Journal of Coastal Research	24	5	1126–1137	West Palm Beach, Florida	September 2008

Holocene Environmental History and Evolution of a Tidal Salt Marsh in San Francisco Bay, California

M. Goman[†], F. Malamud-Roam[‡], and B.L. Ingram[‡§]

[†]Department of Earth and Atmospheric Sciences
3134 Snee Hall
Cornell University
Ithaca, NY 14853-1504, U.S.A.

[‡]Department of Geography
507 McCone Building
University of California
Berkeley, CA 94720, U.S.A.

[§]Department of Earth and Planetary Science
301 McCone Building
University of California
Berkeley, CA 94720, U.S.A.

ABSTRACT

GOMAN, M.; MALAMUD-ROAM, F., and INGRAM, B.L., 2008. Holocene environmental history and evolution of a tidal salt marsh in San Francisco Bay, California. *Journal of Coastal Research,* 24(5), 1126–1137. West Palm Beach (Florida), ISSN 0749-0208.

Analyses of three sediment cores collected from a tidal salt marsh located on the western edge of San Pablo Bay in the San Francisco Bay estuary have produced long-term records of late Holocene marsh development. The records from these cores include a suite of elements, organic carbon content, fossil seeds, pollen, and stable carbon isotopes. The stratigraphy indicates fresher water conditions than present between 3400 and 2000 cal YBP. A tidal marsh became established at China Camp after about 2000 cal YBP; between 2000 cal YBP and approximately 700 cal YBP, conditions in the estuary were apparently more saline and variable. This interval was terminated by at least three or possibly five flood events, as evidenced by coarse clastic materials most likely washed down from the surrounding uplands. These floods represent high rainfall events, possibly El Niño years, and occurred during the late Medieval Climatic Anomaly. Greater plant diversity and pollen from some species with low salt tolerance are found in a core collected near the upland edge of the marsh and date to about 200 years ago, suggesting fresher conditions than today. Over the past 50 years, the diversity of marsh vegetation has decreased, and salt tolerant plants (especially *Salicornia virginica*) have become the dominant species. These changes are likely a result of the impacts of water diversions and upstream dams in the San Francisco Bay watershed.

ADDITIONAL INDEX WORDS: *Holocene climate, marsh development, sea level rise, stable isotopes, pollen, lead, iron.*

INTRODUCTION

In contrast to the eastern seaboard of the United States (*e.g.,* Belknap *et al.,* 1989; Fletcher *et al.,* 1993; Kelley, Gehrels, and Belknap, 1995; Redfield, 1972; Van de Plassche, 1991) and the Pacific Northwest (*e.g.,* Nelson, 1992; Nelson, Jennings, and Kashima, 1996), there are few studies looking at the development of California tidal salt marshes (Cole and Liu, 1994; Mudie and Byrne, 1980; Schwartz, Mullins, and Belknap, 1986). It is possible that suitable study sites are lacking because tectonic forces have precluded tidal marsh formation (Inman and Nordstrom, 1971), and marsh reclamation during the last century has resulted in a significant loss of tidal marsh acreage (Nichols *et al.,* 1986; San Francisco Estuary Project, 1992).

Tidal salt marshes, however, where present, can provide a long and detailed history of not only fluctuations in eustatic and local isostatic sea level (Gehrels, 1999; Gehrels, Belknap, and Kelley, 1996; Gehrels *et al.,* 2002; Witter *et al.,* 2003) but also climate change (*e.g.,* Clark and Patterson, 1985; Davis, 1992; Varekamp, Thomas, and Van de Plassche, 1992). Because the coastal zone of California contains few lacustrine sites with continuous records of Holocene environmental change (*e.g.,* Boyle, Plater, and Anderson, 2003; Reidy, 2002), tidal salt marsh deposits provide a potentially valuable archive of environmental change. In this paper, we examine the effects of both climate and sea level influences on marsh evolution at a tidal salt marsh in San Francisco Bay, California.

SETTING

China Camp is a large (40.5 hectares), relatively pristine, tidal salt marsh that forms part of China Camp State Park (38°02′30″ N, 122°30′00″ W) located on the west side of San Pablo Bay (Figure 1; San Francisco Bay National Estuarine Research Reserve, 2006). In recognition of its ecological significance (*e.g.,* providing habitat for rare and endangered species, such as the salt marsh harvest mouse, and breeding grounds for the California clapper rail, as well as migrating fowl [Josselyn, 1983]), the marsh was included as part of the San Francisco Bay National Estuarine Research Reserve (San Francisco Bay National Estuarine Research Reserve, 2006). Mean water salinity at China Camp was 24.6 practical salinity units (psu) for the period 1965 to 2004 (U.S. Geological Survey, 2003), with a maximum salinity of 33.3 psu and a minimum of less than 1 psu.

Marsh vegetation is clearly zonal (Atwater and Hedel, 1976) and is controlled by tidal inundation and salinity (Adam, 1990; Cuneo, 1987). The low marsh zone is dominated by *Spartina foliosa* (cordgrass), though in 1995 and 1999 the low marsh contained mixed stands of *S. foliosa* and *Scirpus*

DOI: 10.2112/08A-0005.1 received and accepted in revision 20 February 2008.

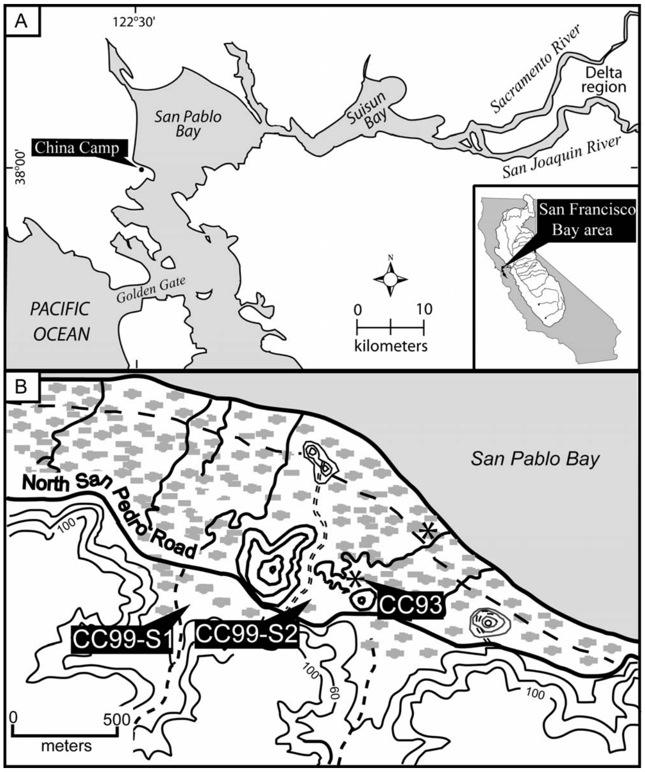

Figure 1. (A) Map showing the San Francisco Bay and key geographic features within the system. Inset map shows the state of California and the major drainages that feed into San Francisco Bay. (B) Detail map of China Camp State Park and the coring localities. The asterisks (*) indicate the location of the monoliths collected for ^{210}Pb dating. Dashed line indicates approximate location of the AD 1850 shoreline. Stippled area represents marsh plain. Topographic contours are in meters.

robustus (bulrush) (Goman, 2001; Malamud-Roam, 2002). The ecotone between low marsh and high marsh is abrupt with *Salicornia virginica* (pickleweed) dominating the high marsh plain. *Distichlis spicata* (salt grass), *Jaumea carnosa* (marsh jaumea), and *Grindelia stricta* (gum plant) are also common components of the higher marsh plain, typically located at slightly higher elevations than the surrounding carpet of *S. virginica.* Marsh vegetation diversity and biomass increases within the transition area between marsh and upland as freshwater runoff from the hills becomes increasingly important and because the construction of North San Pedro Road impeded tidal action (Figure 1). In these regions, the high marsh is presently occupied by a mix of marsh species including *Scirpus californicus, S. robustus, Typha latifolia* (cattail), *Salicornica virginica, D. spicata, G. stricta,* and *Juncus balticus.*

The marsh plain can be divided into an old and young marsh on the basis of tidal channel morphology (Abbe and Bennett, 1991). Sinuous branching tidal channels dissect the old marsh plain (Figure 1), whereas on the young marsh (approximate 150 m from the shoreline) the channels are straight and rarely branch. The young marsh formed following rapid accretion of the shoreline in the late 1880s in response to the input of hydraulic mining debris to San Francisco Bay (Abbe and Bennett, 1991). Mosquito ditches were dug on the marsh surface in the early 1970s and have not been expanded. Gabet (1998) determined that the channels on the old marsh plain are migrating laterally at a rate of 23 $\pm$ 23 mm y^{-1}.

Earlier stratigraphic analysis by Atwater *et al.* (1979) was conducted within the confines of the "young" marsh. Maximum coring was to a depth of ~2 m. Sediment stratigraphy in this region is relatively simple with tidal mudflats overlain by *Spartina* roots, which in turn are overlain by *Salicornica virginica* roots; these changes occur approximately 50 cm below the surface.

