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Late Quaternary relative sea level in Southern California and Monterey Bay

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ABSTRACT

Few records of late Quaternary relative sea level (RSL) are available for the Pacific coast of North America south of San Francisco Bay, a region where RSL data would be particularly useful for constraining vertical rates of tectonic motion. This paper provides the first regional, uplift-corrected late Quaternary RSL history for southern California derived from a compilation of 132 previously published and unpublished radiocarbon ages from nearshore, estuarine, and freshwater deposits in sediment cores from coastal southern California. We also provide a local, uplift-corrected RSL history for Monterey Bay, central California, generated from 48 radiocarbon ages from Elkhorn Slough and surrounding environments. Our resulting compilations show rapid sea-level rise from 15 ka which begins to decelerate to present mean sea level (PMSL) between 6 and 8 ka. Late Holocene (<4 ka) sea-level rise averaged 0.8 ± 0.3 mm a^{-1} in southern California and 1.3 ± 0.19 mm a^{-1} along Monterey Bay in central California. Both rates of late Holocene RSL rise calculated are lower than recent RSL rates from southern California (~1.61 ± 0.34 to 2.4 ± 1.04 mm a^{-1}) and Monterey Bay (1.49 ± 0.95 mm a^{-1}), derived from uplift-corrected, 20th century tide gauge data. This new RSL data fills geographical gaps in relative sea-level histories, as well as provides important datums for local tectonic processes.

1. Introduction

Accelerated rates of sea-level rise in the 20th century have been found to be consistent with global temperature increases during the same period (Kemp et al., 2011). Recent models of future sea level predict additional acceleration over the next century due to thermal expansion, land-based ice loss, and other factors (Church et al., 2013). Records of past sea-level change from around the world provide a baseline for understanding, predicting, and preparing for these future changes.

Attempts have been made to determine a theoretical, ice-equivalent, eustatic sea-level history for the late Quaternary (e.g. Lambeck et al., 2014; Lambeck and Chappell, 2001; Peltier, 2002; Waelbroeck et al., 2002). However, modeled and observed sea-level change around the globe varies from eustatic estimates due to differences in glacial isostatic adjustment (GIA) processes, local tectonics, sediment loading, and steric factors (e.g. Clark et al., 1978; Lambeck and Chappell, 2001; Mitrovica et al., 2011; Pirazzoli, 1991). Quantifying this regional variability in relative sea-level (RSL) histories is necessary to determine how different coastlines have evolved in response to past sea-level rise, to reconstruct paleogeography during times of past human and faunal migrations, and to constrain the past distribution and melting history of ice sheets.

GIA models used to determine past ice-sheet distributions and the rheological properties of the Earth, important parameters for models that predict future sea-level change, require adequate global coverage of RSL data (Lambeck et al., 2014; Lambeck et al., 1998; Mitrovica and Peltier, 1991; Spada et al., 2006). Existing large-scale numerical models of Holocene relative sea-level response (e.g. Clark et al., 1978; Clark et al., 2014; Mitrovica et al., 2001, 2011; Muhs et al., 2012; Reeder-Meyers et al., 2015) suggest in glacial times, southern California fell within a zone of uplift, called the peripheral forebulge, which results from the migration of mantle material from beneath regions of ice load to the periphery of ice sheets. The subsequent postglacial collapse of this forebulge, along with ice sheet melting and gravitational components, would be expected to result in rising sea levels throughout the Holocene (Clark et al., 1978). However, very little RSL data for southern California are available to test these models or to determine differences in the isostatic response of the coastline with varying

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distances from the North American ice sheets along the northeastern Pacific Ocean.

Quaternary RSL data remain scarce for central and southern California in part due to complications that arise from the variable tectonic regimes of these regions. However, these very complications necessitate the establishment of a regional RSL curve: estimates of recent vertical tectonic rates in coastal areas based on elevations of paleo-shoreline features rely on the ability to remove the eustatic and isostatic contributions of relative sea-level change. The magnitudes of Holocene subsidence in individual sedimentary basins and uplift on recent terraces are only quantifiable when comparing site-specific RSL data to a regional curve. Rates of Holocene uplift in southern California have been calculated with the assumption that sea level has not deviated from modern levels in the late Holocene (e.g. Lajoie et al., 1982), which has not been tested for southern California. In fact, Gurrola et al., 2014 pointed out that without comparison to a regional sea-level record, Holocene marine terraces exposed along the coasts of Santa Barbara and Ventura counties thought to represent recent uplift could also be, although unlikely, attributed to a sea-level high stand.

We begin to address these deficits in sea-level data by compiling existing radiocarbon ages derived from coastal, estuarine, and shelf material along central and southern California and correcting these data for long-term tectonic uplift, inconsistent sea-level datums, and variable marine radiocarbon reservoirs. This paper provides the first regional, tectonically corrected late Quaternary RSL history for southern California and a preliminary site-specific RSL history for Monterey Bay on which future GIA and tectonic studies can build.

