

Vegetation and salinity changes over the last 2000 years
at two islands in the northern San Francisco Estuary, California

by

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Section 1—Introduction

The San Francisco Estuary, surrounded by one of the largest urban areas of California, has been heavily modified by human activity (Nichols et al., 1986). A long-standing debate among resource managers of the Estuary concerns the control of freshwater flows and salinity (Jarvis 1921, Jackson and Paterson 1977, SFEP, 1993). Much remains to be learned about the effects of water diversion practices in the Estuary's watershed. Knowledge of past patterns of salinity and flow can provide the context necessary for good management decisions. This study, a palynological investigation of brackish wetland sediments in northern San Francisco Estuary, establishes a record of vegetation, salinity, and flow change over the last 2000 years.

Principles of pollen analysis of sediments

Flowering plants disperse pollen as part of their reproductive cycle. The type and density of plants in an area create a unique "pollen rain" upon the landscape. In aggradational landscapes, the pollen deposition over time is preserved in the sediments. The outer layer of the pollen grain wall, known as the exine, is extremely resistant to decay, and pollen may remain well preserved for thousands or millions of years (Faegri and Iversen, 1989). A comparison of palynomorph abundances in different sedimentary layers, combined with age determination, provides a proxy record of vegetation change through time.

San Francisco Estuary

The San Francisco Estuary, the largest estuary on the west coast of North America, joins California's two largest rivers (the Sacramento and the San Joaquin) and the Pacific Ocean. About 40% of the land area of California (approximately 153,000 km²) drains through the Estuary (Figure 1) (Cohen, 1991). The Estuary formed about 10,000 years ago as the Pacific Ocean, rising at about 2 cm per year, flooded through the Golden Gate (Atwater et al., 1977). The rapid rate of sea level rise at this time limited the formation of tidal marsh. About 8,000 years ago the rate of sea level rise began the decline to the present rate of 0.1–0.2 cm per year, a rate slow enough to allow the formation of extensive tidal

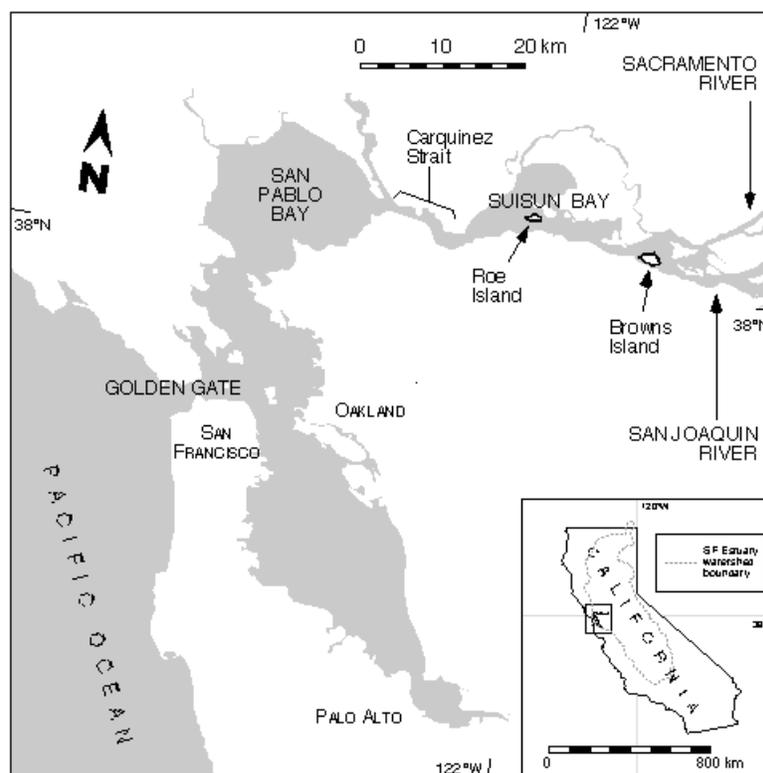


Figure 1. Western portion of San Francisco Estuary. Sampling locations Roe Island and Browns Island drawn with bold outline.

wetlands along the periphery of the Estuary (Atwater et al., 1979). The Estuary consists of two parts: San Francisco Bay (roughly west of Browns Island), and the Delta (east of Browns Island). The open water of San Francisco Bay consists of 4 major embayments and covers about 104,000 hectares to an average depth of 6.1 meters at low tide (Conomos, 1979). The Delta covers 300,000 hectares with hundreds of kilometers of natural and constructed waterways and over 1600 km of levees. Most of the land in the Delta is now below sea level as a result of levee construction and subsequent compaction and decomposition of peat (DWR, 1993).

Hydrology of the Estuary

The Estuary is under the tidal influence of the Pacific Ocean. The volume of the tidal prism is approximately $1.6 \times 10^9 \text{ m}^3$. Tides are mixed semi-diurnal, with an average range of about 1.7 m, decreasing with distance upstream (Cohen, 1991). In contrast, daily inflow of freshwater can vary dramatically but is usually a small fraction of the tidal prism, averaging about $6 \times 10^7 \text{ m}^3$. Total inflow for the year is also highly variable, from about $6 \times 10^9 \text{ m}^3$ during drought to over $75 \times 10^9 \text{ m}^3$ during years of highest precipitation (SFEP, 1992). Inflow is highly seasonal, with a peak average monthly flow in January or February that is typically 8 or 10 times greater than the flow of July or August. Instantaneous inflow can vary from less than $100 \text{ m}^3/\text{s}$ in the late summer and fall, to over $10,000 \text{ m}^3/\text{s}$ after a winter storm (USGS, 1995). This freshwater inflow is superimposed on the tidally forced bi-directional flow that typically peaks at about $9,500 \text{ m}^3/\text{s}$ (summer conditions, measured near Browns Island) (DWR, 1993). About 70% of the

Estuary's freshwater inflow is from the Sacramento River, 20% from the San Joaquin River, and 10% from local tributaries to the Estuary.

Freshwater flow is important to the Estuary in several ways. The abundance of several estuarine species at different levels of the food chain has been shown to positively correlate with a measure of freshwater flow (Jassby, 1992).

Freshwater flow also flushes the effluent from the heavily industrialized shore of the Estuary east of San Pablo Bay toward the ocean (Nichols et al., 1986). In addition, flow is critical in keeping salinity low enough to ensure high water quality for the 20 million people and 4.5 million acres of farmland that depend on water diverted from the Estuary for domestic and agricultural uses (SFEP, 1997).

The mixing of salt and fresh water creates a salinity gradient in the Estuary, the daily characteristics of which are largely determined by the magnitude of freshwater discharge from the Sacramento and San Joaquin rivers (Conomos, 1979). During periods of high flow, the salinity gradient is compressed and moves toward the mouth of the Estuary. High flows also cause vertical stratification of the water column, with lower density fresh river water overlying saline water from the ocean. During low flows the stratification breaks down, and saline ocean water moves further upstream (Jassby et al., 1994). It is believed that, under natural conditions, the transition from fresh to brackish water would most often occur in the Carquinez Strait (Jackson and Paterson, 1977).

Water development and historical salinity intrusion

The first water diversion in the Estuary's watershed was probably an agricultural diversion on the Merced River in 1852 (Jackson and Paterson, 1977).

By 1870, diversions were large and numerous enough that the flow in the San Joaquin River was noticeably reduced. In 1912 the water-intensive cultivation of rice began in the Sacramento Valley. By 1919, rice and other crops had led to diversions from the Sacramento River of $2.8 \times 10^9 \text{ m}^3/\text{yr}$, over one-third the river's annual output (Jackson and Paterson, 1977). Water users along the shore of Suisun Bay had to contend with an increase in salinity as reduced flow allowed ocean water to move upstream.

Although the salinity problems along Suisun Bay at this time were directly attributed to upstream diversions, scattered historical records indicate salinity intrusion into Suisun Bay was within the natural variation of the Estuary. In the summer of 1775 when Juan Manuel de Ayala sailed into Suisun Bay, fresh water was not encountered until at least mid-way through the Bay (Jackson and Paterson, 1977). In the summer of 1841, Commander Ringgold and crew camped near the town of Antioch, six kilometers up the San Joaquin River, and found the water too saline to drink (Jackson and Paterson, 1977).

In 1920, record water diversions for rice production coincided with drought, and salinity intrusion extended further inland than ever previously documented. Water with 1 part per thousand salinity moved up the Sacramento River nearly to the town of Isleton (30 kilometers upstream of Suisun Bay on the Sacramento River) (DWR, 1993). Legal and political battles between the Suisun Bay water users and upstream diverters ensued. Numerous studies judged the feasibility of solutions such as construction of a "salt water barrier" or dam near Suisun Bay (Jarvis, 1921; Young, 1929; DPW, 1931a; DPW, 1931b). By 1931, however, it was concluded that the solution to the salinity intrusion problem, as well as

numerous other benefits, would come through upstream reservoir storage and controlled release. The construction of Shasta Dam for the Central Valley Project (CVP), completed in 1944, was the first in a long series of large water projects developed in the watershed of the Estuary. The CVP built dams on the American, San Joaquin, and Stanislaus rivers, and the State Water Project completed Oroville dam on the Feather River in 1967. In addition to these dams, diversion canals and pumping systems were built to export water from the Delta to agricultural and urban areas to the south. The largest of these canals are the Delta-Mendota Canal and the California Aqueduct, both of which pump water from sloughs in the southern Delta.

The release of reservoir water in the summer and fall has prevented salinity intrusions like those of the 1920s and 1930s from occurring again, however, each of these projects has caused a net loss of fresh water to the Estuary. The combined effects of current water development in the Estuary's watershed reduce the average annual freshwater inflow by over one-half (Nichols et al., 1986; SFEP, 1992). In terms of monthly averages, flows in the spring months, the period when diversions are at a maximum, are reduced one-half to three-quarters from pre-development flow, and the peak flow is much earlier in the year (typically February rather than April or May) (Peterson et al., 1989; SFEP, 1992). Minimum flows in August and September, on the other hand, are considerably higher than in decades prior to the water projects, due to reservoir releases (SFEP, 1997).