FIELD METHODS

Sediment Coring

The marsh was cored on several occasions between 1993 and 1999 using a Livingstone corer. Sediments were cored until further manual retrieval was impossible. The 1993 (CC93) core was located in the tidally dominated *S. virginica* "old" marsh plain, whereas the 1999 cores (CC99-S1 and CC99-S2) were located north and south of North San Pedro Road and have strong upland influences (Figure 1). Two sediment blocks were extracted using a shovel and were used for ^{210}Pb analysis and are located in the young and old *S. virginica* marsh (Figure 1).

Vegetation Surveys

Four vegetation surveys were conducted across the marsh plain at China Camp. These surveys had several goals: (1) to understand the surface plant distribution in relation to tidal inundation and upland influences; (2) to compare surface vegetation to the fossil seed bank and carbon isotopic ratios contained in surface sediments; and (3) to relate surface vegetation to sediment surface characteristics. The results from these data, which have been discussed in detail elsewhere (Goman, 2001; 2005; Malamud-Roam and Ingram, 2001), are used to interpret past environmental changes in the cores.

LABORATORY METHODS AND ANALYSES

Characterization of the Inorganic Component

All cores were described by color (Munsell), texture, and the presence of plant fragments. The CC93 core was sampled for sedimentary grain size and elemental analysis. Grain size analysis followed standard procedures (Folk, 1980), except that a small sample size was used to preserve temporal resolution. Over 40 samples were analyzed for elemental composition. This involved preparation by using a "heavy leach" of HCl and HNO_3 designed to dissolve all elements that are not structurally bound in silicate minerals. Hydrogen peroxide was added after heating to ensure complete oxidation of organic materials (Martin, Creed, and Long, 1992). The acid-digested component of the sediments was analyzed by a Perkin-Elmer Model 3100 atomic absorption spectrometer fitted with an HGA-600 graphite furnace. Samples were analyzed for iron (Fe) and lead (Pb).

Relative amounts of iron found in marsh sediments are used as an analogue for tidal inundation and sediment deposition because more frequently inundated regions have a higher iron concentration (Fletcher *et al.,* 1993; Goman and Wells, 2000; Thomas and Varekamp, 1991). Lead is a known historic contaminant of estuarine sediments and thus provides a useful marker for dating historic sediments (Valette-Silver, 1993).

The CC93 core was also x-radiographed, and magnetic susceptibility and gamma ray density data were obtained at approximately 1-cm intervals along the length of the core. Changes in density reflect changes in lithology, and thus degree of tidal inundation, while magnetic susceptibility can be used as a proxy for the minerogenic composition of the sediments.

Characterization of the Organic Component

Loss-on-ignition (LOI) analysis was used to determine the amount of organic matter in the cores (Dean, 1974). The CC93 core was analyzed for fossil seeds from 1 cm thick samples at 30 levels located at 5–50 cm intervals. The weight of each sample was recorded. Samples were soaked in distilled water overnight with 5–10 ml of sodium hexametaphosphate added to disperse the clays. These samples were then sieved through 2-mm and 500-μm sieves. The organic material retained in the sieves and the fine material that passed through the 500-μm sieve were examined under a dissecting microscope at 70× magnification. Whole seeds and fragments of seeds were identified, counted, and tabulated. Seeds were identified using herbarium samples, a personal reference collection, as well as seed atlases, keys, and floras (Goman, 2001; Hickman, 1993; Martin and Barkley, 1961; Mason, 1957; Montgomery, 1977; Munz, 1973).

Both sediment cores collected in 1999 (CC99-S1 and CC99-S2) were analyzed for carbon isotopes, and CC99-S1 was analyzed for fossil pollen.

Pollen preparation followed standard techniques described by Faegri and Iverson (1989) and a spike of *Lycopodium* was added to the samples (Stockmarr, 1971). Thirty-seven levels were analyzed for pollen with an average sample distance of 10 cm. A Leitz Laborlux microscope at 400× magnification was used for identification and counting. The pollen sum for each level was >300 pollen and spore grains.

Pollen analysis has been used successfully as a proxy for estuarine paleosalinity (*e.g.,* Byrne *et al.,* 2001; Davis, 1992; May, 1999; Mudie and Byrne, 1980) and can provide details of past plant assemblages on the marshes. A pollen salinity index was calculated by dividing the amount of Chenopodiaceae pollen (probably *S. virginica*) by the sum of Chenopodiaceae and Cyperaceae pollen (probably *Scirpus* spp.).

The stable carbon isotopic composition of tidal marsh sediments has been shown to be a reliable indicator of vegetation changes (Byrne *et al.,* 2001; Chmura *et al.,* 1987; Delaune 1986). The isotopic composition of sedimentary organic carbon ($^{13}C/^{12}C$, or $\delta^{13}C$) primarily reflects the source plants, with only slight modifications over time due to decomposition (Chmura and Aharon, 1995; Fogel *et al.,* 1989). While the majority of terrestrial vascular plants are C_3 (average $\delta^{13}C$ = −29‰), certain wetland grasses (specifically *D. spicata* and *S. foliosa*) are C_4 and are thus easily detected by their isotopic composition (average $\delta^{13}C$ = about −12‰). The reasons for the differences in the isotopic composition are well understood (O'Leary 1981, O'Leary, Madhavan, and Paneth, 1992). The $\delta^{13}C$ value can be determined using a gas source mass spectrometer.

A total of 60 samples (5-cm intervals) of material greater than 125 μm from CC99-S1 and 43 samples (5- to 10-cm intervals) from CC99-S2 were processed and analyzed for carbon isotopic composition. This material represents decomposed plant matter mixed with coarser mineral sediments. Sediment samples were pretreated with a 0.1*N* HCl acid bath to remove carbonate material and then rinsed with deionized water. Samples were dried and ground to a fine homogenous powder (Malamud-Roam and Ingram, 2001). Samples weighing between 0.007 and 0.020 g (depending on organic content) were analyzed for $^{13}C/^{12}C$ ratios on an automated 20/20 Europa mass spectrometer. The capsules were dropped automatically into the mass spectrometer and combusted at approximately 1000°C. The CO_2 produced was purified through several traps before introduction into the mass spectrometer. The $^{13}C/^{12}C$ ratios were calibrated against the standard NIST 1547 peach leaves and precision was better than 0.1‰ standard deviation for five replicates (Malamud-Roam, 2002). Stable carbon isotope ratios are reported in the conventional delta notation in per mil (‰) relative to the PeeDee Belemnite standard (PDB), where (Craig, 1957)

$$\delta^{13}C_{sample} = [(^{13}C/^{12}C_{sample})/(^{13}C/^{12}C_{standard}) - 1] \times 1000.$$

Sediment Dating

Fourteen samples, comprising seeds and rhizomes, were radiocarbon dated at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratories (Table 1). All dates are calibrated (Stuiver and Reimer, 1993; Stuiver *et al.,* 1998).

Two sediment blocks were obtained from the *S. virginica* high marsh plain of China Camp. Samples from these blocks were analyzed for ^{210}Pb by counting beta emissions and normalizing the results with a spike of ^{209}Po. After correction for background radiation, ages were determined using the ratio of surface level disintegrations per minute (dpm) (R_0) to target level dpm (R_t). Age (y) = (1/0.03114) log(R_0/R_t).

RESULTS

Determination of Paleoenvironments

Analyses of the cores from China Camp reflect the complex interplay of estuarine and upland influences. To determine marsh paleoenvironments, qualitative and quantitative analyses of sedimentary surface biotic and abiotic characteristics from marshes within the San Francisco Bay estuary were undertaken (Goman, 1996, 2001, 2005; Goman and Wells, 2000; Malamud-Roam, 2002; Malamud-Roam and Ingram, 2001). Table 2 presents a synthesis of the key sediment surface characteristics relevant to China Camp and is used as the basis for interpreting the results from the cores.

Muds, muddy peats, and occasional sand lenses dominate

Table 1. *Radiocarbon data from China Camp State Park, San Pablo Bay, California.*

Depth (cm)[a]	Material Dated	Laboratory Number (CAMS)[b]	Radiocarbon Age[c] (^{14}C YBP)	Calibrated Age Range[d] (1σ)
		CC93		
1 (2)	*Salicornia* seeds	20546	>Modern	0 (0)
25 (41)	*Salicornia* seeds	20547	200 ± 50	0–293 (147)
110 (181)	*Salicornia* seeds	20548	930 ± 130	696–953 (825)
199 (250)[e]	*Salicornia* seeds	20549	690 ± 80	557–673 (615)
295 (303)	*Salicornia* seeds	20550	2330 ± 60	2322–2355 (2339)
447 (450)	*Distichlis* (?) seeds	26039	3260 ± 110	3364–3624 (3494)
580 (580)	*Scirpus* seeds	20551	3960 ± 60	4312–4508 (4410)
		CC99-S1		
55 (63)	*Scirpus* seeds	80346	405 ± 40	509–344 (496)
154 (161)	*Scirpus* seeds	80347	915 ± 40	915–763 (826)
183 (194)	Rhizome[e]	80349	930 ± 40	923–788 (831)
369 (368)	*Scirpus* seeds	80350	2540 ± 40	2743–2511 (2728)
451 (451)	*Scirpus* seeds	75225	3330 ± 40	3633–3474 (3568)
471 (471)	*Scirpus* seeds	75226	3430 ± 60	3816–3591 (3655)
254 (267)	*Scirpus* seeds	80348	520 ± 640[f]	534–1060 (640)

[a] Depths in parentheses are decompacted sediment depths used to calculate rates of sedimentation (Goman, 1996; Malamud-Roam and Ingram, 2004).
[b] Lawrence Livermore National Laboratories, Center for Accelerator Mass Spectrometry (CAMS).
[c] One sigma error range as reported by CAMS.
[d] CALIB 3.0 (Stuiver and Reimer, 1993). Numbers in parentheses are the midpoints of calibrated range.
[e] *Distichlis spicata* rhizomes, implying that date is younger than surrounding material at that depth. Dates are corrected for the larger $\delta^{13}C$ value of this C_4 plant.
[f] CAMS# 80348 has large errors due to the small (10 μg) size.

the sediment cores. Stratigraphic profiles are presented in Figures 2, 3, and 4. A number of sedimentary environments have been identified and correlated between cores and a reconstructed paleoenvironmental history developed. The radiocarbon dates from CC93 and CC99-S1 provide chronostratigraphic control (Table 1). A comparison of the depth to age between CC93 and CC99-S1 shows excellent overall correspondence (Figure 5). Further, analysis of sediment density by gamma ray spectrometry at CC93 (Figure 2) suggests that autocompaction is not a significant problem at the site (Kaye and Barghoorn, 1964). The average density is 1.3 ± 0.1 g cm^{-3}, with little variability between the clay-rich mud and muddy peats. This finding supports the concept of a buoyant-peat model (McCaffrey and Thomson, 1980).