2. Background

2.1. Overall geological setting of the California coast

The southern and central California coast is a tectonically active margin, most generally characterized by right-lateral strike-slip motion along the San Andreas Fault system, with local areas of compression and extension (e.g. Brown, 1990; Drummond, 1981; Simkin et al., 2006). The coastline consists of crustal blocks uplifting or subsiding at different rates. Sections of the coastline undergoing uplift are often characterized by elevated marine terraces of various ages (Muhs et al., 2014). Estuaries are formed within incised valleys that cut these terraces, in tectonic synclines, or behind coastal barriers. Because the continental shelf of much of central and southern California is as narrow as 10–20 km wide, typically less than 200 m deep, and characterized by high wave energy (Draut et al., 2009), most paleo-estuarine deposits formed on the shelf during times of lower sea level, but outside of incised valleys or structural basins, were likely modified or eroded away during postglacial transgression (e.g. Le Dantec et al., 2010; Sommerfield and Lee, 2004).

Existing estuarine deposits beneath modern estuaries (e.g. San Francisco Bay, Atwater, 1979) or preserved in now submerged submarine canyons along the continental shelf (La Jolla Canyon, Shepard and Dill, 1966) in central and southern California record a mixture of tectonic, climatic, and anthropogenic changes in the late Quaternary. The climate of much of coastal southern California is Mediterranean, with cool, wet winters and warm, dry summers (Bakker, 1984). This seasonality results in small fluvial systems exhibiting flashy, storm dominated flow (Warrick and Mertes, 2009; Warrick and Milliman, 2003). Storm supplied sediments comprise a large part of the sediment budget along the coast (Drake et al., 1972; Patsch and Griggs, 2006), and influence the geomorphology of estuarine systems. Estuaries in California have also been highly disturbed by human activity and today are only fractions of their former size (Lohmar et al., 1980; Lafferty, 2005; Nichols et al., 1986; Zedler, 1996).

2.2. Relative sea level

Global GIA models predict that the California coast falls within an intermediate-field zone of forebulge collapse—equivalent to Clark's et al. (1978) Zone II, which predicts consistently rising sea level from ice sheet decay through the Holocene. This prediction is supported by models of deglacial RSL for the Channel Islands, California (Santa Rosa Island, Clark et al., 2014; San Nicolas Island, Muhs et al., 2012; Northern Channel Islands, Reeder-Meyers et al., 2015) that suggest sea level rose dramatically from ~100 m to ~15 m below present mean sea level (PMSL) until ~8 ka, at which point the rise decelerated to present.

While Holocene RSL data exist for the San Francisco Bay region (Atwater et al., 1977; Engelhart et al., 2015; Meyer, 2014), and farther north along the Pacific margin (Clague et al., 1982; Engelhart et al., 2015; Hamiliton et al., 2005; Shugar et al., 2014), only one data-based RSL curve, derived from dating submerged basal transgressive deposits on the Santa Monica shelf (Nardin et al., 1981; updated and expanded by Inman, 1983 and Masters, 1988), exists for southern California. The Santa Monica curve established a rough baseline for the region, but is uncorrected for tectonics and is based on seismic stratigraphy and only six radiocarbon dates, five of which are from shell hash material within transgressive lag deposits on the continental shelf. While many types of coastal transgressive deposits, such as incised valley and back-barrier estuarine deposits, are useful in sea-level reconstructions (Sloss et al., 2004, 2007), basal transgressive lag deposits include material reworked by wave action during the early stages of transgression along a shelf. Because the original depths of the dated shell material, as well as the degree of reworking post-deposition is unknown, reconstructions based on transgressive lag deposits contain at least 10 m of uncertainty in RSL reconstructions (Nardin et al., 1981). The Nardin et al. (1981) curve also suggests the most rapid sea-level rise in the Holocene occurred between 3 and 5 ka, which would require either a GIA response uncharacteristic of an intermediate-field location (Clark et al., 2014) or a eustatic ice-volume equivalent sea-level history inconsistent with current compilations (e.g. Lambeck et al., 2014).

Compilations of RSL data from other intermediate-field locations in the United States such as the Atlantic (Engelhart et al., 2009, 2011a, b) and Gulf coasts (Simms et al., 2007), have been used to test GIA models for these regions and have demonstrated systematic differences in RSL rates of rise related to distance from ice-loading centers. These compilations and models also show no evidence for higher-than-modern RSL during the Holocene in regions located at similar distances from the major ice sheets as southern California. A recent compilation of sea-level data from San Francisco to southern British Columbia, derived from dated saltmarsh deposits, isolation basins, marine and terrestrial materials, and archeological sites (Engelhart et al., 2015), indicates the maximum late Holocene rates of RSL rise occur in northern and central California and decrease to the north as forebulge collapse becomes less influential closer to the margin of the Cordilleran ice sheet. Because of the scarcity of Holocene RSL data in southern California, comparable observational tests of model-derived predictions for glacio-isostatic response and sea-level rise have not been available for the west coast of North America south of San Francisco, California.

3. Methods

3.1. Compilation and indicator type

We used two different types of sea-level indicators in this study: