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Sea level, paleogeography, and archeology on California's Northern Channel Islands

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ABSTRACT

Sea-level rise during the late Pleistocene and early Holocene inundated nearshore areas in many parts of the world, producing drastic changes in local ecosystems and obscuring significant portions of the archeological record. Although global forces are at play, the effects of sea-level rise are highly localized due to variability in glacial isostatic adjustment (GIA) effects. Interpretations of coastal paleoecology and archeology require reliable estimates of ancient shorelines that account for GIA effects. Here we build on previous models for California's Northern Channel Islands, producing more accurate late Pleistocene and Holocene paleogeographic reconstructions adjusted for regional GIA variability. This region has contributed significantly to our understanding of early New World coastal foragers. Sea level that was about 80–85 m lower than present at the time of the first known human occupation brought about a landscape and ecology substantially different than today. During the late Pleistocene, large tracts of coastal lowlands were exposed, while a colder, wetter climate and fluctuating marine conditions interacted with rapidly evolving littoral environments. At the close of the Pleistocene and start of the Holocene, people in coastal California faced shrinking land, intertidal, and subtidal zones, with important implications for resource availability and distribution.

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Introduction

The late Pleistocene and early Holocene are of great interest to coastal archeologists and Quaternary scientists—a time when the Americas were first colonized (Dillehay, 2009; Meltzer, 2009) and evidence for the use of coastal resources all over the world intensified (Erlandson, 2001; Bailey and Milner, 2002). However, rising sea level since the last glacial maximum (LGM) has complicated our understanding of this time period by drowning former coastlines and inundating coastal archeological sites (Shackleton et al., 1988; Westley and Dix, 2006; Bailey and Flemming, 2008). Accurate reconstructions of ancient shorelines allow archeologists to understand better the environments in which people lived, to target areas where older sites might still be above water (i.e., Fedje et al., 2005; Shugar et al., 2005; McLaren et al., 2014), and to explore more efficiently the underwater environment for archeological sites.

Shorelines are complicated places, with dynamic patterns of erosion and deposition acting alongside tectonic and isostatic uplift and subsidence. Applications of global eustatic sea-level curves or relative sea level (RSL) curves derived from distant locations to bathymetric maps are useful for understanding general patterns in paleogeography, but not necessarily the precise timing of important local changes. Higher resolution models of Earth and ice properties can produce RSL curves that account for sea level and isostatic variability at the regional scale (i.e., southern California) and that allow for more detailed interpretations of regional ecological change and settlement patterns (i.e., Fedje et al., 2005; Bailey et al., 2007; Lambeck et al., 2011; Ghilardi et al., 2014; McLaren et al., 2014).

California's Northern Channel Islands (NCI) have contributed significantly to our understanding of early coastal human adaptations in the Americas, and have also been a focus of research into a possible coastal migration route from Asia into the Americas (Erlandson et al., 2007, 2011). The NCI are separated from the California mainland by the Santa Barbara Channel (Fig. 1). Most of the coast of the NCI is characterized by rocky shores and sea cliffs, leading inland either to mountainous slopes or emergent marine terraces dissected by steep-sided canyons. Rocky intertidal zones and subtidal kelp forest ecosystems are extensive, with sandy pocket beaches that form in the lee of headlands (Schoenherr et al., 1999). During the LGM, lowered sea level connected the NCI into a single island known as Santarosae (Orr, 1968) and exposed wide tracts of the now submerged insular shelf.

Accurate reconstructions of late Pleistocene and early Holocene landscapes are essential for interpreting the existing archeological record and locating new sites to expand our understanding of early coastal lifeways. Researchers in southern California have long been interested

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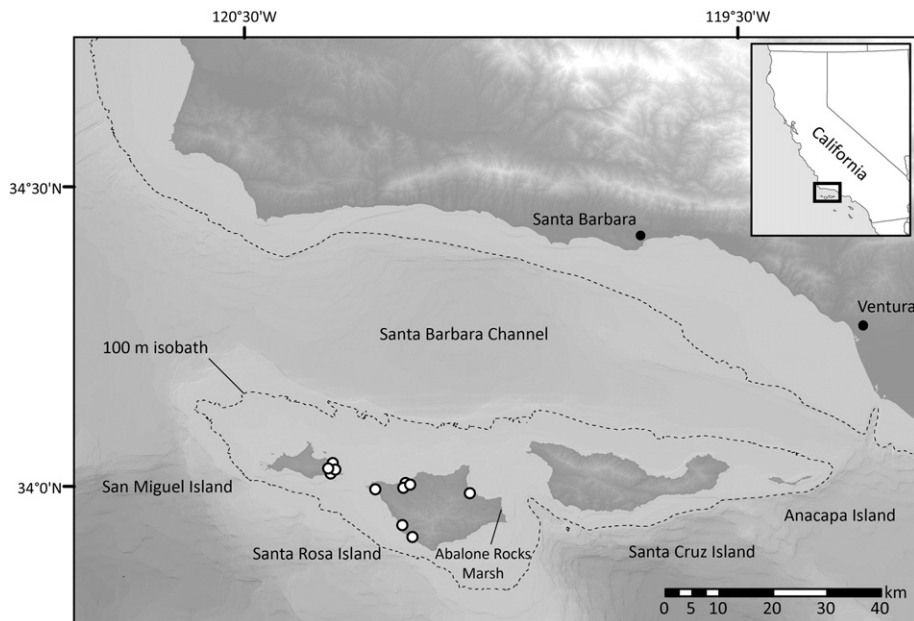
Figure 1. Location and topography (indicated by gray shading), of the Northern Channel Islands, including archeological sites (circles) dated to before 11,000 cal yr BP and the location of the Abalone Rocks Marsh. Data for DEM obtained from the National Elevation Dataset.

in reconstructing ancient shorelines (Orr, 1968; Nardin et al., 1981; Inman, 1983; Johnson et al., 1983; Porcasi et al., 1999; Kinlan et al., 2005; Masters, 2006; Kennett et al., 2008), and recent research has utilized a model of glacial isostatic adjustment (GIA) that explains sea-level fluctuations elsewhere in southern California (Muhs et al., 2012). Here we build on these studies, using a series of GIA-corrected RSL curves for the NCI to produce more accurate estimates of shoreline and landscape evolution after the LGM (Clark et al., 2014). The GIA correction produces significantly different RSL curves across the NCI, with the highest rates of change in the southwest portion of the island chain and the lowest in the northeast. In situations where modeling is the most practical method for reconstructing shorelines, the use of local GIA-corrected RSL curves allows for more accurate estimates of change through time and offers an approach that can be applied to shoreline reconstructions around the world.

