment. Purple sea urchins inhabit wider intertidal ranges (higher and lower in the intertidal and subtidal) than red sea urchin and are more tolerant of increased silt, wave action, and water temperature variations than the more sensitive red sea urchin. This suggests that purple sea urchins may have formed "fronts" and outcompeted red sea urchins when water temperatures warmed. Did islanders knowingly manage nearshore resources by harvesting increasing amounts of sea urchin before they caused an ecological collapse, or did they do it inadvertently? It is hard to say, but my data show that increased amounts of sea urchin were harvested and brought to CA-SMI-603 (likely for consumption) during this period of warmer SST's. I believe people understood the ramifications of unchecked sea urchin populations and actively and opportunistically managed nearshore resources by harvesting and consuming more sea urchins when they became extremely abundant.

The high species richness and functional diversity in southern California kelp forests, including multiple predator-prey interactions involving sea urchins, also makes it more unlikely for sea urchins to proliferate to the extreme of causing large barrens prior to the era of commercial fisheries (Steneck et al. 2002; Steneck 2013). There appears to be some correlation between escalating pressures from human fishing, which often removes most (if not all) predators from shallow marine ecosystems and the development of sea urchin barrens (Steneck 2013), but it seems unlikely that Indigenous islanders impacted nearhsore habitats to this degree. In addition to warmer SST conditions during this time period, however, human reduction of sea otter, sheephead, crustaceans, and abalone populations brought about by several thousand years of harvesting could also have helped release urchin populations from predation pressure and space/food competition, contributing to greater proliferation of sea urchin populations at this time.

I suggest that we simply describe similar assemblages in archaeological midden sites as “urchin lenses,” defined as components where sea urchin remains dominate shell refuse in several modes of quantification (i.e., weight, MNI, density, shellfish indices) – but not implying the existence of urchin barren habitats at the time of harvest.

## Global Archaeological Comparisons

Sea urchins are not among the most common constituents in archaeological shell middens around the world, though they often play secondary dietary roles. Although the level of quantification is not directly comparable, faunal data from coastal middens in Central Chile show patterns of sharp increases in sea urchin harvesting following relatively low sea urchin densities in earlier components (Jerardino et al. 1992). Sea urchin spikes at these sites appear to have begun around 2500 BP after several thousand years of shellfish harvesting recorded at the same and other sites in the region. Sea urchin remains also show increases through time at several sites in Northern Spain beginning at ~16,000 cal BP (see Gutiérrez-Zugasti 2011; Gutierrez-Zugasti et al. 2016). Relative abundances are fairly low however, and their presence is interpreted as the consequence of sporadic gathering. Size frequency distributions at these sites oscillate to some degree, but mean values do not show much difference through time (10.4 to 11.2 mm SD ±1.3-1.6; Gutierrez-Zugasti et al. 2016: Table 3 and Figure 4). Site location and proximity to shorelines also appear to be a factor in sea urchin presence in midden sites, increasing in sites that are near (<500 m) the coast. Gutiérrez-Zugasti (2011) suggests that shorter distances to collection areas allowed for more intensive exploitation of a wider array of marine resources at these sites.

Similarities between the Chilean, Spanish, and Channel Islands sea urchin remains include oscillations through time with a general increasing trend, and relatively homogenous primary size of harvested specimens within the ranges of viable sizes between the El Mazo site in northern Iberia and Cave of the Chimneys. Although sea urchin is described as a steady but low importance food resource in the North Atlantic region at this time, never comprising more than 7 percent of the MNI, relative abundances and densities imply it was a regularly harvested shellfish, at least at some Channel Island sites.

## Inferring the Health of Kelp Forests in the Past from Archaeological Remains

Even though kelp forests in the Southern California Bight appear to have proliferated during the Early Holocene (Kinlan et al. 2005; M.H. Graham et al. 2008), people do not appear to have eaten much sea urchin at this early time. As far as we know, there are no Early Holocene urchin lenses in the region. Something changed significantly, however, during the latter part of the Middle Holocene as indicated by the presence of dense urchin lenses in archaeological sites on multiple islands (San Miguel, San Nicolas, and Santa Rosa) at roughly 4200 cal BP. Patterning in shellfish remains at Cave of the Chimneys shows a stark contrast between the Early and Middle/Late Holocene (Ainis 2012). One reason for this may be that sea level stabilization at ~6 kya allowed for the stabilization and proliferation of nearshore littoral habitats around the Channel Islands. Up until this point nearshore habitats were in constant flux as sea levels rose steadily through the Early Holocene, making human harvesting impacts on littoral resources less noticeable. In addition, human population on the islands increased through time, and particularly in the Middle and Late Holocene. The increase in human population densities on the islands put more pressure on nearshore resources that increased exponentially through time.

Oceanic and climatic factors may also have contributed to this increase in sea urchin at this time. Studies have shown that sea urchin settlement is favored following warm water events (Morgan et al. 2000b; Wing et al. 2003) and that major recruitment events may increase sea urchin densities to destructive levels (Watanabe and Harrold 1991). As I showed in Chapter II, SST reconstructions using stable isotope analysis of mussel shells from this site and Daisy Cave show increased warm water events during Stratum IV occupations. These warm water events could have fostered major recruitment and settlement events and allowed sea urchin populations to increase, even in the absence of relief from predation. Intensive human harvest of major urchin predators such as sea otters and sheephead, as well as competitors for food and space such as red and black abalones may have further helped increase sea urchin populations, making them more attractive to human foragers. In the future, detailed analysis of fish bone and crustacean (crab) remains from these sites will allow me to address the issue of sea urchin predation through time more extensively.

### *Implications for Management*

The faunal records from Cave of the Chimneys, and many shell midden sites on the California's Channel Islands, suggest relative stability in nearshore ecosystems throughout thousands of years of human harvesting. Although there are oscillations in relative abundances and sizes of primarily harvested shellfish and fish, there is no evidence for complete collapse of ecosystems and disappearance of species from the archaeological record, suggesting that sustainable harvesting practices were in place.

In contrast to modern fisheries, my data show that Indigenous Channel Islanders consistently harvested smaller sea urchins and focused primarily on intertidal purple rather than subtidal red sea urchins. Modern red sea urchin fisheries target individuals >89 mm, with strict limits (30 per permit/load) on the number of smaller (between ~40 and 90 mm) specimens that can be taken (14 CA ADC § 120.7). The vast majority of sea urchin remains recovered from CA-SMI-603 suggest that Island Chumash people almost exclusively harvested individuals below these size ranges for over 5500 years. This implies that most sea urchin harvesting was occurring in intertidal zones (rather than subtidal) and suggest that perhaps setting a maximum size restriction, rather than a minimum size restriction, might be more sustainable—a hypothesis biologists have suggested as well (Birkland and Dayton 2005; Kato and Schroeter 1985; Rogers-Bennett 2007).

My data set shows a reversal in the basic approaches of Indigenous vs modern commercial fisheries. Small and medium sized purple sea urchins were harvested in abundance throughout the Holocene but are largely ignored today in favor of larger red sea urchin. If so, this would be another case of indigenous fisheries "fishing up the foodweb" in contrast to the dominant practice of commercial fisheries (as per Erlandson et al. 2009). Like most fish families (e.g., Sciaenidae), the larger female sea urchins produce exponentially more eggs than midsized females (Tegner 1989), suggesting that targeting larger individuals is more detrimental to the reproductive capacity of a population than taking medium sized individuals. In addition to scale, this is the primary contrast between indigenous and commercial fisheries. Indigenous fisheries rarely caught the largest females, relying on a steady supply of younger smaller individuals during spawning season, but commercial fisheries focus on the largest/oldest individuals almost exclusively. It is also possible that the intensive harvesting of purple sea urchin by Indigenous islanders may have helped prevent the development of extreme “urchin barren” habitats that have been documented in recent years.

## Summary and Conclusions

This study provides a method for reconstructing sizes of archaeological sea urchin populations and, in some cases, allows researchers to make strong inferences about the species that were targeted even when specific identification of urchin remains is not possible. Like Campbell (2008a), my study shows how sea urchin demographics can be reconstructed from hemipyramid length measurements, and some aspects of the structure of nearshore habitats where harvesting was occurring can be inferred by comparisons with modern sea urchin populations from known habitats. The in-depth analysis of sea urchin remains from Unit 1 at Cave of the Chimneys demonstrates the long-term sustainability of sea urchin harvesting at Bay Point throughout much of the Holocene. Comparisons of dense sea urchin lenses at other sites on San Miguel Island suggest that they are limited almost exclusively to the Middle Holocene and are often associated with other kelp forest shellfish and fish species such as red abalone and sheephead, etc. After this time, the intensification of marine finfisheries may have refocused the Island Chumash on alternative marine resources as human populations on the islands generally continued to increase during the Late Holocene.

My analysis suggests that the presence of sea urchin lenses are not necessarily a sign of ecological disruption or disequilibrium—especially the development of large urchin barrens—as only healthy and well fed urchins would be collected for their roe. Rather than the dramatic “alternate stable states” of the Aleutian Islands, human harvesting and potential trophic cascades appear to have been short-lived and localized around the Channel Islands. This speaks to the biological diversity, productivity, and resilience of marine ecosystems of the Southern California Bight, where large populations of maritime hunter-gatherer-fishers lived and thrived for millennia prior to the arrival of Europeans. This study also suggests that maritime peoples, like the ancestral Island Chumash, actively shaped the nearshore intertidal ecosystems they depended on through predation on key functional species like sea urchins (see Graham et al. 2003). Furthermore, reconstructions of localized paleo-shorelines and ancient kelp forest distributions (see Kinlan et al. 2005) are now possible and can be correlated with species-specific ecological requirements and size-frequency distributions among sea urchins and other major shellfish prey species. When combined with data for ancient sea surface temperatures and patterns of fishing and bird and marine mammal hunting, archaeologists can explore the impacts of past human harvesting on nearshore and kelp forest ecosystems with increasing resolution. In our current state of rapid climate change and collapsing fisheries, these data have strong interdisciplinary implications for marine scientists and archaeologists alike.

The following chapter concludes my dissertation research. In Chapter VI, I discuss how in-depth archaeological investigations--in which modern life histories and biological/ecological factors are thoroughly integrated with density, relative abundances, and size frequency data of archaeological assemblages—contributes to a more thorough understanding of human eco-dynamics in nearshore habitats. The successful management and conservation of marine fisheries and ecosystems depends on a functional understanding of the complex interactions between climate change and human harvesting and fishing pressures, and how these factors intertwine to affect population and ecosystem dynamics. I propose that archaeological data sets be incorporated in modern kelp forest management databases (i.e. Beas-Luna et al. 2014; Vilalta-Navas et al. 2018), where they can be used as baselines in the establishment of localized, area-specific kelp forest histories.

# CHAPTER VI

## A HOLOCENE RECORD OF HUMAN INTERACTIONS WITH NEARSHORE ECOSYSTEMS AT BAY POINT, SAN MIGUEL ISLAND

### Introduction

Together, Daisy Cave and Cave of the Chimneys contain one of the longest and most continuous records of human occupation in a localized coastal setting anywhere in the Americas. The well-defined chronology of the sites, along with the outstanding preservation of faunal and floral remains, provides an opportunity to examine human-environmental dynamics in a coastal setting through thousands of years of interaction. Island ecosystems are characterized by complex, dynamic, and ever-changing interactions between humans and the terrestrial and marine animal and plant communities that extend deep into the past. Identifying the causes of changes in harvested resources through time requires a holistic approach incorporating biological, ecological, oceanographic, and archaeological datasets.

Although a full synthesis of these datasets remains somewhat incomplete, my dissertation research contributes significantly to this endeavor, and my ongoing work with faunal data (e.g., fish bone, crustacean remains, etc.) from these sites will continue to refine patterning in the human dynamics of coastal forager-fishers and the Island Chumash and their ancestors. In addition, the resulting long-term interdisciplinary datasets provided by studies like this can provide localized histories to inform current management and restoration projects in coastal and island settings (i.e., Haas et al. 2019; Rick et al. 2014).

In this final chapter, I synthesize my dissertation research using archaeological and paleoenvironmental records spanning the Holocene to evaluate the relative health of kelp forest ecosystems in the past and the dynamics of human interactions with the nearshore resources that were the primary focus of their subsistence. The diachronic record provided by archaeological assemblages at these two coastal rockshelter sites have much to offer in terms of long-term ecological understanding and evaluating the resilience of nearshore and kelp forest ecosystems in the region and beyond. For instance, quantifying and tracking relative abundances, sizes, and age profiles of key members of kelp forest ecosystems, like sea urchin, through thousands of years of human collection in a localized setting allows us to evaluate long-term population demographics. These datasets provide us with a proxy for the relative health of nearshore ecosystems through time, allowing us to evaluate long-term human-environmental interactions and discuss how nearshore ecosystems were affected by the dynamic choices of coastal foragers. Broader implications for interpreting marine productivity and climatic shifts from this and similar datasets are also addressed, along with discussion of methods used to reconstruct marine paleo-environments. I present suggestions for incorporating archaeological faunal and paleo-environmental datasets in modern kelp forest data platforms where archaeological data can be used as diachronic baselines for current management and potentially provide deep localized histories for specific regions.

## Methodological Contributions

In this dissertation, I present several methods for inferring human harvesting of seaweeds (marine macroalgae) and seagrasses along with methods for inferring the relative health of nearshore kelp forests in relation to alternative stable-state environments as described in biological literature. In addition, aspects of the stable isotope analysis I conducted on California mussel shells provide improved methods of sampling that show a 4-5-year record on a single shell. These results highlight the need for producing more than one profile shell per archaeological component to capture a fuller range of short-term variability in paleo-SST. Sampling on one of the modern mussel shells also revealed the ability to capture seasonal SST variations during El Niño events, including warmer than average winter and summer values representing the 2014-2016 El Niño phenomenon (Chapter II, Figure 2.5). This demonstrates the potential for identifying similar climatic events in archaeological mussel shells in the region, akin to the work done by Carré et al (2005) along the Peruvian coast. My primary methodological contributions are summarized below.