Sedimentation rates vary significantly within and between the cores. These variations may be due in part to proximity to channels and uplands surrounding the landward edge of the marsh and to sediment type (Table 3). The samples collected from muddy peats, for example, maintain an age resolution of ~4–8 y cm^{-1}, whereas samples collected from muds ranged from ~7–11 y cm^{-1}, based on interpolations between calibrated ^{14}C dates. Within-core variations may also result from storm events, which would alter the sedimentation patterns. On average, a 1-cm sample comprises 6.6 years in the sediment cores collected from the tidal marsh at China Camp.

The ^{210}Pb data from the old marsh plain indicates a mean sedimentation rate of 0.2 cm y^{-1} for the last century (*ca.* 5 y cm^{-1} age resolution) (Figure 6). This compares well with calculated sedimentation rates from regions of the cores with comparable lithology (Table 3). The data from the young marsh plain indicates a perturbation in ^{210}Pb chronology and possibly reflects recent progradation, which may be the result of the incorporation of historic gold mining sediment into the San Francisco Bay system (Gilbert, 1917; Jaffe, Smith, and Torresan, 1998).

Table 2. *Selected surface sediment characteristics and vegetation.*

Sediment Surface Characteristic	Location on Marsh below Mean Higher High Water (<MHHW[a])	Location on Marsh above or equal to Mean Higher High Water (≥MHHW)
Vegetation	*Spartina foliosa*	*Salicornia*
Dominant seeds	No seeds	*Salicornia*
Dominant pollen	Poaceae	Chenopodiaceae/ Amaranthaceae
$\delta^{13}C$ (‰)	−12.68	−27.21
Organic (%)	10.3 ± 0.7	16.3 ± 3.3
Clay (%)	63.9 ± 6.0	63.0 ± 6.9
Iron (g kg^{-1})	55 ± 8.5	43.0 ± 8.9

[a] MHHW is the average height of the higher of the daily tides.

Zonation

The 5000-year-long sediment history at China Camp can be divided into four zones based on the records in cores CC93 and CC99-S1. Zones were designated following a qualitative assessment of the data and chronology of the cores. Material from core CC99-S2 was not dated, but the sediment types and proxy records between the sites show comparable records (Figures 3 and 4). The higher overall LOI values at CC99-S1, and the lower $\delta^{13}C$ values near the surface of CC99-S2 likely reflect the fresher conditions of that site since it is closer to creeks draining the local hill slopes.

Zone 4: ~4700–3400 cal YBP

Zone 4 at CC93 is characterized by inorganic muddy clays (LOI 13% ± 5%), high Fe concentration (31 g/kg ± 6 g/kg),

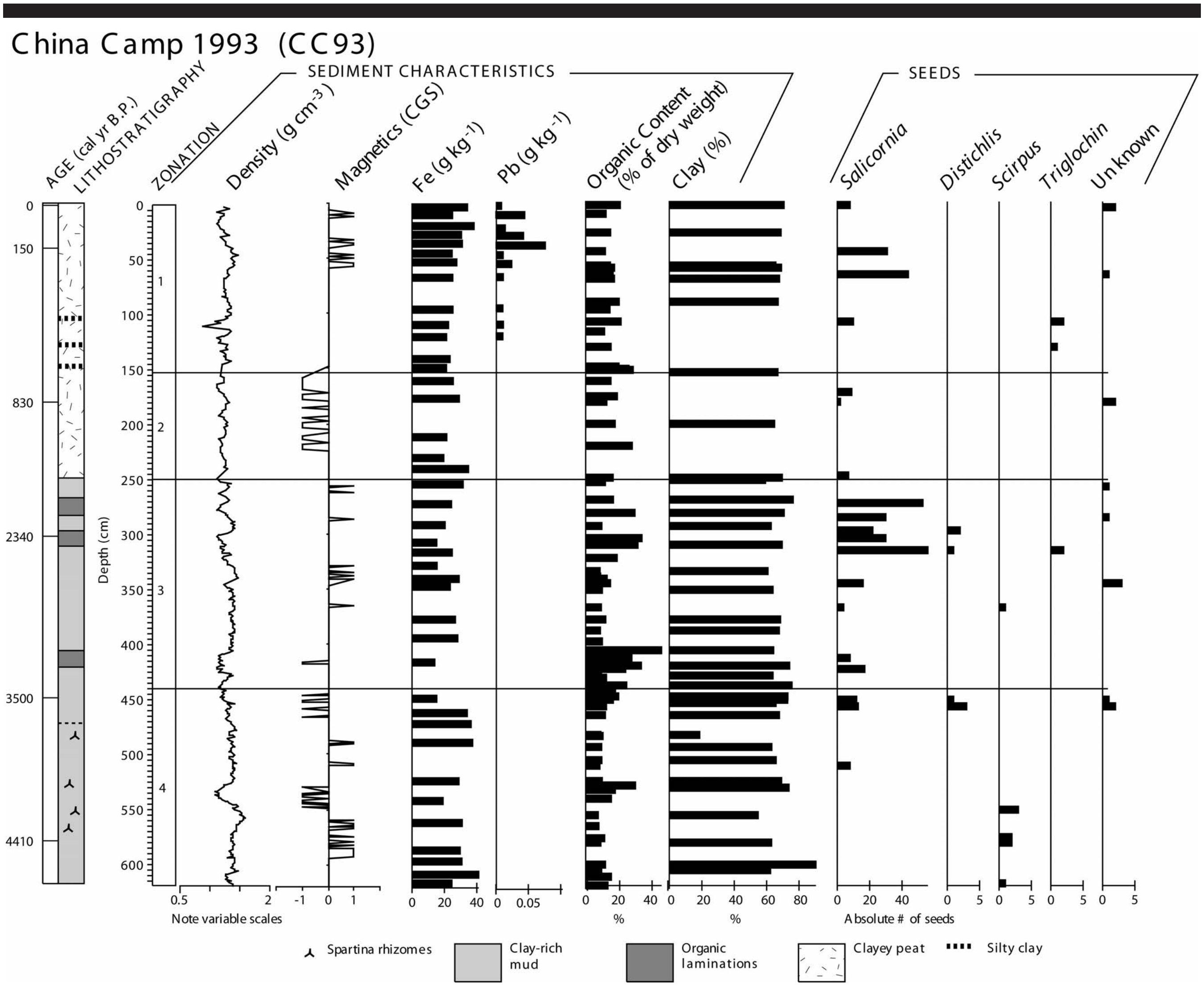

Figure 2. Summary diagram for core CC93, including age, lithostratigraphy, density, magnetic susceptibility, iron and lead abundance, sediment characteristics, and macrofossil stratigraphy.

and *in situ Spartina* (Figure 2). Further inland, at site CC99-S1, sediment is characterized by alternating mud and muddy peat lenses (LOI range 10–69%), Poaceae pollen is abundant, and $\delta^{13}C$ values increase upward from −22.8‰ to as high as −16.9‰ at 450 cm (Figure 3). Overall $\delta^{13}C$ values increase, despite variability in this zone. At 445 cm in core CC99-S1, a 1 cm thick sand lens is present, while a silt lens is present from the more bayward site at CC93 (475 cm depth). These lenses date by interpolation to *ca.* 3570 and 3600 cal YBP, respectively.

Zone 3: ~3400–2000 cal YBP

For the most part, the CC93 core is dominated by clay-rich mud during this period (Figure 2). On three distinct occasions, the core is characterized by the gradual replacement of mud with laminated mud and peat sequences, then peat, and then a return to laminated mud and peat. Using interpolation, the midpoint dates of these units are 3300, 2300, and 2100 cal YBP. Seeds of *Salicornia* and *Distichlis* are present, and Fe averages 23 g kg^{-1} ± 6 g kg^{-1} with lows of 14–15 g kg^{-1} occurring within the mud and peat and peat sections, and peaks (29–31 g kg^{-1}) occurring within the clay-rich mud (Figure 2).