Methods

For interpreting paleoecology, resource distribution, and settlement patterns at the scale of the NCI, modeling is the most practical approach to reconstructing submerged paleoshorelines. Intensive underwater field studies to identify shorelines, including mapping with a submersible or using acoustic technology, are most appropriate at smaller, local scales (e.g., Chaytor et al., 2008), but they are expensive and time consuming. The NCI steep, narrow continental shelf is unlikely to preserve shorelines except during long still-stands, such as those that created the now emergent marine terraces. A recent study attempted to map paleoshorelines on the NCI insular shelf using a variety of multibeam bathymetry data sources, but found that shorelines were likely to be delineated only in limited areas in the eastern part of the NCI (Chaytor et al., 2008).

When modeling is the only way to reconstruct shoreline locations, it is important to have accurate RSL curves. In some cases, these can be derived from local features that are tightly constrained by water depth, such as coral, peat, or marsh. However, those features are not available on the NCI, so shoreline reconstructions must rely on modeled RSL curves combined with bathymetric maps. Recent research has demonstrated that eustatic sea-level curves generated from far-field locations such as New Guinea or Barbados do not accurately reflect RSL change

in southern California (Muhs et al., 2012; see also Mitrovica and Milne, 2003; Kendall et al., 2005). GIA effects are more important in near-field to intermediate-field regions such as California because of closer proximity to large ice sheets.

Although the volume of ocean water at a global scale is inversely related to the volume of glacial ice, the distribution of ocean water is controlled by more complex factors that vary at centennial and millennial time scales (Mitrovica and Milne, 2003). A study of sea-level history on San Nicolas Island (~75 km to the south of the NCI) over the early part of the last interglacial–glacial cycle (120 to 40 ka) showed that relative sea level differed from sites that are distant from North American Pleistocene ice sheets (e.g., New Guinea and Barbados), and identified a model of mantle viscosity (dubbed the LM model) that more accurately predicted sea-level high stands in southern California during that period (Muhs et al., 2012). A second study extended and confirmed that model during the post-LGM period, using the same pairing of ice and Earth models applied to much of the west coast of North America (Clark et al., 2014). Those same models, based on the LM viscosity profile characterized by a lithospheric thickness of 96 km, upper mantle dynamic viscosity of 5×10^{20} Pa s, and lower mantle dynamic viscosity of 5×10^{21} Pa s (Mitrovica and Milne, 2003; Kendall et al., 2005), are used at higher resolution for this study.

These variations in the Earth's lithosphere and mantle, and the effect they have on the distribution of water in the ocean, result in small but significant variability in rates of sea-level change across the NCI. To capture that variability, sea-level curves were produced at approximately 4-km intervals across the NCI platform. We then used a simple, inverse distance-weighted interpolation to produce relative sea-level surfaces for 48 time slices from 20 ka to the present. These surfaces were then subtracted from modern bathymetric and topographic digital elevation models (DEMs) produced by NOAA's Tsunami Inundation Project and the National Geophysical Data Center (Carignan et al., 2009). Shorelines were estimated by extracting the 0-m contour from the new DEM. All geographic analyses were performed using ESRI's ArcGIS v. 10.2.[1]

Nearshore ecosystems around the NCI are controlled primarily by depth. Kelp forests are common marine ecosystems in the region and

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[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

require shallow, subtidal, rocky surfaces within the photic zone for algae attachment. Following Kinlan et al. (2005), the surface available for kelp forest was estimated as the area extending from 1 to 25 m below mean sea-level, and the intertidal zone was estimated as the surface extending from 1 m above to 1 m below mean sea level. River courses were estimated using the hydrological modeling tools in ESRI's ArcGIS v. 10.2, which use elevation and slope to identify the direction that water should flow through each 30 × 30 m cell and then identify the most rapid routes downslope. Cells that collect the most water are isolated and connected together to form streams (deSmith et al., 2007, p. 280). This process may yield inaccuracies on the flat coastal plain, and should be considered as a first approximation of ancient stream courses. The potential location of these streams, however, may prove fruitful for targeting future underwater archeological research in the region.

There are uncertainties in both the ice and Earth models used to produce the relative sea-level curve. Although the Earth model used here has been well constrained through the work of Muhs et al. (2012) and Clark et al. (2014), continuing research may refine aspects of the ice model. The modern DEM has a relatively high degree of accuracy, especially for the shallow shelf areas of interest to this study. Vertical accuracy is estimated to within 5% of water depth, and horizontal accuracy varies between 2 and 10 m, with greatest accuracy in nearshore areas (Carignan et al., 2009). Nevertheless, the modern DEM is not necessarily a good representation of ancient topographic and bathymetric features, because tectonic and sedimentary processes have influenced landforms around the NCI. However, over the relatively short geological time span considered here, these factors should have had limited impact on the reconstruction of NCI paleoshorelines. Although there are exceptions on the northern slope of the NCI platform, the volcanic rocks that dominate many parts of the NCI bedrock geology are resistant to erosion and little sediment has accumulated on most of the continental shelf during the Holocene (Norris and Webb, 1976; Warrick and Farnsworth, 2009). Evidence from across the NCI suggests that tectonic uplift of the NCI platform has been between 0.1 and 0.2 m/ka over the past ~120 ka (Pinter et al., 1998a, 1998b, 2003; Muhs et al., 2014). This would potentially raise the modeled coastline between 2 and 4 m at the LGM at (~20 ka), and incorporation of these small values into the paleogeographic models presented here is not significant. The use of GIA-corrected sea level surfaces is only the first step in more accurately modeled ancient shorelines. Future research should incorporate regional tectonic and sedimentary processes that also influence shoreline configuration, and complementary field-based research into local shoreline positions.