## Inferring Seaweed and Seagrass Harvesting and Shifts in Nearshore Habitats in the Past

In Chapter III, I provide an extensive background of marine macrophyte and seagrass resources in the region, highlighting the likelihood they were harvested for food by Indigenous Islanders despite scant archaeological evidence. The gelatinous nature of marine macrophytes and their lack of calcareous hard parts, contributes to a strong preservation bias, limiting our understanding of their use in the past. However, their high nutritional content, rich diversity and prevalence in the Southern California Bight, and ease of collection, coupled with ethnohistoric and ethnographic accounts of seaweed use in the greater region (west coast of North and South America) suggest that they were likely harvested and consumed on the Channel Islands as well.

Chapter IV, I demonstrated the utility of identifying small non-dietary mollusks commonly found in archaeological shell middens to infer nearshsore paleoenvironmental conditions and human harvesting of marine macrophytes and seagrasses in the past. Identifying and categorizing over 50 taxa of small non-dietary mollusks into four categories based on habitat type (predominantly rock and boulder dwellers with very small amounts of sand and gravel dwellers throughout the sequence), I demonstrated that local nearshore conditions remained relatively stable in the vicinity of these sites for at least the past 10,000 years. The presence of these non-dietary and non-ornamental mollusks strongly suggests that people were harvesting and transporting seaweeds and seagrasses to the sites. We know seagrass was transported to the site to make cordage and other woven objects (Connolly et al. 1995; Vellanoweth et al. 2003), but because seaweeds do not preserve well in most archaeological contexts, we cannot be sure what types of seaweeds were brought back to the sites or whether they were used as sources of food or for other purposes.

Although this dataset did not show dramatic shifts in nearshore habitats in the site vicinity through time, the use of this method could reveal changes in sandy bottom vs. rocky shore habitats at other sites if and when they occurred. Relative abundances of habitat-specific taxa could also provide information on the types of nearshore habitats frequented by coastal foragers, which could be particularly useful if there are a variety of nearshore habitats in the site vicinity. In addition, some of the sand and gravel dwelling mollusks live specifically in the coarse sand and gravely substrate underlying kelp forests and seagrass meadows and can also be found on the bases and holdfasts of kelps and seagrasses. These species may be used as indicators of the ways in which seaweeds and kelps were harvested, for instance, by pulling up entire stalks including bases and holdfasts as opposed to harvesting by cutting off fronds, etc.

Small mollusks that are known commensals of larger shellfish taxa can also contribute to archaeological interpretations of shell midden data. For instance, when larger shells are used as raw materials to manufacture artifacts of technological (i.e., shell fishhooks) or ornamental (i.e., pendants, beads, etc.) design their dearth or absence in shell middens may obscure our knowledge of their harvest patterns and dietary significance. In such cases, the presence of known mollusk commensals can help infer the harvest of these larger shells and allow a more complete reconstruction of human harvesting patterns at a site.

Similarly, the identification of small gastropods that are known seaweed and seagrass associates can infer the harvest of these highly perishable resources in the past. These include small mollusk species that live on kelps, seaweeds, and seagrasses, whose presence in an archaeological midden is likely due to the harvest and transport of the associated macrophytes and/or seagrasses to the site. Some of these small taxa have species-specific relationships to certain kelps and seaweeds, and thus are able to infer the harvesting of specific types of marine macrophytes, while others can be found associated with several taxa and indicate the general harvest of seaweeds.

The identification and quantification of seaweed and seagrass associated gastropods at Cave of the Chimneys showed that significant numbers were present throughout all the archaeological components, suggesting that people regularly harvested marine macrophytes for millennia and transported them up to this rockshelter site. Comparing the density of these taxa showed much higher values during the earlier site occupations (Strata VII and VI ~1323 MNI/$m^3$), when SST was cooler (see Chapter II), suggesting that people harvested more marine macrophytes during the Early Holocene and early Middle Holocene (Stratum V ~995 MNI/$m^3$) than during the later Middle Holocene (Strata IV and III ~350 MNI/$m^3$) and early Late Holocene (~265 MNI/$m^3$).

Kinlan et al. (2005) suggested that the extent of kelp forests around the Northern Channel Islands declined from the Early to Late Holocene, consistent with my shellfish data. My paleo-SST data for the Bay Point area show warmer SSTs during the Middle and early Late Holocene as compared to the Early Holocene (see Chapter II), providing another potential explanation for this patterning. Analysis of seaweed and seagrass associated small gastropods from CA-SNI-40, a large dune site on San Nicolas Island dated to the Middle Holocene, also identified a "shell bake" feature, where black abalone were likely wrapped in seaweed and cooked in an earth oven. Seaweed associated gastropod densities in this feature were more than three times (~1563 MNI/m$^3$ vs. ~484 MNI/m$^3$) what they were in other tested components at the site.

## Reconstructing Size-Frequency Distributions for Harvested Sea Urchin

The relative health of kelp forest ecosystems in the past can also be assessed through fine-grained analysis of size and frequency distributions of their primary consumers, including sea urchins. I developed a regression formula and established primary size class groupings to reconstruct size-frequency distributions of harvested sea urchin in the past. By conducting this analysis on sea urchin remains from Cave of the Chimneys, I was able to demonstrate that people were consistently harvesting medium-sized sea urchins throughout the temporal sequence represented at this site, and that they probably focused on collecting purple sea urchin from intertidal habitats rather than red sea urchins from subtidal habitats. I was also able to examine potential causes for the large accumulation of sea urchin remains in Stratum IV between ~3900 and 4400 cal BP. By comparing a variety of indices (Chapter V, Table 6), I showed that although sea urchin remains are unusually high in Stratum IV, the inclusion of a variety of other shellfish resources suggests relatively healthy nearshore ecosystems that do not resemble a barrens habitat. My paleo-SST study (Chapter II) suggests that ocean water temperatures were warmer during this period, likely contributing to the proliferation of sea urchins. The Island Chumash may have contributed to a proliferation of sea urchin populations by preying on several of their primary predators (sea otters, sheephead, lobsters, large crabs, etc.). It is equally possible, however, that people may have helped prevent the development of urchin barrens by harvesting and consuming thousands of sea urchins when they were abundant. There are a suite of factors that contribute to barrens environments in the modern sense of the term (see Steneck et al. 2002), and it is unlikely that this extreme state would have developed in the Southern California Bight prior to the advent of commercial fisheries, which completely extirpated sea otters from island waters. Even historically, sea urchin barrens in the Southern California Bight have generally been localized, suggesting that indigenous hunting and fishing practices are unlikely to have caused large-scale barrens.

## Fine-tuning Methods in Stable Isotope Analysis of Archaeological Shells

In my stable isotope study and paleo-SST reconstruction for the Bay Point area, I demonstrated that multi-year consecutive sequences can be determined from large California mussel shells, but that more than one fully profiled shell per archeological component is likely required to determine the full range of annual SST variability in a given time period. By drilling extensive profiles (up to 30 samples) on single large California mussel shells from archaeological contexts, I was able to identify multi-year (2-4) consecutive sequences of surface water temperature (Figures 6.1-6.3).

Archaeological California mussel shells have been used extensively to reconstruct SST ranges and establish the seasonality of shellfish collection in multiple studies in the region (e.g., Jew et al. 2013a, b, 2014; Glassow et al. 1994, 2012; Flores 2017; Jazwa et al. 2012, 2015; Kennett 1998, 2005; Rick et al. 2006; Robbins et al. 2013). These generally focus on just the last year of shell growth (or less), however, and often utilize smaller or mid-sized shells (~45-75 mm long) representing the rapid growth that occurs during the first 18-24 months of the mussel’s life. Some attempts have been made to look at longer sequences on larger and longer-lived species such as red abalone, black abalone, and owl limpets (e.g., Watts 2013). My analysis demonstrates that it is feasible to extract multi-year sequences from larger California mussel shells that are capable of recording changes in SST spanning several years (see below). In addition, sampling of a modern mussel shell demonstrated that SST spikes indicative of ENSO events are discernable in

California mussel shells, like Carré et al.'s (2005) analysis of surf clam (*Mesodesma donacium*) shells.

Some archaeological stable isotope studies in the region use one profiled (12+ samples) shell to determine the range of variation in SST for a given archaeological component, assigning season of harvest based on this one sequence (e.g., Jazwa et al. 2012, 2015; Jew et al. 2013a, b, 2014). This method may provide an accurate range in annual SST for the archaeological component in question, but my ANOVA tests examining multiple profiled shells from each component suggest this is not always the case. Statistical comparisons of multiple profiled shells from 10 archaeological components show that in 50 percent of the cases mean values differed significantly between profiled shells from the same stratum (see Discussion in Chapter II), suggesting that season of harvest could have been assigned incorrectly if only one profiled shell was used. Studies using multiple profiled shells (e.g., my study; Flores 2017) are more likely to identify this variation if it exists. Particularly in archeological components encompassing a wide temporal expanse (i.e., several hundred+ years), several profiled shells should be used to examine annual variation in SST for season of harvest studies.

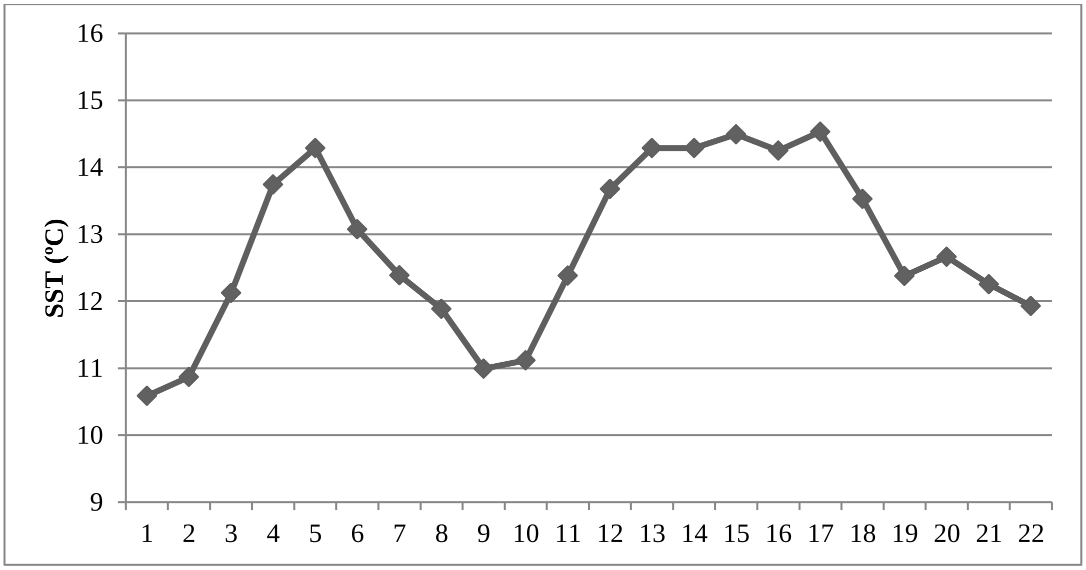


**Figure 6.1.** Reconstructed SST for two consecutive years based on shell carbonate from mussel shell sample #CH.5.2 from Stratum V at Cave of the Chimneys. CH.5.2 is a large broken right valve measuring >52.74 mm in width and was likely ≥150 mm long. Sampling included 22 powdered samples representing ~54 mm of shell growth extending up from the terminal growth band, which is represented as sample #1 on the left side of the horizontal axis.

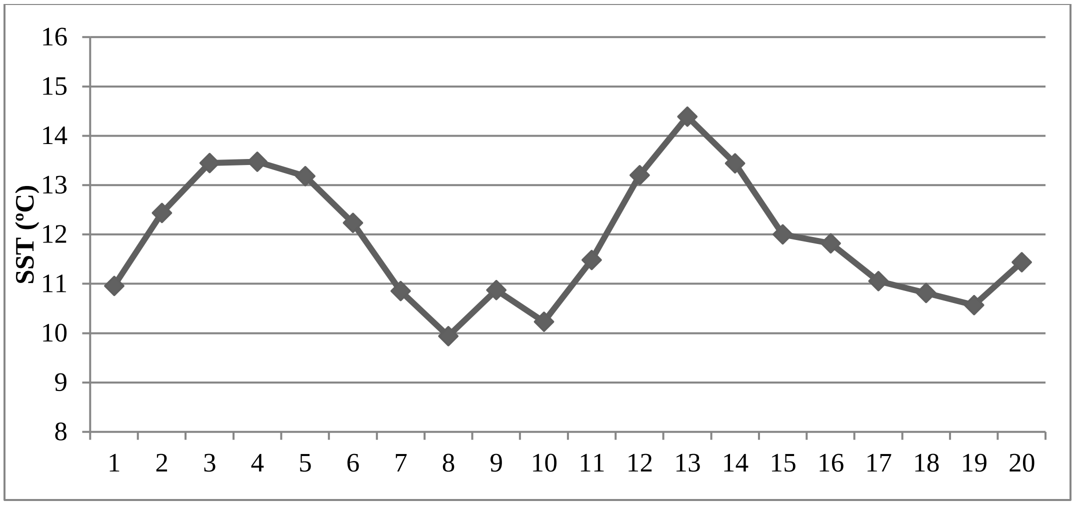


**Figure 6.2.** Reconstructed SST for two consecutive years based on shell carbonate from mussel shell sample #DC.E3.2 from Stratum E3 at Daisy Cave. DC.E3.2 is a broken left valve estimated to have been ~50 mm wide and ~90-100 mm long. Sampling included 20 powdered samples representing ~35 mm of shell growth extending up from the terminal growth band, which is represented as sample #1 on the left side of the horizontal axis. Note the peaks in each year, which show ~1ºC difference in maximum SST values between years. A similar difference is discernable in minimum SST values, which is ~0.5 ºC different between years.