Distribution of wetland plants in the Estuary

The salinity gradient in the northern Estuary is accompanied by a gradient of wetland plant life, with halophytes such as *Spartina* and *Salicornia* in the more saline marshes of San Francisco Bay, and salt-intolerant plants such as *Scirpus* and *Typha* in the Delta. The typical marsh in San Francisco Bay contains about 14 species of wetland plants, while the islands of the Delta typically support about 40 species of freshwater marsh plants (Atwater et al., 1979). Between the Bay and the Delta lies the region of focus of this study, a transitional zone containing both salt and freshwater species. In this study two pollen types are particularly important, the Chenopodiaceae type and the Cyperaceae type. The former is assumed to represent *Salicornia virginica* and possibly *Atriplex* spp., the latter several species of *Scirpus*, namely *Scirpus olneyi*, *Scirpus robustus*, *Scirpus californicus*, and *Scirpus acutus*, and possibly also *Juncus* spp. *Salicornia virginica* is an important component of the Estuary's salt marshes, growing close to mean higher high water and often forming monotypic stands. *Salicornia virginica* ranges upstream as far as Browns Island (Atwater, 1979; Goman, 1996). *Atriplex* spp., found in smaller quantities, has a similar range. The several species of *Scirpus* are found in abundance in the Delta and extend west to the marshes of San Pablo Bay (Atwater, 1979). While most species of *Scirpus* are intolerant of salt water and are therefore restricted to the Delta, one species, *Scirpus robustus*, is more adapted to saline conditions and is not found upstream of Suisun Bay.

Reduction in wetlands

In 1850, there were approximately 140,000 hectares of freshwater marsh in the Delta, and about 80,000 hectares of salt and brackish wetlands along the shoreline of San Francisco Bay (Gilbert, 1917). Today, more than 90% of those

wetlands have been diked, filled, or otherwise altered (Nichols et al., 1986). Conversely, human activities in the watershed have caused the creation of about 7500 hectares of new tidal marsh (Atwater, 1979). The two sites chosen for this study are examples of relatively undisturbed marsh, probably similar to marshes existing in the same area prior to 1850.

Section 2—Methods

Site selection

This thesis is based on cores from two study sites: Browns Island and Roe Island (Figure 1). These sites were chosen because of the low level of human disturbance, and their location within the salinity gradient. It was also assumed that pollen records from the two sites would be different enough to allow reconstruction of recent (i.e. over the last 2,000 years) changes in the salinity gradient.

Browns Island is a 2.8 km² tidal wetland located in the San Francisco Estuary at the confluence of the Sacramento and San Joaquin rivers, approximately 77 kilometers from the mouth of the Estuary (Figures 1, 2). This site is the furthest upstream, and thus the least saline, of the two study sites. Most of the island is below mean higher high water (approximately 1 meter above the National Geodetic Vertical Datum (NGVD) (Atwater and Belknap, 1979)). The island has been tidal for approximately 6,300 years (Goman, 1996). Although evidence of past human activity is present on the island, including mosquito ditches, remnants of small structures (likely duck blinds) and the presence of an abandoned tule-cutting tractor near the core site, there is no evidence of reclamation, dredge spoil disposal, or other major hydrological modification. According to some accounts a bordello was operated on the island (Knight, 1980). In 1978 the island was purchased by the East Bay Regional Park District.

The vegetation of Browns Island has been relatively undisturbed by human activities (Collins, 1998, pers. comm.). The dominant species are *Scirpus* spp. and *Distichlis spicata* (Goman, 1996). In a 182 m transect taken in 1978, extending

north from the central slough, *Scirpus acutus* was found adjacent to the slough (up to 0.9 m NGVD), replaced within 20 m by *Scirpus olneyi* and *Distichlis spicata*, both abundant in the rest of the transect (up to approximately 1 m NGVD) (Atwater and Belknap, 1979). *Salicornia* was found occasionally in the highest portion of the transect. Browns Island appears to be the easternmost extent of several Estuary halophytes, including *Distichlis*, *Triglochin*, and *Salicornia* (Atwater and Belknap, 1979). *Salicornia*'s sparse presence (Atwater et al., 1979; Goman, 1996) is in sharp contrast to its importance in the more saline marshes to the west. Theoretically a change to more saline conditions should result in a marked increase in the species' abundance on the island.

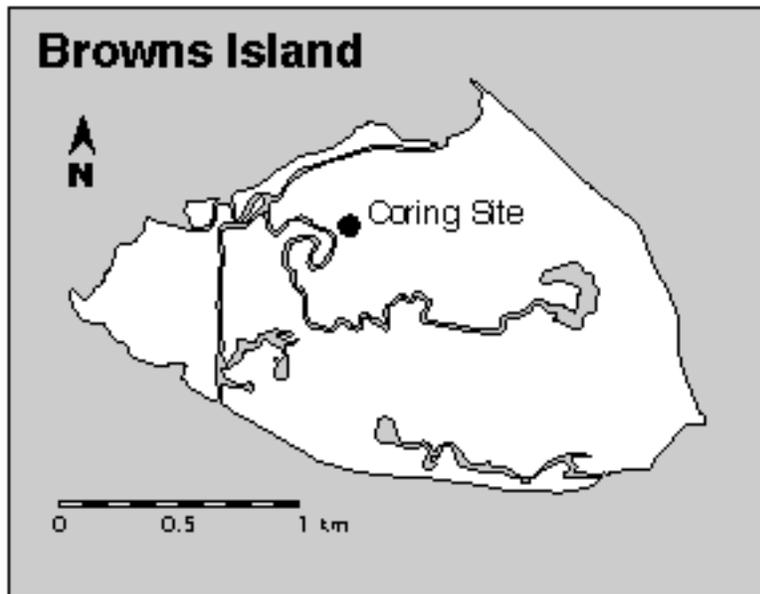


Figure 2. Coring location on Browns Island.

Roe Island with an area of 1.1 km² is located approximately 16 km downstream of Browns Island and 65 kilometers from the mouth of the Estuary (Figures 1, 3). Evidence of past human activity includes what appears to be a small dirt road visible in a 1965 aerial photo (now completely obscured by marsh

vegetation), and several large wooden poles (approximately 30 cm in diameter, and several meters in length) discovered lying underneath vegetation near the sampling site. There is some evidence of past diking along the main channel on the north side of the island. Between 1891 and 1945, a wooden lighthouse was operated at the southernmost point of the island (Shanks and Shanks, 1990). Use of the lighthouse was discontinued shortly after the infamous Port Chicago explosion of 1945, which deposited sections of railroad cars and ship plating on the island (Caul and Todd, 1996). The island is part of the Concord Naval Weapons Station.

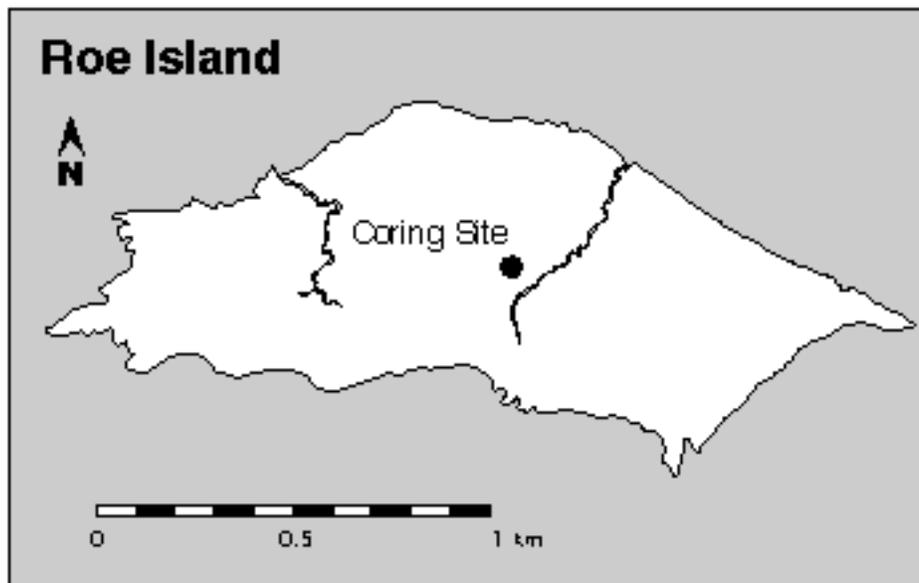


Figure 3. Coring location on Roe Island.

Average salinity, based on monthly readings from 1988–1994, is significantly higher and more variable at Roe Island than at Browns Island (Table 1). This difference in salinity regime affects plant species abundance and distribution. For example, the more saline environment of Roe Island has vigorous stands of *Salicornia virginica*.

	Browns Island	Roe Island
Avg. salinity 1988–94	3.0 psu	7.9 psu
Standard deviation	2.4 psu	4.5 psu
Minimum salinity 1988–94	0.06 psu	0.07 psu
Maximum salinity 1988–94	8.78 psu	16.11 psu

Table 1. Salinity data for Browns Island and Roe Island (USGS, 1998). Salinity units are practical salinity units (psu), indicating indirect measurement using a conductivity meter.

The two islands are in the same subregion of the Estuary and should contain corresponding evidence of any large-scale environmental change, while at the same time, Roe Island’s record should reflect more saline conditions. The two locations should provide a degree of replication, as well as contrast.

The plant cover at the core site at Browns Island (Figure 2) was approximately 60% *Juncus* spp., 20% *Triglochin maritima*, and 10% *Salicornia virginica*. This location hosted the thickest cover of *Salicornia* found on the island. In brackish marshes such as those of Browns Island, *Salicornia* is found only on the higher more saline parts of the intertidal zone (Goman, 1996).

At Roe Island the coring site was located at the center of the island, roughly equidistant from all shorelines, in what was assumed to be an older portion of the island. The plant cover at the core site was roughly 50% *Distichlis spicata* and 50% *Salicornia virginica*.

Core Collection

Core samples were collected with the aid of a hand-operated 5 cm diameter Livingston coring device with locking piston (Figure 4). Each operation of the device recovers up to 1 meter of sediment; the starting depth of each sample is controlled by unlocking the piston at the desired depth. Maximum core depth at Browns Island was 3.5 meters, and at Row Island 4.25 meters.

Core sampling began at 25 cm depth to avoid the tough dense root mass of the upper few centimeters.

The 0–25 cm section of sediment at each site was recovered intact using a shovel. Piston cores were

extruded into plastic (butyrate) tubing, capped, sealed with tape, labeled, and transported to the lab for analysis. Each site was located by taking compass bearings of local landmarks.

X-ray and Loss on Ignition

To establish variations in sediment density, x-radiographs of each core were taken. These were scanned into a Macintosh computer using a Microtek Scanmaker III flatbed scanner with transparency adapter, and depth vs. density plots made using NIH Image 1.6.1. Next, the cores were opened, 1 cm thick sections were cut from each core, and then two 1.3 cm³ subsamples were taken from each section using a 1.3 cm diameter cylindrical metal cutter. One of these subsamples was used for loss on ignition analysis, and the other for pollen analysis.