Most of the ages reported in this paper are modeled calendar ages, given in thousands of years before 1950 with the notation "ka." Ages that reference specific, known events, such as archeological sites or paleontological materials, are derived from calibrated radiocarbon ages and given the notation "cal yr BP." These dates are available in the cited literature, and when necessary were recalibrated at 2 sigma, using the IntCal13 or MarineCal13 curves (Reimer et al., 2013).

Results

Our model reconstructs paleogeography from 20.0 ka through the late Holocene, but our discussion and interpretation focus on the time when sea level was rising, before ca. 6.0 ka. The last sea-level minimum occurred on the NCI at 20.0 ka, when relative sea level reached −111 m on the western end of the platform (33°48′N, 120°36′W) and −101 m on the eastern end (34°12′N, 119°16′W) (Table 1, Fig. 2). Sea level rose steadily throughout the late Pleistocene and early Holocene, with the highest rates of sea-level change (to as high as 22 m per 1000 years) from 13.5 to 8.0 ka (Fig. 3). The Younger Dryas cold period is visible as a slight reduction in rates of RSL rise, as well as reduced rates of change in island landmass, reef extent, and shoreline length. Although the rate of RSL change declines significantly after 8.0 ka, it does not flatten out until about 2.0 ka because of the continuing impact of glacial isostatic adjustments throughout the Holocene. The GIA model suggests that only about 20 m of sea-level rise occurred after 8.0 ka in the west, and 15 m in the east. Sea level was within 2 m of modern throughout the NCI by about 2.0 ka.
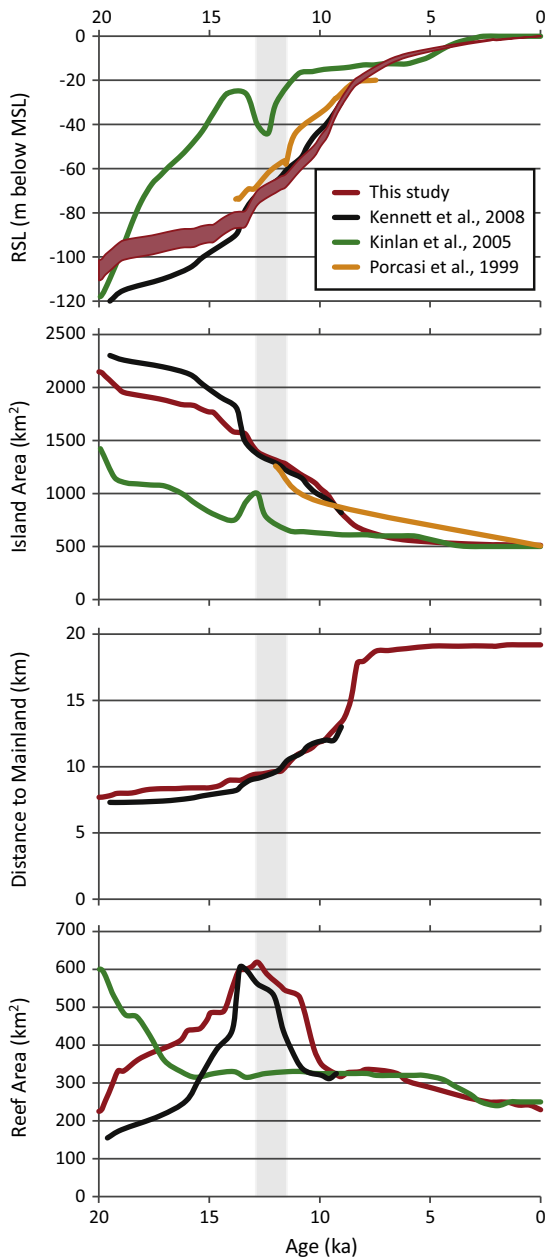
Shoreline reconstructions indicate that Santarosae reached its greatest extent of 2147 km² at 20.0 ka, then shrank rapidly and steadily until the islands began to be separated by water just after 11.0 ka. Anacapa Island separated from the other islands between 10.9 and 10.3 ka, followed by Santa Cruz Island between 9.7 and 9.4 ka. The final separation of Santa Rosa and San Miguel islands occurred between 9.4 and 9.1 ka (Fig. 4). These shoreline separations were gradual processes, with the islands separated by unstable and rapidly changing shallow water environments that are not analogous to anything on the NCI today.

The islands today are made up of about 24% (507 km²) of the total LGM land area. Rates of land loss peaked between about 11.5 and 8.8 ka, when the islands lost more than 200 km² of land per 1000 years (Fig. 3). That rate decreased steadily until about 6.0 ka, at which time the islands lost only about 30 km² per 1000 years. The