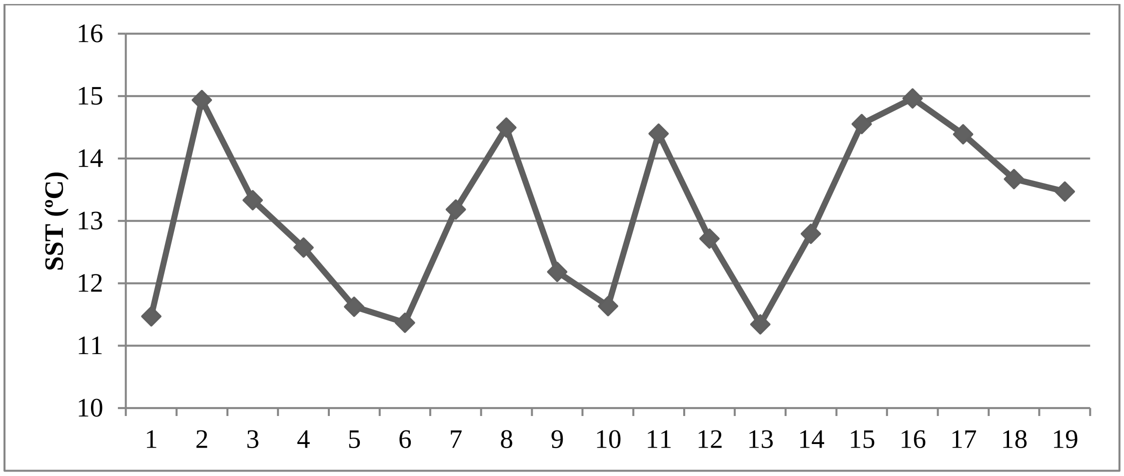


**Figure 6.3.** Reconstructed SST for 3+ consecutive years based on shell carbonate from mussel shell sample #CH.2.2.1 from Stratum II, Level 1, at Cave of the Chimneys. CH.2.2.1 is a broken left valve estimated to have been ~45 mm wide and ~90+ mm long. Sampling included 19 powdered samples representing ~35 mm of shell growth extending up from the terminal growth band, which is represented as sample #1 on the left side of the horizontal axis. Note that all minimum values are roughly congruent though maximum values differ by ~0.5 ºC between some years, showing relative stability.

## Implications from Bay Point Paleo-SST Sequence

## Comparison with the SBB Core SST Sequence

The trans-Holocene nearshore SST sequence for Bay Point presented in Chapter II must be examined at various scales of analysis. Similar to Flores (2017), I found that fluctuations in regional SST records, like the SBB cores, do not always represent localized patterning in SST variations, particularly in areas of intense oceanographic variability and strong upwelling (i.e., the Southern California Bight). This is not surprising as water temperatures shift according to depth and stratification, with some studies even documenting opposing seasonal patterns at different depths in the water column. For instance, Pak et al.'s (2004) analysis of sediment trap foraminifera from the Santa Barbara Basin showed that surface water temperatures increased to 17ºC (July to September 1995) while water temperatures below 20 m dropped to a seasonal low of 12ºC.

Nevertheless, on a broad regional scale, the Bay Point sequence generally compares favorably with the SBB core data in that there are some roughly contemporaneous warmer and cooler phases. Key differences are also discernable at this broad scale, however, in the overall range of $\delta^{18}$O values, which contain similar minimum values, but very different maximum values (~0.6 for the SBB core and 1.79 for the Bay Point sequence). These values suggest that nearshore water temperatures were cooler (more enriched $\delta^{18}$O values) on the northeast coast of San Miguel Island than they were further north and east within the Southern California Bight where the SBB core (ODP 893 A/B, Kennett et al. 2007) was drilled. This makes sense when examining the complex patterns of currents and winds that mix in the region creating a swirl of eddies and wave effects. Figures 6.4 and 6.5 depict some of the oceanographic complexity in the Santa Barbara Basin and show that conditions affecting the location where the cores were taken differ considerably from conditions on various shorelines of the Northern Channel Islands, where human fishing and harvesting of shellfish was occurring. In addition,

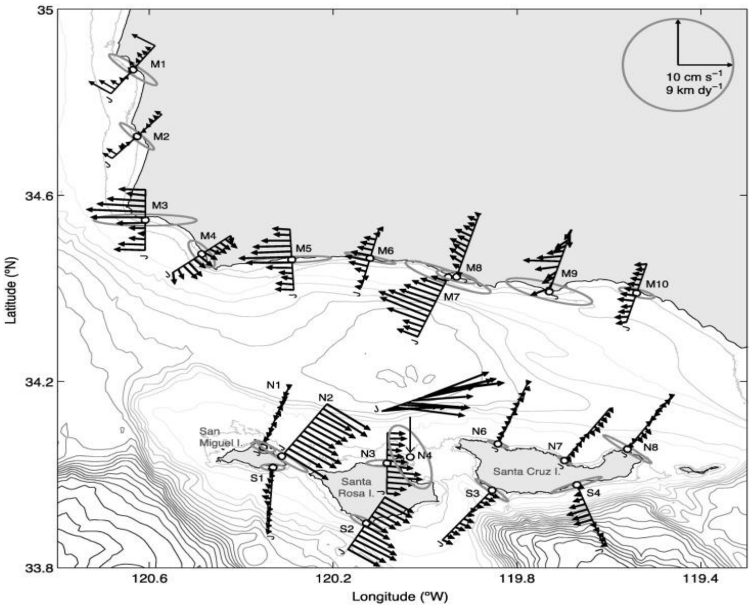


**Figure 6.4.** Time–mean, depth-average flow (arrows) by month, displayed as in Harms and Winant (1998). Dots with white centers indicate mooring locations. The baselines of the arrows are aligned with the minor principal axis ($x$) at each site. January is indicated by "J". The standard deviations of the cross- and along-shelf flow are shown by the semi-minor and -major axes of the principal axis ellipses (gray). Figure from Fewings et al. (2015: Figure 4).

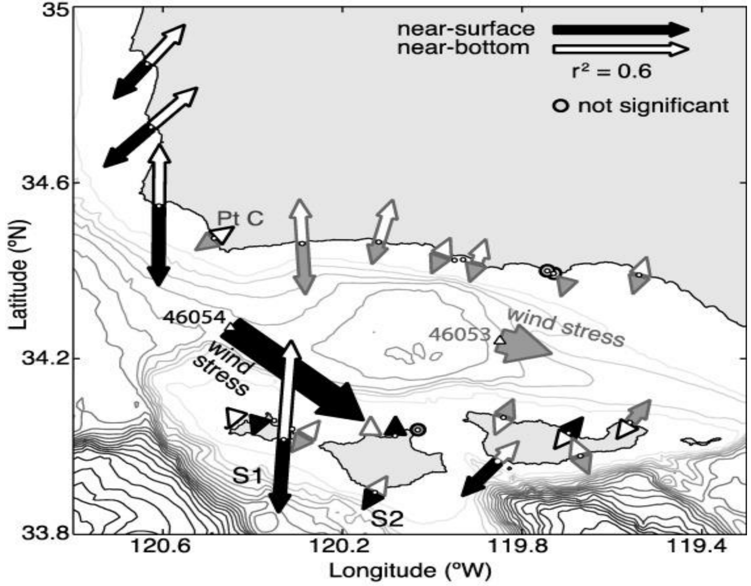


**Figure 6.5**. Correlation of cross-shelf velocity with regional wind stress. Correlation of cross-shelf flow near surface (filled arrows) and near bottom (white arrows) with wind stress; thin arrows are parallel to the local cross-shelf direction. The two wide arrows indicate the mean equatorward wind stress. Small circles near the tails of the thin arrows indicate ADCP locations. Length of thinner arrow indicates $r^2$ at each site. Direction of arrow indicates the flow direction when the wind stress fluctuation is equatorward. Figure from Fewings et al. (2015: Figure 9).

studies have shown that alongshore upwelling-favorable winds are stronger further out in the Bight and away from the California mainland coast (Winant and Dorman 1997; Pickett and Paduan 2003), suggesting they may be contributing more to patterns around San Miguel Island than within the Santa Barbara Basin. The complex situation of warm and cool currents colliding and mixing in various gyres within the Southern California Bight makes this an area where nearshore localized SST sequences should be developed for archaeological interpretations. Large-scale regional trends are useful in determining broad-scale (millennial) patterning and may be more useful in more localized contexts in areas with less oceanographic complexity, but the Southern California Bight is not one of those areas.

The Bay Point sequence shows further fine-grained variation within generally warmer and cooler phases that is not discernable in the SBB cores due to the temporal scale available in this archaeological dataset. Although calibrations and localized delta R variations complicate $^{14}$C dating of archaeological sites, robust chronological models are possible, and the multi-year trends detectable on single shells can be placed within somewhat narrower time frames allowing finer-scaled reconstructions of localized nearshore environments. For instance, the SBB curve shows a warmer phase between ~3,800 and 5,800 BP. Two archaeological components at Cave of the Chimneys fall within this time frame and show a distinct separation of warmer and cooler phases within this one warmer phase on the SBB core and the long-term trend of warmer SSTs since the Early Holocene. Stratum V, dated to the beginning of this warmer phase according to the SBB core (~5,700 to 4,400 cal BP) shows much cooler water temperatures compared to strata III and IV, which occur during the second half of this same warmer phase at ~3,900 to 4,400 cal BP. The warm SST phase is much later and more narrowly defined in the localized Bay Point sequence allowing a more nuanced understanding of shifts in water temperature through time in the nearshore intertidal and kelp forest ecosystems people were harvesting from. Similarly, three archaeological components (strata VI and VII at Cave of the Chimneys, and Stratum C, at Daisy Cave) fall within another one of Kennett’s (2005) warm water phases between ~6,300 and 8,200 cal BP, but archeological data allows us to see a finer-grained pattern of increased warming specifically between

~6,400 and 6,900 cal BP, narrowing this phase within the Bay point study area (see Chapter II, Figure 2.14).

### *Combining SST and Faunal Patterns*

Although faunal analysis from these sites is ongoing, preliminary data are available for comparison with SST trends to examine whether perceived impacts from human foraging are climatically driven or human induced at these sites specifically. As stated above, if water temperature is responsible for increases and decreases in abundance of red abalone in archaeological middens (as per Glassow et al. 2012), we should see decreasing abundances during warm SST phases. This is not the case at Bay Point, suggesting the nature of perceived impacts is more complex than water temperature alone. For instance, red abalone is most abundant during the warmer Middle Holocene occupations at Cave of the Chimneys, where it comprises ~11 to 21% of shell remains by weight as compared to only ~1-3 percent of shell weight in the cooler Early Holocene components (shell weight data from Ainis 2012, Appendix A-1).

Mussels have a higher temperature tolerance than red abalone so they should show increases during warmer phases. The pattern is reversed, however, as the coolest Early Holocene components contain the most mussel (69-75% of shellfish weight) and the warmer Middle Holocene components contain much lower relative abundances of mussel (21-28% of shell weight). Measurements of intact mussel valves from the site (n = 2,036 see Ainis 2012, Table 7 and Figure 24) show larger maximum lengths in mussels from Stratum VII as compared to Stratum VI, suggesting human harvesting was having an effect on mussel size (since SST does not shift significantly between these components) during the Early Holocene when mussel was the primary focus of shellfish gatherers. Although a two-tailed t-test showed no significant differences between mean mussel lengths between these components, the significant drop in maximum values (from 112.71 to 93.91 mm; Ainis 2012, Table 7 and Figure 24) highlights the need to examine full ranges (maxima and minima) in conjunction with mean values (Ainis 2012, Tables 7 and 8). Measurements of intact mussel valves from the Middle Holocene (strata V-III) components show a decreasing trend in maximum size measurements and significant differences between mean values through time, although sizes appear to rebound somewhat during the early Late Holocene (Stratum II); again suggesting the intensity of human harvesting, and not SST shifts, are impacting intertidal mussel beds in the site vicinity.

The pattern for black abalone also contradicts expectations if water temperatures were driving perceived impacts on intertidal shellfish. The relative abundance of black abalone is lower (~4-9%) during the cooler Early Holocene and higher (~6-18%) during the Middle Holocene. In addition, relative abundances of black abalone fluctuate between archaeological components even more than either mussel or red abalone, again suggesting human foraging (and not SST) is affecting local populations in the short-term. My on-going research will include shellfish samples from Daisy Cave and fish bone analysis from both sites to further explore this patterning.

My detailed analysis of shellfish remains from Unit 1 at Cave of the Chimneys shows a stark contrast in the harvesting habitat of shellfish between the Early Holocene and later components (Middle and Late Holocene), suggesting that human decisions about shellfish collection were driving relative abundances of shellfish species at this site (Ainis 2012). Early Holocene components contained higher proportions of taxa inhabiting the middle intertidal zone, and the Middle and Late Holocene components contained higher amounts of taxa that inhabit the lower intertidal and subtidal zones (Ainis 2012, Table 9, Figures 41 and 42), suggesting people were moving further out into the intertidal to harvest shellfish through time. This data suggest that human harvesting decisions related to habitat preference were driving shifts in shellfish at this site. That being said, the one exception is the peak in sea urchin abundance in Stratum IV, which is linked to a peak in warmer SST. The unusual abundance of sea urchin in this component is likely driven by an increase in sea urchin populations brought about by the increase in surface water temperatures at this time (see Chapter V).

