Late Holocene Environmental Variability in the Upper San Francisco Estuary as Reconstructed from Tidal Marsh Sediments

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ABSTRACT: Tidal marsh sediments collected from Browns Island in the lower Sacramento/San Joaquin Delta, California, are used to reconstruct environmental variability over the past 6.8 ka. Calibrated radiocarbon dates provide chronostratigraphic control. Trace metal analyses, grain-size variability, organic content, and macrofossils are used to define short- and long-term variations in relative salinity and inundation frequency. Aggradation began in subtidal fresh water conditions about 6.8 ka. Subtidal aggradation of clayey silts continued until about 6.3 ka, when conditions shifted toward a lower intertidal brackish marsh environment. By 5.1 ka, a brackish marsh plain had evolved, with surface water freshening after 4.1 ka. Conditions returned to brackish similar to the present after 2.3 ka. The uppermost part of the sediments (post-0.9 ka) have elevated trace metal contents probably related to modern contamination leaching downward into the sedimentary column. This initial coarse resolution sampling has also identified several short-period events: an extreme flood (about 0.5 ka) recognized by high mica content and overbank deposition of seeds from the pondweed *Potamogeton* and the foraminifera *Trochominna inflata*; several extreme droughts (about 3.0 ka) recognized by high trace metal contents (Cd and Pb) and high organic content; periods of increased tidal inundation (about 2.2 and 4.5 ka) recognized by high trace metal concentrations, low organic contents, and fossil indicators of inundation.

Introduction

The San Francisco Estuary is an inland arm of the ocean that floods the Sacramento, San Joaquin, and Santa Clara river valleys (Figure 1). The dominant source of fresh water into the estuary is the Central Valley of California, which drains 40% of the state via the Sacramento and San Joaquin rivers. The region has a Mediterranean climate with cool, wet winters and warm, dry summers. Most of the regional precipitation falls as snow in the Sierra Nevada such that discharge peaks in late spring when snow melts. Natural discharge variability is believed to have been quite high. In extreme flood years (*eg*, AD 1861/1862), the tidal range at the Golden Gate dropped to zero and the ocean was said to have been fresh 50 kilometers offshore at the Farallon Islands (Dana 1939). In extreme drought years (*eg*, AD 1841), tidal influence was felt as far upstream as the confluence of the Feather and Sacramento rivers, and brackish water penetrated well into the delta (Thompson 1957). Beginning in AD 1850, levee building, hydraulic gold mining, and channel dredging irreversibly changed the hydrologic balance of the estuary. Today, the discharge regime is highly muted as water is stored in reservoirs on nearly every river in the drainage basin. Since hydrologic monitoring did not begin until well after significant human modification had occurred, we must rely on geological proxy records to reconstruct the natural salinity and discharge variability of the system.

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Figure 1. MAP OF THE SAN FRANCISCO ESTUARY SHOWING CORE SITES (italicized) AND DISTRIBUTION OF PRESENT AND HISTORICAL WETLANDS.
Inset map shows limits of the Sacramento-San Joaquin drainage basin that would have naturally discharged through Carquinez Strait and the Golden Gate. (Base maps from Cohen and Laws 1990).

The Holocene estuary was created when the post-glacial rise of sea level allowed oceanic water to enter the Golden Gate sometime between 11 and 10 ka. Estuarine deposition began about 8.3 ka just inland of the Golden Gate, and by 6.8 ka sea level had risen into the Sacramento-San Joaquin Delta region (Atwater *et al* 1977). As sedimentation on mature tidal marsh plains tends to keep pace with the rate of sea level rise (Pethick 1981; Allen 1990; French and Spencer 1993), marsh plain sediments provide a thick and continuous record of environmental conditions for the last 7.0 ka. We have collected sediment cores from six marshes along the northern arm of the estuary to analyze the spatial characteristics of environmental change (Figure 1). Here we present our analysis of sediments from Browns Island, located downstream of the confluence of the Sacramento and San Joaquin rivers.

Environmental Setting

Browns Island, at the upstream end of Suisun Bay, is within the modern mixing zone between fresh water and salt water. Water chemistry varies both seasonally and interannually with the climatology of the watershed. Salinity drops to near zero values with the spring meltwater pulse and may stay low throughout the year during extreme flood years (*eg,* the 1983 El Niño year). During periods of drought (*eg,* 1976/1977), salinity increases in a sawtooth manner, peaking a little higher each subsequent drought year. Estuarine mixing is maintained by density differences between fresh and saline water rather than by tidal currents, and seasonal salinity stratification is largely controlled by the volume of freshwater inflow (Conomos 1979). The mixing zone moves upstream and downstream largely in response to the volume of freshwater flow; therefore, its location can be used as a proxy for freshwater discharge.