Table 1
Summary of key variables related to sea-level change, at approximately 1000-year intervals during the period of known human occupation. RSL-A occurs at 33°48′N, −120°36′W, and RSL-B occurs at 34°12′N, −119°16′W.
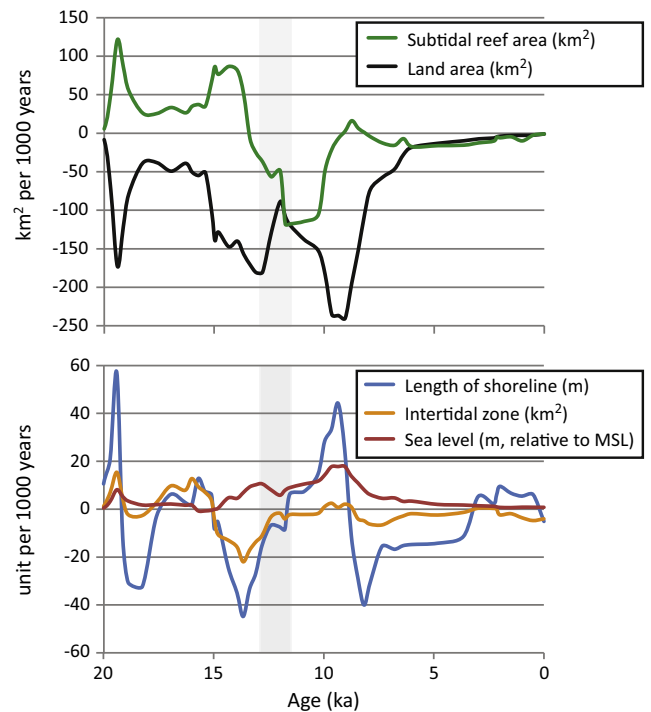
Age (ka)	RSL-A (m below MSL)	RSL-B (m below MSL)	Shoreline length (km)	Island area (km²)	Shortest distance to mainland (km)	Subtidal zone (km²)	Intertidal zone (km²)
20.00	−111	−101	359	2147	7.75	225	30
16.95	−100	−94	374	1877	8.34	413	46
16.00	−96	−87	390	1835	8.38	438	56
14.97	−95	−91	399	1768	8.41	484	65
13.94	−89	−85	373	1585	8.95	555	51
13.09	−81	−74	338	1465	9.21	607	34
12.00	−71	−65	330	1315	9.60	556	29
10.91	−61	−56	321	1186	10.831	391	25
9.05	−32	−28	382	820	13.09	317	28
7.09	−19	−16	349	646	17.97	334	24
6.08	−12	−10	332	582	18.77	322	18
6.00	−9	−8	317	558	19.25	304	16
4.83	−7	−5	301	540	19.08	286	13
3.66	−4	−3	284	527	19.08	266	10
2.98	−3	−2	280	522	19.08	257	10
2.00	−2	−1	288	517	19.10	249	10
1.00	−1	−1	303	512	19.12	242	7
0.00	0	0	298	511	19.20	229	3

Figure 2. Comparison of variables measured in this study to measurements from earlier studies. The Younger Dryas is indicated by a light gray shaded bar. The RSL curve from this study encompasses the fastest and slowest rates of sea-level rise within the NCI platform, from 33°48′N, −120°36′W and 34°12′N, −119°16′W. See text for explanation of the differences between these curves.
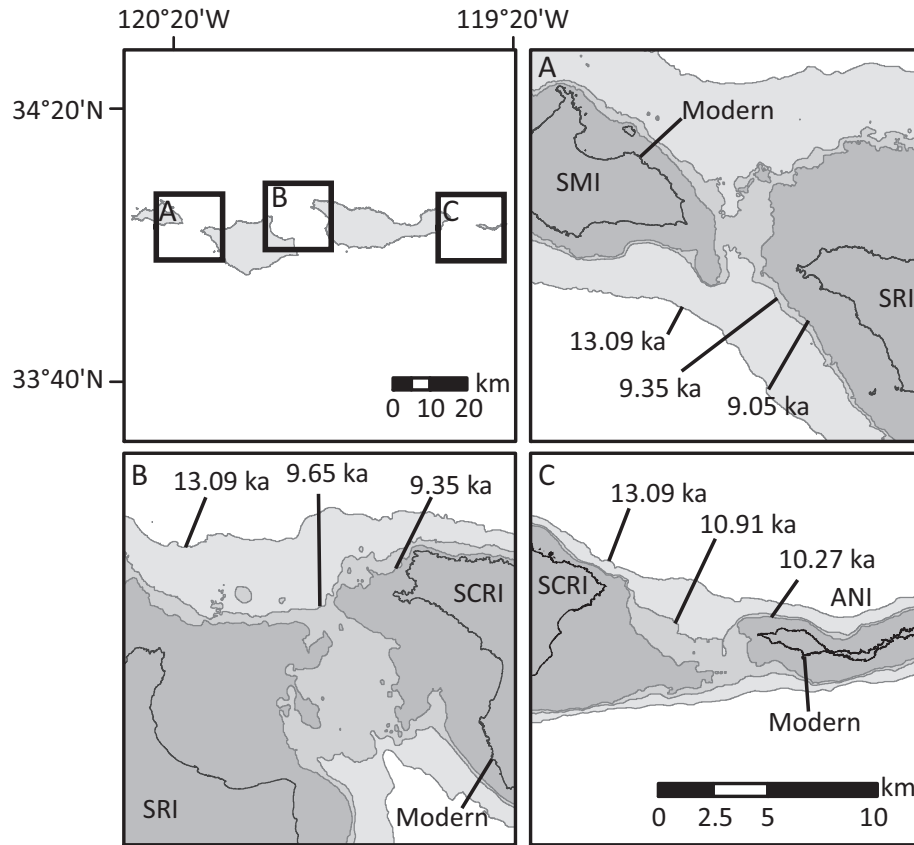

Figure 3. The rate of change for key environmental variables throughout the study period. For each point in time, rates of change were calculated across a 1000-year period. Note that the highest rates of change are represented by either negative or positive deviations from 0. Gray shading indicates the Younger Dryas, from 12.9 to 11.5 ka, when sea-level rise slowed and rates of change move closer to 0 in most variables.

Discussion

Comparing models of NCI sea-level rise

Previous shoreline models in southern California (Fig. 2) have relied either on global sea-level reconstructions from tectonically stable locations far from Pleistocene ice sheets (Porcasi et al., 1999; Masters, 2006; Kennett et al., 2008) or on a curve produced for the Santa Monica Basin, offshore from Los Angeles (Nardin et al., 1981; Graham et al., 2003; Kinlan et al., 2005). The latter are based on a seismic-stratigraphic analysis of the continental shelf paired with five uncalibrated Holocene-age radiocarbon dates from littoral shellfish (Nardin et al., 1981). This curve posits some dramatic sea-level rises, falls, and still-stands throughout the late Pleistocene and Holocene that should be confirmed in the field before being applied to the NCI. Although tectonic and isostatic crustal changes certainly have influenced local sea-level rise in southern California, there is no evidence that local faults or any other mechanisms produced these changes. When used for shoreline modeling, the Nardin et al. (1981) curve produces a much more rapid reduction in island size and a peak in reef extent several thousand years earlier (Fig. 2) (Kinlan et al., 2005).