My study confirms other research on the Northern Channel Islands showing no correlation between changes in shell abundance and/or size and stable isotope data from associated mussel shell carbonate indicative of changes in SST (e.g., Flores 2017; Robbins et al. 2013). Environmental parameters, including SST and littoral substrates and habitats, clearly affect the types of available shellfish available to human collectors;

however, reconstructed paleo-SST data imply that changes in surface water temperature are not driving shifts in types and sizes of harvested shellfish on San Miguel Island.

## Comparison of $\delta^{13}$C and $\delta^{18}$O Datasets through Time

Comparisons of $\delta^{13}$C and $\delta^{18}$O values from modern and archaeological California mussel shells showed no consistent correlation between these isotopic ratios (see Chapter II, Table 1). This suggests that there may not be a clear relationship between $\delta^{13}$C and $\delta^{18}$O for this species. Most shells showed relatively strong negative correlations between these values indicative of increased upwelling during cooler water phases as expected, but others showed weak negative correlations and a few even showed weak positive correlations. No strong positive correlations were noted, however, suggesting variation is present, but not to the degree of producing a complete reversal of expected trends.

General trends in $\delta^{18}$O values show oscillations through time, along with a general increase through time, from the Early Holocene to Late Holocene and Modern, and the absolute lowest values (most depleted, warmer SST) in modern mussel shell samples (Chapter II, Figure 2.6). The trends for $\delta^{13}$C differ as expected, showing most depleted values indicative of upwelling and higher water pH during the Early Holocene, with more enriched values during the Middle Holocene, suggesting less upwelling and mixing with deeper $\delta^{13}$C depleted waters during this time. This may also represent increased stratification of the water column during the late Middle Holocene as suggested by others (i.e., Friddell et al. 2003). After this Middle Holocene peak, there is a drop in enrichment (values are more negative/depleted) continuing through the Late Holocene (Stratum II) and into the modern time (Chapter II, Figure 2.7). The number of extremely depleted outliers is also worth noting, as they are relatively plentiful during the Early Holocene, but no Middle Holocene, Late Holocene, or modern samples show outliers containing depleted $\delta^{13}$C values usually indicative of increased upwelling. In addition, high negative correlations (-0.93 and -0.71) were documented on both modern shell samples, though this may be a result of sample size bias as it is the smallest sample from any component explored in this study. I am conducting ongoing analysis of additional modern shells to further explore this patterning and relate current trends to the long-term record preserved in archaeological samples.

The $\delta^{13}C$ of dissolved inorganic carbon (DIC) is normally lower in upwelled when compared to surface water due to the presence of $^{13}C$ depleted DIC from the remineralization process, allowing $\delta^{13}C$ of DIC to be used as a tracer of upwelling strength (Sheu et al. 1996). Regional studies, however, have shown that there is not always a direct corollary link between SST and marine productivity/upwelling and surface chlorophyll (phytoplankton blooms) particularly in the Southern California Bight, due to oceanographic patterns and high number of eddies further complicating circulation (e.g., Kim et al. 2009; Legaard and Thomas 2006; Santos et al 2011).

My analysis confirms suggestions (i.e., Kim et al. 2009; Santos et al 2011) that biological responses to physical variation are not necessarily linear and often occur in complex ways. It also highlights the need to develop sequences representative of localized patterning and interpretation of stable isotope data with context specific variables (i.e., oceanographic currents and upwelling patterns, offshore wind stress, paleogeography, etc.). Although cooler ocean temperatures are sometimes linked to enhanced upwelling (depleted $\delta^{13}C$ ‰), this is not always the case, and localized factors contributing to these measures must be determined. San Miguel Island is at the northwestern edge of the Southern California Bight, and is less affected by the California Countercurrent and standing eddies (i.e., DiGiacomo and Holt 2001), suggesting that geochemical water trends associated with upwelling may be more detectable here than along the southern California mainland coast (i.e., Santos et al. 2011). I am continuing analysis of $\delta^{13}C$ and $\delta^{18}O$ patterning through time at Bay Point and hope to further quantify the degree and types of variation that occurred during the Holocene, and potentially correlate these trends with additional datasets and proxies for upwelling.

## **Archaeological Contributions to Marine Conservation and Management Efforts**

Long-term interdisciplinary data, like those presented in this dissertation, provide localized histories and elucidate parameters that may be used to guide management and restoration efforts in our current state of ecological degradation and rapid climatic change. Although returning to past conditions is impossible and perhaps even undesirable, archaeological data sets provide glimpses of ecosystem shifts through various stages of climatic change and human presence over thousands of years, presenting an array of options and potential scenarios. The ecosystems of the California Channel Islands (and most places on earth) are characterized by human interactions extending deep into the past (e.g., Boivin et al. 2016; Gill et al. 2019; Rick and Erlandson 2008; and others). The better we understand how human interactions helped shape the ecology and evolution of these and other islands and landscapes through long expanses of time, the more effective we can be in current and future management of these ecosystems (Jackson et al. 2001). My dissertation contributes to the growing body of interdisciplinary studies and models focused on long-term change that are being used as a strategy for enhancing restoration and conservation efforts on the Channel Islands and in other parts of the world (e.g., Rick et al. 2014).

Archaeological datasets have much to contribute to "biocultural approaches to conservation" (as per Gavin et al. 2015). They provide snapshots and examples from a wide variety of ecological and environmental circumstances, climatic fluctuations, socio-cultural situations (i.e., human population size and demographics, social organizations, religious perspectives, historical backgrounds, etc.), and time periods. Thus, they can be used to inform current management and hopefully create effective restoration outcomes within different social-ecological contexts. Social-ecological systems are by their nature complex, dynamic, heterogenous, and often hard to predict as they must be examined in different temporal and spatial scales. They are shaped by a wide variety of thresholds, dynamic variables, feedback loops, and socio-ecological processes (see Gavin et al. 2015). We can learn much about the socioecological context of communities from archaeological datasets that provide information regarding knowledge, innovative technology and management, and adaptive behaviors of indigenous peoples in a variety of spatial and temporal contexts and incorporate this information and patterning in management decisions including conservation and restoration ecology.

### *Archaeological Data as Localized Histories for Kelp Ecosystem Models*

Marine scientists are in a race against time to manage and conserve rapidly declining fisheries and nearshore environments that are increasingly impacted by overfishing, rapid climate change and sea-level rise (Pauley 1995; J.B.C. Jackson et al. 2001). Long-term historical data are desperately needed to set baselines for endangered species and assist in setting recovery targets and creating effective conservation and management plans (McClenachan et al. 2012). It has been acknowledged that the concept of 'baselines' is somewhat arbitrary for marine systems that are in a constant state of alteration and adaptability, responding to a wide array of climatic, physiographic, and oceanographic processes operating on short and long-term scales (Steele 1998). The long history of human interactions with nearshore ecosystems further complicates the notion of defining a baseline state and may even be counterproductive in the sense of which baseline should be utilized (i.e., a hundred years ago, five thousand years ago, ten thousand years ago, etc.) as they are in a constant state of flux, leading to the concept of 'shifting baselines' (as per Pauley 1995; J.B.C. Jackson et al. 2001; see also Campbell et al 2009; Pinnegar and Engelhard 2008). Nevertheless, localized histories of ecosystem shifts examined in the context of natural and/or anthropogenic causes are useful in demonstrating the ranges of potential ecological states for localized marine communities. In this vein, historical ecology is increasingly being used as a tool in conservation focused marine ecology, with researchers highlighting the benefits of new hypotheses and "surprising results" that contribute to a better understanding of ecological dynamics in marine settings (McClenachan et al. 2015).

Successful management, conservation, and restoration in marine ecosystems rely on a functional understanding of the complex interactions between climate change and human induced impacts (i.e., fishing pressure, pollution, etc.) and the effects they have on marine populations and ecosystem dynamics (Harley and Bennett-Rogers 2004). Ecosystem-based management (EBM) approaches based on ecological network models and analyses are valuable in connecting quantitative and conceptual aspects of natural ecosystems and for generating explanations and hypotheses relating to community structure and dynamics, as well as generating hypotheses concerning natural and anthropogenic impacts (Borrett et al. 2014; Clark et al. 2001; Montoya et al. 2006). In this vein, “mass-balanced food web models” are being used to evaluate the conditions and shifts in current kelp forest ecosystems of Alta and Baja California by creating ecological network models that can be compared regionally and used to manage the requirements and relationships within specific kelp forest ecosystems (e.g., Beas-Luna et al. 2014; Vilalta-Navas et al. 2018).

Archaeological datasets have much to offer ecological network models, with emphasis and focus on kelp forest ecosystems specifically. Quantitative ecosystem models are based on species or “functional group” (FG) interactive networks, which are used to understand how human activities influence ecosystems and potentially forecast responses to proposed management directives. Faunal and floral data from archaeological assemblages encompassing dozens or even hundreds of taxa could be added to marine ecological databases, providing long-term perspectives on certain aspects of the ecosystem and shifting-baseline understanding of life-histories for specific kelp forest communities spanning thousands of years. Braje et al. (2015; see also Haas et al. 2019) have demonstrated, for instance, how knowledge of past distributions, abundances, and population structures for black abalone populations around the Channel Islands can be utilized in restoration and conservation efforts. Gill (2016) has also used paleobotanical data from archaeological sites spanning 10,000 years to document the long-term persistence of grassland/coastal prairie habitats on the islands, and the long-term importance of geophytes in the diet of the island Chumash. Such conservation applications of archaeological data can and should be expanded to incorporate many more marine and terrestrial species.

## Summary and Conclusion

My dissertation contains a variety of archaeometric and faunal data from two highly significant multi-component rockshelter sites that have received a great deal of attention and analysis by multiple researchers over the past several decades (see Chapter I). My study contains only a small amount of the wealth of archaeological, environmental, and paleontological data that have been gleamed from these sites. Several ongoing projects (e.g., identification and quantification of fish bone and crab remains, additional stable isotope analysis of different shellfish species, and a season of harvest study for California mussel, to name a few) will continue the important contributions from these sites in the near future. Daisy Cave and Cave of the Chimneys provide a remarkable opportunity for archaeologists and environmental scientists to examine marine and terrestrial ecosystems in a localized setting across a broad expanse of time in relatively fine detail. The datasets constructed here have implications for understanding the deep history of the Island Chumash and the highly dynamic land- and seascapes they inhabited for many millennia, as well as for modern ecological restoration, conservation, and management on the California Channel Islands by documenting the long-term trends and history of one localized setting in the region. I hope to further integrate these datasets with nearshore and kelp forest studies in the region and develop practical models for using archaeological faunal and archaeometric datasets to inform conservation biology.

# APPENDIX:

## STABLE ISOTOPE RESULTS

| Sample No./Provenience | d13C | d18O |
|---|---|---|
| **Modern Bay Point** | | |
| MOD.1a | 0.25 | 0.12 |
| MOD.1b | -0.56 | 1.16 |
| MOD.1c | -0.23 | 0.75 |
| MOD.1d | -0.28 | 0.75 |
| MOD.1e | 0.02 | 0.05 |
| MOD.1f | 0.27 | 0.06 |
| MOD.1g | 0.04 | 0.07 |
| MOD.1h | -0.15 | 0.71 |
| MOD.1i | -0.49 | 0.77 |
| MOD.1j | -0.12 | 0.34 |
| MOD.1k | 0.49 | -0.65 |
| MOD.1l | 0.32 | 0.03 |
| MOD.2a | 0.3785 | 0.0704 |
| MOD.2b | -0.3579 | 1.1748 |
| MOD.2c | 0.1277 | 0.6980 |
| MOD.2d | -0.1638 | 0.4684 |
| MOD.2e | 0.1595 | 0.1692 |
| MOD.2f | 0.1372 | 0.1178 |
| MOD.2g | 0.4090 | -0.1769 |
| MOD.2h | -0.2157 | 0.0607 |
| MOD.2i | -0.1886 | 0.6757 |
| MOD.2j | -0.3614 | 0.7360 |
| MOD.2k | 0.0043 | 0.4661 |
| MOD2.l | 0.0235 | 0.6188 |
| **Stratum II, Chimneys** | | |
| SMI603.2.1a | 0.05 | 1.34 |
| SMI603.2.1b | 0.96 | 0.56 |
| SMI603.2.1c | 0.62 | 0.63 |
| SMI603.2.1d | 0.46 | 0.82 |
| SMI603.2.1e | 0.96 | 0.63 |
| SMI603.2.1f | 0.91 | 0.38 |
| SMI603.2.1g | 0.84 | 0.09 |
| SMI603.2.1h | 0.64 | 0.23 |
| SMI603.2.1i | 0.79 | 0.20 |