Within the mixing zone, flocculation of colloids is enhanced, and this results in a local turbidity maximum (Conomos and Peterson 1977; Burau *et al* 1994). Carquinez Strait is narrow, and tidal currents flush much of the sediment out into San Francisco Bay (Krone 1979, Burau *et al* 1994). Nonetheless, sedimentation rates in the quiet water adjacent to Carquinez Strait historically have yielded remarkably high sedimentation rates. Our comparison of maps from the mid-1800s with recent aerial photographs indicates local shoreline progradation of as much as 1.5 kilometer in the last 150 years. Since trace metals, especially Fe and Pb, are preferentially flocculated out of surface water at low salinity (*eg,* Boyle *et al* 1977; Bourg 1983; Duinker 1983), analysis of sediment trace metal contents can serve as a proxy for water salinity. The spatial relationship between trace metal concentration and salinity gradients in the San Francisco Estuary has been documented in both estuarine water (Flegal *et al* 1991) and in the distribution of trace metals in surface sediments (Peterson *et al* 1972; Ritson and Flegal 1994).

Interpretation of the trace metal records from tidal marsh sediment is complicated by the potential for diagenetic mobilization in the transition zone from oxidizing to reducing conditions (Zwolsman *et al* 1993). Once reducing conditions are stabilized in the saturated subsurface, there is probably little remobilization of trace metals (Bartlett and James 1993). Gleyed surface sediments (blue-gray) at Browns Island with rare brown mottling suggest that saturated and reducing conditions are maintained on the island. Even in the Netherlands, where redox reactions are well documented, trace metal profiles preserve extreme pollution events as discrete peaks (Zwolsman *et al* 1993), and we expect that short-period sedimentary events will also be recognizable in trace metal profiles.

Iron concentration in tidal sediments has also been related to the frequency of tidal inundation (Thomas and Varekamp 1991, Fletcher *et al* 1993). Long-term shifts in Fe content reflect the aggradation of the mud flat to a marsh plain (Fletcher *et al* 1993). These shifts in inundation frequency should also be reflected in changes in sedimentology (lower organic content and higher silt content at lower elevations relative to mean sea level; Fletcher *et al* 1993; Pizzuto and Rogers 1992) and in plant-macrofossil distributions. Thus, the trace metal signature must be interpreted in light of other proxy information within the cores.

Plant distribution within the estuary is also stratified as a function of inundation frequency and salinity (Mall 1969; Josselyn 1983; Atwater *et al* 1979). The tidal marshes of the estuary can be subdivided into three broad categories: salt marsh, brackish marsh, and freshwater marsh. Salt marshes of San Francisco Bay are dominated by *Spartina foliosa* and *Salicornia virginica*; freshwater marshes of the Sacramento/San Joaquin Delta are dominated by *Scirpus californicus*, *Juncus* spp., *Carex* spp., *Salix lasiolepis*, and *Typha* spp. (Atwater *et al* 1979). *Phragmites communis* occurs most commonly in the loser, more brackish areas of the delta (J. West, personal communication). In the intermediate brackish marshes of Suisun Bay, San Pablo Bay, and Carquinez Strait, these plant species overlap, with the addition of a few plants restricted to the brackish environments, including *Scirpus robustus*, *Cordylanthus mollis*, and *Glaux maritima* (Atwater *et al* 1979). Seeds are well preserved within the section and are identifiable to the genus and occasionally species level. Thus, in conjunction with the other sedimentary characteristics of the cores, we use seed zonations as a proxy for regional salinity and tidal inundation variability through time.

Under modern conditions, Browns Island supports vegetation adapted to brackish water, notably *Scirpus acutus*, *Scirpus americanus*, *Typha angustifolia*, *Carex* sp., and *Distichlis spicata*. Exotic plants (*eg*, California fan palm, Japanese honeysuckle, and a species of acacia) were introduced around the turn of the century when a brothel was located at the western end of the island (Knight 1980). Other human modification of the island has been relatively minor — small levees were built around the island's edge, and linear mosquito ditches were cut across the island's surface. Neither of these has been maintained, and the island is one of the most pristine examples of brackish marsh in the San Francisco estuary.