Figure 4. Livingston coring device

Dry weight was obtained by placing a weighed subsample in an oven and heating for 24 hours at 100°C, cooling, and weighing again. Loss on ignition was then determined by placing the sample into a 600°C furnace for 1 hour, cooling, and weighing again. All cooling took place in a dessicator to prevent weighing errors due to uptake of moisture.

Core chronology and description

Accelerator mass spectrometer (AMS) ¹⁴C dating of seeds was used to establish core chronology. The use of seeds avoids uncertainties associated with dating other plant fragments or bulk sediment (Cole and Liu, 1994; Wells, 1995). Plant roots extend into older sediments and can confuse the chronology if they are sampled. Distinguishing root fragments from non-root fragments (e.g. stems) is not always possible, whereas seeds are easily distinguished from all other plant material.

Seeds were picked from a 1-cm section of core under a dissecting microscope, and sent to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory for preparation and dating. About half of the seed samples consisted exclusively of *Scirpus* (from 3 to 10 seeds, each seed being approximately 1 mg), the rest included seeds of *Salicornia* and other unidentified seed types. Only one date was determined on non-seed material. The 345 cm subsample of the Roe Island core was based on wood fragments because no seeds were encountered in this section of the core.

The radiocarbon dates were calibrated using the bidecadal dataset of CALIB rev 3.0.3c for the Macintosh (Stuiver and Pearson, 1993).

Each core was sliced lengthwise and Munsell color, composition (peat/clay), and presence or absence of roots recorded.

Pollen Analysis

Pollen analysis followed standard technique (Faegri and Iversen, 1989). Samples were treated successively with hydrochloric acid, potassium hydroxide, hydrofluoric acid, nitric acid, glacial acetic, and sulfuric acid. Each treatment was followed by a distilled water wash. After treatment with potassium hydroxide, each sample was sieved through a 125 micron mesh to remove large organic debris. Control for pollen density calculations was provided by addition of a known quantity of *Lycopodium* spores (tablet form) to each sample test tube. At the conclusion of treatments, samples were stained with safranin and mounted in silicon oil in preparation for pollen counting. Counting was done at 400X magnification with a Leitz microscope. Identification of pollen grains was aided by published keys (Kapp, 1969; McAndrews, 1973), reference collections and a hypertext markup language (HTML) key of pollen types specific to the San Francisco Estuary wetland environment. The HTML key, developed as part of this project, is available to other researchers via the U.C. Berkeley Department of Geography world wide web server [<http://www.geography.berkeley.edu>]. At each level analyzed between 200 and 700 grains were counted and categorized into approximately 30 different pollen types.

A total of 32 samples each were taken from the Browns Island and Roe Island cores for pollen analysis.

Section 3—Results

Browns Island

¹⁴C Chronology

Nine seed samples were sent to Lawrence Livermore National Laboratory for AMS ¹⁴C dating. One of the results was excluded due to insufficient carbon after pretreatment (0.04 mg). The eight remaining dates are plotted in Figure 5. A linear regression yields an average sedimentation rate of approximately 1.4 mm/year. This is in agreement with other recent measurements of sedimentation

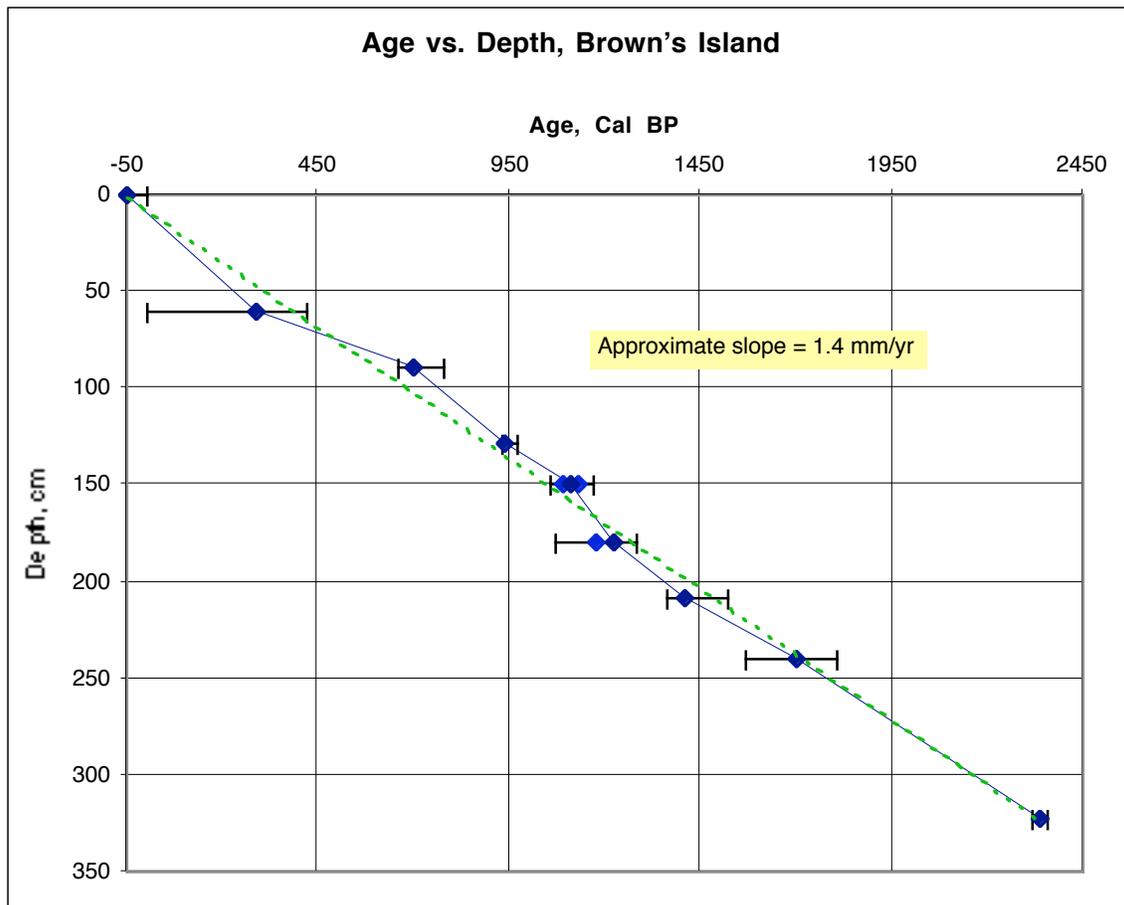


Figure 5. ¹⁴C age vs. depth curve for Browns Island sediment core. Error bars indicate calibrated one-sigma age range. Multiple datapoints indicate multiple intercepts of the calibration curve. Dotted line is a linear regression. The current marsh surface (0 cm) is given a date of -47 BP.

rate in the area (Byrne, 1998, unpublished data), and with the estimated rate of sea level rise for this time period (Atwater et al., 1977). The relative stability of the age vs. depth curve over the last 2500 years indicates that there have been no large vertical movements related to tectonic events, or anthropogenic disturbances such as dredge spoil deposition or excavation.

Possible errors in the chronology results, caused by the small amount of carbon in some samples after preparation and the multiple intercepts of the calibration curve, makes conclusions regarding changes in sedimentation rate tentative. Nevertheless, sedimentation rate appears to have increased considerably between 179 cm and 149 cm (1220 cal yr BP and 1110 cal yr BP), and again between 60 cm (290 cal yr BP) and the surface. The last increase may be related to the movement of sediment into the Estuary as a result of hydraulic mining in the 19th century (Gilbert, 1917). The slowest rate, approximately one-half the average, occurred from 89 cm to 60 cm (700 cal yr BP to 290 cal yr BP). Notably, the three most well-constrained points in the curve, at 322 cm, 129 cm, and 0 cm, are in close alignment with each other and the average sedimentation rate.

Stratigraphy, Loss on Ignition, and X-Radiography

The stratigraphy of the Browns Island core is monotonous. The core consists entirely of peat, except for 25 centimeters of clay-rich peat at the top (Figure 6). Between the surface and 250 centimeters, roots, 1–2 mm in diameter, were found in the vertical growth position.

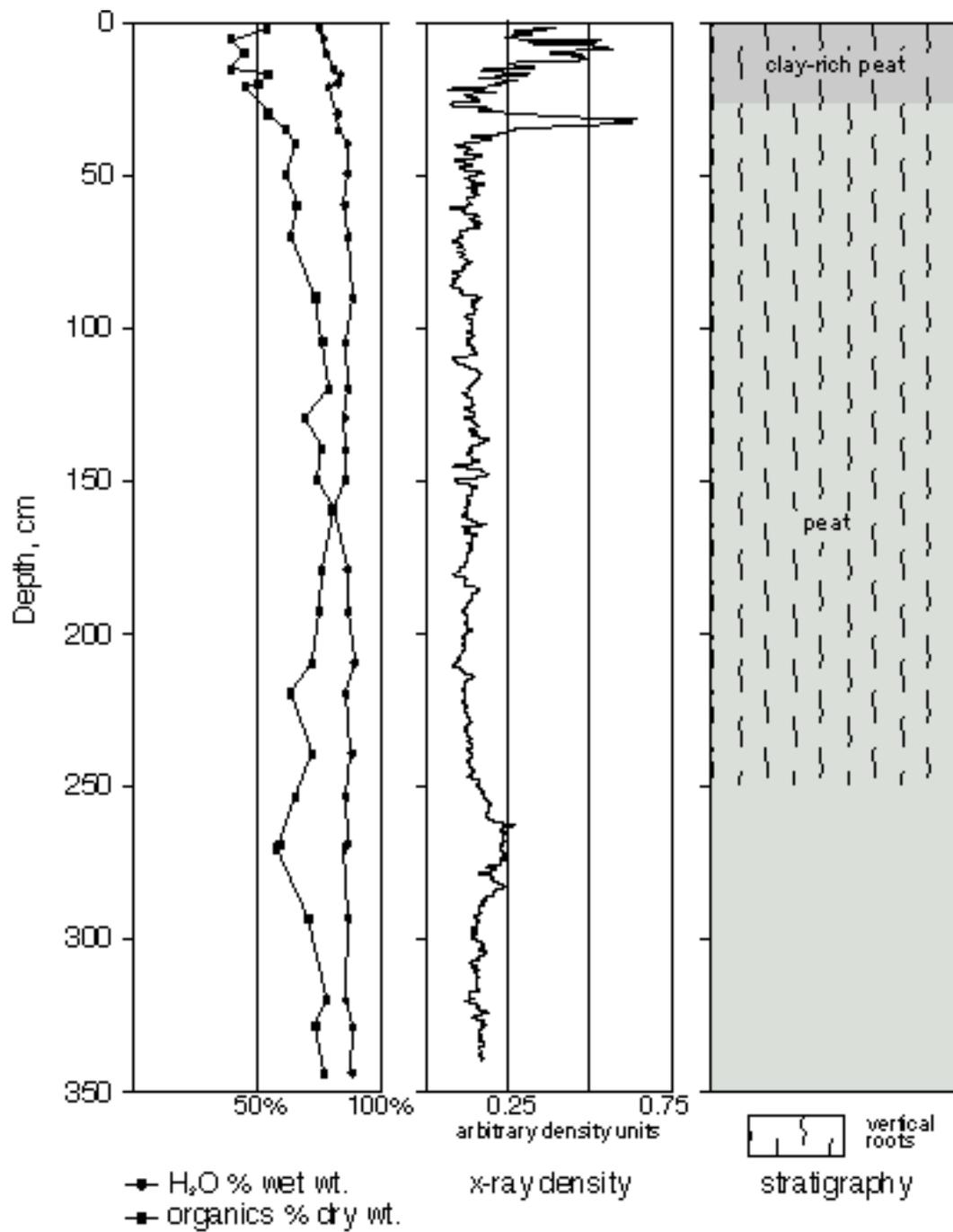


Figure 6. Loss on ignition, x-radiograph density, and stratigraphy description for Browns Island.