| | | |
|---|---|---|
| SMI603.2.1j | 0.21 | 1.07 |
| SMI603.2.1k | 0.35 | 1.10 |
| SMI603.2.1l | 0.61 | 0.85 |
| SMI603.2.2a | 0.3844 | 1.2324 |
| SMI603.2.2b | 0.4360 | 0.9878 |
| SMI603.2.2c | 0.4257 | 0.5721 |
| SMI603.2.2d | 0.3411 | 0.4696 |
| SMI603.2.2e | 0.4887 | 1.0829 |
| SMI603.2.2f | 0.4530 | 1.0565 |
| SMI603.2.2g | 0.7217 | 0.8086 |
| SMI603.2.2h | 0.7512 | 0.7239 |
| SMI603.2.2i | 1.0585 | 0.4990 |
| SMI603.2.2j | 0.8461 | 0.3961 |
| SMI603.2.2k | 0.3750 | 0.5935 |
| SMI603.2.2l | 0.3375 | 1.1096 |
| SMI603.2.1.1a | 0.31 | 0.95 |
| SMI603.2.1.1b | 0.61 | 0.46 |
| SMI603.2.1.1c | 0.66 | 0.87 |
| SMI603.2.1.1d | 0.61 | 1.18 |
| SMI603.2.1.1e | 0.52 | 1.28 |
| SMI603.2.1.1f | 0.71 | 0.99 |
| SMI603.2.1.1g | 0.65 | 0.71 |
| SMI603.2.1.1h | 0.87 | 0.29 |
| SMI603.2.1.1i | 0.76 | 0.59 |
| SMI603.2.1.1j | 0.77 | 1.04 |
| SMI603.2.1.1k | 0.65 | 1.02 |
| SMI603.2.1.1l | 0.77 | 1.06 |
| SMI603.2.2.1a | 0.24 | 1.20 |
| SMI603.2.2.1b | 0.50 | 0.35 |
| SMI603.2.2.1c | 0.45 | 0.75 |
| SMI603.2.2.1d | 0.10 | 0.93 |
| SMI603.2.2.1e | -0.46 | 1.17 |
| SMI603.2.2.1f | -0.17 | 1.23 |
| SMI603.2.2.1g | 0.10 | 0.78 |
| SMI603.2.2.1h | 0.29 | 0.46 |
| SMI603.2.2.1i | 0.09 | 1.03 |
| SMI603.2.2.1j | 0.04 | 1.16 |
| SMI603.2.2.1k | 0.09 | 0.48 |
| SMI603.2.2.1l | -0.03 | 0.90 |

| | | |
|---|---|---|
| SMI603.2.2.1m | -0.26 | 1.24 |
| SMI603.2.2.1n | -0.14 | 0.88 |
| SMI603.2.2.1o | 0.51 | 0.45 |
| SMI603.2.2.1p | 0.98 | 0.35 |
| SMI603.2.2.1q | 0.80 | 0.49 |
| SMI603.2.2.1r | 0.58 | 0.66 |
| SMI603.2.2.1s | 0.57 | 0.71 |
| SMI603.2.2.2a | 1.29 | 0.23 |
| SMI603.2.2.2b | 1.48 | 0.74 |
| SMI603.2.2.2c | 1.22 | 1.11 |
| SMI603.2.2.2d | 1.09 | 1.02 |
| SMI603.2.2.2e | 1.33 | 0.72 |
| SMI603.2.2.2f | 1.27 | 1.26 |
| SMI603.2.2.2g | 1.17 | 0.62 |
| SMI603.2.2.2h | 1.29 | 0.20 |
| SMI603.2.2.2i | 1.09 | 1.33 |
| SMI603.2.2.2j | 1.34 | 0.40 |
| SMI603.2.2.2k | 0.85 | 0.81 |
| SMI603.2.2.2l | 0.95 | 0.91 |
| SMI603.2.3.1a | 0.4900 | 0.3500 |
| SMI603.2.3.1b | 1.0300 | 0.7300 |
| SMI603.2.3.1c | 0.7000 | 0.9100 |
| SMI603.2.3.1d | 0.8907 | 0.0893 |
| SMI603.2.3.1e | 1.0466 | 0.2305 |
| SMI603.2.3.1f | 1.1000 | 0.3100 |
| SMI603.2.3.1g | 1.1422 | 0.5436 |
| SMI603.2.3.1h | 1.1500 | 0.9800 |
| SMI603.2.3.1i | 1.2000 | 0.8100 |
| SMI603.2.3.1j | 1.1600 | 0.9100 |
| SMI603.2.3.1k | 0.9000 | 0.2300 |
| SMI603.2.3.1l | 1.0500 | 0.1700 |
| SMI603.2.3.1m | 1.2900 | 0.6300 |
| SMI603.2.3.1n | 1.1100 | 0.7400 |
| SMI603.2.3.1o | 1.0500 | 1.1000 |
| SMI603.2.3.2a | 0.1633 | 0.8593 |
| SMI603.2.3.2b | 0.0979 | 1.3585 |
| SMI603.2.3.2c | -0.2357 | 1.4094 |
| SMI603.2.3.2d | 0.1161 | 1.4705 |
| SMI603.2.3.2e | 0.1067 | 1.2771 |

| | | |
|---|---|---|
| SMI603.2.3.2f | 0.7538 | 1.2701 |
| SMI603.2.3.2g | 0.4296 | 1.3213 |
| SMI603.2.3.2h | 0.6786 | 0.9937 |
| SMI603.2.3.2i | 0.6514 | 0.7123 |
| SMI603.2.3.2j | 0.3071 | 1.3697 |
| SMI603.2.3.2k | 0.6041 | 1.0834 |
| SMI603.2.3.2l | 0.4587 | 0.8639 |
| SMI603.2.4.1a | 0.1135 | 1.1924 |
| SMI603.2.4.1b | -0.0282 | 0.9733 |
| SMI603.2.4.1c | -0.2867 | 1.1563 |
| SMI603.2.4.1d | -0.1846 | 1.4765 |
| SMI603.2.4.1e | -0.1422 | 1.1407 |
| SMI603.2.4.1f | -0.0350 | 1.0117 |
| SMI603.2.4.1g | -0.1570 | 1.0427 |
| SMI603.2.4.1h | -0.1419 | 1.2792 |
| SMI603.2.4.1i | 0.1305 | 1.1391 |
| SMI603.2.4.1j | 0.2950 | 0.6035 |
| SMI603.2.4.1k | 0.2108 | 1.1157 |
| SMI603.2.4.1l | -0.3123 | 1.2903 |
| SMI603.2.4.1m | 0.0244 | 1.3471 |
| SMI603.2.4.1n | -0.0039 | 1.4619 |
| SMI603.2.4.1o | 0.0486 | 0.7888 |
| SMI603.2.4.1p | -0.0330 | 1.1013 |
| SMI603.2.4.1q | 0.1264 | 1.3038 |
| SMI603.2.4.1r | 0.1813 | 1.3540 |
| SMI603.2.4.1s | 0.1486 | 1.3674 |
| SMI603.2.4.1t | -0.0197 | 1.2735 |
| SMI603.2.4.1u | 0.2314 | 0.8986 |
| SMI603.2.4.1v | 0.2710 | 1.0820 |
| SMI603.2.4.1w | 0.1731 | 1.1790 |
| SMI603.2.4.2a | 0.0765 | 0.3213 |
| SMI603.2.4.2b | 0.1046 | 1.1074 |
| SMI603.2.4.2c | 0.5538 | 0.6226 |
| SMI603.2.4.2d | 0.3905 | 1.0045 |
| SMI603.2.4.2e | 1.0183 | 0.4718 |
| SMI603.2.4.2f | 1.0594 | 0.4937 |
| SMI603.2.4.2g | 0.8936 | 1.0455 |
| SMI603.2.4.2h | 0.8694 | 1.3104 |
| SMI603.2.4.2i | 0.7022 | 0.8522 |

| | | |
|---|---|---|
| SMI603.2.4.2j | 0.1625 | 0.8745 |
| SMI603.2.4.2k | 0.2251 | 0.5131 |
| SMI603.2.4.2l | -0.0577 | 1.0210 |
| **Stratum III, Chimneys** | | |
| SMI603.3.1a | 0.9610 | 0.8923 |
| SMI603.3.1b | 1.2719 | 0.4699 |
| SMI603.3.1c | 1.1774 | 0.3843 |
| SMI603.3.1d | 0.6618 | 1.1077 |
| SMI603.3.1e | 0.9367 | 1.2997 |
| SMI603.3.1f | 1.4269 | 0.3424 |
| SMI603.3.1g | 1.3560 | 0.3552 |
| SMI603.3.1h | 1.3798 | 1.2490 |
| SMI603.3.1i | 1.4257 | 0.7684 |
| SMI603.3.1j | 1.4250 | 0.5399 |
| SMI603.3.1k | 1.0666 | 0.6357 |
| SMI603.3.1l | 1.1639 | 1.4793 |
| SMI603.3.2a | 0.55 | 0.49 |
| SMI603.3.2b | 0.77 | 0.56 |
| SMI603.3.2c | 0.49 | 1.29 |
| SMI603.3.2d | 0.75 | 1.23 |
| SMI603.3.2e | 0.90 | 0.96 |
| SMI603.3.2f | 0.53 | 1.28 |
| SMI603.3.2g | 0.63 | 1.02 |
| SMI603.3.2h | 0.17 | 1.23 |
| SMI603.3.2i | 0.60 | 1.50 |
| SMI603.3.2j | 0.63 | 1.25 |
| SMI603.3.2k | 0.52 | 1.20 |
| SMI603.3.2l | 0.75 | 0.54 |
| SMI603.3.3a | 0.6855 | 0.8268 |
| SMI603.3.3b | 0.7126 | 0.1297 |
| SMI603.3.3c | 0.6604 | 1.0870 |
| SMI603.3.3d | 0.5553 | 1.0587 |
| SMI603.3.3e | 0.8264 | 1.0847 |
| SMI603.3.3f | 0.3846 | 0.8737 |
| SMI603.3.3g | 0.9538 | 0.2955 |
| SMI603.3.3h | 0.7034 | 0.3076 |
| SMI603.3.3i | 0.8215 | 0.8542 |
| SMI603.3.3j | 0.9919 | 1.0182 |
| SMI603.3.3k | 0.9557 | 1.0595 |

|  |  |  |
|---|---|---|
| SMI603.3.3l | 0.9593 | 0.3061 |
| **Stratum IV, Chimneys** |  |  |
| SMI_603.4.1.1a | 0.9175 | 1.3439 |
| SMI_603.4.1.1b | 0.9908 | 0.6766 |
| SMI_603.4.1.1c | 0.9785 | 0.5669 |
| SMI_603.4.1.1d | 1.2743 | -0.0731 |
| SMI_603.4.1.1e | 1.3157 | 0.1514 |
| SMI_603.4.1.1f | 0.9073 | 0.7564 |
| SMI_603.4.1.1g | 0.7040 | 1.2444 |
| SMI_603.4.1.1h | 0.8747 | 1.1918 |
| SMI_603.4.1.1i | 1.0455 | 1.1164 |
| SMI_603.4.1.1j | 1.2307 | 0.8293 |
| SMI_603.4.1.1k | 1.2443 | 0.9160 |
| SMI_603.4.1.1l | 1.6264 | 0.6518 |
| SMI603.4.1.2a | -0.2717 | 0.9363 |
| SMI603.4.1.2b | -0.2789 | 0.7880 |
| SMI603.4.1.2c | -0.1961 | 1.2121 |
| SMI603.4.1.2d | 0.1723 | 1.2449 |
| SMI603.4.1.2e | 0.0820 | 0.8208 |
| SMI603.4.1.2f | 0.1531 | 1.2302 |
| SMI603.4.1.2g | 0.3691 | 1.2248 |
| SMI603.4.1.2h | 0.6774 | 1.1953 |
| SMI603.4.1.2i | 0.7862 | 1.1296 |
| SMI603.4.1.2j | 0.7265 | 0.8767 |
| SMI603.4.1.2k | 0.5971 | 0.3870 |
| SMI603.4.1.2l | 0.1934 | 1.0673 |
| SMI603.4.1.2m | 0.5247 | 1.0573 |
| SMI603.4.1.2n | 0.8515 | 1.0032 |
| SMI603.4.1.2o | 0.8514 | 0.8165 |
| SMI603.4.1.2p | 0.9461 | 0.6868 |
| SMI603.4.1.2q | 1.0099 | 0.6797 |
| SMI603.4.1.2r | 0.8654 | 0.6910 |
| SMI603.4.1.2s | 0.9796 | 0.6447 |
| SMI603.4.1.2t | 0.8735 | 0.3253 |
| SMI603.4.2.1a | 0.4623 | 1.0268 |
| SMI603.4.2.1b | 0.4501 | 0.7044 |
| SMI603.4.2.1c | 0.6049 | 0.4129 |
| SMI603.4.2.1d | 0.8611 | 0.3503 |
| SMI603.4.2.1e | 0.2497 | 0.7219 |

| | | |
|---|---|---|
| SMI603.4.2.1f | 0.3744 | 0.9142 |
| SMI603.4.2.1g | 0.3117 | 0.7953 |
| SMI603.4.2.1h | 0.3411 | 0.9653 |
| SMI603.4.2.1i | 0.4149 | 1.0049 |
| SMI603.4.2.1j | 1.0623 | 0.4145 |
| SMI603.4.2.1k | 0.8018 | 0.2361 |
| SMI603.4.2.1l | 0.1752 | 0.9123 |
| SMI603.4.2.2a | 1.0777 | 1.1648 |
| SMI603.4.2.2b | 1.3045 | 0.3328 |
| SMI603.4.2.2c | 0.4880 | 0.8536 |
| SMI603.4.2.2d | 0.8761 | 0.8918 |
| SMI603.4.2.2e | 0.3838 | 1.0268 |
| SMI603.4.2.2f | 1.0338 | 0.9069 |
| SMI603.4.2.2g | 1.3190 | 0.5359 |
| SMI603.4.2.2h | 1.2617 | 0.3847 |
| SMI603.4.2.2i | 0.6265 | 0.7278 |
| SMI603.4.2.2j | 0.7125 | 0.7276 |
| SMI603.4.2.2k | 0.6992 | 1.1784 |
| SMI603.4.2.2l | 0.9450 | 1.1626 |
| SMI603.4.2.3a | 0.7546 | 0.3696 |
| SMI603.4.2.3b | 0.2463 | 0.9665 |
| SMI603.4.2.3c | 0.5492 | -0.3850 |
| SMI603.4.2.3d | 1.0478 | 0.0649 |
| SMI603.4.2.3e | 1.0779 | 0.2451 |
| SMI603.4.2.3f | 0.8204 | 0.9177 |
| SMI603.4.2.3g | 0.7902 | 0.7533 |
| SMI603.4.2.3h | 0.9031 | 0.8812 |
| SMI603.4.2.3i | 1.1159 | 0.8222 |
| SMI603.4.2.3j | 1.2036 | 0.6450 |
| SMI603.4.2.3k | 1.4446 | -0.0793 |
| SMI603.4.2.3l | 1.1389 | 0.3200 |
| **Stratum V, Chimneys** | | |
| SMI_603.5.1.1a | 1.0655 | 1.1159 |
| SMI_603.5.1.1b | 1.5666 | 0.5367 |
| SMI_603.5.1.1c | 1.2175 | 0.1852 |
| SMI_603.5.1.1d | 1.2348 | 0.1806 |
| SMI_603.5.1.1e | 0.9627 | 1.0534 |
| SMI_603.5.1.1f | 0.6034 | 1.2416 |
| SMI_603.5.1.1g | 1.1103 | 1.0999 |

