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A Late Holocene Reconstruction of Coastal Salt Marsh Net Accretion Rates and Environmental Change from Three Sites in Southern California

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A Late Holocene Reconstruction of Coastal Salt Marsh Net Accretion Rates and Environmental Change from Three Sites in Southern California

A thesis submitted in partial satisfaction

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in Geography

by

Lauren Nicole Brown

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ABSTRACT OF THESIS

A Late Holocene Reconstruction of Coastal Salt Marsh

Net Accretion Rates and Environmental Change from

Three Sites in Southern California

by

Lauren Nicole Brown

Master of Arts in Geography
University of California, Los Angeles, 2014
Professor Glen M. MacDonald, Chair

Coastal marshes are complex ecogeomorphic feedback systems that require further investigation on the Southern California coast to understand potential responses to sea level rise (SLR). Long-term accretion rates – deposition and erosion of mineral and organic matter – form a basis of understanding processes in the marsh related to SLR responses. From sediment cores, I reconstruct the net accretion rates of three marshes using radiocarbon dating methods and analyze loss on ignition (LOI) data to understand the physical properties of the sedimentary record in the three marshes. Average net accretion rates for Tijuana Estuary are 1.0 ± 0.94 mm yr^{-1}, for Upper Newport Bay are 1.0 ± 0.4 mm yr^{-1}, and for Morro Bay are 8.0 ± 8.3 mm yr^{-1}. Over the past 2000 cal YBP, all net accretion rates kept pace or exceed rates of SLR (when compared to historic SLR of 0.6 to 2 mm yr^{-1}); however, only Morro Bay exhibits historic net accretion rates high enough to compare to possible rates of SLR associated with projected sea level gains of 0.3 to 1.6 m on the Pacific coast through 2100. Core stratigraphies indicate marsh conditions change frequently and the current *Spartina spp.* and *Salicornia spp.* marsh vegetation

communities are geologically recent features in their present locations, existing from 700 to 1000 cal YBP. The future under continued human modification of coastal systems, climate change, and accelerated SLR merit continued research into the dynamics of coastal salt marsh systems on the California coast.

The Thesis of Lauren Nicole Brown is approved

Richard F. Ambrose

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Glen M. MacDonald, Committee Chair

University of California, Los Angeles

2014

For my mother, who is the greatest supporter of my education,
the greatest believer in my abilities,
and the greatest asset for achieving my dreams.

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Introduction

The coastal salt marsh system is highly valued for its ecosystem services (Zedler & Kercher, 2005), habitat for endangered species (Zedler, 1996), and exceptional biological productivity (Ibáñez, Morris, Mendelssohn, & Day, 2012). For these and other reasons, Costanza et al. (1997) globally rank coastal salt marshes among the most valuable of all ecosystem types and Barbier et al (2011) estimate an average value of $10,000 per hectare. With the inevitability of accelerated climate change from anthropogenic greenhouse gas emissions and increasing pressure from habitat loss and land-use changes, a large amount of research over the past few decades works to identify and mitigate threats to coastal marsh systems. Of all the challenges to come, accelerated sea level rise (SLR) merits particular concern for coastal salt marsh systems.

General consensus on the reality of accelerated SLR has largely been achieved; however, uncertainties still exist in terms of the possible magnitude of total increase as well as the speed and manner in which seas will rise. Lower limits of many projections suggest 30 to 40 cm of rise by the year 2100 while the upper extent ranges from 1 to 2 meters (Cayan et al., 2008; Grinsted, Moore, & Jevrejeva, 2010; Horton et al., 2008; IPCC, 2007; Jevrejeva, Moore, & Grinsted, 2010; National Research Council, 2012; Rahmstorf, 2007; Vermeer & Rahmstorf, 2009). Of particular relevance to the California coast, the National Research Council (NRC) used regional sea level and tectonic data to project 42 to 167 cm of SLR on coasts south of Cape Mendocino by 2100 (relative to sea levels measured in 2000). The Intergovernmental Panel for Climate Change (IPCC) published Assessment Report 5 in 2013 which projects that sea levels in 2100 could be 33 to 66 cm above 2000 levels under a moderate climate change scenario and 52 to 98 cm above 2000 levels under worst case emission scenario projections (Stocker et al., 2013).

Even the most conservative SLR estimates indicate coasts will experience considerable deviation from the past 2000 to 4000 years of very stable sea levels. Researchers have looked at local and global proxies and find that SLR fluctuated between about 0.6 mm yr^{-1} to 2 mm yr^{-1} over the past several millennia (Gehrels et al., 2006; Grinsted et al., 2010; Kemp et al., 2011). Paleo-sea-level reconstructions as well as historic sea level records indicate that SLR has already experienced a small rate increase just in the past 200 years (Church & White, 2011; Donnelly, 2004; Gehrels et al., 2006; Gehrels, Hayward, Newnham, & Southall, 2008). While estimates in the rate of acceleration vary based on the study, most indicating that SLR rates for the past 200 years range between 2 to 3 mm yr^{-1}, the consensus attributes this acceleration to rising temperatures from increased inputs of carbon in the atmosphere during the Industrial Revolution.

Changes in sea level are an integral part of coastal salt marsh ecosystems. Plants are highly adapted to natural diurnal and seasonal variations, as well as moderate rates of longer term change. Before human modification of natural marsh systems, no substantial evidence of marshes sinking or "drowning" under SLR, such as the subsidence observed in marshes on the Atlantic and Gulf coasts of the US, exists (Kirwan & Megonigal, 2013). Most previous studies of vertical accretion – deposition and erosion of mineral and biotic material – establish that rates of accretion correlate with (or slightly exceed) changes in mean sea level (MSL) (Cahoon et al., 2006). Modeling studies of marsh feedback processes prove that adjustment to changes in rates of SLR are possible, however marshes tend to lag behind changes in sea level by about 20 years (Kirwan et al., 2010). Furthermore, there are limits on the possibilities of adaptation based on limiting factors like sediment supply and plant productivity (Kirwan et al., 2010; Morris, Sundareshwar, & Nietch, 2002). Accelerated SLR coupled with modification of watersheds, land use, and ecological function within coastal marshes themselves indicate that the future will bring many previously unseen challenges for the continued health and existence of salt marshes on the California coast.

Theoretically, the position of marsh surface elevation relative to MSL determines stability and health of a salt marsh. The tolerances for vegetation to different levels of submergence, salinity, and other conditions control elevation with aid of abiotic processes controlling sediment deposition, re-suspension and hydrology. In a marsh system with fully-functioning feedback mechanisms, plant productivity often serves as the element which responds (either positively or negatively) to the change in relation between elevation and MSL, correcting the marsh back into balance. This indicates that a theoretical optimum of plant productivity exists for marsh elevation relative to MSL in every individual marsh. Marshes can tolerate sub-optimal productivity as sea level and elevation vary up to a critical breaking point where either the marsh will no longer be able to grow and subside under the tide, or fill in and no longer be within the tidal range (Kirwan et al., 2010; Morris, Sundareshwar, & Nietch, 2002). The flexibility of factors which contribute to marsh elevation – the most influential factor for productivity – determines overall marsh adaptability to changes in sea level. The interaction between geologic, hydrologic, and biotic feedbacks which result in stability or instability of marsh surface elevation is therefore a particularly relevant avenue for research when considering the future of coastal marsh ecosystems facing accelerated SLR. If marsh drowning represents a new phenomenon caused by human modification of natural ecosystem feedbacks, as Kirwan et al. (2013) claim, understanding these feedbacks is key to protecting these critical habitats.

Empirical and modeling studies have looked into the many factors which contribute to marsh surface elevation. Elevation is controlled by accretion and subsidence – including local tectonic influences and sediment compaction that can be divided into shrink-swell effects in the short term and shallow subsidence in the long-term (Cahoon et al., 2006; Cahoon, Reed, & Day, 1995; J. C. Callaway, Nyman, & DeLaune, 1996; Reed & Edge, 2002). In situ measurements of accretion and subsidence in marshes help to identify the general trend of elevation change and the major processes which contribute to the elevation changes. For example, after observation and modeling of the marshes on the US Gulf Coast, researchers attribute the high rates of accretion and sediment compaction to the large quantities of fine, compactable sediments deposited therein, which are highly susceptible to shrink-swell effects and shallow subsidence (Blum & Roberts, 2009; Reed, 2002). In contrast, marshes on the US West coast do not benefit from the same sediment supply and do not suffer from the same risk of subsidence (Cahoon et al., 2006; Cahoon, Lynch, & Powell, 1996; French, 2006). While such differences appear to be a positive sign for the long-term survival of marshes on the West coast, the fact remains that West coast marshes are fundamentally different ecosystems and will likely require different mitigation measures from those on the Gulf and East coasts. Instead of decreasing compaction, low sediment delivery may cause subsidence from a lack of material to replenish the marsh surface. A better understanding of marshes on the Pacific Coast is therefore crucial for implementation of conservation methods that will address the specific challenges facing marshes in California.

The geomorphologic setting of the Southern California coast differs dramatically from the East and Gulf coasts due to topography (marshes are more limited in area and restricted to shores without bluffs or cliffs) and the Mediterranean climate regime of summer drought and winter rains. The Mediterranean pattern of precipitation means that marshes receive intermittent fluvial sediment input, with rivers and channels often remaining dry except after rainfall events during the wet season. Additionally, differences in sediment type, plant biology, and less severe land subsidence (in relation to the Gulf coast) seemingly reduce the threat of subsidence in Southern California compared to the East and Gulf coasts. In a global comparison of 200 marshes, such differences proved to decrease the rates of sediment accretion and rates of elevation change in marshes along the Pacific Coast of the US (Cahoon et al., 2006). To gain a better understanding of marsh ecosystems in California, I aim to describe the history of sediment accretion and determine key areas of further research into paleoenvironmental changes to the salt marsh elevation-MSL balance in several coastal salt marsh sites.