X-radiography shows increased density in the upper 20 cm and from approximately 265 cm to 290 cm. Density measurements between 30 and 36 cm are not available due to a problem with the x-radiograph film exposure. The x-radiography shows some “density bands” throughout the core, but no sand lenses or other sedimentary features were found that corresponded to these bands.

Loss on ignition results generally correspond with the observed stratigraphy and x-radiography (Figure 6), showing an increase in inorganic content in the upper 25 cm and a maximum in the lower portion of the core at 275 cm. The less organic sediments tend to hold less water, as seen in the upper 25 cm.

Pollen analysis

Of the 32 Browns Island samples processed for pollen counting, 4 were uncountable due to insufficient pollen. A pollen diagram of key taxa for the remaining samples is presented in Figure 7. The overall pollen record shows little variation. The largest changes in occur in the upper 5 cm, where the Chenopodiaceae type increases dramatically, and the Cyperaceae type drops off. At 2 cm, the uppermost level counted, the high Chenopodiaceae level has dropped about half, and *Triglochin* increases. The Compositae type shows an overall gradual decrease in abundance towards the present. Total pollen density is variable, from a minimum of 16,000 grains/cm³ at 21 cm to a maximum of 141,000 grains/cm³ at 70 cm. The pollen density maximum at 70 cm is consistent with the decreased sedimentation rate of that time period (see ¹⁴C chronology, above) if it is assumed that no change in pollen deposition rates occurred. It seems unlikely that the slowing in sedimentation rate was the result of upward

tectonic movement of the marsh, since the ratios of marsh pollen at this time are not substantially different than in adjacent sections. Upward movement would cause changes in vegetation composition that would appear in the pollen record. Rather, the change in sedimentation rate may be related to changes in fluvial-detrital sediment delivery to the study site.

Browns Island Selected Marsh Taxa (Site A)

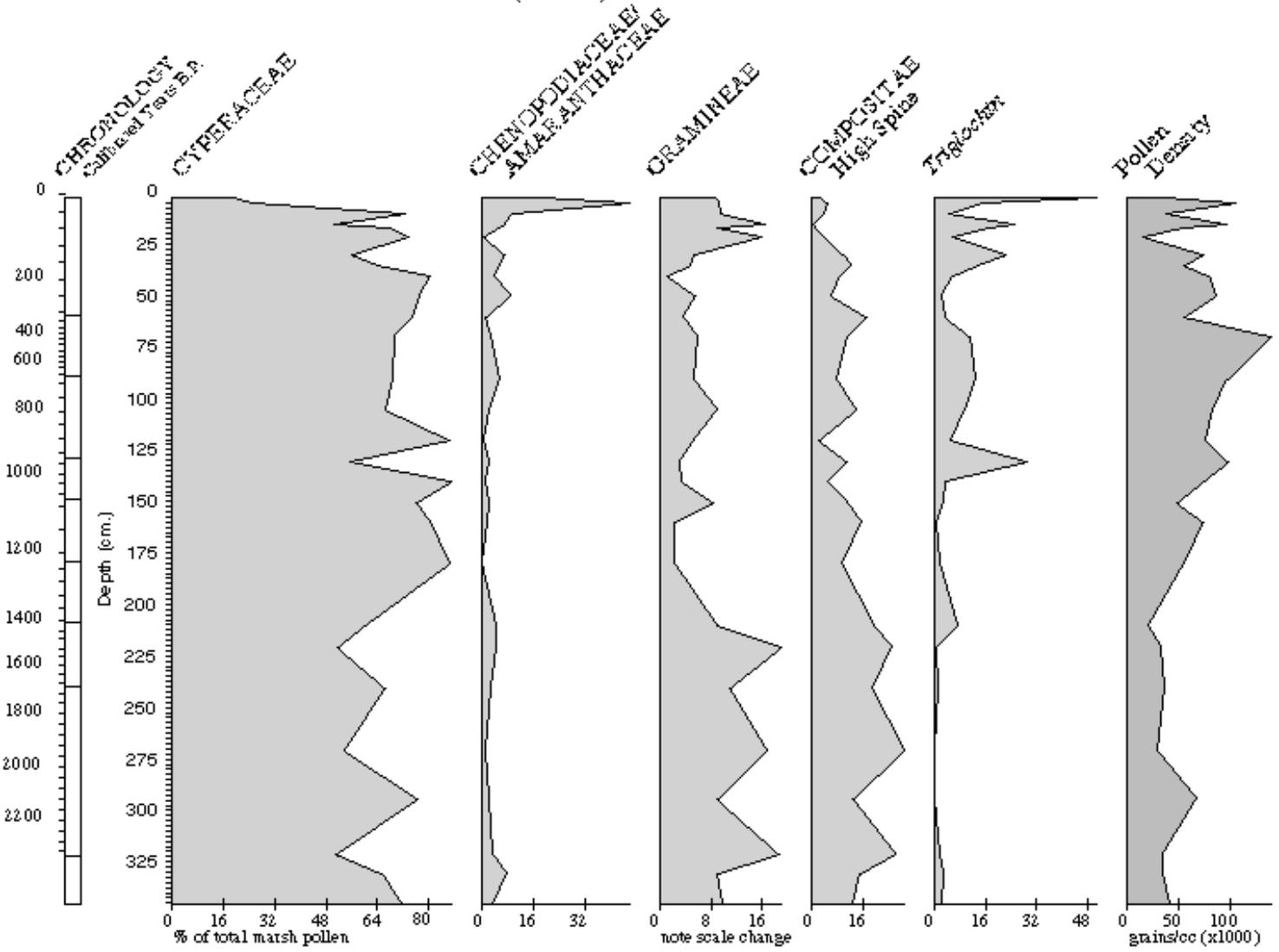


Figure 7. Browns Island pollen diagram.

Roe Island

^{14}C Chronology

Nine seed samples and one organic fragment sample were sent to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory for AMS ^{14}C dating. One of the seed samples was rejected prior to analysis due to insufficient carbon after pretreatment. The nine remaining dates are plotted in Figure 8. A linear regression yields an average sedimentation rate of approximately 1.5 mm/year, similar to the measured rate at Browns Island (1.4

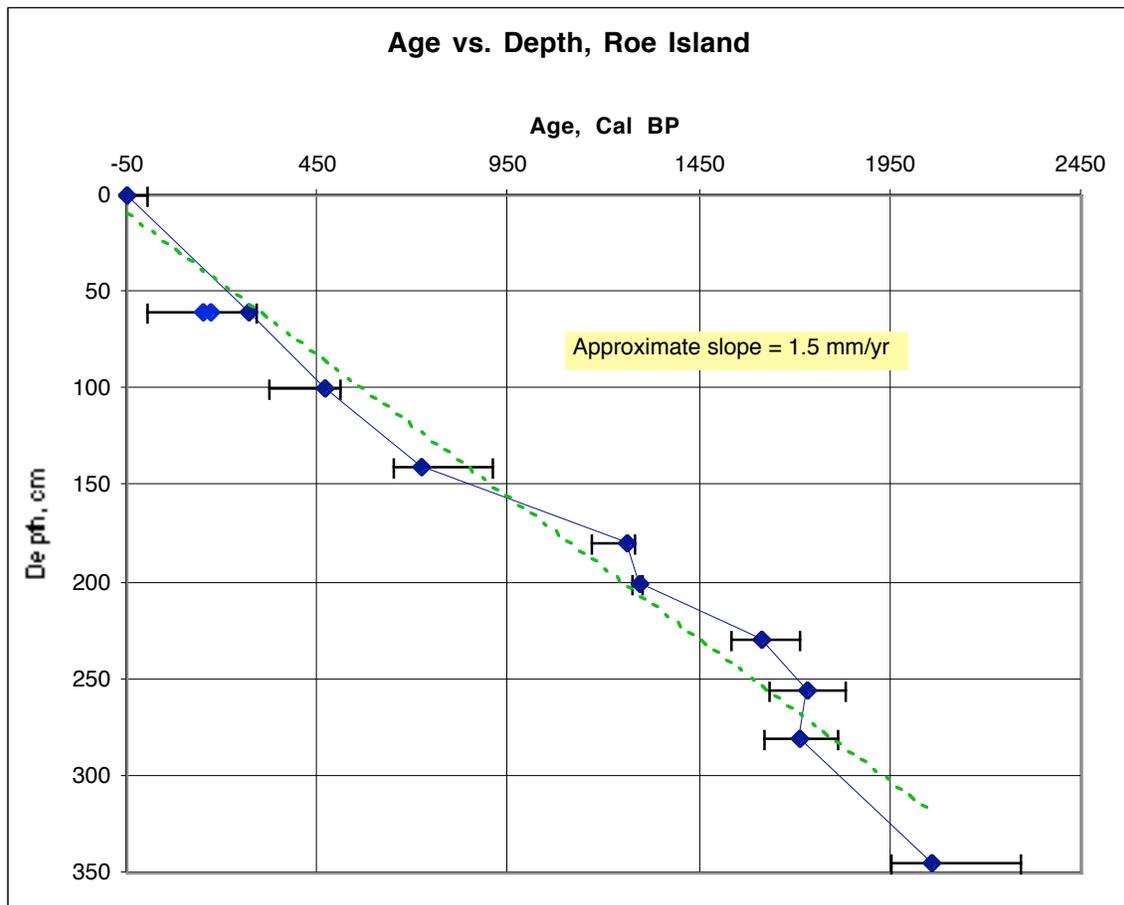


Figure 8. ^{14}C age vs. depth curve for Roe Island sediment core. Error bars indicate calibrated one-sigma age range. Multiple datapoints indicate multiple intercepts of the calibration curve. Dotted line is a linear regression. The current marsh surface (0 cm) is plotted with an age of -47 BP.

mm/year) and other recent measurements of sedimentation rate in the area (Byrne, 1998, unpublished data), and are in agreement with the estimated rate of sea level rise for this time period (Atwater et al., 1977). The slightly higher sedimentation rate at Roe Island compared to Browns Island, if real, could be related to a subtle tectonic down-dropping of Roe Island, which is located on the Suisun tectonic block. The Suisun tectonic block is separated from Browns Island, located on the Montezuma block, by the east-dipping Pittsburg thrust fault (Band, 1997, pers. comm.) Roe Island's age vs. depth curve contains considerably more variation than the curve of Browns Island, including one reversal between 255 cm and 280 cm. This reversal calls into question the validity of the 280 cm date. However, given that the remaining dates are in proper sequence, and that the 280 cm date is within the one-sigma error range of the overall trend, the chronology as a whole is assumed to be reliable.