Methods

We have collected piston core samples from two sites on the marsh plain at Browns Island. The first core site (BI-1992) is about 0.3 kilometer inland of the island's northern edge. The second core site (BI-1993) is more central, about 0.75 kilometer inland from the island's northern edge. BI-1992 cores extend to a depth of 780 centimeters; BI-1993 cores extend to 1060 centimeters. In addition, a monolith (roughly $125 * 10^3$ cm^3) of the surficial peats was excavated from the BI-1993 coring location.

The tidal marsh sediments are dominantly peat and clayey peat, with blue clayey silts at the base. Before being opened, cores were first archived by x-ray (BI-1992 and BI-1993), gamma ray and magnetic susceptibility (BI-1993 only). After description of large macrofossils and soil characteristics, subsamples were taken for water content, organic content (by loss-on-ignition), grain-size analysis (silt:clay ratios), and trace metal content. A second sample was sieved, and the sand fraction, if present, was described.

We used a Perkin-Elmer model 3100 Atomic Absorption Spectrometer equipped with an HGA-600 Graphite Furnace for the analysis of trace metals in cored sediments. Subsamples for trace metal analyses (about 2 cc.) were taken at 10- or 50-cm intervals except for the section from 230 to 350 centimeters, where samples were taken every 1 centimeter. Bulk sediment samples were digested in a hot solution of 30% HNO_3 and 10% HCl for 45 minutes; after cooling, 1 mL of 30% H_2O_2 was added to the samples. The material was then filtered and the filtrate retained for analysis. According to Varekamp (1991), this is a heavy leach that will digest both organic matter and pedogenic pyrite but will not remove metals that are structurally bound within silicate minerals. Replicates were run for Fe samples from the 1992 core; the difference between the metal concentrations obtained from the replicate runs was about 1% of the total concentration.

Accelerator Mass Spectrometer radiocarbon ages on individual *Scirpus* seeds provide the chronostratigraphic control. Since peat deposits contain organic material with a variety of ages, it is important to date distinct peat components (Wells 1994; Nelson 1992; Belknap *et al* 1989). Dates on seeds from thin layers within the core yield the most consistent chronology; *ie,* rare stratigraphic reversals and nearly linear sedimentation rates (r^2=0.98). All radiocarbon dates discussed herein have been calibrated to the dendrochronological time scale (Stuiver and Reimer 1993).

Sedimentology

Sediments at Browns Island range from clayey silts to clayey peats (Figure 2). The sediments are saturated throughout the section. Water content ranges from 25% in the clayey silts to 90% in the peat layers. Sediment density ranges from 0.70 gm/cc in peat to 1.9 gm/cc in clayey silt. Sediment density increases rapidly within the upper few decimeters of the section and then remains relatively constant through zones of similar sediment composition (*ie,* within the peats or the silts). This implies that most of the compaction of the peat occurred shortly after burial. The high variability of organic content in the uppermost 50 centimeters reflects the low density of uncompacted plant materials. Roots, up to 1.5 centimeter in diameter, remain intact to depths of 30 centimeters. Below this depth, large roots have begun to collapse and decay, and by 50-cm depth all root debris has collapsed and flattened. There is also a strong correlation between organic content and clay content (r^2=82%). Both values peak between 300 and 600 centimeters and then drop off to