Mud and clayey peats are present in the more landward core (CC99-S1). Organic content in this section is higher than 25% throughout, with a maximum of almost 40% at 382 cm (Figure 3). The carbon isotopic value declines from a maximum value of −18.1‰ at 435 cm to a minimum of −25.6‰ at 360 cm, and remains low. This represents a decrease in the fraction of C_4 plant material contributing to the sedimentary carbon from about 60% to less than 10%. Marsh taxa comprise the majority of the pollen from 435 to 405 cm, but

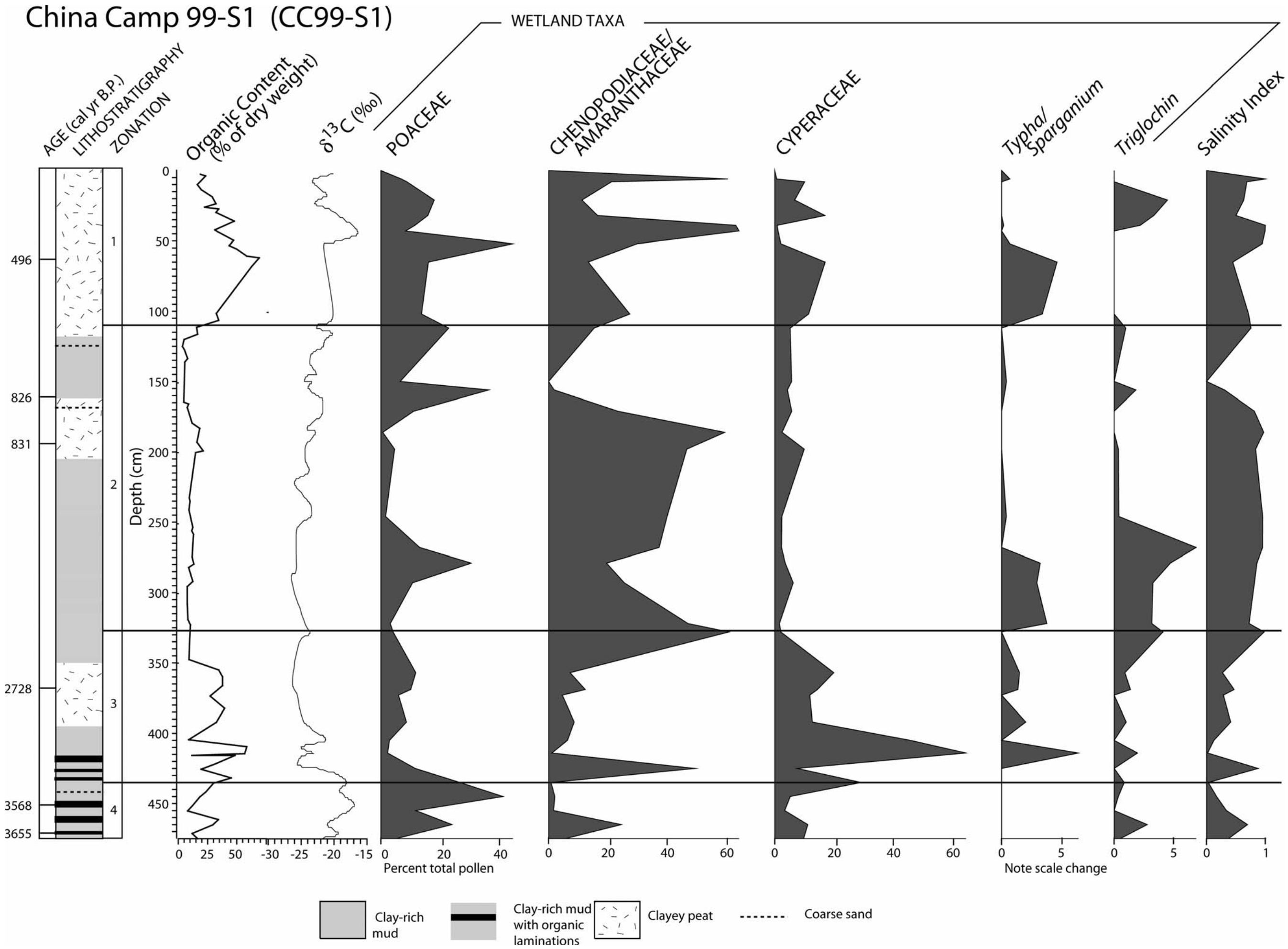

Figure 3. Summary diagram for core CC99-S1, including age, lithostratigraphy, organic content, stable carbon isotopic, and pollen stratigraphy for the CC99-S1 core. The salinity index is calculated by dividing the total Chenopodiaceae pollen by the sum of Chenopodiaceae and Cyperaceae pollen (unity reflects 100% dominance by Chenopodiaceae pollen).

drop to low percentages (lowest at 26%) over the next 50 cm of the core before increasing again at 357 cm (Figure 3). The marsh pollen in the first half of this zone is primarily Cyperaceae (*Scirpus* spp.) and Chenopodiaceae (*Salicornia virginica*), with low percentages of Poaceae. *Typha* also appears in this zone, paralleling the Cyperaceae pollen. The salinity index during this period fluctuates, but shows a general increase in salinity toward the later part of this zone and into the next zone.

Zone 2: 2000–680 cal YBP

Core CC93 is dominated by clayey peats (LOI 19% ± 5), relatively low and stable Fe (26 g kg^{-1} ± 6 g kg^{-1}), and *Salicornia* seeds (Figure 2). Magnetic susceptibility data show consistent negative values during this zone (prior to this period magnetic susceptibility was variable with no apparent trend) (Figure 2).

The comparable interval in CC99-S1 is dominated by clay-rich sediments with little organic material (LOI 11% ± 4%; Figure 3). The δ^{13}C values increase up zone toward C_4 types, and the pollen salinity index is high (median of 0.81). The sedimentation rate during this period is low in both cores (CC99-S1 0.92 mm y^{-1} and CC93 0.81 mm y^{-1}; Table 3). Two sand beds are present between 164 and 162 cm and 129 and 123 cm in CC99-S1, possibly corresponding to two silty clay layers present in CC93 at 150–146 cm and 128–124 cm.

Zone 1: 680–0 cal YBP

Core CC93 is characterized by muddy peats (LOI = 18.1% ± 5%), low Fe concentrations (27 g kg^{-1} ± 5 g kg^{-1}), and *Salicornia* and *Triglochin* seeds (Figure 2), whereas CC99-S1 is characterized by peats with increasing LOI (maximum of 80%), high δ^{13}C values (maximum of −16.4‰), and Poaceae and *Triglochin* pollen (Figure 3). Magnetic susceptibility data show consistent positive values during the later part of this

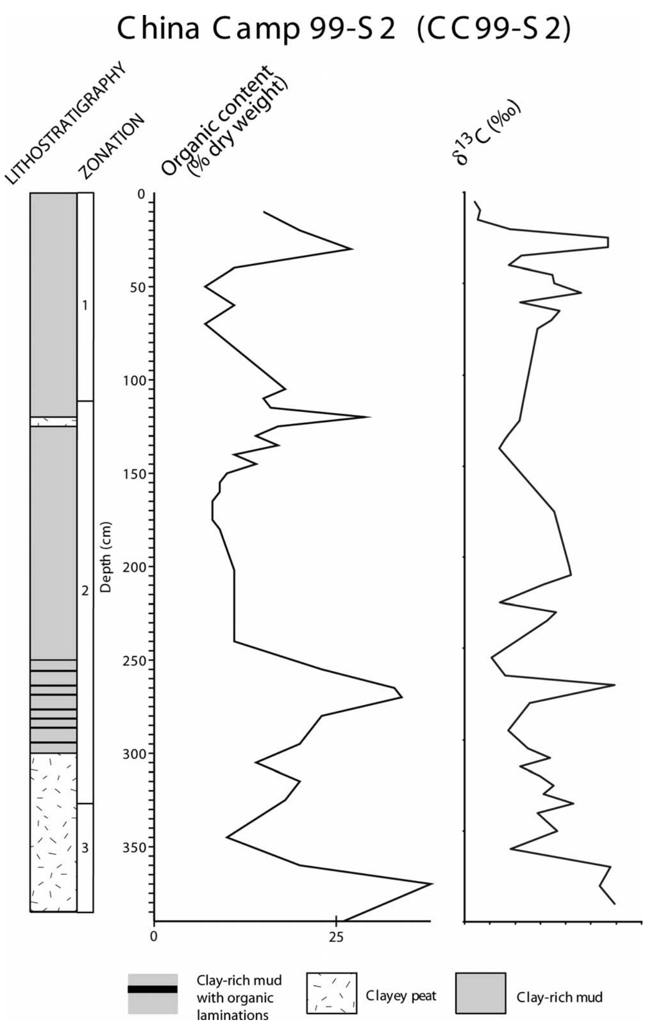

Figure 4. Summary diagram for core CC99-S1, including lithostratigraphy, organic content, and carbon isotopic stratigraphy for the CC99-S2 core.