| | | |
|---|---|---|
| SMI_603.5.1.1h | 1.0202 | 1.0421 |
| SMI_603.5.1.1i | 1.5358 | 0.6699 |
| SMI_603.5.1.1j | 1.5375 | 0.4290 |
| SMI_603.5.1.1k | 1.3171 | 0.5052 |
| SMI_603.5.1.1l | 1.2831 | 1.1627 |
| SMI603.5.2a | 0.72 | 1.41 |
| SMI603.5.2b | 1.10 | 1.34 |
| SMI603.5.2c | 0.93 | 1.03 |
| SMI603.5.2d | 1.32 | 0.63 |
| SMI603.5.2e | 1.18 | 0.50 |
| SMI603.5.2f | 1.00 | 0.80 |
| SMI603.5.2g | 1.23 | 0.97 |
| SMI603.5.2h | 0.97 | 1.09 |
| SMI603.5.2i | 0.68 | 1.31 |
| SMI603.5.2j | 1.01 | 1.28 |
| SMI603.5.2k | 0.97 | 0.97 |
| SMI603.5.2l | 1.10 | 0.65 |
| SMI603.5.2m | 1.12 | 0.50 |
| SMI603.5.2n | 0.77 | 0.50 |
| SMI603.5.2o | 0.59 | 0.45 |
| SMI603.5.2p | 0.88 | 0.51 |
| SMI603.5.2q | 0.71 | 0.44 |
| SMI603.5.2r | 0.66 | 0.69 |
| SMI603.5.2s | 0.69 | 0.97 |
| SMI603.5.2t | 0.35 | 0.90 |
| SMI603.5.2u | -0.03 | 1.00 |
| SMI603.5.2v | 0.83 | 1.08 |
| SMI603.5B.1a | 0.6340 | 0.3389 |
| SMI603.5B.1b | 0.8219 | 0.5600 |
| SMI603.5B.1c | 0.6478 | 0.7322 |
| SMI603.5B.1d | 0.4137 | 1.0732 |
| SMI603.5B.1e | 0.6438 | 1.3381 |
| SMI603.5B.1f | 0.6914 | 0.8688 |
| SMI603.5B.1g | 0.8558 | 0.6177 |
| SMI603.5B.1h | 0.5779 | 1.1192 |
| SMI603.5B.1i | 0.7898 | 1.3685 |
| SMI603.5B.1j | 0.7658 | 1.3124 |
| SMI603.5B.1k | 0.6841 | 1.4056 |
| SMI603.5B.1l | 0.8616 | 1.4061 |

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|---|---|---|
| SMI603.5B.1m | 0.7774 | 1.3123 |
| SMI603.5B.1n | 0.9815 | 1.0942 |
| SMI603.5B.1o | 0.9349 | 0.9967 |
| SMI603.5B.1p | 0.8151 | 0.8373 |
| SMI603.5B.1q | 0.8533 | 0.8611 |
| SMI603.5B.1r | 0.3562 | 1.1815 |
| SMI603.5B.2a | 0.08 | 1.02 |
| SMI603.5B.2b | 0.27 | 1.14 |
| SMI603.5B.2c | 0.53 | 0.42 |
| SMI603.5B.2d | 0.61 | 0.78 |
| SMI603.5B.2e | 0.88 | 0.55 |
| SMI603.5B.2f | 0.30 | 0.53 |
| SMI603.5B.2g | 0.47 | 1.03 |
| SMI603.5B.2h | 0.54 | 0.77 |
| SMI603.5B.2i | 0.54 | 1.32 |
| SMI603.5B.2j | 0.96 | 0.83 |
| SMI603.5B.2k | 0.88 | 0.90 |
| SMI603.5B.2l | 0.55 | 1.13 |
| SMI603.5C.1a | 1.07 | 1.35 |
| SMI603.5C.1b | 1.14 | 0.88 |
| SMI603.5C.1c | 0.71 | 0.89 |
| SMI603.5C.1d | 0.72 | 1.11 |
| SMI603.5C.1e | 0.91 | 1.38 |
| SMI603.5C.1f | 1.07 | 1.40 |
| SMI603.5C.1g | 1.34 | 0.18 |
| SMI603.5C.1h | 1.17 | 0.72 |
| SMI603.5C.1i | 0.65 | 1.33 |
| SMI603.5C.1j | 0.63 | 1.56 |
| SMI603.5C.1k | 0.93 | 1.10 |
| SMI603.5C.1l | 1.03 | 1.14 |
| SMI603.5C.2a | 1.87 | 0.79 |
| SMI603.5C.2b | 1.50 | 0.23 |
| SMI603.5C.2c | 1.43 | 0.33 |
| SMI603.5C.2d | 1.05 | 0.63 |
| SMI603.5C.2e | 0.98 | 0.76 |
| SMI603.5C.2f | 1.26 | 1.12 |
| SMI603.5C.2g | 1.45 | 1.13 |
| SMI603.5C.2h | 1.60 | 1.16 |
| SMI603.5C.2i | 1.76 | 1.15 |

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|---|---|---|
| SMI603.5C.2j | 1.62 | 0.82 |
| SMI603.5C.2k | 1.33 | 0.45 |
| SMI603.5C.2l | 1.24 | 0.29 |
| **Stratum VI, Chimneys** |  |  |
| SMI_603.6.1a | 0.96 | 1.48 |
| SMI_603.6.1b | 0.50 | 0.79 |
| SMI_603.6.1c | 0.27 | 1.41 |
| SMI_603.6.1d | 0.60 | 1.64 |
| SMI_603.6.1e | 0.99 | 1.22 |
| SMI_603.6.1f | 0.86 | 0.71 |
| SMI_603.6.1g | 0.63 | 0.73 |
| SMI_603.6.1h | 0.42 | 0.56 |
| SMI_603.6.1i | 0.47 | 1.24 |
| SMI_603.6.1j | 0.39 | 1.79 |
| SMI_603.6.1k | 1.15 | 1.01 |
| SMI_603.6.1l | 0.71 | 0.63 |
| SMI603.6.2a | 0.1763 | 1.3561 |
| SMI603.6.2b | 0.2900 | 0.9927 |
| SMI603.6.2c | 0.5039 | 0.8348 |
| SMI603.6.2d | 0.2548 | 0.3079 |
| SMI603.6.2e | 0.5660 | 0.7742 |
| SMI603.6.2f | 0.5758 | 1.1118 |
| SMI603.6.2g | 0.5404 | 1.2034 |
| SMI603.6.2h | 0.5916 | 1.2938 |
| SMI603.6.2i | 0.8304 | 1.3605 |
| SMI603.6.2j | 0.4904 | 0.1850 |
| SMI603.6.2k | 0.3432 | 0.3978 |
| SMI603.6.2l | 0.1566 | 0.9608 |
| SMI603.6.2m | 0.3835 | 1.2951 |
| SMI603.6.2n | 0.2388 | 1.1561 |
| SMI603.6.2o | 0.5373 | 1.1231 |
| SMI603.6.2p | 0.7495 | 0.3377 |
| SMI603.6.2q | 0.7529 | -0.0622 |
| SMI603.6.2r | 0.1311 | 0.7431 |
| SMI603.6.2s | 0.0824 | 1.1656 |
| SMI603.6.2t | 0.5589 | 0.9493 |
| SMI603.6.2u | 0.8951 | 1.0923 |
| SMI603.6.2v | 0.6712 | 0.7116 |
| SMI603.6.2w | 0.9609 | 0.2742 |

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|---|---|---|
| SMI603.6.2x | 0.9158 | 0.0731 |
| SMI603.6.2y | 0.9038 | 0.8450 |
| SMI603.6.2z | 0.5974 | 1.0795 |
| SMI603.6.2aa | 0.7564 | 1.1401 |
| SMI603.6.2ab | 0.9592 | 1.2826 |
| SMI603.6.2ac | 1.0005 | 1.1527 |
| SMI603.6.2ad | 0.9882 | 0.3237 |
| SMI603.4.6.6a | 0.7064 | 1.2383 |
| SMI603.4.6.6b | 1.5475 | 0.2480 |
| SMI603.4.6.6c | 1.1946 | 0.8244 |
| SMI603.4.6.6d | 0.9094 | 1.0134 |
| SMI603.4.6.6e | 1.0016 | 0.9868 |
| SMI603.4.6.6f | 1.2559 | 1.0498 |
| SMI603.4.6.6g | 1.4224 | 0.7205 |
| SMI603.4.6.6h | 1.3526 | 0.6960 |
| SMI603.4.6.6i | 1.0100 | 0.9665 |
| SMI603.4.6.6j | 0.9213 | 1.1400 |
| SMI603.4.6.6k | 0.9750 | 1.1514 |
| SMI603.4.6.6l | 0.8045 | 1.1626 |
| SMI603.6.7a | 0.2438 | 0.8471 |
| SMI603.6.7b | 0.0323 | 0.6484 |
| SMI603.6.7c | -0.1533 | 1.3065 |
| SMI603.6.7d | 0.4639 | 1.2424 |
| SMI603.6.7e | 0.8062 | 1.3965 |
| SMI603.6.7f | 0.8702 | 1.3307 |
| SMI603.6.7g | 0.7008 | 1.0956 |
| SMI603.6.7h | 0.8704 | 0.7051 |
| SMI603.6.7i | 0.9200 | 0.5169 |
| SMI603.6.7j | 1.0621 | 0.4132 |
| SMI603.6.7k | 0.5997 | 0.2895 |
| SMI603.6.7l | 0.6237 | 0.5382 |
| SMI603.6.7m | 0.3876 | 0.3964 |
| SMI603.6.7n | 0.0716 | 0.6464 |
| SMI603.6.7o | -0.3096 | 1.0189 |
| SMI603.6.7p | -0.4479 | 1.0692 |
| SMI603.6.7q | 0.5307 | 1.3370 |
| SMI603.6.7r | 0.7350 | 1.4494 |
| SMI603.6.7s | 0.8398 | 1.5468 |
| SMI603.6.7t | 0.6574 | 1.2551 |

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|---|---|---|
| SMI603.6.8a | 0.2792 | 0.8573 |
| SMI603.6.8b | 0.2653 | 0.7307 |
| SMI603.6.8c | 0.2305 | 1.2694 |
| SMI603.6.8d | 0.3615 | 0.9452 |
| SMI603.6.8e | 0.8387 | 0.6482 |
| SMI603.6.8f | 0.5472 | 0.7573 |
| SMI603.6.8g | 0.3057 | 1.1209 |
| SMI603.6.8h | -0.0368 | 1.2943 |
| SMI603.6.8i | 0.3566 | 1.5575 |
| SMI603.6.8j | 0.5126 | 1.3347 |
| SMI603.6.8k | 0.6402 | 1.1143 |
| SMI603.6.8l | 0.6646 | 0.7164 |
| SMI603.6.8m | 0.8030 | 0.3886 |
| SMI603.6.8n | 0.4775 | 1.1200 |
| SMI603.6.8o | 0.4265 | 1.0515 |
| SMI603.6.8p | -0.0367 | 1.3821 |
| SMI603.6.8q | 0.7107 | 1.0992 |
| SMI603.6.8r | 1.0940 | 0.5810 |
| SMI603.6.8s | 1.2598 | 0.3117 |
| SMI603.6.8t | 1.3764 | 0.4056 |
| **Stratum VII, Chimneys** | | |
| SMI_603.7.1a | 0.67 | 1.33 |
| SMI_603.7.1b | 1.09 | 0.88 |
| SMI_603.7.1c | 0.44 | 0.63 |
| SMI_603.7.1d | 0.41 | 1.72 |
| SMI_603.7.1e | 0.87 | 1.59 |
| SMI_603.7.1f | 0.73 | 1.06 |
| SMI_603.7.1g | 0.95 | 0.67 |
| SMI_603.7.1h | 0.44 | 1.47 |
| SMI_603.7.1i | 0.90 | 1.19 |
| SMI_603.7.1j | 0.61 | 0.50 |
| SMI_603.7.1k | -0.08 | 0.57 |
| SMI_603.7.1l | -0.39 | 0.99 |
| SMI603.7.2a | 0.51 | 1.23 |
| SMI603.7.2b | 0.32 | 0.65 |
| SMI603.7.2c | 0.11 | 0.37 |
| SMI603.7.2d | 0.04 | 0.78 |
| SMI603.7.2e | -0.34 | 0.92 |
| SMI603.7.2f | -0.72 | 1.27 |