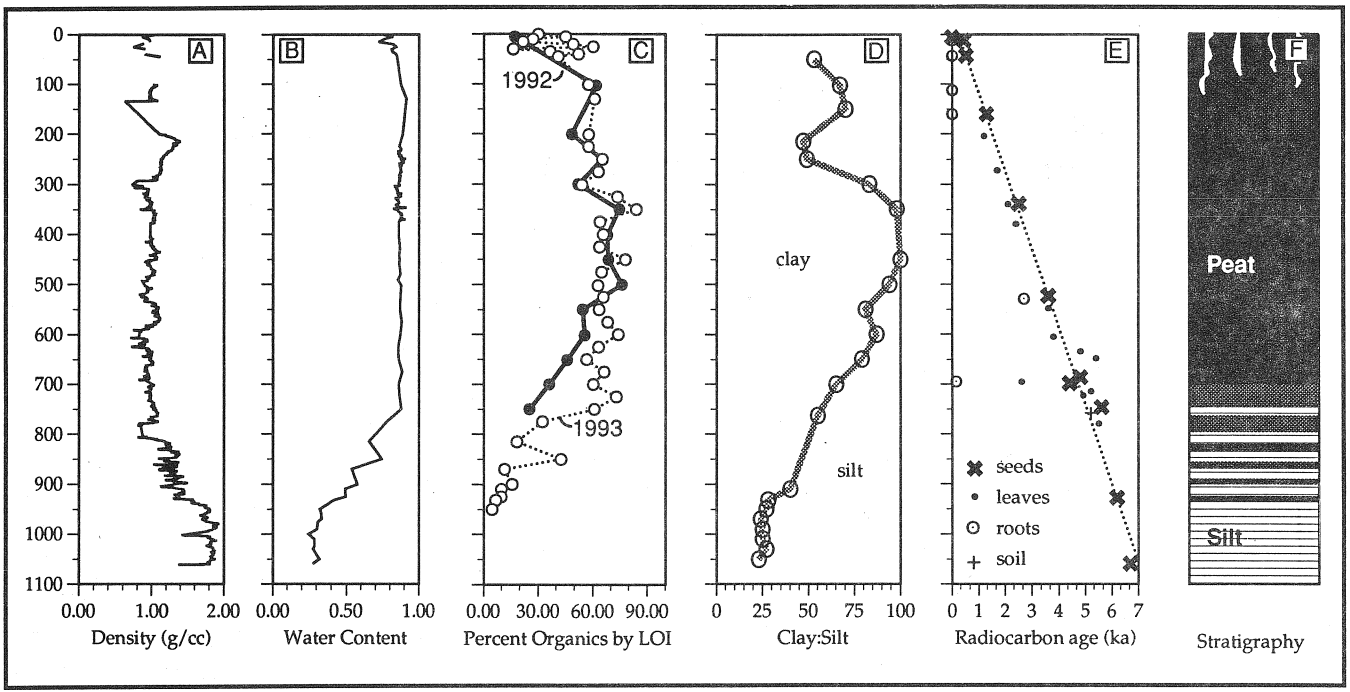

Figure 2. CHANGES IN CHARACTERISTICS OF TIDAL MARSH SEDIMENTS WITH DEPTH AT BROWNS ISLAND.
A. Density (g/cc) for core BI-1993. Upper 100 cm by traditional method, below 100 cm by gamma ray spectrometry.
B. Water content for core BI-1993.
C. Percent organics by loss-on-ignition.
D. Clay:silt ratios. Upper 7-meters core BI-1992; Lower 7 meters core BI-1993
E. Calibrated radiocarbon age from the various components with both cores.
F. Stratigraphy.

very low values at the base of the cores. The consistently low density and high water content suggest that little compaction has occurred and that changes in sediment composition reflect changes in the nature of sediment delivery to and accumulation on the marsh.

The resolution of the sedimentary record is constrained by the nature of marsh sedimentation and sediment diagenesis. X-radiographs of our cores show that fine-scale sedimentary laminations are often preserved and suggest that bioturbation is minimal. The fine-scale variations in the density log (Figure 2A) also reflect these changes in sediment composition and imply little vertical mixing or bioturbation of the detrital sediment. However, root penetration clearly introduces younger organic material to depths of perhaps as much as 1-2 meters. In the sediment monolith, roots are observed to penetrate through silt bands while leaving them largely intact. Stumpf (1983) also observed only minor bioturbation in tidal marshes in the eastern United States, and this is substantiated by recent work using the ^{137}Cs dating method (*eg,* Zwolsman *et al* 1993).

Since the bulk of organic material is autochonous root debris, increases in inorganic sediment content reflect increases in the allocthonous sediment supply. Thin silt layers occur sporadically throughout the peat section (*ie,* at 0.15, 0.45, 2.5, and 3 meters depth) and are most likely the deposits of overbank flood events. Extreme floods during 1983 and 1986 were observed to flush terrigenous sediment well into San Pablo Bay and out through the Golden Gate, and water turbidity increased markedly during these floods. The discrete silt layers preserved in the core (1-2 millimeters thick) probably represent a single extreme-flood season or even a peak flood.