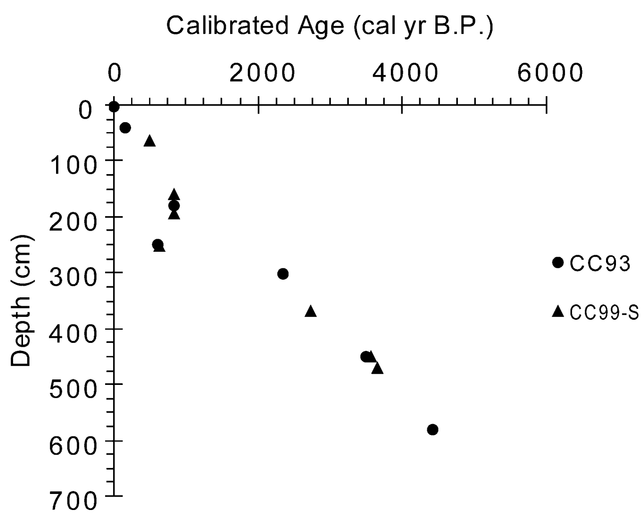

Figure 5. Plot of calibrated radiocarbon ages (cal YBP) *vs.* depth in core (cm) for cores CC93 and CC99-S1.

zone (Figure 2). In CC93, peaks in Pb occur at 42, 33, and 7 cm (0.07, 0.03, and 0.04 g kg^{-1}; Figure 2).

DISCUSSION

Tidal Marsh Development

The sediment cores from China Camp State Park demonstrate the stratigraphic succession of tidal mudflat to low marsh and high marsh. At the most bayward site (CC93) at 4700 cal YBP, conditions were subtidal because clay-rich muds and high Fe concentrations indicate a long inundation period; occasional *Spartina foliosa* roots, which occur in growth position, suggest that the rate of sea level rise was declining such that this plant, which is a pioneer species, could colonize the intertidal zone (Josselyn, 1983). The generally low LOI values also suggest that overall conditions were subtidal. At the more inland and topographically higher site of CC99-S1, *S. foliosa,* a plant that occupies the mudflats, was present, as reflected in the high isotopic values, indicating that *S. foliosa* was the dominant vegetation.

The vegetation changes seen in zone 3 at CC99-S1, represented by a drop in $\delta^{13}C$ values and an increase in pollen from Cyperaceae (*Scirpus* spp.) and *Typha* spp., indicate a freshening of conditions experienced at the site beginning about 3400 years ago and continuing until about 2000 years ago. Declines in estuarine salinity and inferred increases in river flow from the San Joaquin and Sacramento rivers, which de-

Table 3. *Calculated rates of sedimentation for China Camp State Park, San Pablo Bay, California.*

Sediment Accumulation Rate Depth Range (cm)[a]	Dominant Sediment	Sediment Accumulation Rate (cm y^{-1})	Deposition Time (y cm^{-1})
	CC93		
1–25 (2–41)	Inorganic peat	0.27	3.77
25–110 (41–181)	Inorganic peat	0.21	4.84
110–295 (181–303)	Mixed	0.08	12.41
295–447 (303–450)	Mixed	0.13	7.86
447–580 (450–580)	Clay-rich mud	0.14	7.05
	CC99-S1		
0[b]–55 (0–63)	Muddy peat with peat lens and roots	0.13	7.81
55–154 (63–161)	Clay-rich mud with some muddy peat in top cm	0.30	3.37
154–183 (161–194)	Muddy peat	6.60	0.15
183–369 (194–368)	Clay-rich mud	0.09	10.90
369–451 (368–451)	Mixed	0.10	10.24
451–471 (451–471)	Mixed	0.23	4.35
		Average	
		0.70	6.6

[a] Depths in parentheses are decompacted sediment depths used to calculate rates of sedimentation (Goman, 1996; Malamud-Roam and Ingram, 2004).
[b] Surface sediment is assumed to have a modern age.

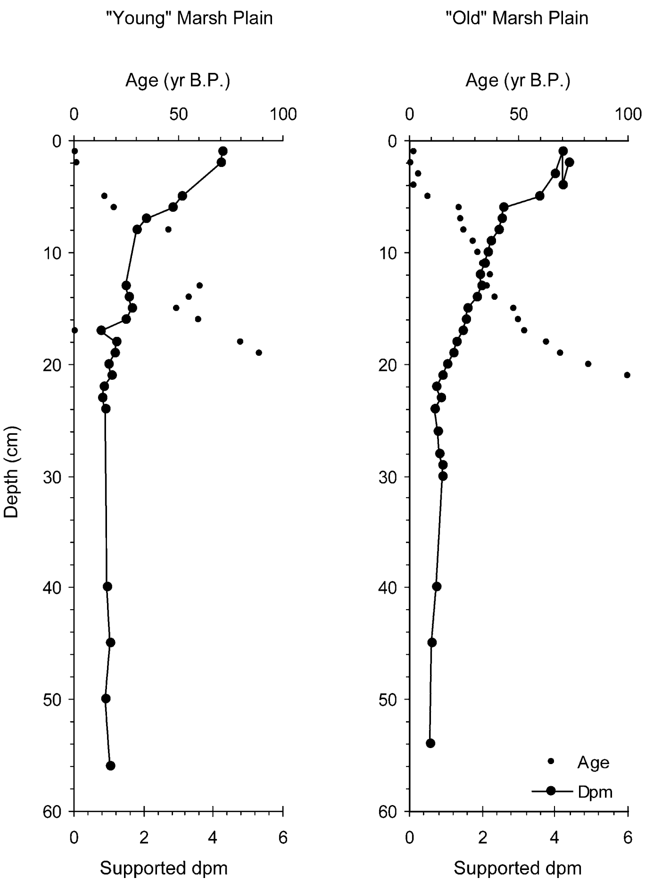

Figure 6. ^{210}Pb data for the two sediment monoliths collected from the "young" and "old" marsh plain. The connected dots measure the rate of radioactivity in the core in disintegration per minute (dpm), and the dates are calculated based on this decay (see text).

liver over 90% of the freshwater inflow to the estuary (Peterson *et al.,* 1989), are documented from elsewhere within the estuary. Goman (1996, 2001) and Goman and Wells (2000) used multiple proxy data from modern brackish and freshwater sites in Suisun Bay and San Pablo Bay and determined a period of increased fluvial discharge between 3800–2000 cal YBP. Strontium and oxygen isotopic data also indicate a period of increased freshwater inflow at this time, as identified by an overall decline in salinity within bay cores collected from San Pablo Bay and Richardson Bay (Ingram and DePaolo, 1993; Ingram, Ingle, and Conrad, 1996a, 1996b).

However, the complex lithostratigraphy at CC93 suggests either fluctuations in the rate of relative sea level (RSL), or fluctuations in estuarine circulation, such that deposition was enhanced in this part of San Pablo Bay. Enhanced sedimentation would have caused incipient marsh emergence; however, a decline in sedimentation or increase in RSL would have caused submergence of these marsh surfaces. These fluctuations occurred during the overall fresher water conditions.

By 2000 years ago, the generally fresher conditions experienced within the bay system appear to have ended. Decreased LOI values and low sedimentation rates (less than 1 mm y^{-1}; Table 1) depict an impoverished marsh during much of the approximately 1300 years in zone 2. These conditions suggest a reduction in freshwater inflow to the site, reducing the influx of inorganic detrital sediments and inhibiting plant growth. It could be argued that the low organic content reflects subtidal conditions. However, surface sediments collected from China Camp and several other marshes around the northern reach of San Francisco Bay also have measured organic content as low as 10% (Goman, 2005; Malamud-Roam, 2002; F. Malamud-Roam, unpublished data). Typically, *S. virginica* dominates in these marshes, and the pollen and $\delta^{13}C$ values reflect this dominance in zone 2, though shifts in the $\delta^{13}C$ record reflect some input from *S. foliosa,* suggesting that elevation of the marsh plain at the sites of CC99-S1 and CC99-S2 during this period was not at MHW (mean high water) and more likely at MTL (mean tide level) (Mahall and Park, 1976a, 1976b).

The stratigraphy for core CC99-S2 is similar to that of CC99-S1, including an early period with fluctuating organic content and isotopic values shifting between relatively high and low input values of C_4 vegetation (probably *S. foliosa*; see Malamud-Roam and Ingram, 2001), followed by a prolonged period of low organic content. The two cores are compared by depth, rather than age, because CC99-S2 was not dated. The LOI values for CC99-S2 below 270 cm are generally above 20%, with a maximum of 34% occurring at 305 cm. The $\delta^{13}C$ values for CC99-S2 are generally higher (less negative) than for CC99-S1 and more variable in the lower section of the core.

Interestingly, CC93 also has very low rates of sedimentation for this period (0.08 cm y^{-1}; Table 3); further, the magnetic susceptibility data are indicative of a decline in mineralogic material reaching the site (Figure 2). This suggests that marsh accretion and the decline in RSL rise by this time were sufficient to enable the formation of a *Salicornia*-dominated tidal marsh plain.

Paleoclimate records from sites throughout the estuary, California, and the West indicate this period was marked by droughts, some lasting centuries (Cook *et al.,* 2004). Isotopic compositions from sediment cores from sites in the San Francisco Bay show that during the last 2000 years salinity was higher than present-day, nondiversion values and was more variable (Ingram and DePaolo, 1993; Ingram, Ingle, and Conrad, 1996a, 1996b), reflecting reduced and variable freshwater inflow through the Sacramento–San Joaquin delta (the Delta) as well as an increasing trend in the rate of sea level rise (Malamud-Roam, 2000). Tidal marsh cores reflect the increased abundance of salt tolerant plants at several sites in the northern reach of the estuary (*e.g.,* Byrne *et al.,* 2001; Goman and Wells, 2000; Malamud-Roam and Ingram, 2004). Decreased inflow through the Delta, as well as lower precipitation in the local watershed, would result in increased salinity and also decreased influx of sediments to the local tidal marshes.

By *ca.* 700 cal YBP, the data from the core sites indicate maturation of the marsh to high marsh levels, with tidal conditions similar to present. The upper sediments in the cores also contain evidence of human modifications to the estuary during the last 200 years. In core CC99-S1, the sediments above 39 cm are highly inorganic and at CC93 the magnetic susceptibility data is also suggestive of an increase in mineralogic material to the marsh plain; a pattern also recognized in the upper sediments of numerous marsh sites within the northern reach of the estuary (*e.g.*, Byrne *et al.,* 2001; Goman and Wells, 2000; Malamud-Roam, 2002; Malamud-Roam and Ingram, 2004; May, 1999). These mineral-rich sediments may represent the influx of sediments washed in during and after the hydraulic mining of the late 1850s–1884 (Gilbert, 1917; Jaffe, Smith, and Torresan, 1998). They may also reflect changing land use practices in the surrounding San Francisco Bay region, including hay production and cattle ranching, which in many cases led to very high sediment inputs into local streams (Collins, 1998).

Relatively high isotopic values and increased importance of Cyperaceae and Poaceae pollen detected in CC99-S1 during most of the last 200 years suggest relatively fresh conditions. The Poaceae pollen, most likely is from *D. spicata* (found on the marsh above MHW), which, while being salt tolerant, is indicative of fresher conditions than *S. virginica* in a salt marsh setting (Byrne *et al.,* 2001). However, the near-surface sediments reveal evidence of increased salinity experienced at the sites in recent history. Chenopodiaceae pollen increases sharply in the top 5–7 cm of CC99-S1 (Figure 3), a pattern seen in other marsh cores from the San Francisco Bay estuary (*e.g.,* Malamud-Roam, 2002; May, 1999).

Interpolating dates based on the sedimentation rates at sites CC99-S1 and CC93 suggests that these near-surface sediments may reflect vegetation responses occurring in the last 60 years. These vegetation responses result from human modifications of estuary hydrology, particularly freshwater diversions and the construction of dams on major tributaries during the 1940s. Modern flows to the Sacramento–San Joaquin delta are now less than 40% of historic, prediversion levels (Nichols *et al.,* 1986). It has been argued that the average annual estuarine salinity has not significantly changed during the last century despite significant alteration of the hydrology of its watershed (Fox, Monogan, and Miller, 1990). This likely reflects management practices that control freshwater influx to alleviate the consequences of overall reduced flows, such that the extremes of high salinity occurring in the dry season, or low salinity during the rainy season, have been moderated (Knowles, 2000; Malamud-Roam, 2002; May, 1999). Knowles (2000) used models of estuarine salinity to determine how monthly salinity patterns in the estuary have changed over the 20th century and found that average salinity for the month of May has increased steadily throughout the San Francisco Bay estuary during this century (Knowles, 2000; see also Knowles and Cayan [2002] for a discussion of the possible impacts of anthropogenic climate change on estuarine salinity). The impact of such a change in seasonal patterns of estuarine salinity on marsh vegetation may cause reduced flushing during the critical periods of seedling establishment, possibly resulting in a shift to more salt tolerant plant taxa.

Peaks in Pb concentrations (maximum 0.184 g kg^{-1}; Goman, 1996) from surface sediments collected across the marsh, indicate anthropogenic sources of Pb within the marsh presumably from the in-wash of Pb used as a gasoline additive. A near surface peak at 7 cm (0.04 g kg^{-1}) approximately corresponds to AD 1960 (Figures 2 and 6). Surface levels of contamination are for the most part, an order of magnitude less, possibly reflecting the positive effects of the introduction of unleaded gasoline after AD 1970 (Goman, 1996; Schmidt and Reimers, 1991). These data are in agreement with the comprehensive analysis of historical trends in metal contamination in San Francisco Bay by Hornberger *et al.* (1999). Interestingly, the highest down-core Pb concentration occurs at 42 cm (0.074 g kg^{-1}), which corresponds approximately to 150 years ago. It is likely that this peak in Pb concentration marks contamination from the Selby lead smelter, which was located adjacent to San Pablo Bay and began operation in the late 1800s and ceased operation by AD 1970 (Ritson *et al.,* 1999).

Evidence for High Rainfall and El Niño Events

Sand and silt beds are found within the cores from China Camp. The beds with larger grain sizes are found in the more landward site (CC99-S1), while the site closer to the bay (CC93) has silt and silty-clay lenses. The changes in grain size are marked by well-defined contacts indicating that they were deposited over a relatively short time interval and that bioturbation has not obscured the deposits. We hypothesize that these discrete layers correlate with significant rainfall events that occurred within the local China Camp watershed, washing coarse clastic material down the upland slopes into the marsh. The larger-sized material was deposited closest to the slope while the smaller-sized grains were distributed in the direction of the bay.

The earliest evidence for a high rainfall event, occurring at *ca.* 3600 cal YBP, is found in both CC99-S1 and CC93 cores. These layers correlate with evidence for a large flood event that affected the San Francisco Bay estuary and the Delta system as a whole (Goman and Wells, 2000; West, 1977) and also correlate with other records in California that show an unusually wet period around 3800–3600 cal YBP (*e.g.,* Enzel *et al.*, 1989; Stine, 1990).

Two sand lenses are present within zone 2 at CC99-S1. The oldest, at 164–162 cm, is dated to *ca.* 830 cal YBP, while the younger, much thicker (6 cm) lens is dated by interpolation to *ca.* 700 cal YBP Three silt lenses are present at CC93; however, the interpolated ages place them within zone 1. The older silt layer at 150 cm is ~ 675 years old, while the middle layer at 128 cm is ~570 years old. Based upon age interpolation, it is possible that the youngest sand layer (CC99-S1) and oldest silt layer (CC93) are coeval. The third silty-clay layer present within zone 1 at CC93 is present at 108 cm, which dates by interpolation to 470 cal YBP. It is possible that this younger silty-clay deposit may correlate with flood deposits identified at Browns Island, located close to the confluence of the Sacramento and San Joaquin rivers (Goman and Wells, 2000), within the Sacramento Valley (Sullivan, 1982), and further south within the Santa Barbara Basin (Schimmelmann, Lange, and Meggers, 2003; Schimmelmann *et al.,* 1998). Schimmelmann, Lange, and Meggers (2003) and

Schimmelmann *et al.* (1998) suggest that this event may correspond to a strong El Niño precipitation event.

While further radiocarbon analysis is required to determine whether any of the clastic layers found in CC99-S1 are coeval with those in CC93, the clastic layers are interpreted as recording three, possibly five, high or extreme precipitation events within the China Camp watershed. These events occurred during the period between 850 and 450 years BP, the earlier part of which is coeval with the Medieval Climate Anomaly (1050–650 BP; see Stine, 1994 for nomenclature), and have an estimated return frequency of approximately one event every 100 years. This result compares well with Jones and Kennett's (1999) oxygen isotope data from the central California coast, which indicates greater seasonal variation in sea surface temperatures between 700 and 500 years ago as a result of El Niño. Our data from China Camp suggest that El Niño events may have been more frequent and stronger in the past because recent historic El Niño events (such as the AD 1983 event) are not recorded in the sediments.

Using a regional winter (November to April) precipitation index for the last 130 years for northern California, Johnstone (2007), determined that there is a strong 15-year El Niño oscillation. Active El Niño periods are associated with precipitation extremes in northern California while inactive stages are characterized by droughts. Because of its latitude, the central California coast may experience wetter, drier, or normal precipitation during El Niño years. Flood evidence in the marsh sediments at China Camp may be an indicator of periods in the past when the central coast was more heavily affected by stronger El Niño years.

CONCLUSIONS

The stratigraphic data from China Camp reveals a complex history of salinity changes reflecting conditions within San Pablo Bay. Fresher water conditions than modern prevailed between 3400 and 2000 cal YBP. Following this period until about 700 cal YBP, conditions within San Pablo Bay were more saline and variability was greater. The 400-year period between 850 and 450 cal YBP is distinguished from later and earlier periods by evidence for high precipitation events, which may correlate with estuary-wide floods, possibly related to El Niño. Geochemical evidence indicates the likelihood of pronounced salinity intrusions and also freshening conditions within this period. The impacts of historic water diversions and retention by dams upstream since the mid-20th century are also reflected in core stratigraphy since plant diversity decreases in the near surface deposits.

Thus, the multiproxy data from China Camp indicates that tidal salt marshes not only have the potential to record changes in local sea level, but also provide a valuable source for determining local (*e.g.,* flood events) and more regional (*e.g.,* prolonged droughts or periods of higher moisture) El Niño and La Niña climate events, and as such their potential as recorders of climate change has been undervalued. Further, the relatively small number of years encompassed in a single 1-cm sample indicates that intensive sample collection (every 0.5–1 cm) from tidal salt marsh cores is appropriate, thus permitting high-resolution climate reconstructions that would have a resolution on the order of decades to millennia.

ACKNOWLEDGMENTS

This research was supported in part by the National Science Foundation under Grant No. 0117531 and by a University of California, Berkeley Stahl grant.