With this work, I will document net accretion rates from the mid- to late-Holocene in three salt marsh sites. I hypothesize that past rates of accretion in Southern California will approximate past rates of SLR, indicating little influence of subsidence related to land movement or sediment compaction, as indicated by previous studies of sites like those in Southern California (Cahoon et al., 2006; French, 2006). I will compare the average rate of accretion as well as determine the rate of accretion in high, mid, and low marsh vegetation zones; sites of the lowest elevations in the marsh, dominated by *Spartina spp,.* and most highly influenced by tides, generally show higher rates of net accretion than those sites at higher elevations which are dominated by *Salicornia spp* in east coast marshes (Morris et al., 2002). Comparison between the historical rate of relative sea level rise (RSLR) and individual marsh net accretion rates will give a preliminary indication of the local conditions which influence the capacity for feedback mechanisms to adapt to accelerated SLR. Finally, physical sediment characteristics will contain evidence of any large shifts in marsh dynamics. For instance, changes in sediment source and accretion rates can be observed towards the present in regions which have experienced large-scale European and modern land-use impacts (such as deforestation) in their drainage basins (Kirwan, Murray, Donnelly, & Corbett, 2011). I will use several physical characteristics of sediment cores taken from the study sites to test for possible evidence of environmental change which would indicate promising avenues for research into historical marsh feedback mechanisms in Southern California.

Study Sites

As mentioned above, precipitation defines the Southern California climate. In Mediterranean type climate regimes, summers typically are warm and dry followed by cool, wet winters. On the coast temperatures almost never drop below freezing and average about 20°C (Zedler, 1982). In areas outside

Figure 1 - Multi-Site Map: Google Maps image of (from south to north) Tijuana River Estuary, Upper Newport Bay, and Morro Bay.

of the main tidal system, highly seasonal precipitation results in variable soil salinities that can be hypersaline during the dry period and close to that of freshwater marshes during high surface run-off events. Extreme storm and flood events are normal in the Southern California climate (Zedler, Nordby, & Kus, 1986). For the coastal marsh ecosystem, the mild temperatures and variable precipitation result in an abundance of salt tolerant, succulent plants (e.g. *Salicornia spp.*). Lowest elevations in the marsh support grasses like *Spartina foliosa*. Plants native to the in Southern California salt marshes include: *Salicornia virginica, S. bigelovii* (also known as *Sarcocornia*)*, S. subterminalis, Distichlis spicata, Batis maritima, Jaumea carnosa, Suaeda californica, Triglochin maritima, T. concinnum, Frankenia grandifolia, Limonium californicum, Monanthochloe littoralis, Juncus acutus,* and *Cordylanthus maritimus* (Purer, 1942; Zedler, 1982; Zedler, 1977).

I selected 3 sites to analyze in this study in order to have varied geographic perspectives and geomorphological settings. From south to north, the sites are Tijuana River Estuary, Upper Newport Bay, and Morro Bay [see Fig. 1].

Tijuana River Estuary

The southernmost site, Tijuana River Estuary is located at 32°35'N, 117°7'W and covers 1000 ha (Wallace, Callaway, & Zedler, 2005; Zedler, 1977). The Tijuana River provides the system's freshwater from a watershed which crosses between the United States and Mexico, starting in the US Laguna Mountains in the north to the Mexican Sierra de Juárez Mountains at the southern extent (Farley, Ojeda-Revah, Atkinson, & Eaton-González, 2012). The estuary lies on a gently sloping coastal plain. Aerial photography from the early 20th century shows that little change has occurred in the location and form of the two discharge channels of the Tijuana River and the open lagoon, but stream-flow and land use modifications have altered the natural ecology (Zedler et al., 1986). During extreme runoff events, flooding from the Tijuana River will fill the northern arm of the estuary (where the study sites is located), and, when combined with higher tides, have led to observations of large sedimentation events on the order of tens of centimeters of sediment in some areas near tidal creeks over a 6 month period (Wallace et al., 2005). In selection of my specific study areas, I avoided those places most likely to have high rates of sedimentation from these runoff events.

Fig. 2 - Google maps images of Tijuana River Estuary and core locations for cores 1-8 in the northern arm of the marsh.

Fig. 3 - Google maps images of Newport Bay and core locations for cores 1-4 in Upper Newport Bay.

Tijuana Estuary sees mean temperatures of 17°C and receives a mean annual precipitation total of about 25 cm (Zedler et al., 1986) . The estuary has been a site of rich ecological study (Mudie & Byrne, 1980; Wallace et al., 2005; Weis, Callaway, & Gersberg, 2001; Zedler & Kercher, 2005; Zedler, 1982, 1996), with typical Southern California salt marsh vegetation monitored and classified into low, mid, and high marsh zones by Zedler (1977). Modern accretion rates over all vegetation types vary from 1.3 to 9.5 mm yr^{-1} (Wallace et al., 2005). These rates are consistent with the pre-European rates of approximately 1 mm yr^{-1} and present observations of up to 10 mm yr^{-1} documented in some sites near or in Tijuana Estuary (Mudie & Byrne, 1980).

Upper Newport Bay

Situated at 33°38'N, 117°53'W in Orange County, Upper Newport Bay is 3 miles long. Marshes fringe the terraced cliffs, composed of Miocene epoch marine deposits which form the basin. Before the 1900s, the bay's only tributary and sediment source was the Santa Ana River. Due to agriculture, ranching, and hydrologic modification in the 20th century, the sediment supply for the marshes in Upper Newport Bay shifted to the San Diego Creek – a watershed which did not reach the bay before European settlement. In response to the increased sedimentation and stream flow, the bay was channelized to its modern form in 1920. Dredging and channel maintenance occurred throughout the 20th century and still occur to some degree for maintenance of the channel (Trimble 2003).

Despite the historic documentation of anthropogenic sedimentation increases, the natural cycle of flooding events must also be considered. Trimble (2003) cites that mean annual precipitation for the latter half of the 20th century was 35.5 cm near the marsh, but notes that the ranged from as little as 10.5 cm to as much as 88.1 cm in single years. The unique channel geomorphology and local SLR rate of 3 mm yr^{-1} of Upper Newport Bay inspired Masters & Inman (2000) to estimate accretion rates of 1.5 mm yr^{-1} over the past century, about 0.5 mm higher than those estimates from marshes with flatter geomorphic settings like Tijuana River Estuary. While Upper Newport Bay differs from the other two study sites in that it is not an estuarine marsh, the extreme runoff events and rate of local SLR indicate favorable conditions for high accretion rates, as evident by the multiple dredging projects which have taken place in the bay. Assumptions that the high level of accretion relates only to anthropogenic land-use and stream modification have however been challenged by Trimble (1997).

Vegetation in the Upper Newport Bay marsh broadly adheres to the typical Southern California marsh vegetation mentioned above. Vogl (1966) conducted a thorough survey of the Newport Bay marshes, subjectively dividing them into zones based on species composition consistent with the zones found in Zedler (1977); he specifies that his classification is subjective, calling the communities a "continuum", species in one zone blending and mixing with species in other zones, rather than quantifiable units with distinct boundaries.

Morro Bay

Located at 35°20'N and 120°49'W the estuary that forms the marsh at Morro Bay covers 472 hectares (Gerdes, Primbs, & Browning, 1974). Though currently a lagoon due to modifications by the Army Corps of Engineers starting in the 1900s, Morro was originally a bay protected by a mobile

Fig. 4 - Google maps images of Morro Bay and core locations for cores 1-11 in the marsh.

sandspit in a depression formed by the intrusion of ocean into the continent. It received freshwater from three streams: Chorro Creek, Los Osos Creek, and Morro Creek. Morro Creek was diverted, however, and now drains into the ocean north of the bay. Originally, the mouth of the bay split around a large volcanic neck protruding above the water and a sandspit protected the bay from the open ocean toward the south. From historic records, the natural migration of the sandspit is well-known (Mikkelsen, Hildebrandt, & Jones, 2000). Periods where the sand filled the opening of the bay and cut off the open marine influence were documented; such bay closures are linked with high levels of soil salinity and some plant mortality in the marsh due to drought (Zedler, 1982). Since the Army Corps of Engineers closed the northern entrance to the bay with sediment fill in 1910 and deepened the remaining entrance channel for passage of vessels, the bay remains perpetually open to marine waters and the migration of the sandspit is minimal (Gerdes et al., 1974). The estuary receives freshwater from Los Osos and Chorro Creeks, with Chorro Creek being the main influence on the study area.

Temperatures near Morro Bay average slightly cooler than the more southern marshes at 14° C. The bay receives, on average, about 40 cm of precipitation a year (Ford, 1997). While still characteristic of Mediterranean type climatic patterns of warm, dry summers and cool, wet winters, Morro Bay is slightly more temperate than the previous two sites in this study. For reasons not completely understood, *Spartina foliosa* is absent in Morro Bay (Gerdes et al., 1974).

In the 1990s, work on the Morro Bay river delta and salt marsh was conducted by Jaqueline Gallagher and Richard L. Ford. Gallagher sampled 63 sediment cores throughout Chorro delta and used radiocarbon dating, stratigraphy, foraminifera and pollen analysis to date marsh initiation as well as reconstruct rates of SLR and marsh accretion. She estimates only a small marsh existed at Morro Bay before 2,000 calibrated radiocarbon years ago (cal YBP) and presents a model of marsh progradation through time based on core stratigraphy. She reports average SLR over the past 4,000 cal YPB was 1.68 mm yr^{-1}, with periods with as much as 3 mm yr^{-1} around 2,500 cal YBP to 1,500 cal YBP (possibly due to tectonic activity). Gallagher finds accretion rates on the scale of 1-2 mm yr^{-1} for the periods before 1870 (horizon defined by the presence of invasive eucalyptus pollen in the sediment record) and notes a significant increase in accretion to a rate of 12.5 mm yr^{-1} starting in 1870 (Gallagher, 1996). Gallagher attributes this increase in sedimentation to European settlement and land use changes increasing the sediment deposition in the delta at this time. Ford models modern accretion through ^{137}Cs dating, sediment traps, maker horizons, and subsurface stratigraphy to conclude that the average rate of accretion in the delta from 1991-1993 was 7.1 mm yr^{-1}. He suggests that the last 100 years of accretion in Morro Bay demonstrate a trend of increasing accretion, mostly due to fluvial processes but with a large tidal influence as well (Ford, 1997). Compared to studies in the more southern estuaries and marshes of California, the studies of Morro Bay indicate a high-accreting environment which is heavily influenced by terrestrial run-off.