The global sea-level reconstructions used by Porcasi et al. (1999), Masters (2006), and Kennett et al. (2008) are based on empirical observations from locations in the Atlantic, Pacific, and Caribbean. These are broadly in agreement with the modeled curve for the NCI but with some important differences (Fig. 2). These empirically based curves generally estimate the LGM low stand at about −120 m, while the model used here varies from −110 m below MSL in the southwest part of the study area to −100 m in the northeast. Subsequent rise occurs faster in the distant locations, and the curves converge during the last few millennia of the Pleistocene. This is when Santarosae is divided into individual islands, and so the new curve coincidentally produces similar times for island separation to earlier estimates (Fig. 4) (Porcasi et al., 1999; Kennett et al., 2008).

extent of subtidal surface available for kelp forest peaked around 13.0 ka at about 600 km² when the island's shape and offshore bathymetry were optimal, with much of the flat, coastal plain drowned under shallow water. It decreased rapidly to about 315 km² at 9.0 ka, and then decreased slightly throughout the Holocene to reach about 220 km² today (Figs. 2 and 5). The most rapid rates of reef area loss occurred just after the Younger Dryas and remained high through about 10.0 ka.

Changes in the length of the shoreline, and therefore in the potential extent of rocky intertidal ecosystems, have been much more variable through the late Pleistocene and Holocene (Fig. 3). Shoreline extent was at its greatest (~400 km) at about 15 ka, and decreased through the end of the Pleistocene. It increased again to about 380 km around 9 ka as the larger islands were separated by water, and then decreased steadily through the rest of the Holocene (Table 1).

Figure 4. Detail of the sequence of island separation, compared to the shoreline at the earliest known human occupation about 13,000 cal yr BP. SMI is San Miguel Island, SRI is Santa Rosa Island, SCRI is Santa Cruz Island, and ANI is Anacapa Island.

The most significant difference between the model presented here and previous sea-level curves used in the NCI is a surprisingly large difference in RSL along a gradient from the southwest to the northeast of the NCI platform. This is the result of variability in the GIA corrections across space. For example, at 15.0 ka, the application of a single, uniform RSL curve to the entire NCI would significantly alter the shape and location of the northern shore of Santarosae (Fig. 6). Even at the relatively limited regional scale of the NCI, the accommodation of a variable GIA correction is essential to produce more reliable estimates of shoreline locations (see also Clark et al., 2014).

Paleogeography and ecological change through time

Terrestrial environments

New shoreline and elevation models presented here have important implications for paleoecology on the NCI, including adjustments in the timing of island separation (Fig. 4) and models of potential stream courses (Fig. 5). The physical landscape of late Pleistocene Santarosae was unlike the modern NCI, with a broad coastal plain that persisted on the western islands well into the early Holocene (Fig. 5). This coincides with an LGM and late Pleistocene climate that was generally wetter and cooler than modern (Heusser, 1998; Stott et al., 2002), and these distinct physical and climatic conditions supported somewhat different ecosystems than those present today.

Pollen from the Santa Barbara Basin and other locations around southern California suggest that conifer forests expanded on the NCI and elsewhere in southern California during the late Pleistocene (Heusser, 1998; Anderson et al., 2010). On the NCI, the large, flat coastal plain (Fig. 5) may have been a favorable habitat for Bishop pine (*Pinus muricata*), which prefers sandy soils and is an effective colonizer (Junak et al., 2007). This hypothesis is supported by limited pollen and macrobotanical material from Daisy Cave on San Miguel Island (West

and Erlandson, 1994; Erlandson et al., 1996), Arlington Canyon on Santa Rosa Island (Kennett et al., 2008), and Canada de los Sauces on Santa Cruz Island (Anderson et al., 2010). On the other hand, conifer pollen is rare from the beginning of the upland Soledad Pond sequence on Santa Rosa Island, beginning 12.0 ka (Anderson et al., 2010). Anderson et al. (2010) suggest that pine may have been restricted to lower elevations such as the coastal plain, which agrees with these paleogeographic reconstructions. In addition, much of the northwestern-most part of this area, north of San Miguel Island, may have been covered by active sand dunes (Muhs et al., 2009).

Oak and other woodland communities are limited today on the NCI (except on parts of Santa Cruz Island), and the pollen core from Soledad Pond (Anderson et al., 2010) suggests that this was true at least through the last two millennia of the Pleistocene. Woodland taxa today are found only on protected, north-facing slopes and canyon bottoms of the two larger islands, although individual oak trees are scattered in some shrubland and grassland communities. Neither climate change nor the paleogeographic changes modeled here are likely to have changed in distribution significantly. However, the largest perennial streams host riparian woodlands below about 460 m in elevation, including deciduous species that are rare elsewhere (Junak, et al., 2007). Hydrologic modeling suggests that these habitats, although never extensive, expanded significantly at the LGM and shifted into modern distributions when the coastal plain disappeared during the early Holocene (Fig. 5). Deciduous woodlands may have expanded with streams, but likely were never dominant features on the landscape.