The woody fragments at 345 cm yielded a date of 2060 cal yr BP, slightly younger than predicted by the regression. However the one-sigma range (1950–2290 cal yr BP) does encompass the regression line. This result suggests dates on organic debris at this site may be useful at depths where seeds are not available. Comparisons between seed dates and debris dates at the same depth would be a logical next step in addressing this question.

As with the Browns Island curve, uncertainties in the chronology make conclusions regarding changes in sedimentation rate tentative. Nevertheless, sedimentation rate appears to have increased relative to the average rate from 280 cm to 230 cm (1710 cal yr BP to 1610 cal yr BP) (spanning the reversal), and again from 200 cm to 180 cm (1290 cal yr BP to 1260 cal yr BP). As with Browns

Island, the above-average sedimentation between 60 cm and the surface may be related to hydraulic mining activity (Gilbert, 1917). The lowest rate, approximately one-half the average, occurred from 180 cm to 140 cm (1260 cal yr BP to 720 cal yr BP).

Stratigraphy, Loss on Ignition, and X-Radiography

The stratigraphy of the Roe Island core is more varied than the Browns Island core (Figure 9). Peat from the surface to 9 cm is followed by clay-rich peat to 205 cm, and a section of clay with peaty intrusions, possibly decayed roots or rhizomes, from 205 to 225 cm. Clay-rich peat follows until 290 cm, then another clay layer with intrusions appears at 290 cm, turning to clay with fine roots at 320 cm. Another clay layer with peaty intrusions occurs from 385 cm to the end of sampling at 425 cm. There are two sections with coarse vertical roots, from the surface to 25 cm, and from 80 to 125 cm. Fine roots are found throughout the core, suggesting the presence of plants throughout the period represented by the core.

X-radiography supports the stratigraphic description, with lowest densities in peat, higher densities in clay-rich peat, and highest densities in clay and clay with peaty intrusions. The overall trend is increasing density with depth. Although the x-radiography suggests many “density bands” throughout the core, no sand lenses or other sedimentary features were found that corresponded to these bands.

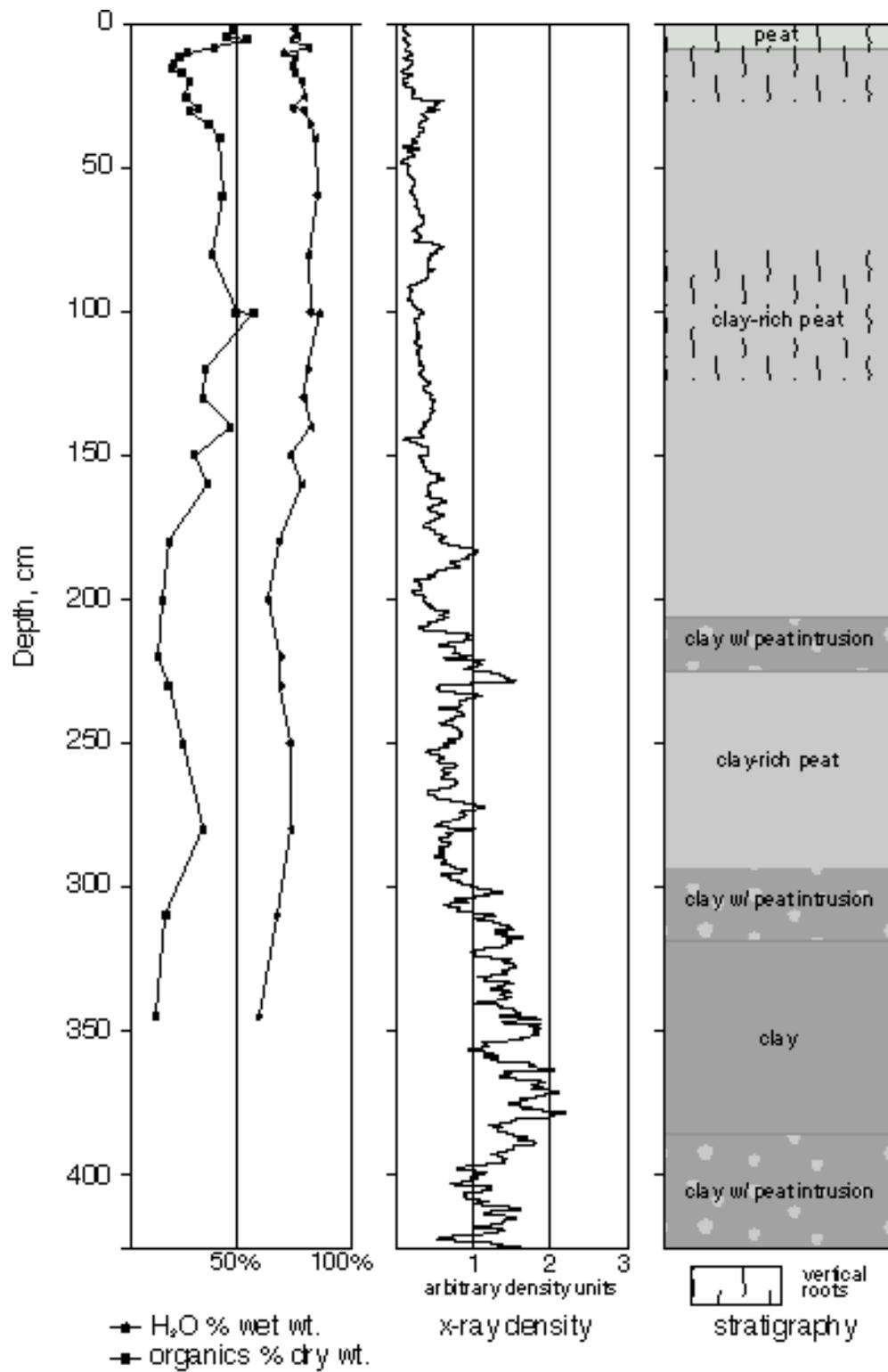


Figure 9. Loss on ignition, x-radiograph density, and stratigraphy description for Roe Island.

Loss on ignition results generally agree with the observed stratigraphy and x-radiography (Figure 9), showing a peak in organic content in the upper 9 cm, decreasing downcore. A second peak in the organic content occurs at 101 cm, in a section of clay-rich peat. Overall, the Browns Island core has a much higher organic content, consistent with the observed differences in the stratigraphies of the two sites.

Pollen analysis

Of the 32 Roe Island samples selected for pollen counting, 1 was lost during processing. A pollen diagram of key taxa for the remaining samples is presented in Figure 10. As in the Browns Island diagram, the largest changes occur near the surface. In contrast to the Browns Island core, however, large changes occur throughout. At 10 cm, the Chenopodiaceae/Amaranthaceae group reaches its highest level, with a corresponding drop in Cyperaceae. Chenopodiaceae remain high until 2 cm, the uppermost sample, when abundance drops off, a pattern matched at Browns Island. The *Triglochin* type remains highly variable throughout the record. Pollen density is variable, with a minimum of 28,000 grains/cm³ at 80 cm, and a prominent high of 179,000 grains/cm³ or greater from 130 cm to 150 cm. This high density section is slightly offset from but generally consistent with the period of low sedimentation rate from 140 to 180 cm (see ¹⁴C chronology, above) if it is assumed that no change in pollen deposition rates occurred. However, unlike the record at Browns Island, the marsh pollen ratios during this period undergo substantial change, not inconsistent with uplift of the marsh. The increase in Chenopodiaceae observed is consistent with a rise in marsh elevation as the cause of the lower sedimentation rate. An alternative explanation is that the rise in Chenopodiaceae is due to increased salinity from low freshwater flow, and low flow caused the lower sedimentation rate.

Roe Island Selected Marsh Taxa (Site A)