Additionally, the USGS surveyed Morro Bay in 2010 using ^{137}Cs dating and feldspar marker horizons to assess the possibility of increased sedimentation leading to infilling of the bay. The report concludes that no evidence of increased sedimentation is evident at Morro Bay; rates of accretion in the low marsh sites vary from 1.5 to 6.2 mm yr^{-1} and in the high marsh vary from 1.2 to 1.9 mm yr^{1}. The author notes that annual sedimentation has, in fact, decreased since a similar study was performed in 2004. Changes in elevation at the site were also measured using the sediment elevation table (SET) method (Cahoon, Lynch, & Perez, 2002) and found to be only slightly lower than rates of accretion, likely due to compaction (Callaway, 2010).

Methods

Field Methods

Eight sediment cores were collected in September, 2012 from Tijuana River Estuary; four sediment cores were collected in February, 2013 at Upper Newport Bay; and 11 sediment cores were collected in March, 2013 at Morro Bay. Individual core locations can be seen in Figures 2-4. A 1m long Russian Auger was used for all sediment recovery. Coring ceased when beach sands, marine shell-rich intertidal muds or bedrock was encountered. Cores range from 1 to 6m, depending on the depth of those basal sediments. From each marsh, 3 or more coring sites were established to survey sediments in the low, mid, and high marsh vegetation zones (Zedler, 1977). Zones were defined by field observation of species composition, by elevation, and by distance from open water or channels. Samples were wrapped in the field and transported to the UCLA where they were stored in a cold room at 4°C.

Historic Vegetation

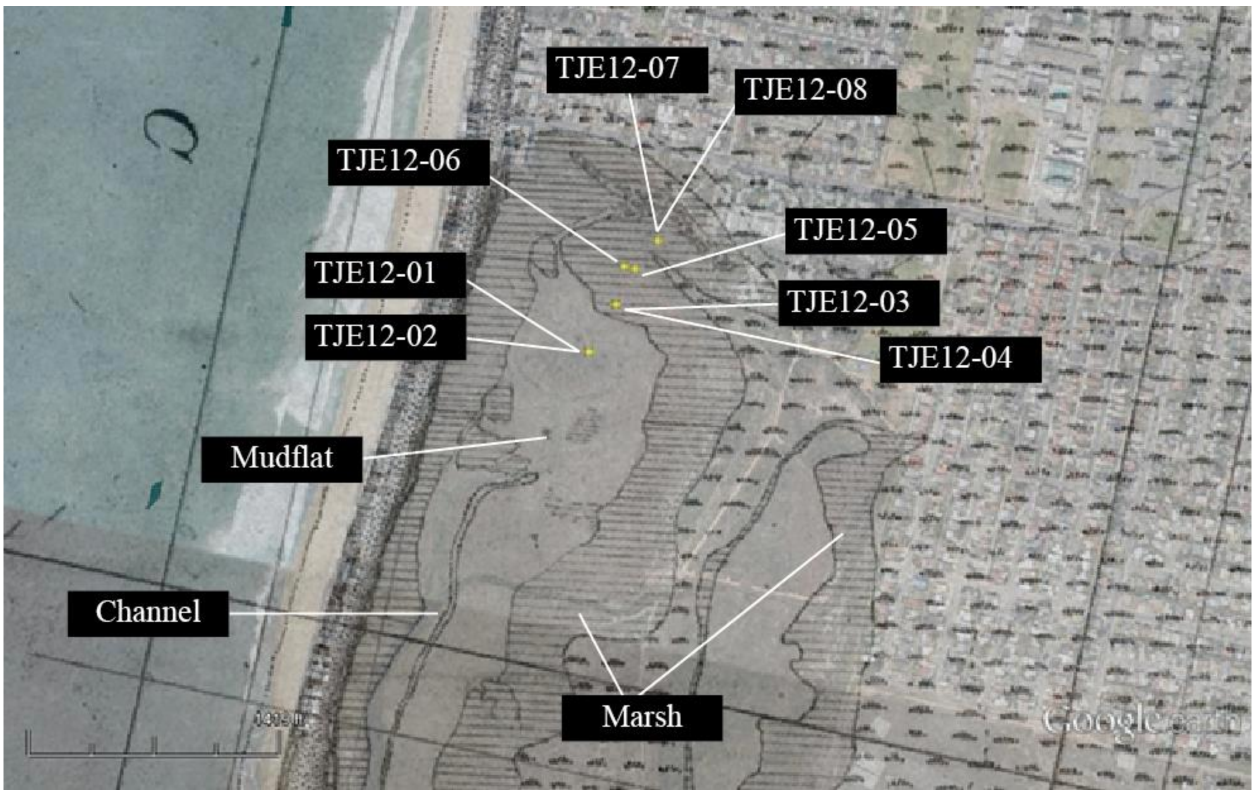

Figure 5 – Historic vegetation survey from 1852 superimposed upon modern Google Earth satellite imagery. Cores 1 and 2 were taken in what appears to have been mudflat and has since filled and become low marsh Spartina spp. *marsh. Overlay image from Dept. of Commerce* (1989)*.*

In 1807 the US government sponsored a survey initiative to survey the coastline. The National Oceanic and Atmosphere Administration (NOAA) maintains a database of over 6,000 maps created in response to that initiative during the late 1800s to early 1900s (US Department of Commerce, n.d.). With this database, 19th and 20th century survey maps can be overlaid on modern Google Earth imagery to compare changes in shorelines, vegetation, development, and more. Although map symbols often vary between cartographers, a generalized key allows for the designation of vegetation types (Grossinger, Askevold, & Collins, 2005). When coring, I used the initial maps from each site as reference to search for locations with the longest marsh presence. A map of Tijuana Estuary [Figure 5] with the 1852 survey overlain shows that cores 1 and 2 are located in an area indicated as mudflat while all other cores are within the designated marsh vegetation. At Upper Newport Bay [Figure 6], all cores are located in the area indicated as mudflat. And at Morro Bay [Figure 7], cores 4 to 9 are within the marsh vegetation zone, while cores 1 to 3 are in areas indicated to be mudflats during the 1884 survey. Core 11 was taken in an area of *Salicornia* vegetation, but this survey indicates that it may have been open water about 120 years before present day.

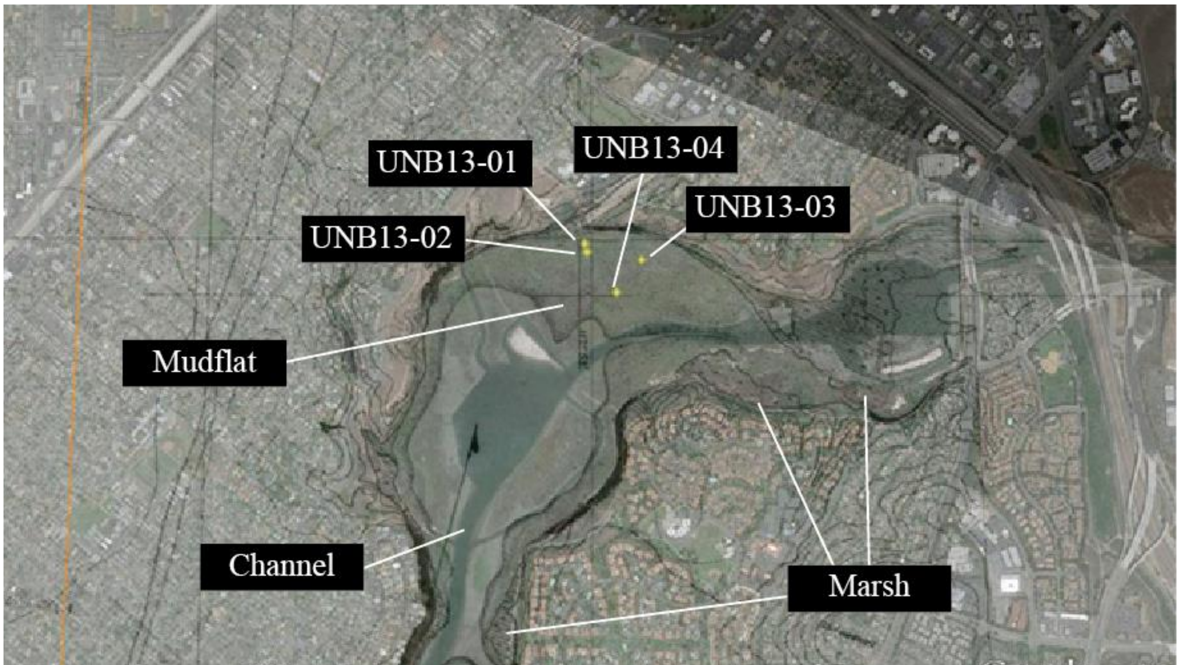

Figure 6 – Historic vegetation survey from 1875 superimposed upon modern Google Earth satellite imagery. All cores were taken from areas designated mudflat during that survey. Modern vegetation is a mix of Salicornia *and* Spartina*. Overlay image from Dept. of Commerce* (1989).

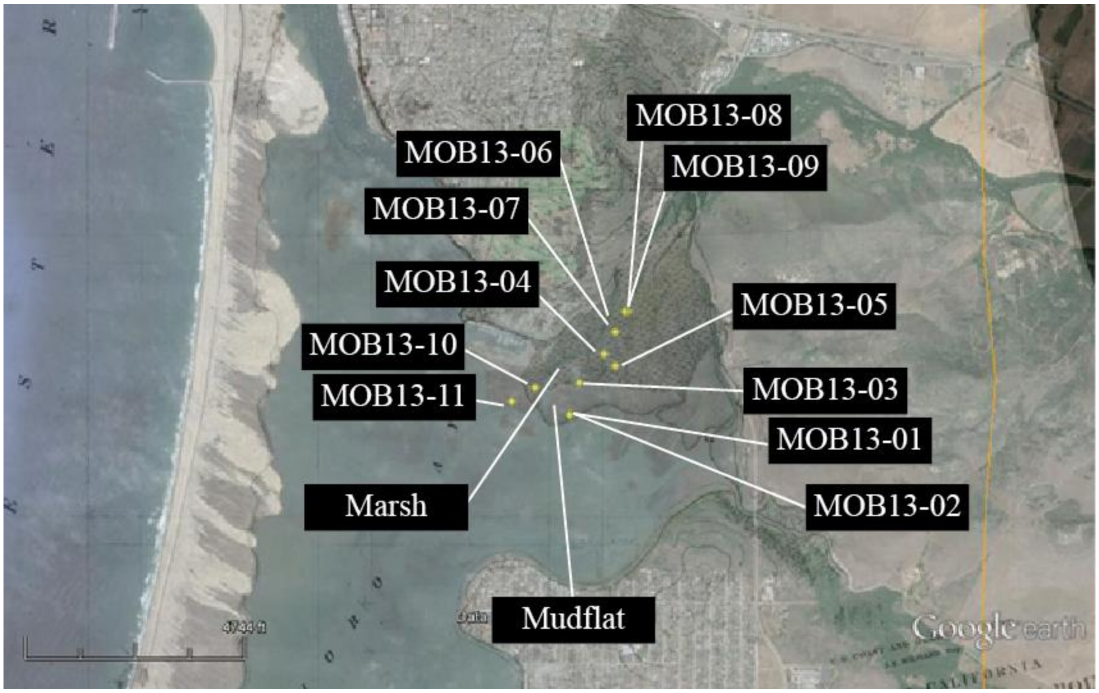

Figure 7 - Historic vegetation survey from 1884 superimposed upon modern Google Earth satellite imagery. Cores 1,2,3 and 10 are in area designated as mudflat from the survey. Core 11 is located where open water is indicated. All other cores were taken from areas that were labeled as marsh vegetation during this survey. Overlay image from Dept. of Commerce (1989).

Physical Sediment Characteristics

Cores were photographed and any visible changes in color or sediment type or content were documented with the aid of the Munsell Sediment Color Chart. Magnetic susceptibility of sediment characteristics were taken using the Bartington MS3 magnetic susceptibility equipment and software (Thompson & Battarbee, 1975). Cores were sliced into one centimeter intervals. From each contiguous samples, a 1cubic cm sample was extracted, dehydrated, burned in furnace at 550°C for 4 hours, and then 950°C for 1 hour to calculate water content as a percentage of wet weight, bulk density in grams per cubic centimeter, and organic content and carbonate content as a percentage of bulk density [Table 1] (Heiri, Lotter, & Lemcke, 2001).

Table 1 – *Formulas for LOI % Content Calculations*

% Water Content	$\frac{WW - DW}{WW}\ x\ 100$	DW = dry weight WW = wet weight LOI_1 = weight post 550°C LOI_2 = weight post 950°C
Bulk Density	$\frac{DW}{1\ cc}$	
% Organic Matter	$\frac{DW - LOI_1}{DW}\ x\ 100$	
% Carbonate Content	$\frac{LOI_1 - LOI_2}{DW}\ x\ 100$	

Chronology and Accretion Rates

Macrofossil samples for radiocarbon dating were taken from basal sediments in all collected cores. Horizons of particular interest, such as abrupt color or texture transitions, were also sampled. As often as possible, dating of plant macrofossils was avoided to minimize the error associated with dating intrusive below-ground material, namely roots (which can give an anomalously young age); though when no other organic samples were identified in horizons of interest, plant macrofossils were used. Plant macrofossils were limited to those deposited horizontally in the sample, with identifiable stomata, or identifiable as aboveground matter. Two bulk sediment samples of 0.1 g were also taken from cores in Tijuana Estuary only due to lack of any datable material.

Radiocarbon dating was conducted at the UC Irvine Keck Radiocarbon lab using an accelerator mass spectrometer (AMS). Macrofossils from plants were dried, weighed, subjected to an acid-alkali-acid wash, combusted in a sealed tube with cobalt powder and then graphitized; carbonate samples were dried, weighed, leached and hydrolyzed, before undergoing graphitization as per the small-sample method used in the KCCAMS/UCI facilities (Santos, Moore, & Southon, 2007). This method allowed for the processing of organic samples as small as 0.05g. Results from the AMS method were calibrated using the online CALIB program. Marine shells were calibrated with the Marine09 calibration curve while organics were calibrated using the IntCal09 terrestrial calibration curve (Reimer et al., 2011). Any samples which were clearly enriched with modern carbon (i.e. dating to the post-bomb era) were not included in the analysis of net accretion rates, though they have been calibrated using CaliBomb and appear in the results section of this paper (Reimer, Brown, & Reimer, 2008).

Results

Radiocarbon dating

The uncalibrated and calibrated results from ^{14}C dating of 36 samples appears in Table 1. Samples from the post-bomb era (enriched with modern carbon) appear in the table, but they are not used in any of the following analyses. Where these samples appear below radiocarbon results that were not enriched with modern carbon, I assume those samples are from intrusive organic material, likely roots, and do not accurately reflect the age of the horizon from which they were removed from. Where samples taken from the top 50 cm of the cores returned results enriched with modern carbon, further dating methods will need to verify the likelihood that these samples could also be intrusive material versus the possibility that the samples reflect the true age of the deposit.

Table 2 – Radiocarbon Dating Results and Calibrated Ages

Tijuana River Estuary	**UCI AMS #**	***Depth (cm)***	***Material***	***^{14}C Age***	**±**	***Cal. Age Range (YBP)***	***Mean Cal Age (YBP)***
TJE12-1	115767	144	*Spartina*	560	15	539-554	555
TJE12-03	128226	54	*Distichlis*	-980	50	19.2-22.1*	20.62*
TJE12-04	128227	54	*Distichlis*	-3000	90	39.2-50.1*	44.655*
	128228	74	Salicornia	-530	30	55.3-561*	55.77*
TJE12-06	128236	47	Bulk sediment	2320	40	1937-2055	1999**
	128237	97	Bulk sediment	2070	45	1631-1668	1714**
TJE12-07	115842	131	*Spartina*	1575	20	1415-1425	1467
TJE12-08	115843	142	*Spartina*	1610	30	1418-1466	1485
Upper Newport Bay	**UCI AMS #**	**Depth (cm)**	**Material**	**^{14}C Age**	**±**	**Cal. Age Range (YBP)**	**Mean Cal Age (YBP)**
UNB13-01	128212	48	Shell	-1270	15	24.2-26.0*	25*
	128213	97	Shell	1410	15	684-743	719
UNB13-02	128229	49	*Spartina*	-1340	70	24.4-54.6*	39*
	128214	127	Shell	665	20	1-495	505
UNB13-03	128215	497	Shell	5465	15	5574-5415	5599
UNB13-04	121794	0	*Spartina*	0	20	-249	0
	121807	232	Shell	830	20	151-157	254
	121795	533	Shell	-1025	30	20.1-22.1*	21*
	121808	600	Shell	5240	25	5312-5415	5368
Morro Bay	**UCI AMS #**	**Depth (cm)**	**Material**	**^{14}C Age**	**±**	**Cal. Age Range (YBP)**	**Mean Cal Age (YBP)**
MOB13-01	128200	198	Shell	765	15	140-233	182
	128201	256	Shell	780	15	145-166	195
MOB13-02	128220	51	*Spartina*	175	15	13-May	185
	128202	199	Shell	810	15	148-161	234
	124425	317	Shell	975	20	335-342	392
MOB13-03	128203	268	Shell	825	15	231-286	254
MOB13-04	128221	249	*Spartina*	80	20	-2	96
MOB13-06	128205	98	Shell	1030	15	429-475	452
MOB13-07	124426	199	Shell	1230	20	554-617	586
	128206	449	Shell	3030	15	2491-2610	2561
MOB13-08	128223	56	*Distichlis*	190	60	-33	178
	128207	112	Shell	1180	15	511-565	545
	128222	151	Salicornia	-275	15	57.1-57.2*	57*
	128208	197	Shell	830	15	238-285	258

MOB13-09	128224	52	*Distichlis*	245	15	288-303	295
	128225	93	*Spartina*	-75	15	57.1-58.7*	57*
	128209	199	Shell	930	15	303-380	348
MOB13-10	128210	197	Shell	995	15	389-458	419
MOB13-11	128211	199	Shell	785	40	140-256	189

* Sample enriched with modern carbon; calibrated using CaliBomb; not included in accretion data
** Bulk sediment date

The oldest sediments at Tijuana River Estuary date to 1999 cal YBP from a bulk sediment date. Dates on discrete material from ~1.5 m into the marsh at Tijuana date slightly younger (as bulk sediments typically return anomalously old dates) to about 1500 cal YBP. Shells from basal sediments in Upper Newport Bay returned the oldest dates from this study: 5400-5600 cal YBP. The majority of samples taken from Morro Bay dated surprisingly young; most plant and shell material from 2-3 m deep proved to be less than 500 years old. The oldest sample, from 4.5m depth, dated to 2500 cal YBP. Therefore, from Tijuana Estuary and Morro Bay the cores contain a record spanning approximately 2000 years whereas Upper Newport Bay reflects an over 5000 year record.

Age-depth models for 3 cores (selected for high resolution LOI and stratigraphic analyses) were calculated using the statistical modeling software Bacon 2.2 (Blaauw & Christen, 2011). The resulting weighted mean ages appears on the y-axes for Fig. 5-7.

Accretion

Accretion rates for all ^{14}C dates from the pre-bomb era appear in Table 3. For the sake of conformity with those cores that only have a single basal date, all accretion rate data are calculated from basal dates without correcting for any changes in rate over time. As such, this analysis looks at net accretion. A site mean accretion rate was calculated. Additionally, accretion rate means for the low, mid, and high marsh ecologic zones were calculated. Cores were classified into marsh zones based on field vegetation and elevation classification. Max, min, and mean accretion along with a comparison to SLR and mean zonal accretion rates can be seen in Fig. 5.

The average rate of accretion at Tijuana River Estuary is 1.0 mm $yr^{-1} \pm 0.94$. Upper Newport Bay shows a comparable rate of accretion of 1.0 mm $yr^{-1} \pm 0.4$. With only one core from the mid and high marsh sites, Tijuana Estuary shows significant decrease in accretion rates from the low to mid to high marsh core locations. Upper Newport Bay shows an accretion increase from the single core in the high marsh to the cores in the mid marsh, but the single core from the low marsh site at Newport actually has a lower rate of accretion than that of even the high marsh [see Table 2].

Morro Bay presents a different sedimentation environment than the other two marshes in this study and shows a high amount of variability in accretion rate from core to core. The average rate of accretion at Morro Bay is 8.1 mm $yr^{-1} \pm 8.3$. There are multiple sites in Morro Bay with accretion rates from 10 to 20 mm yr^{-1} (an order of magnitude higher than Tijuana Estuary, Upper Newport Bay, and past SLR rates). Because most of the radiocarbon dates from Morro Bay are from the past 500 years, the higher rate of accretion could be a result of the different time period covered by the Morro Bay sediment cores; temporal variation, however, is not the only explanation for these differing rates of accretion, which I will examine in the Discussion section of this paper. Habitats in high marsh at Morro prove to have lower rates of accretion that are within the range of past SLR rates, on the scale of 2.0 mm $yr^{-1} \pm 0.15$. Both mid and low marsh sites average closer to the mean of 10 mm of accretion per year.

Table 3 – Accretion Rates

Tijuana River Estuary	Depth (cm)	Material	Mean Cal. Age (YBP)	Accretion Rate (mm/yr)	Accretion Site Means (mm/yr)
TJE12-1	14	*Spartina*	555	2.6	**Sitewide**
TJE12-06	47	Bulk sediment	1999	0.20	1.02 ± 0.94
	97	Bulk sediment	1714	0.60	**Low Marsh**
TJE12-07	13	*Spartina*	1467	0.90	2.6 ± 0
TJE12-08	14	*Spartina*	1485	1.0	**Mid Marsh**
					0.95 ± 0.05
					High Marsh
					0.4 ± 0.1

Upper Newport Bay	Depth (cm)	Material	Mean Cal. Age (YBP)	Accretion Rate (mm/yr)	Accretion Site Means (mm/yr)
UNB13-01	97	Shell	719	0.7	**Sitewide**
UNB13-02	12	Shell	505	1.7	1.0 ± 0.4
UNB13-03	49	Shell	5599	0.9	**Low Marsh**
UNB13-04	23	Shell	254	9.1	0.7
	60	Shell	5368	0.7	**Mid Marsh**
					1.3 ± 0.4
					High Marsh
					0.7

Morro Bay	Depth (cm)	Material	Mean Cal. Age (YBP)	Accretion Rate (mm/yr)	Accretion Site Means (mm/yr)
MOB13-01	19	Shell	182	10.9	**Sitewide**
	25	Shell	195	13.1	8.1 ± 8.3
MOB13-02	51	*Spartina*	185	2.8	**Low Marsh**
	19	Shell	234	8.5	10.6 ± 1.4
	31	Shell	392	8.1	**Mid Marsh**
MOB13-03	26	Shell	254	10.6	9.8 ± 7.8
MOB13-04	24	*Spartina*	96	25.9	**High**
MOB13-06	98	Shell	452	2.2	1.95 ± 0.15
MOB13-07	19	Shell	586	3.4	
	44	Shell	2561	1.8	
MOB13-08	56	*Distichlis*	178	3.1	
	11	shell	545	2.1	
	19	shell	258	26.6	
MOB13-09	52	*Distichlis*	295	7.6	
	19	shell	348	1.8	
MOB13-10*	19	shell	419	16.1	
MOB13-11*	19	shell	189	5.7	

*MOB13-10 and 13-11 are excluded from the average because they are not part of the low-mid-high marsh transect

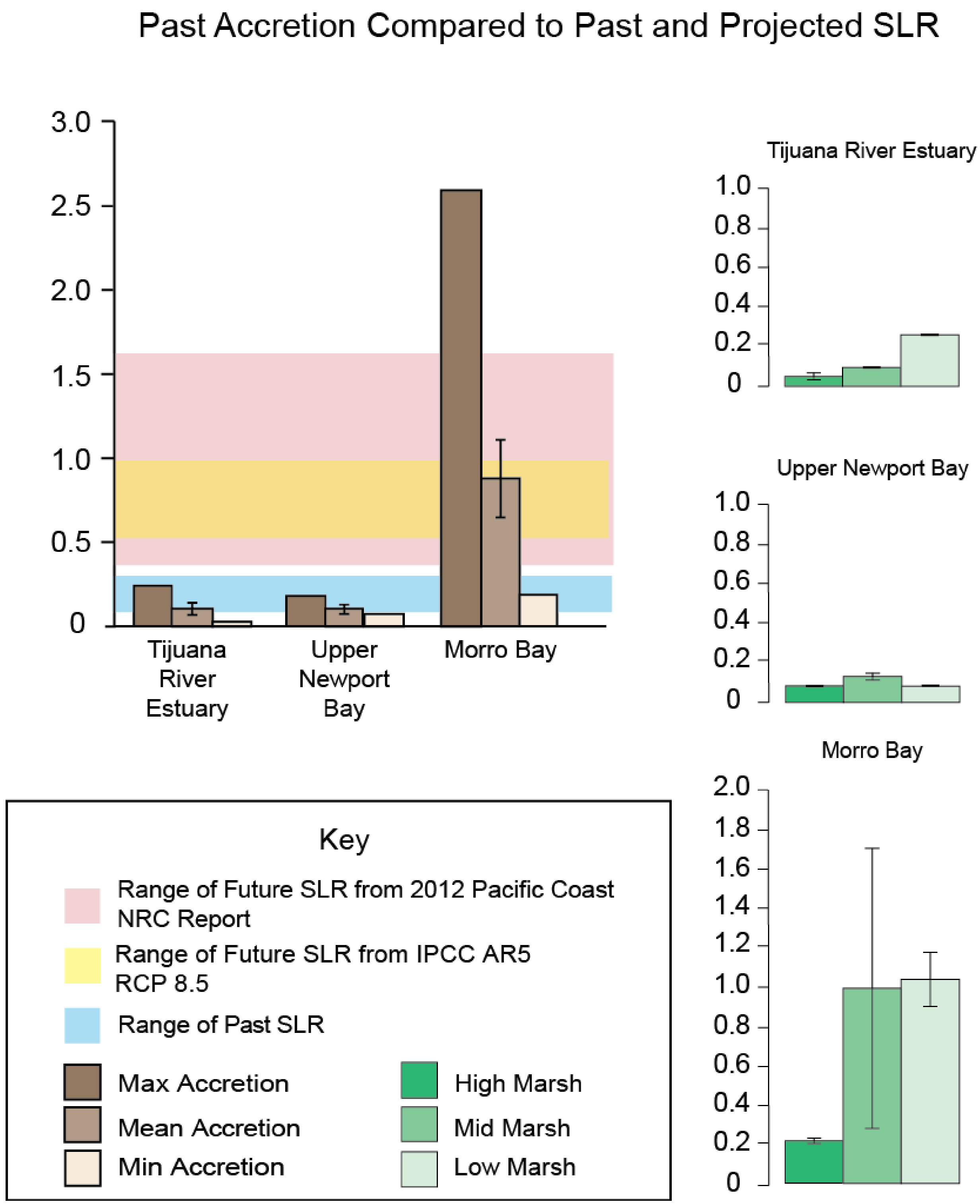

Figure 8 – The max and min net accretion rates as well as the mean net accretion rate are shown in the graph on the left. These rates are compared with past and projected rates of SLR. On the right, mean accretion for low, mid, and high marsh zones are reported by study site. Error bars reflect one standard deviation.

Stratigraphy and Environmental Changes

Cores from all three marshes typically show a top layer of peat-like, highly organic marsh sediment [i.e. Figure 9]. This layer varies from about 10 cm to a full meter. Some cores, especially those in Morro Bay, have occasional silty-sand lenses which interrupt the marsh sediments [see Figure 10]. Beneath the marsh sediments, a water-rich, silt layer commonly contains shells from intertidal snails and bivalves (e.g. *Cerithideae spp.* or *Tagelus spp.*). Most cores terminate in coarse-grained, basal marine or bedrock sediments. In Tijuana River Estuary the basal layer which appears in cores 1, 2, 3, 5 and 6 is a particularly distinct bright red, likely indicative of the weathered bedrock which the marsh is located upon.

One core from each marsh was subjected to magnetic susceptibility testing and centimeter-resolution LOI. The stratigraphy diagrams appear in Fig. 8-110. While the environments of these three marsh systems vary, the stratigraphies do show several commonalities. Most obviously, all cores show increases in organic content towards the top, a reflection of marsh establishment and increased organic deposition, largely of plant matter. At Tijuana Estuary [Figure 9], increases in carbonate content occur below these marsh horizons as further evidence of a change in habitat from intertidal mudflats to salt marsh; marine shells have increased levels of carbonate and are likely the reason for this signal. Shifts seen in the magnetic susceptibility diagram are indicative of a change in sediment source or content (Thompson & Battarbee, 1975). In most cores, these shifts occur in the recent past or towards the present. Knowing the land use changes of these systems, observed changes in sedimentation regimes likely relate to European colonization and subsequent urbanization (Gallagher, 1996; Kirwan et al., 2011). Bulk density increases, such as the section of core from 400-600 cal YBP at Upper Newport Bay [Figure 10] could also be indicative of land use changes leading to increased runoff and increased sedimentation in coastal marsh ecosystems after European colonization.

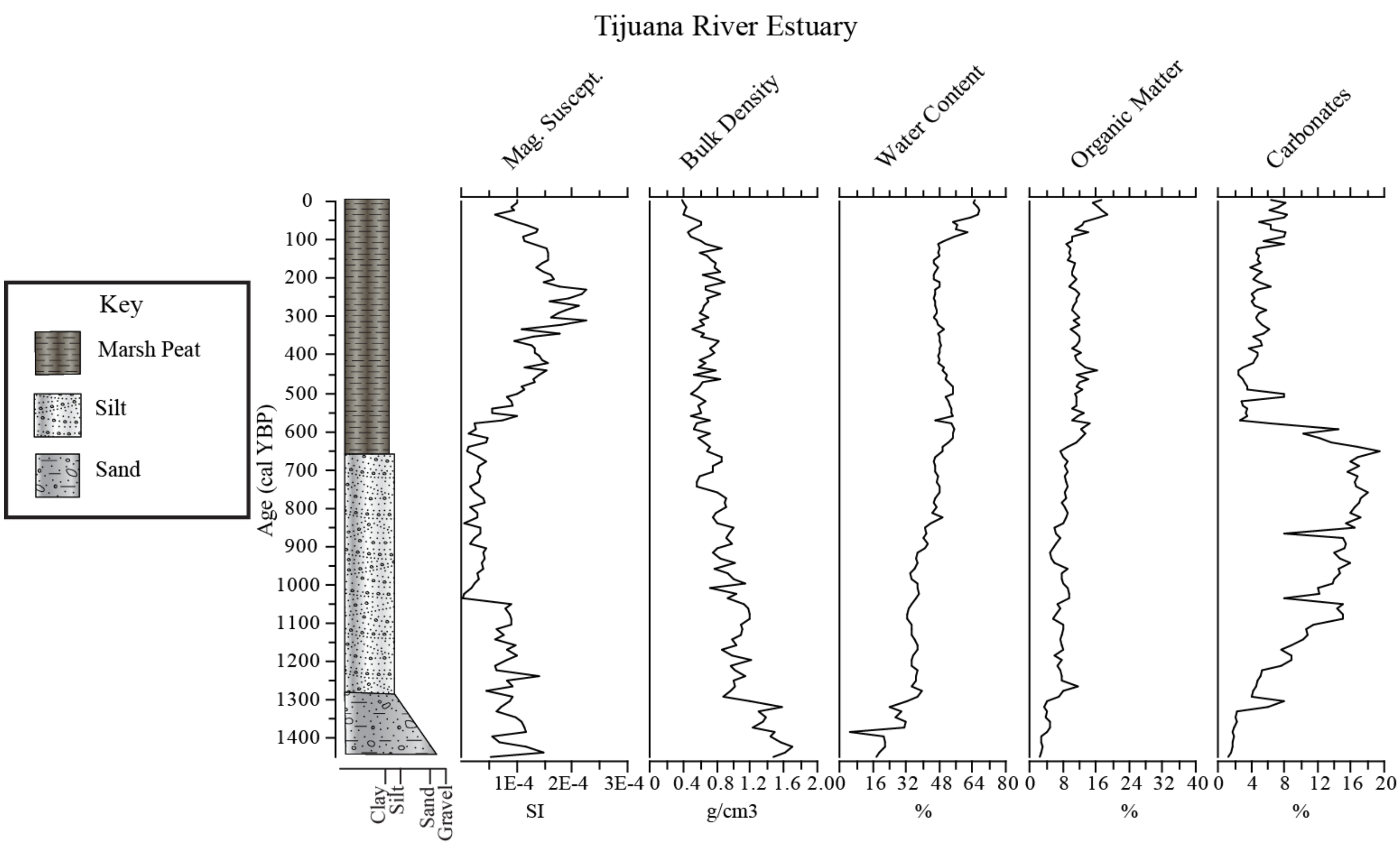

Figure 9 - Stratigraphic diagram of core TJE12-07 from Tijuana River Estuary. Core has a basal date of 1467 YPB, giving an accretion rate of 0.95 mm yr-1. Color, texture, and macrofossil content as well as changes in organic and carbonate content indicate that marsh first appeared at this site around 60 cm in depth, an estimated 650 cal YBP. Sediments below the marsh interface likely signify that an intertidal mudflat was present in the area before that time. Core terminates in coarse marine sands.

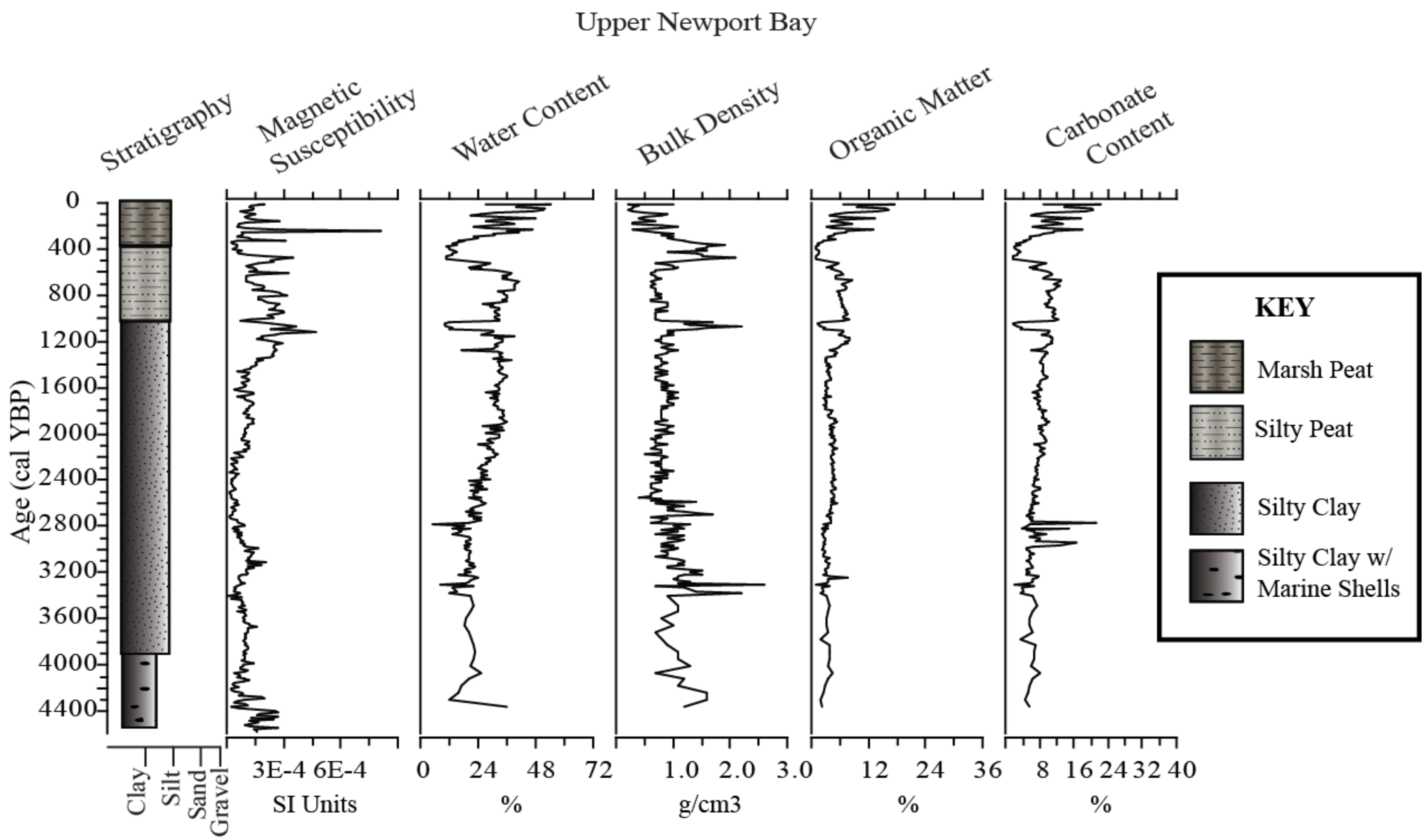

Figure 10 - Stratigraphic diagram of core UNB13-03 from Upper Newport Bay. Core has a basal date of 5599 YPB, giving an accretion rate of 0.9 mm yr-1. Color, texture, and macrofossil content as well as changes in organic and carbonate content indicate that marsh first appeared at this site around 94 cm in depth, an estimated 1000 YBP. Clay-rich silt below the marsh interface likely signifies that an intertidal mudflat was present in the area before that time. Marine shells are present in the bottom 2 m of the core.

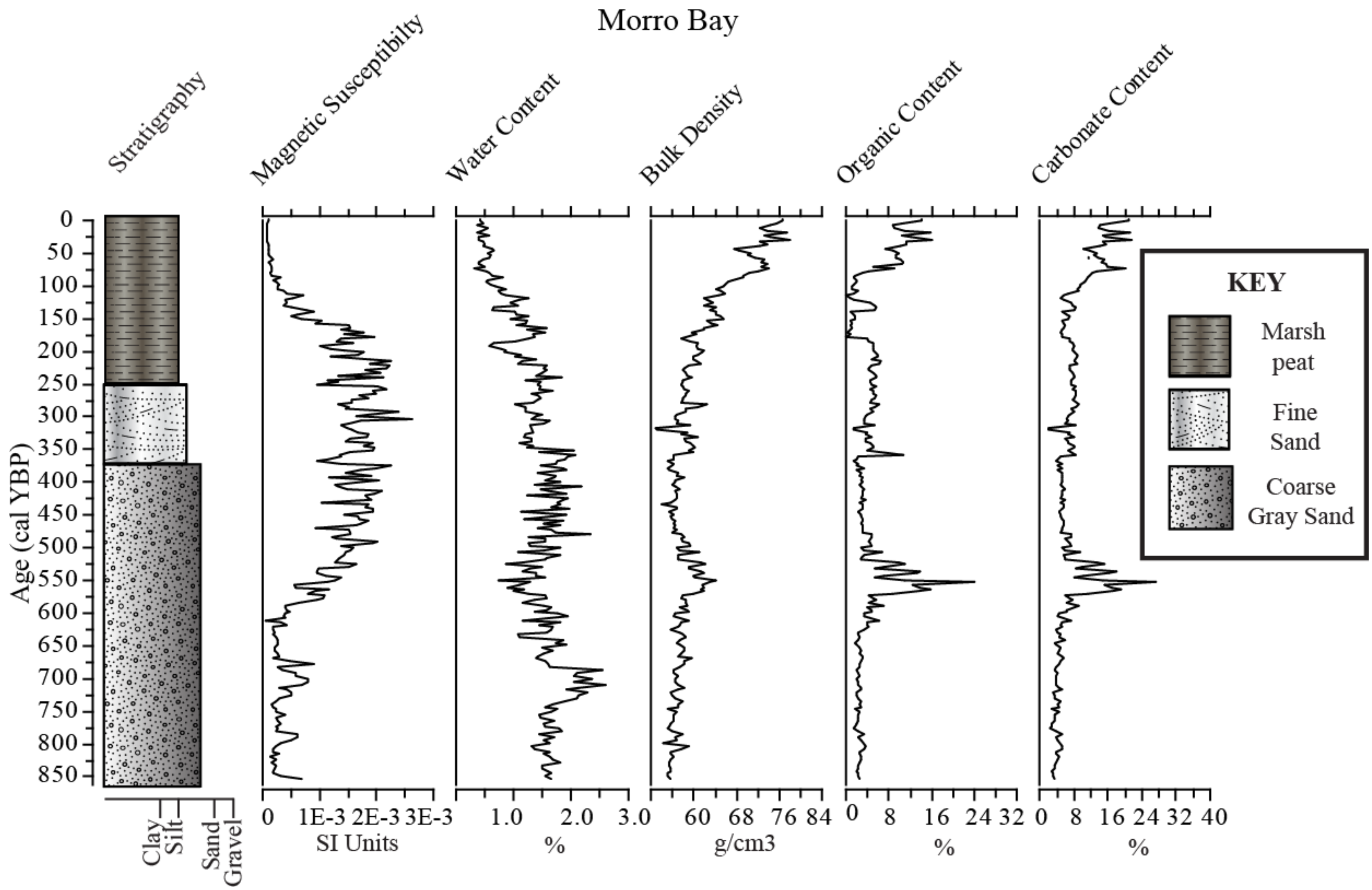

Figure 11 - Stratigraphic diagram of core MOB13-01 from Morro Bay. Core has a basal date of 195 YPB, giving an accretion rate of 13.1 mm yr-1. Color, texture, and macrofossil content as well as changes in organic and carbonate content indicate that marsh first appeared at this site around 79 cm in depth, an estimated 60 YBP. Sediments below the marsh interface are coarse and sandy, possibly indicative of an intertidal channel being present before the marsh began to form.

To obtain an estimate of marsh initiation at their current locations (to be later verified by higher resolution dating methods) I used the Bayesian statistical modeling software Bacon 2.2 to create an age-depth model for all cores. Depth of marsh initiation (in terms of marsh vegetation presence in its current location) is indicated by visible disappearance of marsh macrofossils as well as a sudden drop in organic content or increase in carbonate content from LOI results. The stratigraphic diagram indicates that marsh plant macrofossils and higher levels of organic content appear at Tijuana approximately 650 cal YBP. The same linear interpolation of core stratigraphy similarly shows the first indications of marsh presence at Upper Newport Bay around 900 to 1000 cal YBP [Figure 10]. Most cores from Morro Bay, like the one seen in Figure 11, are younger than the two previous sites. Therefore, Figure 11 shows preservation of marsh vegetation only for the past 250 cal YBP at the location. Using this single, eldest date obtained from Morro Bay and a linear interpretation of the age-depth relationship to calculate the age of the marsh peat interface with silt horizons, I estimate 600 cal YBP as the oldest evidence of marsh species in the Morro Bay record. However, because of the lack of records extending beyond this 600 year estimate, it is less certain than the estimates at Tijuana and Newport. While these estimates will need to be tested with higher-resolution dating, overall, the ^{14}C results indicate that salt marshes in their current locations on the Southern California are a recent feature on the California coast, likely appearing after 1000 YBP.

Sea Level Rise

Past

For marsh sites in Tijuana River Estuary and Upper Newport Bay, comparisons between calculated accretion rates from the past several millennia remain within empirical reconstructions of SLR rates of about 1 - 3 mm yr^{-1} during that time (Kemp et al., 2011). Accretion rates calculated from cores in the high and mid marsh zones of Morro Bay also seem consistent with past SLR. In contrast, the lower marsh zone in Morro Bay exhibits accretion rates of over 10 mm yr^{-1}, an order of magnitude greater than SLR and accretion in the mid and upper sites of the same marsh. This may signify that there are alternate processes governing marsh surface elevation in the low marsh at Morro Bay that do not play a significant role in Tijuana River Estuary or Upper Newport Bay. One such explanation could be that the sampling site at Morro Bay is more closely linked with Chorro River delta system; deltaic marshes tend to have higher rates of sedimentation without significant elevation changes due to the higher energy environment, whereas backbarrier marshes (like Newport) and estuaries (like Tijuana) have lower sedimentation and good concordance between accretion and elevation change (Cahoon et al., 2006).

Present and Future SLR

Assuming stable sediment supply, surface runoff, and biotic productivity, I have extrapolated the average rates of accretion from the past few thousand years of marsh accretion in Southern California as an elementary comparison to projections for accelerated SLR [see Figure 12]. I also assume a general rate of 1 mm yr^{-1} of tectonic subsidence, as cited in the National Research Council's 2012 review of sea level

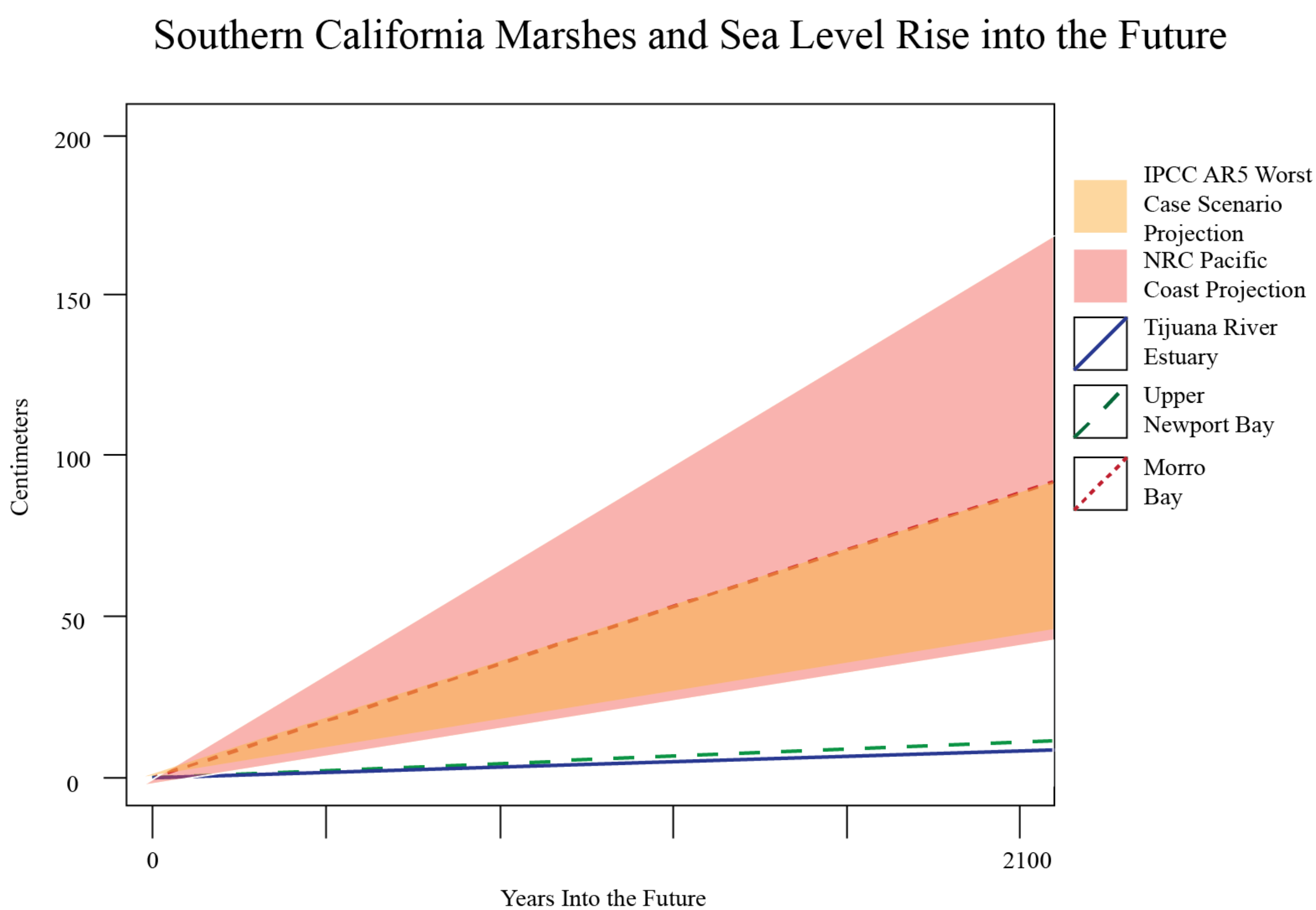

Figure 12 – Using the long term net accretion rates from Tijuana Estuary, Upper Newport Bay, and Morro Bay, a linear extrapolation to the year 2100 allows for a comparison of the difference between long-term accretion rates and projected accelerated SLR. While the IPPC projection indes that the accretion rate for the low sites in Morro Bay could be enough to keep pace with SLR, the other marshes do not have accretion rates equal to even the lower limits of these projected estimates of SLR.

rise on the Pacific coast. This estimate of tectonic forcing of the marsh elevation may miss much of the more subtle effects of regional and local tectonic changes due to natural forces or anthropogenic caused land subsidence (National Research Council, 2012).

By 2100, vertical accretion in Tijuana River Estuary will have added a mean estimate of 8.7 cm elevation gain to the marsh surface; with this accretion estimate and assuming the steady tectonic subsidence of 1 mm yr^{-1}, Tijuana could conceivably expect a total surface elevation gain of 0.1 cm. In Upper Newport Bay, an estimation using mean net accretion projects an accretion gain of 8.6 cm elevation by 2100; because the estimated subsidence rate is equal to the rate of accretion, no elevation gain would be seen in this steady-state scenario. These estimates fall about 40 cm short of even the most conservative estimates from the IPCC AR5 and the NRC (2012) report. Extrapolating the average rate of accretion from Morro Bay, however, indicates that a possible 71.3 cm of net accretion and a total of 62.1 cm of total elevation gain with tectonic subsidence may be expected by 2100. That puts the elevation gain at Morro firmly above the lower limits for the NRC SLR projection, but still about 80 cm below the upper limit. The upper limit of the worst case scenario (RCP8.5) from the IPCC AR5, however, is roughly equivalent to the 62.1 cm of elevation gain in Morro Bay.

Discussion

Radiocarbon dating from basal sediments in all three marsh sites shows that the current salt marsh ecosystems on the coast of Southern California are a geologically recent development. This is consistent with expansion of marsh vegetation seen in Tijuana Estuary since the 1852 survey [Figure 5], the expansion of marsh vegetation seen in Upper Newport Bay since 1875 [Figure 6], and the expansion of marsh vegetation as well as progradation of marsh into Morro Bay since 1884 [Figure 7]. Bayesian age-depth modeling compared with stratigraphic core diagrams shows that characteristic marsh macrofossils and high levels of organic content do not appear until after 1000 YBP in most cores [see Figures 9-11], leading to the conclusion that marsh vegetation was not well established in the coring sites until after that date. Interpolation of basal radiocarbon dating, however, misses the more nuanced changes in accretion rate and can therefore only offer preliminary estimates of marsh initiation. Gallagher (1996) estimates that marshes could have been present at 2,000 cal YBP in Morro Bay, so higher resolution dating of sediment may prove that marshes are older than the estimate I have provided. Cores will undergo further chronological analysis, including ^{137}Cs and ^{210}Pb dating for a more accurate picture of how accretion rates have varied within the more recent past. With this preliminary work on stratigraphies and basal ^{14}C, increasing the resolution of dates will present a complete picture of the past several millennia of sediment dynamics in coastal salt marshes on the Southern California coast.

Net accretion rates calculated from these radiocarbon results show that rates of accretion and rates of SLR are closely tied in Tijuana Estuary and Upper Newport Bay. This close tie is typical of autochthonous marshes, or those marshes with low sediment delivery and little subsidence (Cahoon et al., 2006; French, 2006). Because net accretion does not take tectonic uplift and subsidence processes into account, it is important to mention that the NRC (2012) uses a general estimate of 1 mm yr^{-1} of subsidence along the California coast south of Cape Mendocino. Regional variation, however, means much error is associated with this estimation due local subsidence factors. With elevation increase from tectonics and net accretion, rates of elevation change at Tijuana and Upper Newport remain consistent with historical SLR at about 2-3 mm yr^{-1}. Generally elevation change “keeps up” with sea level, or slightly surpasses the rate of SLR by a millimeter or two when subsidence is not an issue (Cahoon et al., 2006; French, 2006; Morris et al., 2002).

In contrast, Morro Bay sees rates of accretion much higher than rates of past SLR, but covers a more limited time period. Modern rates of accretion have been measured at 5 and 6 mm yr^{-1}, therefore the long term net average of approximately 8 mm yr^{-1} is not suspect (Callaway, 2010). Alternative dating methods, such as ^{210}Pb and ^{137}Cs also will cross-validate some of the very young dates seen in Morro Bay. While I do not believe these dates to be a result of laboratory or calibration error, explanations for the high rates of accretion in these areas have not been made completely clear in this study. Neither have the more modern studies of current accretion rates at Morro Bay, despite some concern for Bay infilling which Callaway (2010) deems unsubstantiated.

Some probable explanations for the discrepancy between the two southernmost sites and Morro include the likelihood that the core sites are located close enough to tidal channels that accretion rates have been biased; Christiansen et al. (2000) used several sites on the East Coast to validate the hypothesis that accretion varies spatially in marshes and is greatest near tidal channels. Additionally, tidal channels may have destroyed long-term history of marsh accretion at Morro due to an increase in surface runoff from European settlement in the past 200 years, as see in an East Coast study at Plum Island Estuary (Kirwan et al., 2011). At Plum Island Estuary, European deforestation resulted in rapid expansion of the marsh. Further testing of the Morro Bay delta would clarify if the same phenomenon was occurring here. Morro Bay also has seen significant human modification, and recent studies document the Chorro River delta's expansion (Ford, 1997; Gallagher, 1996). Dissertations by both Ford and Gallagher verify the high rate of accretion at about 7 mm yr^{1} in the Chorro River Delta over the past several hundred years.

With the previous studies and the radiocarbon results from this work, Morro Bay presents itself as a unique deposition environment, different from Tijuana and Newport due to its nature as a deltaic marsh. Further investigation into the long-term history of Morro Bay will need to be conducted in order to determine a more accurate estimation for when salt marsh vegetation first colonized the bay.

Unlike Morro Bay, accretion rates in the coastal salt marshes at Tijuana River Estuary and Upper Newport Bay track with reconstructed rates of SLR for the past few millennia. Even with tectonic subsidence of 1 mm yr^{-1} (National Research Council, 2012), vertical elevation would have kept pace or only been increasing 1 mm yr^{-1} faster than SLR during some time periods in the past. These few millimeters difference likely are within the range of variation that marsh ecosystems can tolerate and adapt to, as per Kirwan et al (2010). But with the large difference in the accretion rates seen in this study, questions still remain about the way in which accretion and SLR interact to influence the elevation of the marsh surface. There are multiple studies looking into the mechanisms behind marsh elevation (Allen, 1995; French, 1993; Krone, 1987; Morris et al., 2002; Swanson et al., 2012); the majority of reference sites have been on marshes along the East Coast of the US. These marshes differ from the West Coast marshes in terms of their sediment load and trend toward compaction and drowning. According to these data, Tijuana Estuary and Upper Newport Bay marshes do not appear to be greatly influenced by subsidence processes, especially to the degree seen in the salt marshes on the Gulf and East coasts of the US. However, subsidence may play a larger role in the marsh at Morro Bay. The rate of accretion of 6 mm yr^{-1} plus 1 mm of tectonic forcing would have resulted in a rate of accretion much higher than any rates of SLR seen in the past. Even with the assumption that these increased rates correspond with the increase in SLR to about 3 mm yr^{-1} since the Industrial Revolution, the rate of accretion for these sites indicate that sediment supply may be the more important factor in the lower marsh sites at Morro Bay, but still not to the degree seen in East and Gulf coast marshes. The findings of this study reiterate the importance of studying regional subsidence and compaction of belowground material on marsh elevation.

In terms of the environmental changes seen at Tijuana, Newport and Morro during past several hundred years, the most interesting transitions for future investigation are the indications of marsh initiation in the sediment cores. Most cores from this study reveal that marshes have only been established in their current locations for about 1000 years or less. Though there are indications from other marsh studies that marshes in their present locations could be closer to 1000-2000 years old (Gallagher, 1996; Mudie & Byrne, 1980), further work on chronological control for the sediment cores in this study will help resolve this difference. Other environmental changes of interest include the possibility of a record of European settlement leading to increased rates of sedimentation and changes in sediment source from channel diversions and vegetation alterations. Morro Bay, because of the 200-year time scale of most of the cores obtained, will be a particularly relevant avenue for research into what human changes to the environment altered natural marsh processes. If ample evidence of marsh alteration by human activities exists, predicting the future stability of marshes in the next century becomes more problematic. Increases in sedimentation from land use change can lead to higher rates of accretion which may not persist now that urban runoff and channel damming replace sediment-rich surface runoff from deforestation in the past 200 years. Monitoring modern accretion and elevation changes in Southern California marshes is more important than ever with the possibility for changes from even then past 200 years of altered accretion regimes in the marshes.

Overall, stability of coastal salt marshes in Southern California into the future looks bleak. Projections of SLR compared with historical rates of sedimentation indicated marshes could reach threshold points where SLR is too great for accretion and elevation change to maintain a viable marsh platform. In a modeling study by Kirwan et al. (2010) using an Atlantic Coast marsh system with high rates of accretion, when SLR was 5 mm yr^{-1} greater than accretion, marshes drown within 30-40 years. The uncertainty surrounding how fast and how much sea levels will increase indicate that even Morro Bay, with a recent history of high sedimentation, will need close monitoring of sedimentation, hydrology, and biotic activity as well as careful management to ensure that the marsh can remain above the tide.

Conclusions

Evidence from long-term sediment accretion in three Southern California marshes, spanning the past 2000 to 5000 years, shows that rates of accretion kept pace with rates of SLR. For the most part, the effects of forcings such as tectonic subsidence and sediment compaction have little obvious influence in these marshes, typical of marshes with low sediment delivery and low rates of elevation change (French, 2006). Further verification of this finding will be necessary for modeling purposes. However, the difference in sedimentation and hydrologic regimes from marshes in the Eastern and Gulf Coasts of the US demonstrates that West Coast marshes are unique and require unique modeling interpretations to fully understand the ways in which SLR will effect marsh elevation in the future.

Differences between accretion rates in low, mid, and high marsh zones are inconsistent across marsh sites. There are observable differences in accretion from these zones, but only Tijuana shows evidence of increased accretion rates in low marsh regions.

The physical properties of the 3 cores analyzed in this study demonstrate that marshes on the California coast have a dynamic and sensitive record of change through time. The interface between marsh peat and silt or sand indicate that environment became favorable for marsh expansion into areas not previously colonized. Increases of bulk density toward the top of cores point to a possible effect of European colonization on watersheds resulting in increased sediment delivery to marshes.

The prospect of accelerated SLR will be one of the greatest challenges facing marsh ecosystems over the next 2100 years. Extrapolation of past rates of accretion demonstrate that 2 of the 3 study sites do not have a historical rate of sedimentation equal to rates of projected SLR. This could mean that these marshes will drown or recede in the future. With an estimated 70% of coastal wetland habitation already lost to urbanization in California (Ambrose, unpublished) the understanding of accretion, SLR, and marsh surface elevation on the West Coast is critical.

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