The dramatic changes in land area and the separation of the islands during the terminal Pleistocene and early Holocene (Figs. 4 and 5) also had important implications for terrestrial animals, including pygmy mammoth (*Mammuthus exilis*) and Columbian mammoth (*Mammuthus columbi*). The extirpation of mammoths occurred around 13,000 cal yr BP, a time of rapid sea-level rise and dramatic reductions in
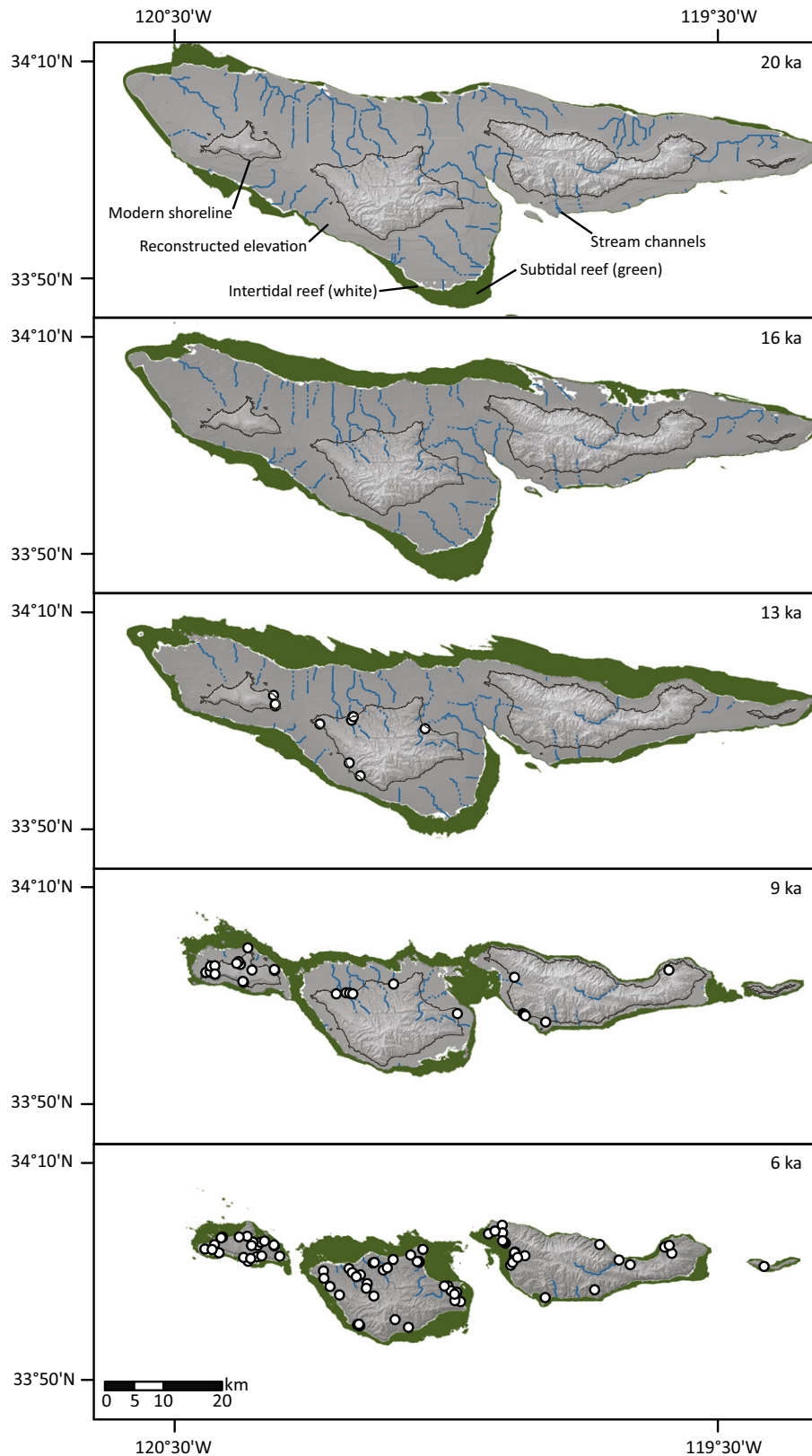
Figure 5. Reconstruction of post-LGM topography of Santarosae and the Northern Channel Islands (NCI), including estimated stream courses on the coastal plain, kelp forest reef extent (shown in green and estimated as the area between 1 and 25 m below sea level) and rocky intertidal zones (shown in white and estimated as the area between 1 m above and 1 m below sea level). Archeological sites dating to 1000 years before and after the shoreline estimate are also shown (circles). The hydrologic model represents potential stream courses on the coastal plain, including those areas where streams would have merged in the past, such as in the bay formed by the isthmus of Santa Cruz and Santa Rosa Islands. The actual extent of streams on the NCI would be heavily dependent on precipitation, and disturbances to the modern system limit our understanding of the relationship between precipitation and the amount of water in streams (Engle, 2006).
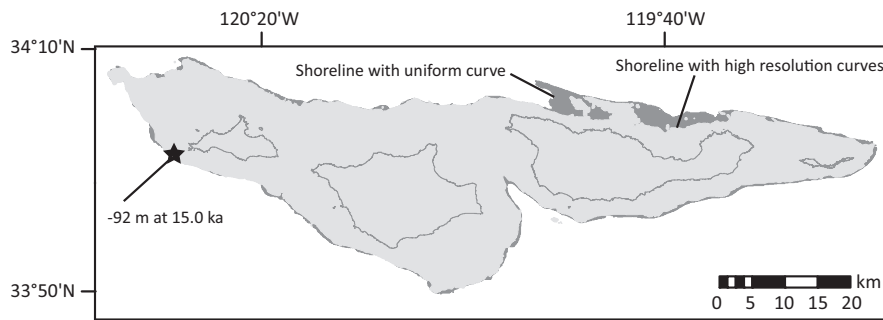
Figure 6. When GIA-corrected RSL curves are modeled at a high spatial resolution of about 4 km, they yield significantly different results than a uniform RSL curve applied across the entire region. In this example at 15.00 ka, the GIA-corrected sea level varies from 92 to 87 m below MSL, and produces the shoreline represented by light gray. If a uniform value of 92 m below MSL (which is modeled at the location indicated by the star) were applied to the entire NCI, the result is the shoreline represented by dark gray. The uniform RSL model would fail to identify bays that appear to have formed along the northern shore of modern Santa Cruz Island, and would misdirect efforts to locate early archeological sites.

the coastal plain habitat (Figs. 2 and 3) that would have been ideal for mammoths (Agenbroad et al., 2005; Rick et al., 2012). The Channel Islands contain few terrestrial mammals and the precise timing of the appearance of island gray foxes (*Urocyon littoralis*), island spotted skunks (*Spilogale gracilis*), and island deer mice (*Peromyscus maniculatus*) is the subject of considerable debate. The predecessors of all three animals may have colonized the islands during the human era (e.g., 13,000 cal yr BP or later) around the time Santarosae was becoming four separate islands or after the break-up (Johnson et al., 1983; Rick, 2013). Recent genetic research indicates that the island foxes diverged from their mainland ancestors between 9.2 and 7.1 ka, towards the end of the breakup of Santarosae, suggesting that these animals may have arrived on the NCI during a period of considerable paleogeographic and ecological instability (Hofman et al., in press). Shoreline changes may have also impacted coastal dune ecosystems, terrestrial land bird distributions (e.g., island scrub-jays, *Aphelocoma insularis*), pinniped haul-outs and rookeries, and seabird breeding colonies, topics that require additional research in light of the new GIA RSL shoreline reconstructions.

Littoral environments

The location and extent of intertidal and subtidal ecosystems were controlled by sea-level rise during much of the study period. Rocky shores probably emerged as sea level dropped and fluvial sediment was carried out of the littoral system. As sea level began to rise, estuary systems likely evolved as river mouths that existed during the LGM sea-level low-stand were drowned by marine transgression, and then transformed to marsh and lagoon systems as sea level stabilized (Graham et al., 2003). Sandy beaches probably developed later, when sediment was able to accumulate in the nearshore environment after sea level stabilized and stream valleys infilled (Masters, 2006).

Paleogeographic reconstructions provide more detail for this generalized description of ecological change. Shoreline length, which determines the spatial extent of intertidal ecosystems, peaked around 14.5 ka, decreased throughout the late Pleistocene, and increased again as the islands begin to separate around 11.0 ka (Table 1). Subtidal surface area, which is measured as the area between 1 and 25 m below sea level and approximates the potential extent of kelp forest (following Kinlan et al., 2005) peaked slightly later, around the time of the first known human occupation, about 13.0 ka (Fig. 2). More research is needed into the impact of particularly rapid sea-level rise on intertidal and subtidal ecosystems, which may have been less productive during times of rapid change in geomorphology if ecosystems did not have time to develop fully (Fig. 3).

A gently sloping nearshore shelf and wetter climate during the late Pleistocene may have been a good setting for estuarine and marsh ecosystems at the mouths of larger streams. When Santarosae existed, the streams in Old Ranch Canyon on eastern Santa Rosa Island and Christy Canyon on western Santa Cruz Island likely joined together before entering the ocean on the southern side of the former Santa Rosa–Santa Cruz isthmus (Fig. 5). The large, protected bay on the southern side of this isthmus probably persisted until the islands separated about 9.5 ka. Although there is no direct evidence for the ecological community this bay supported, it is possible that a terminal Pleistocene shell at CA-SRI-708, from a clam species (*Chione undatela*) most commonly found in estuarine environments, was harvested from this area (McLean, 1978; Rick et al., 2013).

A fluctuating marine climate operated alongside these changes in the nearshore paleogeography. There is a general trend of warming sea surface temperatures (SSTs) from the LGM through the Holocene in the Santa Barbara Channel region (Kennett et al., 2000; Hill et al., 2006; Hendy, 2010), but a reduction in the strength of the California Current may have reduced marine productivity throughout the eastern North Pacific in the millennia following the LGM (Sabin and Pisias, 1996). Overall marine productivity rose during the Bølling–Allerød warm period (15.0–12.9 ka), just as the potential extent of kelp forest was at its greatest but rates of change in available subtidal area were extremely high. The brief paleogeographic stabilization during the Younger Dryas period coincided with a reduction in productivity (Kennett et al., 2008). The Holocene was characterized by alternating periods of warm SSTs/lower productivity and cool SSTs/higher productivity (Kennett et al., 2007; Grelaud et al., 2009), alongside a decreasing trend in the area available for both rocky intertidal and kelp forest ecosystems.

The archeological record provides paleoecological data that can help refine these patterns. Estuarine shellfish are found in archeological sites on eastern Santa Rosa Island between about 11,000 and 5900 cal yr BP, where they are associated with the emergence of the Abalone Rocks estuary (Fig. 1) (Rick et al., 2005b, 2013; Rick, 2009). However, shoreline reconstructions suggest that this would have been a very dynamic environment and that other estuaries may have formed in the embayments that emerged on the southern shore of Santarosae during the late Pleistocene (Fig. 5). The presence of aquatic birds at the ca. 11,700 year old SRI-512 site on northwestern Santa Rosa Island similarly suggests that the mouth of nearby Arlington Canyon may have supported a freshwater marsh at this time (Erlandson et al., 2011). Small numbers of Pismo clams (*Tivela stultorum*), a sandy shore species (McLean, 1978), are found around 9200 cal yr BP at CA-SRI-6 (Erlandson et al., 1999) and CA-SRI-568 (Reeder-Myers, 2014a), and around 7500 cal yr BP at CA-SCRI-109 (Glassow et al., 2008), but are not widespread on the islands until after 5000 cal yr BP (Rick, 2009). These early dates for sandy shore species probably reflect the rapidly evolving littoral environment, where small, localized ecosystems could emerge and disappear over short periods of time.

During the middle and late Holocene, sea-level rise probably had a reduced impact on ecology. Rates of change approach zero in RSL rise, land inundation, and intertidal and subtidal surface loss after about 6.0 ka (Figs. 2 and 3). Shoreline length continued to fluctuate, but at

lower frequencies than during previous millennia. As human populations increased during the second half of the Holocene (Rick et al., 2005a; Glassow et al., 2007), their influence may have replaced paleogeography in its destabilizing effect on terrestrial and nearshore ecosystems.