Trace Metals

There is a strong contrast in the trace metal concentrations between the upper and lower sections of the core (Figure 3). Above 600 centimeters, the correlation between organic content and trace metals is poor ($r^2 < 40\%$); below this level the correlations are high ($r^2 = 70\text{-}97\%$). The concentrations of Cd and Pb are positively correlated with organic concentration, while Fe is negatively correlated. Concentrations of Pb and Fe (0.408 and 44.66 mg/kg respectively) are high at the surface of the marsh. Lead drops to pre-modern levels by 1 meter depth (0.035 mg/kg), and Fe drops to pre-modern levels by 2 meters depth (20.76 mg/kg). Metal values generally remain low between 2 and 6 meters depth except for several discrete peaks in the concentrations of Cd and Pb. Between 6 and 8 meters, Pb and Cd concentrations increase but Fe values remain low; below 8 meters, Pb and Cd levels drop but Fe values increase.

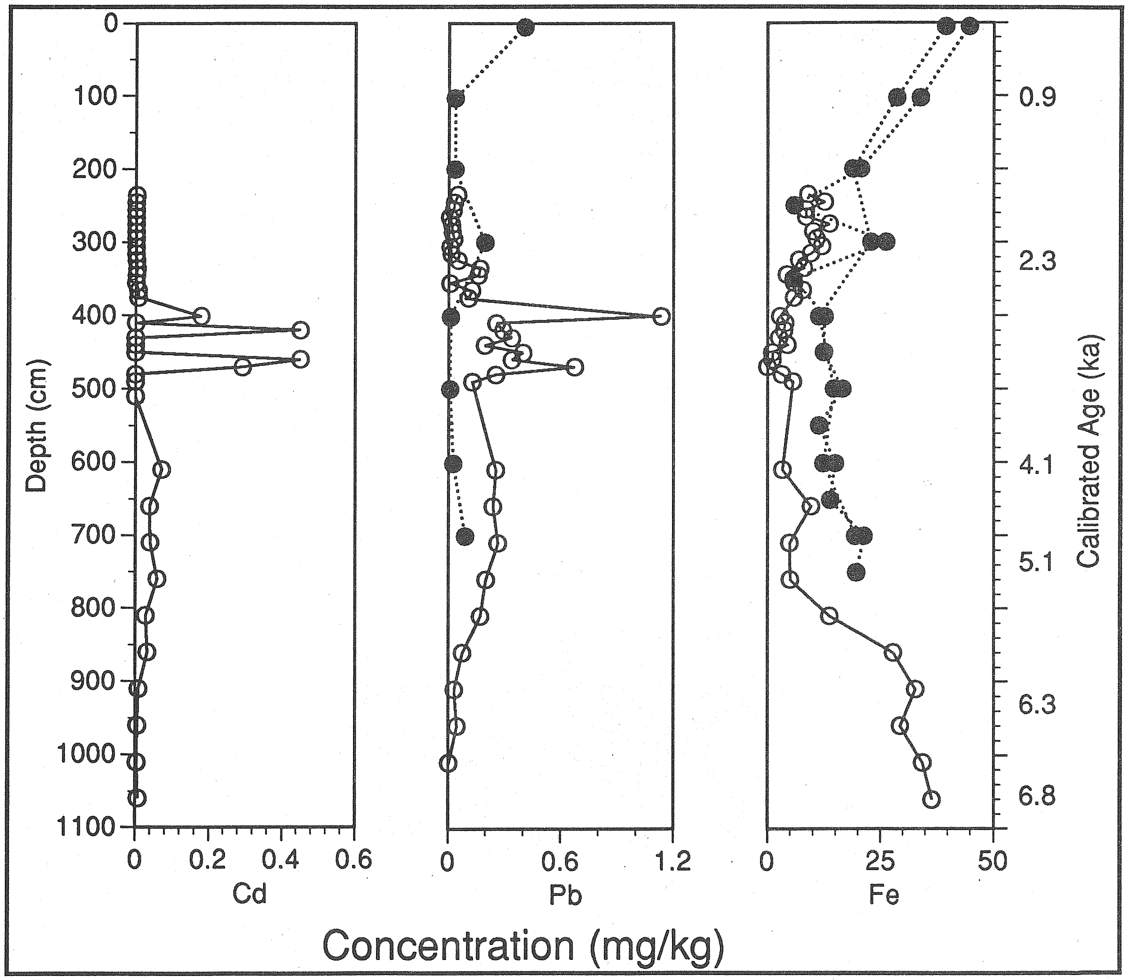

Figure 3. TRACE METALS AS A FUNCTION OF DEPTH AT BROWNS ISLAND.
Solid circles indicate values from core BI-1992; open circles indicate values from core BI-1993.
High resolution data (1-cm sampling intervals) between 200 and 400 cm depth in core BI-1993 have been averaged over decimeter for plotting here.

In addition to these long period trends, several discrete peaks are observed in the data. At 3 meters depth, Pb and Fe have small peaks; between 4 and 5 meters depth, there are several coincidental peaks in Pb and Cd; at 6.5 meters depth, Fe peaks; and at 7.6 meters depth, Cd peaks. In general, the more soluble elements (Cd and Pb) vary coincidentally but Fe behaves in an opposite fashion. As Cd is enriched in sea water, Cd peaks should reflect more saline inundation, and Pb, being transitional between Fe and Cd, should reflect moderate drought conditions.

Macrofossils

Stem, leaf, and root materials were described continuously throughout the cores and seeds were described at discrete intervals (Figure 4). Above 3.25 centimeters, the macrofossils are similar to the plants found on the island today; *Scirpus* seeds are common throughout this zone (BI-1992), *Scirpus americanus* roots are present to at least 0.5 meter depth (BI-1993) and *Distichlis* roots are present in the upper 20 centimeters. A few *Cyperaceae* seeds are also present in these uppermost sediments. Within a thin silt layer at 1 meter depth, seeds from the pondweed *Potamogeton* were found in BI-1992, and several foraminifera (*Trochomina inflata*) were found at this same depth in BI-1993. The presence of two species (*T. inflata* and *Potamogeton*) that live exclusively in the subtidal regions of the marsh within a discrete silt layer is indicative of a large overbank flood.