Many people helped during the course of this study in the field and laboratory as well as with helpful discussions; they include L. Wells, M. Gabbet, S. Huse, M. Monahagn, R. Worthington, L. Reidy, D. Wahl, E. Watson, S. Starratt, P. Weber, P. Schweikhart, S. Kegley, K. Malamud-Roam, B. Roark, R. Amundson, M. May, R. Byrne, and D. Sloan. We thank P. Brooks for help with the mass spectrometry and R. Kayan, U.S.G.S., for help with the magnetic susceptibility and gamma ray equipment. We would like to thank S. Starratt and an anonymous referee for helpful comments.

LITERATURE CITED

Abbe, T. and Bennett, A., 1991. China Camp State Park Site. *In: Map of China Camp Park.* San Francisco, California: Philip Williams and Associates, Limited.

Adam, P., 1990. *Salt Marsh Ecology.* New York: Cambridge University Press, 461p.

Atwater, B.F. and Hedel, C.W., 1976. Distribution of Tidal-Marsh Plants with Respect to Elevation and Water Salinity in the Natural Tidal Marshes of the Northern San Francisco Bay Estuary, California: U.S. Geological Survey Open-File Report 76-389, 41p.

Atwater, B.F.; Conrad, S.G.; Dowden, J.N.; Hedel, C.W.; Macdonald, R.L., and Savage, W., 1979. History, landforms, and vegetation of the estuary's tidal marshes. *In:* Conomos, T.J. (ed.), *San Francisco Bay: The Urbanized Estuary.* San Francisco: Pacific Division, American Association for the Advancement of Science, pp. 347–385.

Belknap, D. F.; Shipp, R.C.; Stuckenrath, R.; Kelly, J.T.; and Borns, H.W., Jr., 1989. Holocene sea-level change in coastal Maine. *Maine Geological Survey,* 40, 85–105.

Boyle, J.F.; Plater, A.J., and Anderson, R.S., 2003. A 65 ka High Resolution Terrestrial Climate Record from Laguna de Las Trancas, Central Coast, California. *In: Program with Abstracts, XVI INQUA Congress,* 154.

Byrne, R.; Ingram, B.L.; Starratt, S.; Malamud-Roam, F.; Collins, J.N., and Conrad, M.E., 2001. Carbon-isotope, diatom, and pollen evidence for late Holocene salinity change in a brackish marsh in the San Francisco Estuary. *Quaternary Research,* 55, 66–76.

Chmura, G.L. and Aharon, P., 1995. Stable carbon isotope signatures of sedimentary carbon in coastal wetlands as indicators of salinity regime. *Journal of Coastal Research,* 11, 124–135.

Chmura, G.L.; Aharon, P.; Socki, R.A., and Abernathy, R., 1987. An inventory of ^{13}C abundances in coastal wetlands of Louisiana, USA: vegetation and sediments. *Oecologia* (Berlin), 74, 264–271.

Clark, S.J. and Patterson III, W.A., 1985. The development of a tidal marsh: upland and oceanic influences. *Ecological Monographs,* 55, 189–217.

Cole, K.L. and Liu, G.W. 1994. Holocene paleoecology of an estuary on Santa Rosa Island, California. *Quaternary Research,* 41, 326–335.

Collins, L., 1998. Sediment Sources and Fluvial Geomorphic Processes of Lower Novato Creek Watershed. Report to Marin County Flood Control and Water Conservation District, San Rafael, CA.

Cook, E.R.; Woodhouse, C.A.; Easkin, C.M.; Meko, D.M., and Stahle, D.W., 2004. Long-term aridity changes in the western United States. *Science,* 306, 1015–1018.

Craig, H., 1957. Isotopic standards for carbon and oxygen correction factors for mass-spectrometric analysis of carbon dioxide. *Geochimica Cosmochimica Acta,* 12, 133–149.

Cuneo, K.L.C., 1987. San Francisco Bay Salt Marsh Vegetation, Geography and Ecology: A Baseline for Use in Impact Assessment and Restoration Planning. Berkeley, California: University of California, Ph.D. thesis, 751p.

Davis, O.K., 1992. Rapid climatic change in coastal southern California inferred from pollen analysis of San Joaquin Marsh. *Quaternary Research,* 37, 89–100.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology,* 44, 242–248.

Delaune, R.D., 1986. The use of $\delta^{13}C$ signature of C_3 and C_4 plants in determining past depositional environments in rapidly accreting marshes of the Mississippi river deltaic plain, Louisiana, U.S.A. *Chemical Geology,* 59, 315–320.

Enzel, Y.; Cayan, D.R.; Anderson, R.Y., and Wells, S.G., 1989. Atmospheric circulation during Holocene lake stands in the Mojave Desert: evidence of regional climate change. *Nature,* 341, 44–47.

Faegri, K. and Iverson, J., 1989. *Textbook of Pollen Analysis,* 4th edition. New York: John Wiley, 328p.

Fletcher, C.H., III; Van Pelt, J.E.; Brush, G.S., and Sherman, J., 1993. Tidal wetland record of Holocene sea-level movements and climate history. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 102, 177–213.

Fogel, L.; Spague, E.K.; Gize, A.P., and Frey, R.W., 1989. Diagenesis of organic matter in Georgia salt marshes. *Estuarine, Coastal and Shelf Science,* 28, 211–230.

Folk, R.L., 1980. *Petrology of Sedimentary Rocks.* Austin, Texas: Hemphill Publishing Company, 170p.

Fox, J.P.; Monogan, T.R., and Miller, W.J., 1990. Trends in freshwater inflow to San Francisco Bay from the Sacramento-San Joaquin delta. *Water Resources Bulletin,* 26(2), 101–116.

Gabet, E.J., 1998. Lateral migration and bank erosion in a saltmarsh tidal channel in San Francisco Bay, California. *Estuaries,* 21, 745–753.

Gehrels, W.R., 1999. Middle and late Holocene sea-level changes in eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS C-14 dates on basal peat. *Quaternary Research,* 52, 350–359.

Gehrels, W.R.; Belknap, D.F.; Black, S., and Newham, R.M., 2002. Rapid sea-level rise in Gulf of Maine, USA, since AD 1800. *Holocene,* 12(4), 383–389.

Gehrels, W.R.; Belknap, D.F., and Kelley, J.T., 1996. Integrated high-precision analyses of Holocene relative sea-level changes: lessons from the coast of Maine. *Geological Society of America Bulletin,* 108, 1073–1088.

Gilbert, G.K., 1917. Hydraulic-Mining Debris in the Sierra Nevada. U.S. Geological Survey Professional Paper, 105, 154p.

Goman, M., 1996. A History of Holocene Environmental Change in the San Francisco Estuary. Berkeley, California: University of California, Ph.D. thesis, 310p.

Goman, M., 2001. Statistical analysis of modern seed assemblages from the San Francisco Bay: applications for the reconstruction of paleo-salinity and paleo-tidal inundation. *Journal of Paleolimnology,* 24, 393–409.

Goman M., 2005. The development and application of a statistical calibration model of marsh sediment characteristics to the stratigraphic record. *Journal of Sedimentary Research,* 75(3), 398–408.

Goman, M. and Wells, L.E., 2000. Trends in riverflow affecting the northeastern reach of the San Francisco Bay Estuary over the last 7000 years. *Quaternary Research,* 54, 206–217.

Hickman, J.C. (ed.), 1993. *The Jepson Manual: Higher Plants of California.* Berkeley and Los Angeles, California: University of California Press, 1400p.

Hornberger, M.I.; Luoma, S.N.; Van Geen, A.; Fuller, C., and Anima, R., 1999. Historical trends of metals in the sediments of San Francisco Bay, California. *Marine Chemistry,* 64, 39–55.

Ingram, B.L. and DePaolo, D.J., 1993. A 4300 year strontium isotope record of estuarine paleosalinity in San Francisco Bay, California. *Earth and Planetary Science Letters,* 119, 103–119.

Ingram, B.L.; Ingle, J.C., and Conrad, J.C., 1996a. A 2000 yr record of Sacramento-San Joaquin River inflow to San Francisco estuary, California. *Geology,* 24, 331–334.

Ingram, B.L.; Ingle, J.C., and Conrad, J.C., 1996b. Stable isotope record of late Holocene salinity and river discharge in San Francisco Bay, California. *Earth and Planetary Science Letters,* 141, 237–247.

Inman, D.L. and Nordstrom, C.E., 1971. On the tectonic and morphologic classification of coasts. *The Journal of Geology,* 79, 1–21.

Jaffe, B.E.; Smith, R.E., and Torresan, L.Z., 1998. Sedimentation and Bathymetric Change in San Pablo Bay: 1856–1983. U.S. Geological Survey Open-File Report 98–759, 1 sheet.

Johnstone, J., 2007. Decadal Cycles of ENSO Amplitude and Winter Precipitation in Northern California. Technical Report 77 of the Interagency Ecological Program for the San Francisco Estuary, 120.

Jones, T.L. and Kennett, D.J., 1999. Late Holocene sea temperatures along the central California Coast. *Quaternary Research,* 51, 74–82.

Josselyn, M., 1983. The Ecology of San Francisco Bay Tidal Marshes: A Community Profile. Washington, DC: U.S. Fish and Wildlife Services, Division of Biological Services., FWS/OBS Report 83/82, 102p.