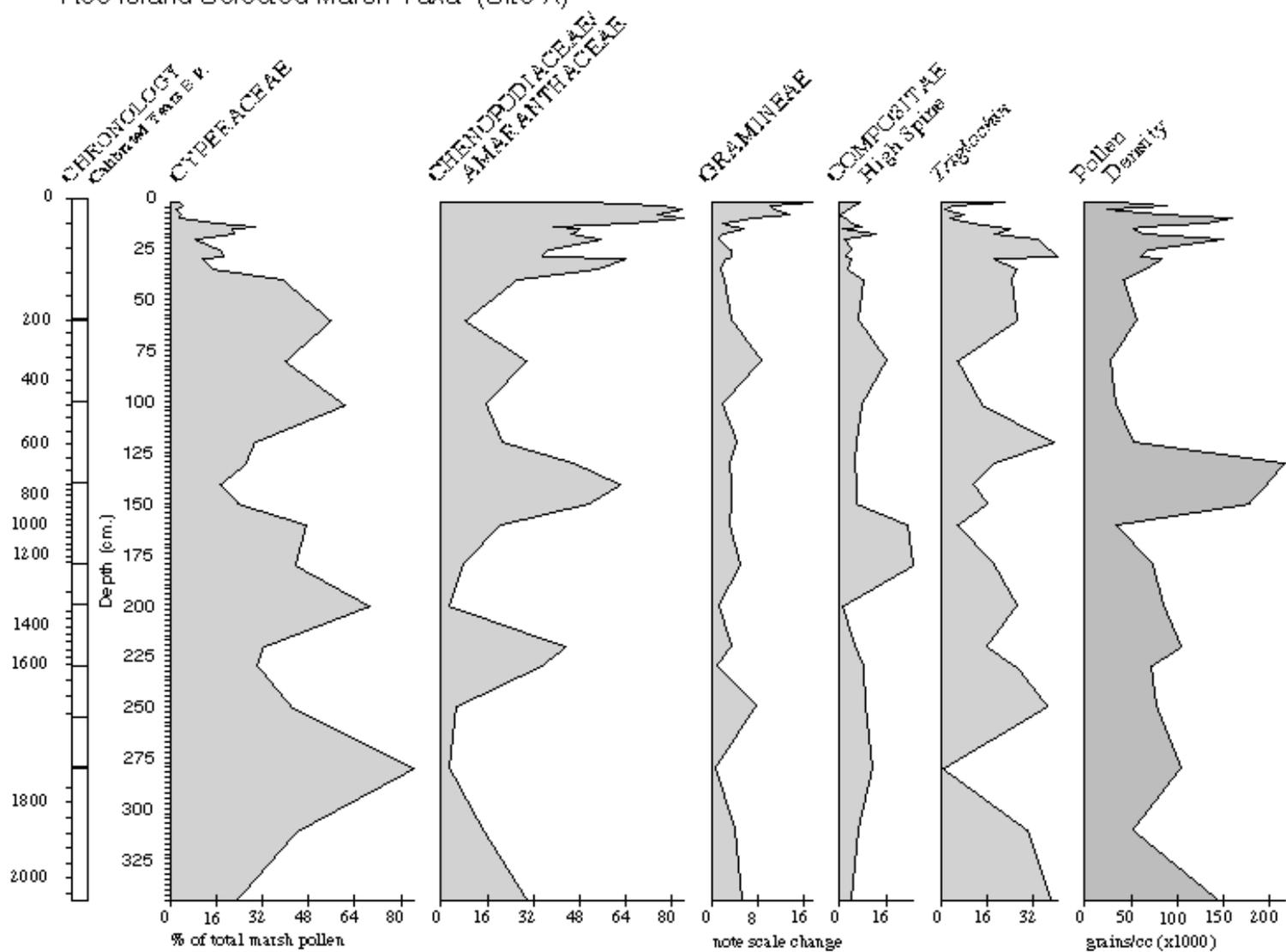


Figure 10. Roe Island pollen diagram.

Overall differences between the Browns Island and Roe Island diagrams demonstrate the effects of the islands' differing salinity regimes. As expected, pollen of halophytes is consistently found in greater abundance at Roe Island than at Browns Island, and pollen of more salt-intolerant plants is consistently found in greater abundance at Browns Island than at Roe Island (Table 2).

Average Chenopodiaceae pollen abundance over time, expressed as a percentage of total marsh pollen, is significantly higher at Roe Island (40%) than at Browns (6%). Average abundance of *Triglochin* is also significantly higher at Roe (20%) than at Browns (9%). On the other hand, abundance of Cyperaceae pollen is significantly higher at Browns (66%) than at Roe (29%). Abundance of Poaceae (Gramineae) pollen is also significantly higher at Browns (8.4%) than at Roe (4.8%).

The Poaceae and Compositae pollen types, although significant components of total marsh pollen, have little use as salinity indicators because genera within these families are indistinguishable from each other and include both halophytes and freshwater species. For example, the Poaceae family includes both the halophyte *Distichlis* and the freshwater *Phragmites*; it is unlikely the pollen of the two can be distinguished.

Marsh Taxa	Browns Island		Roe Island	
	Average % abundance	Standard deviation	Average % abundance	Standard deviation
Cyperaceae	65.6	16.4	28.6	20.4
Poaceae (Gramineae)	8.4	5.0	4.8	3.9
Chenopodiaceae	5.7	8.8	39.8	24.1
<i>Triglochin</i>	9.2	11.3	20.0	11.9
Compositae High Spine	11.2	7.5	6.8	5.9

Table 2. Summary statistics for pollen abundance at Browns Island and Roe Island. Quantities are expressed as percentage of total marsh pollen.

Section 4—Discussion

Plants as indicators of salinity

The distribution of wetlands plants in the San Francisco Estuary is strongly correlated with salinity regime (Atwater and Hedel, 1976). Salinity has been proposed as the most important physical factor in salt marsh plant distribution on the Pacific Coast (Zedler, 1982). Temporary or permanent changes in salinity regime can cause corresponding changes in wetland plant distributions. Substantial changes can occur in a single year or even at little as two to three months. Collins and Foin (1992) observed changes in tule culm diameter with changes in salinity from 1991 to 1992 in Suisun Bay. Atwater et al. (1979) documented a decrease in size, abundance and range of *Scirpus* west of the Delta during the drought of 1976–1977, accompanied by an expansion of *Salicornia* into areas previously dominated by *Scirpus*. The same study also recorded an expansion of the halophyte *Spartina* toward the Delta. Conversely, Zedler (1983) documented a change in a San Diego marsh from *Salicornia* and other marsh halophytes to *Scirpus* and other freshwater species in response to unusually high inputs of fresh water from the San Diego River.

The pollen record at Browns and Roe Islands over the last 2500 years provides information on salinity variations during this period, and allows comparisons of relative salinity prior to and concurrent with water development. Two taxa in particular are useful indicators of salinity: Chenopodiaceae and Cyperaceae. High Chenopodiaceae abundance and low Cyperaceae abundance is interpreted as indicative of more saline conditions, and high Cyperaceae

abundance and low Chenopodiaceae abundance is interpreted as indicative of more fresh conditions. The taxa are useful indicators for the following reasons:

1. Chenopodiaceae species (mainly *Salicornia virginica*) are dominant in saline environments found west of the study area, and Cyperaceae species (mainly *Scirpus* spp.) are dominant in freshwater environments found east of the study area.

2. Although typically found slightly higher in the marsh, *Salicornia virginica* has been observed to replace *Scirpus* during drought (Atwater et al., 1979), and *Scirpus* has been observed to invade an area dominated by *Salicornia* with change to more fresh conditions (Zedler, 1983).

3. Chenopodiaceae and Cyperaceae pollen are readily identified, easily distinguished, and even when damaged, not prone to confusion with other taxa, permitting counts of high accuracy.

4. Previous authors have also used these taxa as salinity indicators (Davis, 1992; Chmura, 1994; Cole and Liu, 1994).

Scirpus robustus, more tolerant of saline conditions than other members of the Cyperaceae, is found west of Browns Island to San Pablo Bay. This species weakens the association of Cyperaceae pollen with freshwater conditions. However, the range and salt-tolerance of *Scirpus robustus* is very limited in comparison to the members of the Chenopodiaceae, and the interpretive strategy should still be valid. The validity of the strategy is also supported by the overall abundance differences between the islands noted above, which are in agreement with expectations based on salinity differences between the islands.

Regional trends

If salinity changes large enough to affect the region as a whole have occurred, both islands' records should contain evidence of these changes. Figure 11 is a comparison of the ratio of Chenopodiaceae to the sum of Chenopodiaceae and Cyperaceae for Roe and Browns Islands, plotted against time in calendar years BP. The record at Browns Island contains less variation than that at Roe. This is attributed to Browns Island's upstream location, which buffers it from smaller changes in salinity regime that effect Roe Island. Roe is thus seen as more sensitive in recording more subtle salinity changes. Roe Island shows several shifts in the ratio indicating increased salinity in the last 2000 years. Higher salinity peaks occur at 2000 cal yr BP, from 1700 cal yr BP to 1400 cal yr BP, from 900 to 600 cal yr BP, and from 150 cal yr BP to present. The more subtle variation at Browns Island provides results that are less clear, but peaks at 1500 cal yr BP and 700 cal yr BP are in general agreement with the record at Roe. The clearest correspondence between the two records occurs in the last 25 years. Here, change is dramatic, with both islands at their highest abundance ever of Chenopodiaceae. At Browns, Chenopodiaceae exceeds by 5 times any previous value, reaching 49% of total marsh pollen (Figure 7). At Roe, Chenopodiaceae reaches 84% (Figure 10). Corresponding drops in Cyperaceae occur at both locations. These results suggest that conditions during the last 25 years have been more saline than at any other time during the past 2000 years. The record at Roe further indicates unprecedented change to more saline conditions dating from about AD 1944, about the time of the completion of Shasta Dam on the Sacramento River and the Friant-Kern Canal on the San Joaquin River. It is important to note that calculated dates in this portion of the cores are subject to

large error, as the ^{14}C dates used in the calculation (from 60 cm; 270 and 290 cal yr BP) are near the upper bounds of the ^{14}C method.

In examining the relationship between plants and salinity, it is important to consider the timing and magnitude of salinity changes (Zedler and Beare, 1986). The results of this study suggest that salinity intrusion, which was greatest in the 1920s and 1930s, and has since been reduced due to reservoir releases each summer and fall, is not the controlling influence on *Salicornia* abundance at the study sites. Coinciding as it does with the construction of the large water projects, the rise to peak *Salicornia* abundance appears to be related to hydrological changes from these projects. One of the largest changes wrought by the water projects is the loss of high spring flows, and it may be that the absence of these flows, which in previous years could have provided a critical flush of salts from the soils of *Scirpus* and other salt-intolerant plants, was a primary cause of the *Salicornia* increase.

Some studies have suggested that the average annual volume of freshwater to the Estuary since the 1920s has remained fairly constant, due to increased rainfall in the Central Valley or other factors (Peterson et al., 1989; Fox et al., 1990). These studies acknowledge a reduction in flow during spring months, but conclude increased flows in the other months keep the annual volume stable. The results of this study would support such a conclusion only if spring flows were the critical factor in controlling the observed vegetation change indicating more saline conditions.