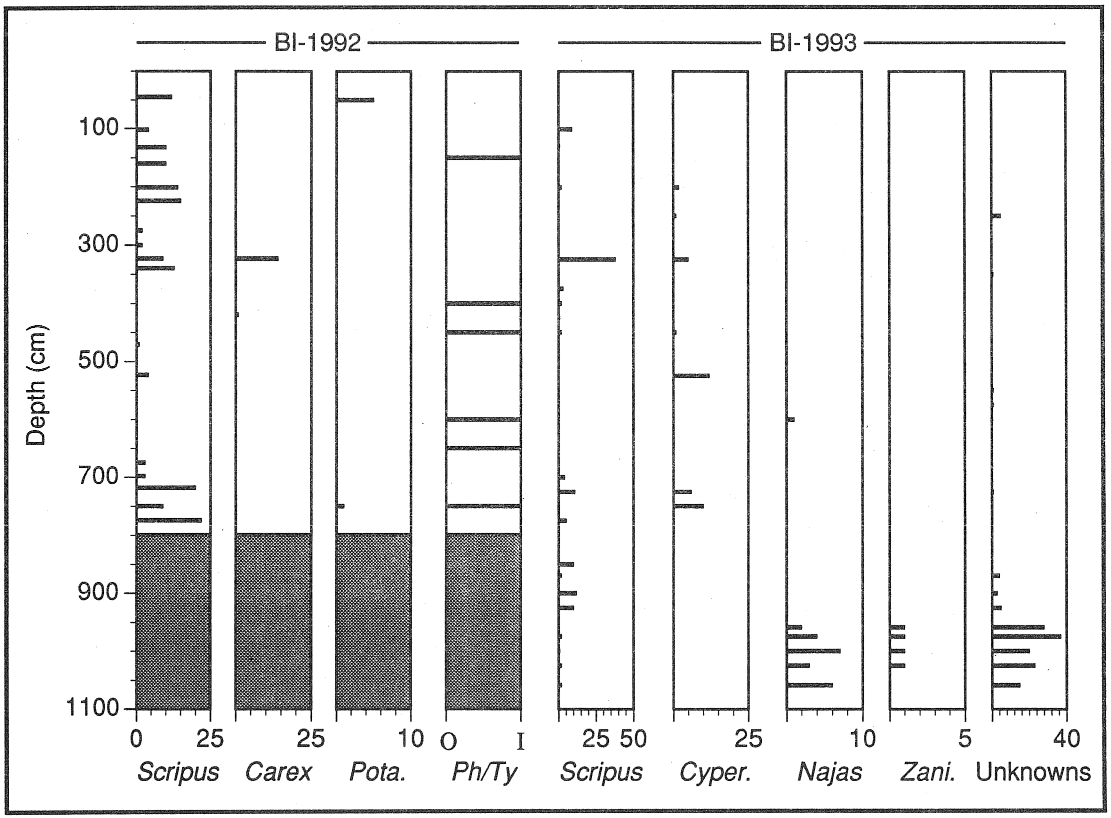

Figure 4. MACROFOSSIL COUNTS AS A FUNCTION OF DEPTH IN THE SEDIMENTS FROM BROWNS ISLAND.
Horizontal bars reflect the number of seeds counted in 1-cm-thick sediment layers for *Scirpus, Potamogeton, Cyperaceae, Najas,* and *Zanichellia.* The category Ph/Ty records the presence or absence (I/O) of stems from either *Phragmites* or *Typha* species.

At 3.0 and 3.5 meters depth, there is a small peak in frequency of *Scirpus* and *Cyperaceae* seeds. Between 3.5 and 7 meters depth, the frequency of all seeds decreases markedly, with only an occasional *Scirpus* or *Cyperaceae* seed present. However, stems and leaves fro *Typha/Phragmites* (we have not established a difference between the stem fragments of these two species) are common in this depth range. At 7 meters depth, the frequency of *Scirpus* seeds increases again and then drops off below 9.5 meters. Below 9.5 meters, seeds from *Najas* and *Zanichellia*, which do not occur on Browns Island today but are present farther upstream in the delta, become common. There is also an abundance of seeds from 21 unidentified species below 9.5 meters, suggesting that the regional diversity of plant life was high during this time.

Stratigraphic Interpretation and Environmental History

We subdivide the stratigraphy at Browns Island into six zones, numbered from the top (youngest) to bottom (oldest). Here we provide a stratigraphic interpretation of the deposits starting at the base of the section and working up.

The basal sediments of Zone 6 (9.5-10.6 m; 6.3-6.8 ka) are laminated clayey silts. The two identified seed types fro this level are submersed fresh to brackish water plants, *Najas* (water nymphs) and *Zanichellia* (horned pondweed). Many of the unidentified seed types in this section may be detrital seeds washed in from upstream and deposited with the detrital mud. The low levels of Cd and Pb suggest that the water tended toward fresh; the high Fe levels confirm the subtidal nature of deposition (Thomas and Varekamp 1991). We, therefore, interpret this zone to have been deposited on a fresh to slightly brackish subtidal mudflat with conditions similar to those upstream near Sacramento today.

Zone 5 (7.5-9.5 m; 5.1-6.3 ka) is a section of mud (clayey silt) interbedded with thin peat layers. The laminated structure of these sediments can be observed on the density logs (Figure 2A). The gradual increase in Cd and Pb through this zone suggest that the water was becoming more saline as sea level rose, and the decrease in Fe indicates a decrease in frequency of tidal inundation. This is confirmed by the increased frequency of *Scirpus* seeds, as *Scirpus* does not grow in subtidal conditions. Thin discrete peat layers within the muds probably result from plant colonization of the mudflats and their subsequent burial by subtidal mud. This stratigraphy indicates that the rates of sea level rise and sedimentation alternatively superseded each other such that incipient marshes formed and were subsequently drowned.

Zone 4 (6.0-7.5 m; 4.1-5.1 ka) sediments are peats with decreasing inorganic content with time. Cd levels are high in this zone, while Fe levels remain low. The frequency of *Scirpus* seeds decreases upward, and *Cyperaceae* seeds are present around 7 meters depth in the BI-1993 core. *Phragmites/Typha* leaf sheaths are present throughout. At 7.5 meters depth, *Potamogeton* seeds are present in a layer that also has high Cd levels. The concurrence of *Potamogeton* with a trace metal indicator of high salinity suggests a rapid submergence and abrupt increase in relative sea level, perhaps resulting from a tectonic subsidence event. The apparent stratigraphic inversions indicated by radiocarbon dates from this zone may have resulted from local erosion and redeposition of marsh sediments. However, the submergence event was not sufficient to bury the peats in subtidal mud. The upper part of this zone is characterized by low-density peats that rapidly expand when the cores are cut open. We interpret Zone 4 to indicate deposition in a brackish tidal marsh with the possibility of tectonic subsidence occurring about 5 ka.