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|---|---|---|
| SMI603.7.2g | -1.17 | 1.49 |
| SMI603.7.2h | -0.74 | 1.47 |
| SMI603.7.2i | -0.06 | 0.85 |
| SMI603.7.2j | 0.00 | 0.81 |
| SMI603.7.2k | 0.91 | 0.76 |
| SMI603.7.2l | 0.65 | 0.50 |
| SMI603.7.6a | 0.7488 | 0.9259 |
| SMI603.7.6b | 0.2642 | 1.5543 |
| SMI603.7.6c | 0.2240 | 1.5404 |
| SMI603.7.6d | 0.6173 | 1.2343 |
| SMI603.7.6e | 1.0528 | 0.7095 |
| SMI603.7.6f | 1.1229 | 0.2831 |
| SMI603.7.6g | 0.3955 | 0.8275 |
| SMI603.7.6h | 0.4334 | 0.9771 |
| SMI603.7.6i | 0.3272 | 1.0798 |
| SMI603.7.6j | 0.1448 | 1.1992 |
| SMI603.7.6k | 0.2546 | 1.3305 |
| SMI603.7.6l | 0.5981 | 1.3900 |
| SMI603.7.7a | 0.8378 | 0.7680 |
| SMI603.7.7b | 0.6445 | 0.0795 |
| SMI603.7.7c | -0.1969 | 0.9311 |
| SMI603.7.7d | -0.1746 | 1.4382 |
| SMI603.7.7e | 0.0609 | 1.1748 |
| SMI603.7.7f | 0.6355 | 0.6407 |
| SMI603.7.7g | 0.5710 | 0.2204 |
| SMI603.7.7h | 0.6142 | 0.7084 |
| SMI603.7.7i | 0.6203 | 1.0050 |
| SMI603.7.7j | 0.5430 | 1.3068 |
| SMI603.7.7k | 0.2672 | 1.1183 |
| SMI603.7.7l | 0.4828 | 1.1279 |
| SMI603.7.7m | 0.2027 | 1.2362 |
| SMI603.7.7n | 0.3435 | 1.2221 |
| SMI603.7.7o | 0.8065 | 0.9554 |
| SMI603.7.7p | 0.9660 | 0.2872 |
| SMI603.7.7q | 0.7136 | 0.9636 |
| SMI603.7.7r | 0.5721 | 0.7574 |
| SMI603.7.7s | 0.0559 | 1.0106 |
| SMI603.7.7t | -0.0729 | 1.2471 |
| SMI603.7.8a | 0.4217 | 1.2541 |

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|---|---|---|
| SMI603.7.8b | -1.1919 | 1.0837 |
| SMI603.7.8c | -0.4160 | 1.3254 |
| SMI603.7.8d | 0.2774 | 0.7268 |
| SMI603.7.8e | 0.4007 | 0.4678 |
| SMI603.7.8f | 0.4147 | 0.8053 |
| SMI603.7.8g | 0.0699 | 1.1578 |
| SMI603.7.8h | -0.1876 | 1.4363 |
| SMI603.7.8i | -0.1113 | 1.4245 |
| SMI603.7.8j | 0.0788 | 1.5338 |
| SMI603.7.8k | 0.3215 | 1.1546 |
| SMI603.7.8l | 0.6618 | 0.8837 |
| SMI603.7.8m | 0.8583 | 0.5854 |
| SMI603.7.8n | -0.0256 | 1.0180 |
| SMI603.7.8o | 0.5168 | 1.1900 |
| SMI603.7.8p | 0.0235 | 1.3362 |
| SMI603.7.8q | 0.4061 | 1.2983 |
| SMI603.7.8r | 0.5770 | 1.4460 |
| SMI603.7.8s | 0.7685 | 1.1575 |
| SMI603.7.8t | 0.6351 | 1.2350 |
| SMI603.7.9a | 0.4122 | 1.6240 |
| SMI603.7.9b | 0.4694 | 1.0300 |
| SMI603.7.9c | -0.0379 | 1.1452 |
| SMI603.7.9d | -0.0352 | 1.5966 |
| SMI603.7.9e | 0.3222 | 0.3837 |
| SMI603.7.9f | 0.1987 | 1.3961 |
| SMI603.7.9g | 0.2152 | 1.5303 |
| SMI603.7.9h | 0.1651 | 1.3834 |
| SMI603.7.9i | 0.4688 | 1.4142 |
| SMI603.7.9j | 0.5191 | 0.9866 |
| SMI603.7.9k | 0.8587 | 0.1612 |
| SMI603.7.9l | 0.5063 | 0.4638 |
| SMI603.7.9m | -0.2683 | 0.9345 |
| SMI603.7.9n | -0.3247 | 1.1851 |
| SMI603.7.9o | 0.0365 | 1.2243 |
| SMI603.7.9p | 0.5066 | 0.9725 |
| SMI603.7.9q | 0.5503 | 1.0275 |
| SMI603.7.9r | 0.7261 | 1.3033 |
| SMI603.7.9s | 0.5789 | 0.6853 |
| SMI603.7.9t | 0.6150 | 1.0922 |

| **Stratum A, Daisy Cave** | | |
|---|---|---|
| DC.D6.A.1a | 0.4695 | 0.4349 |
| DC.D6.A.1b | 0.1989 | 1.1476 |
| DC.D6.A.1c | 0.5184 | 0.9481 |
| DC.D6.A.1d | 0.8985 | 0.7456 |
| DC.D6.A.1e | 0.6180 | 1.0428 |
| DC.D6.A.1f | 0.4198 | 1.0592 |
| DC.D6.A.1g | 0.5167 | 1.0143 |
| DC.D6.A.1h | 1.0321 | 0.0637 |
| DC.D6.A.1i | 0.7819 | 0.8033 |
| DC.D6.A.1j | 0.7113 | 1.0197 |
| DC.D6.A.1k | 0.7508 | 1.0506 |
| DC.D6.A.1l | 0.7131 | 0.6004 |
| DC.D6.A.6a | 1.2703 | 0.6725 |
| DC.D6.A.6b | 1.1992 | 0.6136 |
| DC.D6.A.6c | 1.0248 | 0.3661 |
| DC.D6.A.6d | 1.3032 | 0.2772 |
| DC.D6.A.6e | 1.4303 | 0.1713 |
| DC.D6.A.6f | 1.3496 | 0.2867 |
| DC.D6.A.6g | 1.1473 | 0.7730 |
| DC.D6.A.6h | 0.8631 | 0.9456 |
| DC.D6.A.6i | 0.9520 | 1.0163 |
| DC.D6.A.6j | 1.0819 | 0.8791 |
| DC.D6.A.6k | 0.8413 | 1.1335 |
| DC.D6.A.6l | 0.8572 | 1.0464 |
| DC.D6.A.6m | 0.9522 | 1.0240 |
| DC.D6.A.6n | 1.0798 | 0.9502 |
| DC.D6.A.6o | 1.1287 | 0.8694 |
| DC.D6.A.6p | 0.9120 | 0.7107 |
| DC.D6.A.6q | 1.3512 | 0.5474 |
| DC.D6.A.6r | 1.2266 | 0.4582 |
| DC.D6.A.6s | 1.2885 | 0.4437 |
| DC.D6.A.6t | 0.8402 | 0.5387 |
| DC.D6.A3.1a | 0.2379 | 1.0055 |
| DC.D6.A3.1b | 0.4512 | 1.2569 |
| DC.D6.A3.1c | 0.2197 | 1.3810 |
| DC.D6.A3.1d | 0.5316 | 0.6212 |
| DC.D6.A3.1e | 0.6014 | 1.1287 |
| DC.D6.A3.1f | 0.5715 | 0.9390 |

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|---|---|---|
| DC.D6.A3.1g | 0.3136 | 1.1471 |
| DC.D6.A3.1h | 0.6914 | 0.6444 |
| DC.D6.A3.1i | 0.4324 | 1.2046 |
| DC.D6.A3.1j | 0.2684 | 1.1053 |
| DC.D6.A3.1k | 0.9199 | 0.2859 |
| DC.D6.A3.1l | 0.1636 | 1.1583 |
| **Stratum C, Daisy Cave** | | |
| DC_D6_C_1a | 0.4726 | 0.0080 |
| DC_D6_C_1b | 0.5195 | 0.1475 |
| DC_D6_C_1c | -0.3779 | 0.4889 |
| DC_D6_C_1d | -0.0011 | 1.0730 |
| DC_D6_C_1e | 0.5104 | 0.5077 |
| DC_D6_C_1f | -0.0806 | 0.7084 |
| DC_D6_C_1g | 0.2726 | 0.7782 |
| DC_D6_C_1h | 0.0067 | 0.3820 |
| DC_D6_C_1i | 0.0642 | 0.6388 |
| DC_D6_C_1j | 0.2517 | 0.8199 |
| DC_D6_C_1k | 0.0144 | 0.7159 |
| DC_D6_C_1l | -0.3460 | 1.0439 |
| DC.D6.C.2a | -0.6486 | 1.1314 |
| DC.D6.C.2b | 0.3716 | 1.3860 |
| DC.D6.C.2c | 0.4396 | 1.2592 |
| DC.D6.C.2d | 0.6747 | 1.3251 |
| DC.D6.C.2e | 0.8739 | 1.5197 |
| DC.D6.C.2f | 0.8645 | 1.0945 |
| DC.D6.C.2g | 0.8047 | 0.6880 |
| DC.D6.C.2h | 0.4768 | 0.9185 |
| DC.D6.C.2i | 0.1640 | 0.8759 |
| DC.D6.C.2j | 0.8308 | 1.1800 |
| DC.D6.C.2k | 1.1532 | 1.1233 |
| DC.D6.C.2l | 0.9943 | 0.5501 |
| DC.D6.C.7a | 0.7665 | 1.3186 |
| DC.D6.C.7b | 1.0948 | 0.9444 |
| DC.D6.C.7c | 0.5575 | 1.3529 |
| DC.D6.C.7d | 0.8453 | 1.4520 |
| DC.D6.C.7e | 1.0455 | 1.4181 |
| DC.D6.C.7f | 0.8558 | 1.4602 |
| DC.D6.C.7g | 0.8406 | 0.7964 |
| DC.D6.C.7h | 0.8180 | 0.9650 |

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|---|---|---|
| DC.D6.C.7i | 0.6116 | 0.5667 |
| DC.D6.C.7j | 0.6068 | 1.0634 |
| DC.D6.C.7k | 0.8412 | 1.1950 |
| DC.D6.C.7l | 1.3927 | 1.3395 |
| DC.D6.C.8a | 0.8700 | 1.2604 |
| DC.D6.C.8b | 0.9856 | 0.5435 |
| DC.D6.C.8c | 0.2779 | 1.1792 |
| DC.D6.C.8d | -0.0889 | 1.4189 |
| DC.D6.C.8e | -0.2852 | 1.4471 |
| DC.D6.C.8f | 0.3051 | 1.1218 |
| DC.D6.C.8g | 0.8898 | 1.1356 |
| DC.D6.C.8h | 1.1456 | 1.1395 |
| DC.D6.C.8i | 1.0827 | 1.2910 |
| DC.D6.C.8j | 1.0498 | 1.1684 |
| DC.D6.C.8k | 1.0918 | 0.6156 |
| DC.D6.C.8l | 1.5798 | 0.0177 |
| DC.D6.C.9a | 0.5655 | 0.6584 |
| DC.D6.C.9b | 0.8313 | 0.4361 |
| DC.D6.C.9c | 0.6055 | 0.3140 |
| DC.D6.C.9d | 0.4906 | 0.2828 |
| DC.D6.C.9e | 0.0884 | 0.7879 |
| DC.D6.C.9f | 0.3829 | 0.8844 |
| DC.D6.C.9g | 0.7753 | 0.8194 |
| DC.D6.C.9h | 0.5511 | 0.7923 |
| DC.D6.C.9i | 0.5263 | 0.9477 |
| DC.D6.C.9j | 0.8182 | 0.7780 |
| DC.D6.C.9k | 0.8152 | 0.7472 |
| DC.D6.C.9l | 0.7278 | 0.6837 |
| DC.D6.C.9m | 0.8862 | 0.0232 |
| DC.D6.C.9n | 0.9159 | -0.0913 |
| DC.D6.C.9o | 0.7360 | 0.0458 |
| DC.D6.C.9p | 0.5133 | -0.1160 |
| DC.D6.C.9q | 0.1984 | -0.2732 |
| DC.D6.C.9r | 0.1887 | -0.2764 |
| DC.D6.C.9s | 0.2086 | -0.1099 |
| DC.D6.C.9t | -0.5896 | 0.2787 |
| DC.D6.C.10a | 0.6896 | 1.4237 |
| DC.D6.C.10b | 0.5826 | 0.1921 |
| DC.D6.C.10c | -1.1117 | 1.3201 |