Kaye, C.A. and Barghoorn, E.S., 1964. Late Quaternary sea-level change and crustal rise at Boston, Massachusetts, with notes on the autocompaction of peat. *Geological Society of America Bulletin,* 75, 63–80.

Kelley, J.T.; Gehrels, W.R., and Belknap, D.F., 1995. Late Holocene relative sea-level rise and the geological development of tidal marshes at Wells, Maine, USA. *Journal of Coastal Research,* 11(1), 136–153.

Knowles, N., 2000. Modeling the Hydroclimate of the San Francisco Bay-Delta Estuary and Watershed. San Diego, California: University of California, Ph.D. thesis, 291p.

Knowles, N. and Cayan, D.R., 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. *Geophysical Research Letters,* 29(18), 1891, 4 pp, doi: 10.1029/2001GL014339.

Mahall, B.E. and Park, R.B., 1976a. The ecotone between *Spartina foliosa,* Trin. and *Salicornia virginica* L. in salt marshes in northern San Francisco Bay: 1. Biomass and production. *Journal of Ecology,* 64, 421–433.

Mahall, B.E. and Park, R.B., 1976b. The ecotone between *Spartina foliosa,* Trin. and *Salicornia virginica* L. in salt marshes in northern San Francisco Bay: 2. Soil water and salinity. *Journal of Ecology,* 64, 793–809.

Malamud-Roam, K. 2000. Tidal Regimes and Tide Marsh Hydroperiod in the San Francisco Estuary: Theory and Implications for Ecological Restoration. Berkeley, California: University of California, Ph.D. thesis, 850p.

Malamud-Roam, F. 2002. A late Holocene history of vegetation change in San Francisco estuary marshes using stable carbon isotopes and pollen analysis. Berkeley, California: University of California, Ph.D. thesis, 200p.

Malamud-Roam, F. and Ingram, B.L., 2001. Carbon isotopic compositions of plants and sediments of tide marshes in the San Francisco Estuary. *Journal of Coastal Research,* 17, 17–29.

Malamud-Roam, F. and Ingram, B.L., 2004. Late Holocene $\delta^{13}C$ and pollen records of paleosalinity from tidal marshes in the San Francisco Bay Estuary, California. *Quaternary Research,* 62, 134–145.

Martin, A.C. and Barkley, W.D., 1961. *Seed Identification Manual.* Berkeley and Los Angeles: University of California Press, 221p.

Martin, T.D.; Creed, J.T., and Long, S.E., 1992. Sample preparation procedure for spectrochemical determination of total recoverable elements. *In*: Smoley, C.K. (ed.), *Methods for the Determination of Metals in Environmental Samples.* Boca Raton, Florida: CRC Press, pp. 15–24.

Mason, H.L., 1957. *A Flora of the Marshes of California.* Berkeley and Los Angeles: University of California Press, 878p.

May, M.D., 1999. Vegetation and Salinity Changes over the Last 2000 years at Two Islands in the Northern San Francisco Estuary, California. Berkeley, California: University of California, Master's thesis, 55p.

McCaffrey, R.J. and Thomson, J., 1980. A record of accumulation of sediment and trace metals in a Connecticut salt marsh. *Advances in Geophysics,* 22, 165–236.

Montgomery, F.H., 1977. *Seeds and Fruits of Plants of Eastern Canada and Northeastern United States.* Toronto: University of Toronto Press, 232p.

Mudie, P.J. and Byrne, R., 1980. Pollen evidence for historic sedimentation rates in California coastal marshes. *Estuarine and Coastal Marine Science,* 10, 305–316.

Munz, P.A., 1973. *A California Flora.* Berkeley and Los Angeles, California: University of California Press, 224p.

Nelson, A.R.; Jennings, A.E., and Kashima, K., 1996. An earthquake history derived from stratigraphic and microfossil evidence of relative sea-level change at Coos Bay, southern coastal Oregon. *Geological Society of America Bulletin,* 108(2), 141–154.

Nichols, F.H.; Cloern, J.E.; Luoma, S.N., and Peterson, D.H., 1986. The modification of an estuary. *Science,* 231, 567–573.

O'Leary, M.H., 1981. Carbon isotope fractionation in plants. *Phytochemistry,* 20, 553–567.

O'Leary, M.H.; Madhavan, S., and Paneth, P., 1992. Physical and chemical basis of carbon isotope fractionation in plants. *Plant Cell and Environment,* 15, 1099–1104.

Peterson, D.H.; Cayan, D.R.; Festa, J.F.; Nichols, F.H.; Walters, R.A.; Slack, J.V.; Hager, S.E., and Schemel, L.E., 1989. Climate variability in an estuary: effects of riverflow on San Francisco Bay. *In:* Peterson, D.H. (ed.), *Aspects of Climate Variability in the Pacific and the Western Americas.* Geophysical Monograph, volume 55, pp. 419–442.

Redfield, A.C., 1972. Development of a New England salt marsh. *Ecological Monographs,* 42, 201–236.

Reidy, L.M., 2002. Using non-native pollen as chronological markers in lake sediments from San Francisco, California. *In: Papers and Proceedings of the Applied Geography Conferences,* volume 25, pp. 69–75.

Ritson, P.I.; Bouse, R.M.; Flegal, A.R., and Luoma, S.N., 1999. Stable lead isotopic analyses of historic and contemporary lead contamination of San Francisco Bay estuary. *Marine Chemistry* 64, 71–83.

San Francisco Bay National Estuarine Research Reserve, 2006. San Francisco Bay National Estuarine Research Reserve Website. http://sfbaynerr.org/reserves/ (accessed April 2008).

Nelson, A.R., 1992. Discordant ^{14}C ages from buried tidal-marsh soils in the Cascadia subduction zone, south Oregon coast. *Quaternary Research,* 38, 74–90.

San Francisco Estuary Project, 1992. *State of the Estuary: A Report on Conditions and Problems in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary.* Oakland, California: Association of Bay Area Governments, 267p.

Schimmelmann, A.; Lange, C.B., and Meggers, B.J., 2003. Palaeoclimatic and archaeological evidence for a ~200-yr recurrence of floods and droughts linking California, Mesoamerica and South America over the past 2000 years. *The Holocene,* 13(5), 763–778.

Schimmelmann, A.; Zhao, M.; Harvey, C.C., and Lange, C.B., 1998. A large California flood and correlative global climatic events 400 years ago. *Quaternary Research,* 49, 51–61.

Schmidt, H., and Reimers, C.E., 1991. The recent history of trace metal accumulation in the Santa Barbara Basin, southern California borderland. *Estuarine, Coastal and Shelf Science,* 33, 485–500.

Schwartz, D.L.; Mullins, H.T., and Belknap, D.F., 1986. Holocene geological history of a transform estuary: Elkhorn Slough, California. *Estuarine, Coastal and Shelf Science,* 22, 285–302.

Stine, S. 1990. Late Holocene fluctuations of Mono Lake, eastern California. *Paleogeography, Paleoclimatology, Paleoecology,* 78, 333–381.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature,* 369, 546–549.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores,* 8, 615–621.

Stuiver, M. and Reimer, P.J., 1993. Extended ^{14}C data base and revised Calib 3.0 ^{14}C age calibration program. *Radiocarbon,* 35, 215–230.

Stuiver M.; Reimer, P.J.; Bard, E.; Beck, J.; Burr, G.S.; Hughen, K.A.; Kromer, B.; McCormac, G.; Van der Plicht, J., and Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon,* 40(3), 1041–1083.

Sullivan, D.G. 1982. Prehistoric Flooding in the Sacramento Valley: Stratigraphic Evidence from Little Packer Lake, Glenn County, California, Berkeley, California: University of California, Master's thesis, 90p.

Thomas, E. and Varekamp, J.C., 1991. Paleo-environmental analyses of marsh sequences (Clinton, Connecticut): evidence for punctuated rise in relative sea level during the latest Holocene. *Journal of Coastal Research,* Special Issue No. 11, 125–158.

U.S. Geological Survey, 2003. Water Quality of San Francisco Bay: A Long-Term Program of the U.S. Geological Survey. http://sfbay.wr.usgs.gov/access/wqdata (accessed April 12, 2004).

Valette-Silver, N.J., 1993. The use of sediment cores to reconstruct historical trends in contamination of estuarine and coastal sediments. *Estuaries,* 16, 577–588.

Van de Plassche, O., 1991. Late Holocene sea level fluctuations on the shore of Connecticut inferred from transgressive and regressive onlap boundaries in salt-marsh deposits. *Journal of Coastal Research* Special Issue No. 11, 150–179.

Varekamp, J.C.; Thomas, E., and Van de Plassche, O.,1992. Relative sea-level rise and climate change over the last 1500 years. *Terra Nova,* 4, 293–304.

West, G.J, 1977. Late Holocene Vegetation History of the Sacramento-San Joaquin Delta, California. Unpublished report prepared for California Department of Water Resources under Interagency Agreement B-5O 173 by the Cultural Heritage Section of the California Department of Parks and Recreation, 20p.

Witter, R.C.; Kelsey, H.M., and Hemphill-Haley, E., 2003. Great Cascadia earthquates and tsunamis of the past 6700 years, Coquille River estuary, southern coastal Oregon. *Geological Society of America Bulletin,* 115(10), 1289–1306.