Zone 3 (3.25-6.0 m; 2.3-4.1 ka) sediments are clayey peats with very high organic content and only rare *Scirpus* or *Cyperaceae* seeds. Leaf sheaths of *Phragmites/Typha* are present throughout. We interpret the absence of seeds and high organic content to indicate deposition in a relatively freshwater tidal marsh. This is confirmed by the generally low metal concentrations in this zone. However, three discrete peaks i the Cd and Pb curves around 3 ka (401, 420, and 460 centimeters depth) indicate salinity intrusion and drought did occur during this time. It is interesting, however, that although the bulk sediment suggests lower mean salinity, the absence of laminations and silt bands suggests a lower frequency of extreme floods. Therefore, we interpret this to be a period when mean freshwater discharge was higher than modern while extreme drought was more common than extreme flood.

Zone 2 (1.0-3.25 m; 0.9-2.3 ka) sediments are peats with somewhat lower organic content than observed in Zone 3. The frequency of *Scirpus* seeds is higher here, especially in core BI-1992, and a few *Cyperaceae* seeds are present. The abundance of Scirpus and Cyperaceae seeds at the base of this zone may indicate a rather abrupt return to more brackish conditions at about 2.3 ka. At 3 meters depth (about 2.2 ka), there is a peak in concentrations of Pb and Fe. The increased inorganic content of the peat at this depth indicates either increased inundation frequency, decreased local organic production, or both. The coincidence of the peak in metals concentration with the decrease in organic content suggests there was an increase in inundation frequency most likely resulting from an increase in relative mean sea level.

Zone 1 (0-1.0 m; 0-0.9 ka) sediments are peats with elevated levels of Pb and Fe. Live roots are common in the upper 25 centimeters and probably extend throughout this section. The sediments have low densities and high water content. Atwater (1980) noted the presence of *Distichlis spicata* rhizomes to depths of about 1 meter, and we identified *Scirpus* seeds, *Scirpus americanus* roots, and *D. spicata* roots in this zone. A 1-centimeter-thick silty clay layer at 45 centimeters depth (0.5 ka) contains abundant sand-sized mica grains, seeds from the pondweed *Potamogeton*, and the agglutinated foraminifera *Trochominna inflata*. The detrital mica is most likely derived from the batholithic rocks of the Sierra

Nevada. In conjunction with seeds from a plant that grows exclusively in the open water of the marsh channels, this deposit indicates a large freshwater flood. A second thin silt band was observed at 15 centimeters depth (0.35 ka) in the BI-1993 monolith. Therefore, we interpret Zone 1 sediments to record conditions similar to those on Browns Island today: predominantly brackish water with occasional large-scale floods.

Summary and Conclusions

Peat sediments from Browns Island record paleoenvironmental conditions in the upper San Francisco Estuary during the later Holocene. By 6.8 ka, tidal waters had inundated the downstream end of the Sacramento/San Joaquin Delta, and subtidal deposition began in relatively fresh water. Intertidal marsh sedimentation was initiated by 5.1 ka, and the marsh plain aggraded in brackish water until 4.1 ka. Between 4.1 and 2.3 ka, local water freshened, indicating increased discharge from the Sacramento/San Joaquin drainage basin. After 2.3 ka, brackish conditions returned that continue to the present day. Enhanced trace metal concentrations at the surface result from modern metal contamination in the estuary.

stratigraphic data imply that shorter-period extreme events occurred throughout the later Holocene. The preservation of fine-scale laminations throughout much of the section indicates that these high-frequency events are common and well preserved. Examples of these short-period events are:

- Extreme flooding (*eg*, about 0.5 ka) recorded by thin silt layers with allocthonous fossil and terrigenous debris.
- Several extreme droughts (about 3.0 ka) recorded by a peak in Cd and Pb content during a period of relatively high organic deposition.
- Increased tidal inundation (about 2.2 and 4.5 ka) recorded by peaks in trace metals concentrations and relatively low organic content. These events may have resulted from catastrophic submergence during large earthquakes.

High-resolution sampling now in progress should allow us to resolve the relationships between changes in the long-term mean conditions described above and changes in the frequency of shorter-period extreme events. Preliminary data suggest extreme drought and salinity intrusion occurred even during periods when the mean freshwater discharge from the Sacramento/San Joaquin drainage basin was higher than modern values.

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