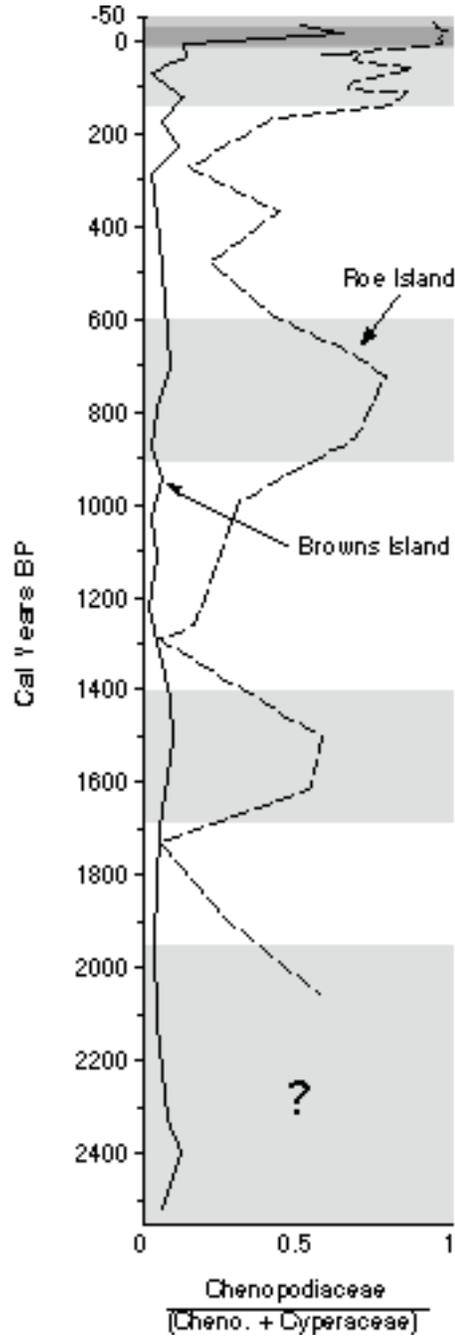


Figure 11. The ratio of Chenopodiaceae to sum of Cyperaceae and Chenopodiaceae for Browns and Roe Islands, data plotted on the same time axis. Shading is estimation of salinity regimes, darker is more saline. Surface (0 cm) is assigned a date of -47 BP.

An intriguing change is the drop in Chenopodiaceae in both records at the highest level counted (2 cm), suggesting a partial reversal from the high salinity conditions at 5 cm. The 2 cm data points may reflect the extremely wet winter of 1984 or other wet years, or could be indicative of changing water diversion practices creating conditions less favorable to *Salicornia* expansion. Also occurring at this level is a dramatic rise at Browns Island of *Triglochin*. A high-resolution pollen diagram of the top twenty centimeters, replicated within and among islands, with strong chronological control, would be invaluable in pinpointing changes seen in this section. A possible complication of such a strategy is the unknown amount of bioturbation that has occurred in the sediments, tending to limit the resolution.

Salinity as an indicator of freshwater flow

If wetlands plants are useful indicators of salinity regime, and salinity regime can be related to freshwater flow, the pollen record at Roe and Browns Islands should be useful for identifying changes in freshwater flow into the Estuary. The freshwater flow into the Estuary is a function of the climate of the watershed and, in recent decades, flow diversions upstream of the Estuary.

Salinity in the northern Estuary is directly controlled by freshwater outflow from the Delta (Conomos et al., 1979). The greater the freshwater discharge into the Estuary, the further saline waters are pushed toward the mouth. At a given location, higher discharge results in a drop in salinity. This is most readily demonstrated by seasonal flow variation and accompanying spatial variation in salinity (Peterson et al., 1989). Models have been developed to relate freshwater flow to salinity in the Estuary (Peterson et al., 1989; Ingram and DePaolo, 1993).

Changes in the volume of the Estuary can effect the salinity–flow relationship. Jaffe et al. (1996) have shown that substantial changes in the bathymetry of San Pablo Bay have occurred since 1850, likely due to hydraulic mining activities in the Estuary’s watershed. Rising sea level also affects the Estuary’s volume. Overall, however, it is believed that sedimentation and sea level rise have offset each other over the last several thousand years, keeping Estuary volume nearly constant (Ingram and DePaolo, 1993).

Comparisons with other long-term records

Figure 12 is a compilation of selected paleoclimatic records for the San Francisco Estuary and California for the last 2000 years, along with shading indicating the salinity regime as determined from this study. The Y-axis is of arbitrary magnitude, indicating conditions of lower estuarine salinity or higher precipitation in the positive direction. The upper two records, Ingram et al. (1996a) and Ingram et al. (1996b), are proxy measurements of San Francisco Estuary salinity derived from oxygen and carbon isotopic measurements of fossil bivalves. The second two records, Stine (1990) and LaMarche (1974), are lake level and tree-ring records from an area directly east of the Estuary and just east of the Sierra Nevada mountain range. As the majority of precipitation for this region of California arrives via storms travelling west-to-east, climate records for areas east of the Estuary should be related to the Estuary’s flow and salinity.

The record of Ingram et al. (1996b) was obtained from a sediment core in the southern part of San Francisco Estuary, and appears to correspond with this study’s indication of more saline conditions from 600–900 cal yr BP. Correspondences for other time periods are not clear. Ingram et al. (1996a) is

based on a sediment core taken from San Pablo Bay. This record is relatively short, ending about 740 cal yr BP, and complete comparison with this study's results are not possible. There is no clear correspondence.

The Stine (1990) record is a lake level record from Mono Lake. Mono Lake has no outlet; lake level is largely controlled by the relative magnitudes of evaporation and freshwater input from the eastern slope of the Sierra Nevada. As with Ingram et al. (1996b), there appears to be a correspondence between Stine (1990) and this study's indication of more saline conditions in the Estuary between 600–900 cal yr BP, although the lake level peak at about 850 cal yr BP appears incongruous. The dry period concluding with the Mono Lake lowstand at 950 cal yr BP is also not reproduced in this study.

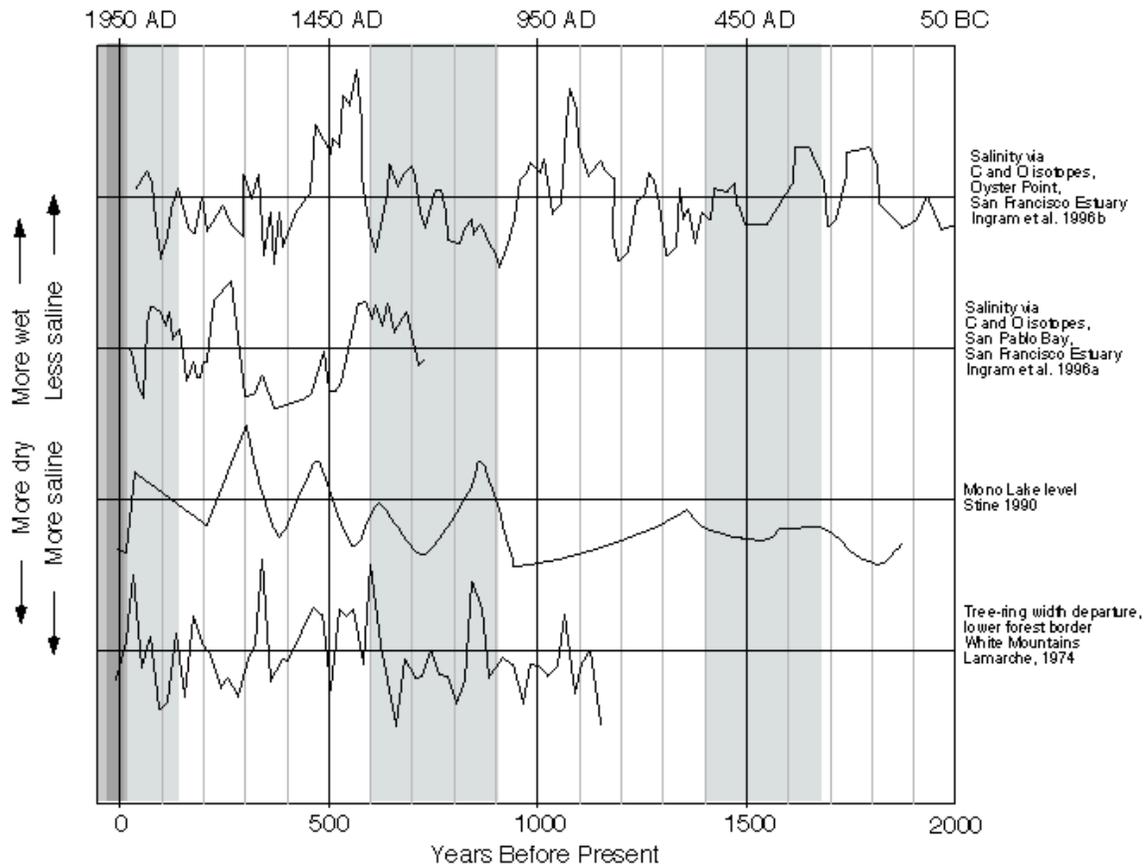


Figure 12. Comparison of paleoclimatic records for California. Y-axis magnitude is arbitrary. Shading indicates salinity regime as determined by this study (see Figure 11).

LaMarche (1974) is a record of variation in tree-ring width of bristlecone pines in the White Mountains of California. There appears to be a correspondence between the LaMarche record and this study's indication of more saline conditions in the Estuary from 600–900 cal yr BP, although there is an incongruity similar to that found in the Stine record at about 850 cal yr BP.

Overall, the records discussed above support this study's conclusion that the period 600–900 cal yr BP was a time of reduced inflow (i.e. reduced watershed precipitation) and increased salinity for the San Francisco Estuary. This period

also corresponds to a period of increased fire frequency in giant sequoia of the Sierra Nevada (Swetnam, 1993). This consistency between different studies also decreases the likelihood that the changes seen 600-900 cal yr BP are due to tectonic movement of the marsh. On the other hand, the Roe record's indications of higher salinity from 1400–1680 cal yr BP show no clear correspondence with the two other records that cover that time period.

Effects of human diversion activities of recent years should be captured by both this study's record and the Ingram (1996 a, b) records, but the Ingram records do not correspond well with this study's indications of increased salinity during the period where the records overlap (40–140 cal yr BP). This lack of correspondence may be in part because this study and the Ingram studies use different salinity proxies. For example, the proxies may have differing responses to seasonality of salinity changes.

Other sources of vegetation change

A key assumption of this study is that the pollen changes observed are due to vegetation changes caused by salinity changes. Other factors that can change wetland plant abundances include human disturbance, invasion of exotic species, and changes in rainfall on the islands. Issues of human disturbance were addressed in the *Methods* and *Results* sections. Although some exotic species, such as *Lepidium latifolium*, were noted at both islands, exotic species were insignificant at the sampling locations. Annual rainfall totals from 1900–1990 for the town of Antioch (6 km upstream of Browns Island) show a slight increase over time, tending to cause changes opposite to those observed (NOAA, 1998).

The potential for lateral tidal channel migration to cause changes in species abundance is not clear, but the author's comparisons of modern maps of San Francisco Estuary channel networks with early surveys (dating from 1850 to 1860) show tidal marsh channels to be remarkably stable, especially laterally, over a 100 year period.