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|---|---|---|
| DC.D6.C.10d | -0.3637 | 1.1280 |
| DC.D6.C.10e | 0.3096 | 0.9935 |
| DC.D6.C.10f | 0.7453 | 1.0692 |
| DC.D6.C.10g | 1.3512 | 0.4602 |
| DC.D6.C.10h | 1.0270 | 0.1767 |
| DC.D6.C.10i | 0.6173 | 0.9130 |
| DC.D6.C.10j | 0.4937 | 1.1374 |
| DC.D6.C.10k | 0.5601 | 1.1117 |
| DC.D6.C.10l | 0.4132 | 1.1884 |
| **Stratum D/E, Daisy Cave** | | |
| DC.D6.D.1a | 0.5803 | 1.2359 |
| DC.D6.D.1b | 0.5170 | 0.5713 |
| DC.D6.D.1c | 0.4153 | 1.0482 |
| DC.D6.D.1d | 0.5881 | 1.0858 |
| DC.D6.D.1e | 1.2778 | 0.4790 |
| DC.D6.D.1f | 0.5989 | 0.9762 |
| DC.D6.D.1g | 0.5984 | 1.3834 |
| DC.D6.D.1h | 1.3056 | 1.2394 |
| DC.D6.D.1i | 0.9430 | 0.4215 |
| DC.D6.D.1j | 0.9092 | 0.4551 |
| DC.D6.D.1k | 0.6612 | 0.2276 |
| DC.D6.D.1l | 0.4544 | 0.5428 |
| DC.D6.D.1m | 0.2794 | 0.7467 |
| DC.D6.D.1n | 0.1236 | 0.9541 |
| DC.D6.D.1o | 0.2335 | 1.2789 |
| DC.D6.D.1p | 1.1410 | 0.5218 |
| DC.D6.D.1q | 1.0230 | 0.2805 |
| DC.D6.D.1r | 0.9567 | 1.2952 |
| DC.D6.D.1s | 1.1251 | 1.2064 |
| DC.D6.D.1t | 1.3036 | 1.3447 |
| DC.D6.E2.1a | 0.2276 | 1.4730 |
| DC.D6.E2.1b | 0.0733 | 1.3825 |
| DC.D6.E2.1c | -0.2619 | 1.1818 |
| DC.D6.E2.1d | -0.7319 | 1.6053 |
| DC.D6.E2.1e | -0.2791 | 1.7346 |
| DC.D6.E2.1f | 0.3205 | 1.6414 |
| DC.D6.E2.1g | 0.5784 | 0.6197 |
| DC.D6.E2.1h | 0.3137 | 0.7118 |
| DC.D6.E2.1i | 0.1210 | 1.2888 |

| | | |
|---|---|---|
| DC.D6.E2.1j | 0.4098 | 1.2956 |
| DC.D6.E2.1k | 0.6330 | 1.4869 |
| DC.D6.E2.1l | 0.5073 | 1.4211 |
| DC.D6.E2.1m | 0.4802 | 1.3516 |
| DC.D6.E2.1n | 0.4804 | 1.4463 |
| DC.D6.E2.1o | 0.4031 | 1.2817 |
| DC.D6.E2.1p | 0.5986 | 0.9436 |
| DC.D6.E2.1q | 0.5607 | 0.8343 |
| DC.D6.E2.1r | 0.3762 | 0.5301 |
| DC.D6.E2.1s | 0.1797 | 0.5035 |
| DC.D6.E2.1t | -0.0787 | 0.7841 |
| DC.D6.E2.1u | -0.9689 | 0.8229 |
| DC.D6.E2.1v | -1.0573 | 1.0904 |
| DC.D6.E2.1w | -1.1487 | 1.4873 |
| DC.D6.E2.2a | 1.1856 | 1.0942 |
| DC.D6.E2.2b | 1.2436 | 0.4415 |
| DC.D6.E2.2c | 1.1471 | 0.5228 |
| DC.D6.E2.2d | 0.7593 | 0.5543 |
| DC.D6.E2.2e | 0.5383 | 0.7316 |
| DC.D6.E2.2f | 0.4689 | 0.7455 |
| DC.D6.E2.2g | 0.4639 | 0.7754 |
| DC.D6.E2.2h | 0.4033 | 1.0653 |
| DC.D6.E2.2i | 0.4635 | 1.0210 |
| DC.D6.E2.2j | 0.6136 | 1.0588 |
| DC.D6.E2.2k | 0.7620 | 0.7568 |
| DC.D6.E2.2l | 1.1707 | 0.1898 |
| DC.D6.E2.2m | 1.0834 | 0.0840 |
| DC.D6.E2.2n | 0.8649 | -0.0115 |
| DC.D6.E2.2o | 0.6120 | 0.1949 |
| DC.D6.E2.2p | 0.3885 | 0.5235 |
| DC.D6.E2.2q | -0.0731 | 0.6987 |
| DC.D6.E2.2r | 0.1871 | 1.0027 |
| DC.D6.E2.2s | 0.6200 | 1.0673 |
| DC.D6.E3.1a | 0.9521 | 1.2829 |
| DC.D6.E3.1b | 1.0642 | 1.0667 |
| DC.D6.E3.1c | 0.9347 | 0.7686 |
| DC.D6.E3.1d | 0.7310 | 1.1488 |
| DC.D6.E3.1e | 0.7777 | 1.2437 |
| DC.D6.E3.1f | 1.1831 | 1.4646 |

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|---|---|---|
| DC.D6.E3.1g | 1.0640 | 1.4472 |
| DC.D6.E3.1h | 0.9545 | 0.9254 |
| DC.D6.E3.1i | 0.7387 | 0.9583 |
| DC.D6.E3.1j | -0.0422 | 1.3840 |
| DC.D6.E3.1k | 0.4074 | 1.2714 |
| DC.D6.E3.1l | 0.9880 | 1.7054 |
| DC.D6.E3.2a | 0.9168 | 1.2329 |
| DC.D6.E3.2b | 0.9459 | 0.8696 |
| DC.D6.E3.2c | 0.9596 | 0.6213 |
| DC.D6.E3.2d | 0.9317 | 0.6158 |
| DC.D6.E3.2e | 0.9951 | 0.6871 |
| DC.D6.E3.2f | 0.6419 | 0.9195 |
| DC.D6.E3.2g | 0.5956 | 1.2590 |
| DC.D6.E3.2h | 0.7379 | 1.4830 |
| DC.D6.E3.2i | 0.7470 | 1.2535 |
| DC.D6.E3.2j | 1.0424 | 1.4122 |
| DC.D6.E3.2k | 0.9291 | 1.1051 |
| DC.D6.E3.2l | 0.9806 | 0.6822 |
| DC.D6.E3.2m | 0.8624 | 0.3904 |
| DC.D6.E3.2n | 0.5559 | 0.6235 |
| DC.D6.E3.2o | 0.1401 | 0.9762 |
| DC.D6.E3.2p | -0.0497 | 1.0212 |
| DC.D6.E3.2q | 0.0076 | 1.2088 |
| DC.D6.E3.2r | 0.1850 | 1.2678 |
| DC.D6.E3.2s | 0.5228 | 1.3288 |
| DC.D6.E3.2t | 1.1009 | 1.1163 |
| DC.D6.E4.1a | 0.9078 | 1.5113 |
| DC.D6.E4.1b | 0.2825 | 1.1758 |
| DC.D6.E4.1c | -0.0731 | 0.8051 |
| DC.D6.E4.1d | -0.7846 | 1.2210 |
| DC.D6.E4.1e | -0.5763 | 1.6667 |
| DC.D6.E4.1f | -0.0784 | 1.5065 |
| DC.D6.E4.1g | 0.3716 | 1.5057 |
| DC.D6.E4.1h | -0.2038 | 0.8539 |
| DC.D6.E4.1i | 0.2916 | 0.3877 |
| DC.D6.E4.1j | -0.3606 | 0.9282 |
| DC.D6.E4.1k | -0.2902 | 1.2330 |
| DC.D6.E4.1l | -0.4213 | 1.1465 |
| DC.D5.E4.2a | 0.9493 | 0.4274 |

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|---|---|---|
| DC.D5.E4.2b | 0.5402 | 0.6274 |
| DC.D5.E4.2c | 0.1481 | 1.1517 |
| DC.D5.E4.2d | 0.2876 | 1.3609 |
| DC.D5.E4.2e | 0.5756 | 1.3041 |
| DC.D5.E4.2f | 1.1939 | 1.2252 |
| DC.D5.E4.2g | 1.2339 | 0.8906 |
| DC.D5.E4.2h | 0.6347 | 0.7795 |
| DC.D5.E4.2i | 0.4199 | 0.7422 |
| DC.D5.E4.2j | 0.4426 | 0.4947 |
| DC.D5.E4.2k | 0.3997 | 0.5460 |
| DC.D5.E4.2l | 0.2636 | 0.4606 |
| **Stratum F, Daisy Cave** | | |
| DC_D6_F1_1a | 1.0927 | 0.3228 |
| DC_D6_F1_1b | 0.8955 | 0.6028 |
| DC_D6_F1_1c | 0.6332 | 1.1537 |
| DC_D6_F1_1d | 0.7558 | 1.3145 |
| DC_D6_F1_1e | 0.9039 | 1.0834 |
| DC_D6_F1_1f | 1.1331 | 0.8060 |
| DC_D6_F1_1g | 1.1073 | 0.5938 |
| DC_D6_F1_1h | 0.9344 | 0.5267 |
| DC_D6_F1_1i | 0.3810 | 1.2833 |
| DC_D6_F1_1j | 0.5571 | 1.4248 |
| DC_D6_F1_1k | 1.3004 | 0.8230 |
| DC_D6_F1_1l | 1.0148 | 0.5833 |
| DC.D6.F1.5a | 0.8747 | 1.0180 |
| DC.D6.F1.5b | 1.2275 | 0.2761 |
| DC.D6.F1.5c | 0.9083 | 0.0825 |
| DC.D6.F1.5d | 0.6118 | 0.3800 |
| DC.D6.F1.5e | 0.4765 | 0.8277 |
| DC.D6.F1.5f | 0.1166 | 1.0382 |
| DC.D6.F1.5g | 0.3591 | 1.3284 |
| DC.D6.F1.5h | 0.4253 | 1.3749 |
| DC.D6.F1.5i | 0.7325 | 1.4147 |
| DC.D6.F1.5j | 1.0360 | 1.0335 |
| DC.D6.F1.5k | 1.0523 | 0.8760 |
| DC.D6.F1.5l | 0.9628 | 0.7843 |
| DC.D6.F1.5m | 0.7006 | 0.7715 |
| DC.D6.F1.5n | 0.4195 | 0.5730 |
| DC.D6.F1.5o | 0.5168 | 1.0521 |

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|---|---|---|
| DC.D6.F1.5p | 0.5819 | 1.2172 |
| DC.D6.F1.5q | 0.3173 | 1.2117 |
| DC.D6.F1.5r | 0.6916 | 1.2885 |
| DC.D6.F1.5s | 0.7221 | 1.0020 |
| DC.D6.F1.5t | 0.6216 | 0.7709 |
| DC.D6.F1.5u | 0.4949 | 0.6598 |
| DC.D6.F1.5v | 0.5689 | 0.7512 |
| DC.D6.F1.5w | 0.4714 | 0.5568 |
| DC.D6.F1.5x | 0.5865 | 1.2054 |
| DC.D6.F1.6a | 0.6446 | 1.1219 |
| DC.D6.F1.6b | 0.2991 | 1.0731 |
| DC.D6.F1.6c | 0.5685 | 0.9283 |
| DC.D6.F1.6d | 0.6551 | 0.4332 |
| DC.D6.F1.6e | 0.4158 | 0.1943 |
| DC.D6.F1.6f | 0.0528 | 0.5654 |
| DC.D6.F1.6g | -0.1893 | 0.5492 |
| DC.D6.F1.6h | -0.3153 | 0.8574 |
| DC.D6.F1.6i | -0.3929 | 1.0152 |
| DC.D6.F1.6j | -0.3174 | 1.0729 |
| DC.D6.F1.6k | -0.2981 | 1.1904 |
| DC.D6.F1.6l | -0.2185 | 1.3186 |
| DC.D6.F1.6m | 0.3045 | 1.1562 |
| DC.D6.F1.6n | 0.8470 | 1.0223 |
| DC.D6.F1.6o | 0.7719 | 1.1219 |
| DC.D6.F1.6p | 1.0185 | 1.0216 |
| DC.D6.F1.6q | 1.1214 | 0.9617 |
| DC.D6.F1.6r | 0.8249 | 0.5988 |
| DC.D6.F1.6s | 0.7060 | 0.4159 |
| DC.D6.F1.6t | 0.6324 | 0.5058 |
| DC.D6.F1.6u | 0.5084 | 0.1042 |
| DC.D6.F1.6v | 0.0446 | 0.3567 |
| DC_D6_F2_1a | 0.4895 | 1.7879 |
| DC_D6_F2_1b | 0.6326 | 1.4744 |
| DC_D6_F2_1c | 0.8832 | 1.2144 |
| DC_D6_F2_1d | 1.1821 | 0.6501 |
| DC_D6_F2_1e | 0.9326 | 0.1441 |
| DC_D6_F2_1f | 0.5576 | 0.2985 |
| DC_D6_F2_1g | 0.2051 | 0.7603 |
| DC_D6_F2_1h | 0.1737 | 0.9807 |

| | | |
|---|---|---|
| DC_D6_F2_1i | 0.4513 | 1.1312 |
| DC_D6_F2_1j | 0.5924 | 0.9665 |
| DC_D6_F2_1k | 0.7111 | 1.2525 |
| DC_D6_F2_1l | 0.7440 | 0.8134 |
| DC.D6.F2.5a | 1.3021 | 0.6939 |
| DC.D6.F2.5b | 1.2556 | 0.5471 |
| DC.D6.F2.5c | 1.2551 | 0.5897 |
| DC.D6.F2.5d | 1.2111 | 0.0591 |
| DC.D6.F2.5e | 0.9841 | -0.2315 |
| DC.D6.F2.5f | 0.6578 | -0.2349 |
| DC.D6.F2.5g | 0.3517 | 0.0577 |
| DC.D6.F2.5h | 0.2376 | 0.1286 |
| DC.D6.F2.5i | 0.0439 | 0.5424 |
| DC.D6.F2.5j | -0.5338 | 0.8241 |
| DC.D6.F2.5k | -0.3531 | 0.8926 |
| DC.D6.F2.5l | -0.2645 | 0.9134 |
| DC.D6.F2.5m | -0.1757 | 0.9322 |
| DC.D6.F2.5n | 0.7046 | 1.0955 |
| DC.D6.F2.5o | 0.4662 | 0.7679 |
| DC.D6.F2.5p | 0.2049 | 1.0042 |
| DC.D6.F2.5q | 0.2781 | 1.0878 |
| DC.D6.F2.5r | 0.1710 | 1.1658 |
| DC.D6.F2.5s | 0.3238 | 0.4580 |
| DC.D6.F2.5t | 0.8805 | 0.5053 |

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