Archeological implications

The first people on the NCI lived in a different landscape than what is present today. The earliest evidence for human occupation on the islands is human remains dated to ~13,000 cal yr BP from the Arlington Springs site (CA-SRI-173) on northwestern Santa Rosa Island (Orr, 1962, 1968; Johnson et al., 2002, 2007). This occupation is well before the islands began to separate (Fig. 4), and coincides roughly with the peak in subtidal reef area (Fig. 2). We have little direct evidence for how people were using terrestrial resources during this period, although recent research indicates that corms and small seeds contributed to human diets on the islands throughout the Holocene (Reddy and Erlandson, 2012; Gill, 2014). The earliest known archeological sites on the NCI are found on western Santa Rosa and eastern San Miguel islands adjacent to a broad and relatively shallow stretch of insular shelf (Fig. 1). This is due in part to a research focus on these two islands and field strategies that focused on interior caves, freshwater springs, toolstone sources, and broad viewsheds (Erlandson et al., 2011; Rick et al., 2013). Most of the evidence for this earliest period of human occupation was likely eroded by rising sea level.

A series of sites on the emergent marine terraces of Santa Rosa and San Miguel islands, many of which include Paleocoastal stemmed points and crescents, were occupied from about 12,200 to 11,000 cal yr BP, and suggest a relatively small population relying on diverse marine food sources including birds, fish, shellfish, and sea mammals (Erlandson et al., 1996, 2011; Braje et al., 2013; Erlandson, 2013; Glassow et al., 2013; Jew et al., 2013; Rick et al., 2013). Some of these sites are close to high-quality chert cobbles exposed in marine terrace deposits, and many sites also contain heavily eroded shell middens, numerous chipped stone tools, and debris from the production of stone tools (Erlandson and Braje, 2008; Erlandson et al., 2011). Other sites are deeply buried under Holocene sediments and contain diverse faunal and artifactual assemblages (Erlandson et al., 2011), while still others have produced only chipped stone tools diagnostic of Paleocoastal occupations (Braje et al., 2013; Rick et al., 2013). This diversity of site types suggests a flexible settlement strategy well adapted to the changing environments of the late Pleistocene, including reducing land mass and coastal plain, shrinking subtidal surface area, and decreasing shorelines and intertidal zones.

Between 10,000 and 8000 cal yr BP, sites become more common on the islands, and at least 42 have been documented to date. These are mostly small shell midden sites located close to the contemporary coast (Erlandson et al., 2009, 2015). Subsistence continued to focus on rocky intertidal shellfish, although a small paleoestuary on eastern Santa Rosa Island attracted people throughout much of the early Holocene and terminal Pleistocene (Rick et al., 2005b). Evidence for fishing continues to be limited, except at some sites such as Daisy Cave (Rick et al., 2001), and evidence for hunting is relatively rare in faunal and artifact assemblages. Both ecologically and culturally, the early Holocene is a period of adjustment when human settlement and subsistence systems begin to intensify as ecosystems stabilize. A broad coastal plain around Santa Rosa and San Miguel islands would still have presented a distinct terrestrial environment from the modern, but pollen evidence, while limited, suggests that plant communities were similar to those of the present. Between 7.0 and 6.0 ka, sea level rise probably ceased to have a significant influence over either ecology or site visibility on the NCI.

Paleogeographic reconstructions serve as a reminder that we are missing a large portion of the archeological record of human settlement of the NCI and other coastal regions during the late Pleistocene and early Holocene. Most sites known before 10,000 cal yr BP on the NCI

were interior sites located hundreds or thousands of meters from the shoreline. However, settlement patterns throughout the Holocene were more heavily focused on coastal areas and models indicate that this should have been true during the late Pleistocene as well (Reeder-Myers, 2014b). The apparent sharp increase in site frequency after 9000 cal yr BP (Fig. 5) is, to some extent, the result of better site visibility.

Future underwater research on the previously exposed coastal plain could focus on the large streams on the northern side of Santa Rosa Island throughout the late Pleistocene, the unusual bay and wide intertidal areas on the northern side of Santa Cruz Island between about 16.0 and 14.0 ka, and the large bay that likely formed on the southern side of the former isthmus between Santa Cruz and Santa Rosa islands between about 16.0 and 10.0 ka. However, this study demonstrates that the application of a single RSL curve to the entire NCI could produce misleading results for underwater mapping and survey projects aiming to discover early sites (Fig. 6). Underwater survey is the only way to obtain definitive evidence for either paleogeographic or archeological change on the late Pleistocene and early Holocene NCI coastline, but these activities must be guided by the most accurate possible models.

Conclusions

This model of paleogeography and paleoecology builds on previous efforts to produce reliable estimates of shoreline change on the NCI by incorporating a more complex GIA-corrected model of sea level rise, and complements other recent research on the west coast of North America (Shugar et al., 2005; Clark et al., 2014; McLaren et al., 2014). The results of the present study allow for a more comprehensive examination of the ecological and archeological implications of those changes. The first people to colonize the NCI likely faced relatively rapid changes in available rocky intertidal, kelp forest, and terrestrial ecosystems because of rising sea level and a variable climate. The rate of those changes peaked just before the Younger Dryas and again during the early Holocene, but began to decrease significantly after about 6.0 ka (Fig. 3). Collectively, these data demonstrate that change appears to be a constant factor in NCI ecosystems, and the adaptive resilience that island ecosystems and organisms have evolved will be a key part of their survival through the Anthropocene (see Rick et al., 2014).

On the NCI, differences of only a few meters in sea level can make large differences in shoreline locations under certain conditions, particularly along the more gently sloping insular shelf on the northern side of the islands (Fig. 6). In areas with more gradually sloping continental shelves (e.g., North America's Atlantic and Gulf coasts), these differences could translate into kilometers of error in shoreline reconstructions. Even in areas located far from the LGM ice sheets, GIA corrections are essential to more accurate estimates of shoreline locations and interpretations of paleogeography, ecological change, and archeological patterns.

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