An alternative explanation for the increase in salinity observed in the record, unrelated to flows, is the effect of sea level rise. However, the sudden salinity peak in the top section of the core and the repeated salinity peaks earlier conflict with the change that would be expected from the gradual, stable sea level rise established for this region (Atwater et al. 1977).

Section 5—Conclusion

The results of this study indicate varying levels of oceanic influence on the Estuary over the last 2500 years, with periods of high salinity alternating with periods of low salinity. Unprecedented in the record is the shift to more saline conditions recorded in the last 10 cm or 70 years of sediment. At both Roe Island and Browns Island we see in this portion of the core the highest levels of *Salicornia* pollen and the lowest levels of *Cyperaceae* pollen of the entire 2500 year record. This implies that modern conditions are substantially more saline than conditions present at any other time in the past 2500 years. The timing of the shift to more saline conditions suggests that water diversion projects since 1944 played a major role in bringing about current conditions. Relations between salinity and marsh plant distribution are complex (Zedler and Beare, 1986), and the particular changes to the hydrograph that are responsible for the observed pollen change and accompanying shift in wetland plant life are unclear. Evidence suggests, however, the alteration of spring flows is important. The very top level analyzed on both islands, 2 cm, shows a partial reversal of the increase in *Salicornia*, while *Cyperaceae* levels remain low. This suggests a change in the salinity regime during the last two decades to one less favorable to *Salicornia*.

Evidence from this study and corresponding evidence from other paleoenvironmental studies indicates a period of relatively low precipitation in the Estuary watershed and high salinity in the Estuary from 600–900 cal yr BP. Another period of low precipitation and high salinity, not as well supported by results from other studies, extends from 1400–1680 cal yr BP.

Further research

Given the striking changes contained in the upper 20 cm of core from both study sites, and the relevance this time period has for understanding the modern diversion-influenced state of the Estuary, a more detailed investigation of this section of the record is called for. Viewing these recent changes in the context of the long-term record provides a means of assessing their magnitude. Timing these changes as accurately as possible will allow us to make better connections between water development activities and their effects on the Estuary, invaluable information for managing the Estuary's condition. Pb-210 dating technique would be ideal for refining the chronology of the upper sediments. A study of sub-centimeter sampling of cores would determine if it is possible to recover a higher resolution record of the changes observed in the upper sediments. Replication of sampling and analysis both within the current study sites and at additional adjacent sites would verify and strengthen the conclusions of this study, both for recent and long-term change.

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Site	Core number	Depth (cm)	Lab ID number	Description of sample	Conventional C14 date	S.D.	Calibrated date BP	upper bound	lower bound	Add'l intercepts	Sed rate mm/yr
Browns	A2	60	46627	2.5 Scirpus seeds	240	80	290	420	0		1.79
Browns	A6	89	40777	3 Scirpus seeds, 6 smaller seeds	810	80	700	780	660		0.71
Browns	A7	129	40778	7 Scirpus seeds, 3 smaller seeds	1050	40	940	970	930		1.67
Browns	A7	149	46624	5 Scirpus seeds, 3 smaller seeds	1210	50	1110	1170	1060	1130, 1090	1.18
Browns	A7	179	40779	7 smaller seeds	insuff C			-	-		-
Browns	A7	179	46625	10 Scirpus(?), some hollow	1270	80	1220	1280	1070	1180	2.73
Browns	A8	209	46626	8 Scirpus seeds, 4 smaller	1560	50	1410	1520	1360		1.58
Browns	A9	240	40780	3 Scirpus seeds, 4 other	1780	80	1700	1810	1570		1.07
Browns	A10	322	40781	4 Scirpus seeds	2330	70	2340	2360	2320		1.28
Roe	A7	60	46615	2.5 Scirpus seeds, 1 larger seed(?), 5 smaller seeds	190	50	270	290	0	170, 150	2.22
Roe	A7	100	46616	5 Scirpus seeds (1 damaged)	390	60	470	510	320		2.00
Roe	A8	140	46617	4 Scirpus seeds	820	140	720	910	650		1.60
Roe	A8	180	46618	4 Scirpus seeds	1300	60	1260	1280	1170		0.74
Roe	A8	200	46619	6 Scirpus seeds	1370	40	1290	1300	1270		6.67
Roe	A9	230	46620	5 Scirpus seeds (1 damaged)	1720	80	1610	1710	1530		0.94
Roe	A9	255	46621	3 Scirpus seed, 8 smaller	1830	60	1730	1830	1630		2.08
Roe	A9	280	46622	3 Scirpus seeds, 13 smaller seeds	1800	60	1710	1810	1620		-
Roe	A9	310	-	3 Scirpus seeds, 2 smaller seeds	insuff C			-	-		-
Roe	A10	345	46623	8 woody fragments	2110	90	2060	2290	1950		1.86

Appendix Table 1. Results of AMS ¹⁴C dating. All dating performed at Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory.

Depth (cm)	2	5	10	15	17	20	21	30	35	40	50	60	70	90	105	120
TT empty	5.554	5.099	4.903	5.105	5.065	5.022	5.098	5.02	5.517	5.302	5.592	5.553	5.31	5.029	5.51	5.102
TT + Wet	6.418	6.386	6.15	6.522	6.258	6.38	6.094	6.147	6.614	6.689	6.761	6.764	6.518	6.409	6.723	6.375
Wet Sed																
Cruc Empty	8.755	8.292	8.709	8.732	8.292	8.852	7.509	8.297	8.223	8.754	8.724	8.759	6.979	8.223	8.431	8.925
Cruc + wet	9.776	9.871	9.835	10.11	9.439	10.21	8.576	9.412	9.361	10.05	9.779	10.09	8.225	9.662	9.62	10.29
Cruc + dry	9.002	8.661	8.957	8.991	8.477	9.086	7.732	8.493	8.412	8.928	8.864	8.951	7.141	8.385	8.594	9.102
Cruc + ash	8.868	8.515	8.846	8.889	8.376	8.967	7.631	8.386	8.295	8.814	8.778	8.824	7.037	8.265	8.469	8.962
% wet	76%	77%	78%	81%	84%	83%	79%	82%	83%	87%	87%	86%	87%	89%	86%	87%
% org	54%	40%	45%	39%	55%	51%	45%	55%	62%	66%	61%	66%	64%	74%	77%	79%

49	Depth (cm)	130	140	150	160	180	193	210	220	240	254	270	271	294	321	330	345
	TT empty	5.645	5.304	5.087	5.279	5.076	5.574	5.331	5.019	5.084	5.04	5.273	5.011	5.034	5.493	5.289	5.268
	TT + Wet	6.957	6.654	6.425	6.545	6.286	6.792	6.604	6.393	6.42	6.366	6.703	6.332	6.209	6.737	6.672	6.689
	Wet Sed																
	Cruc Empty	8.754	6.98	8.699	8.224	8.337	7.509	6.568	8.286	8.426	8.287	7.052	6.571	8.638	9.205	8.713	9.204
	Cruc + wet	10.01	8.16	10.01	9.215	9.64	8.67	7.855	9.634	9.803	9.556	8.368	7.932	9.797	10.44	9.95	10.51
	Cruc + dry	8.934	7.143	8.879	8.417	8.508	7.66	6.703	8.478	8.588	8.464	7.227	6.77	8.786	9.381	8.848	9.359
	Cruc + ash	8.808	7.019	8.745	8.261	8.378	7.546	6.605	8.355	8.47	8.348	7.123	6.654	8.681	9.243	8.748	9.239
	% wet	86%	86%	86%	81%	87%	87%	90%	86%	88%	86%	87%	85%	87%	86%	89%	88%
	% org	70%	76%	74%	81%	76%	75%	73%	64%	73%	66%	59%	58%	71%	78%	74%	77%

Appendix Table 2. Wet weight and loss-on-ignition results for Browns Island samples.

Depth (cm)	2	4	5	8	10	12	14	15	17	20	25	29	30	35	40	60
TT empty	5.524	5.292	5.532	5.095	5.448	5.082	5.105	5.26	5.009	5.523	5.586	5.261	5.588	5.01	5.024	5.296
TT + Wet	6.628	6.489	6.268	6.718	6.721	6.79	6.3	6.515	6.247	6.725	7.032	6.425	6.944	6.034	6.206	6.784
Wet Sed																
Cruc Empty	8.628	8.783	8.736	8.672	6.818	7.505	8.857	8.672	8.713	8.853	8.699	7.509	8.714	8.393	7.509	8.858
Cruc + wet	9.542	9.894	9.47	10.23	7.91	9.061	10.05	10.05	10.04	10.03	9.989	8.757	10.03	9.559	8.593	10.23
Cruc + dry	8.857	9.039	8.927	8.961	7.139	7.887	9.166	9.027	9.036	9.105	8.965	7.831	8.992	8.605	7.682	9.066
Cruc + ash	8.745	8.921	8.823	8.844	7.046	7.789	9.095	8.949	8.95	9.029	8.889	7.722	8.908	8.524	7.608	8.974
% wet	75%	77%	74%	81%	71%	75%	74%	74%	76%	79%	79%	74%	79%	82%	84%	85%
% org	49%	46%	54%	40%	29%	26%	23%	22%	27%	30%	29%	34%	30%	38%	43%	44%

Depth (cm)	80	100	101	120	130	140	150	160	180	200	220	230	250	280	310	345
TT empty	5.285	5.304	5.081	5.077	5.019	5.03	4.985	5.624	5.285	5.074	5.572	5.029	5.104	5.297	5.027	5.299
TT + Wet	6.712	6.74	6.247	6.369	6.559	6.463	6.487	6.909	6.957	6.636	7.055	6.497	6.681	6.754	6.657	6.991
Wet Sed																
Cruc Empty	7.259	8.853	8.922	8.581	8.224	8.037	6.98	7.053	8.847	8.628	8.925	8.97	8.892	8.332	8.755	8.925
Cruc + wet	8.589	10.29	10.15	9.999	9.727	9.42	8.571	8.395	10.63	10.28	10.2	10.42	10.42	9.664	10.39	10.62
Cruc + dry	7.506	9.115	9.096	8.851	8.537	8.282	7.407	7.339	9.407	9.228	9.32	9.421	9.305	8.683	9.286	9.606
Cruc + ash	7.408	8.984	8.996	8.752	8.424	8.165	7.27	7.231	9.285	9.116	9.256	9.327	9.193	8.557	9.181	9.501
% wet	81%	82%	86%	81%	79%	82%	73%	79%	69%	64%	69%	69%	73%	74%	68%	60%
% org	40%	50%	57%	37%	36%	48%	32%	38%	22%	19%	16%	21%	27%	36%	20%	15%

Appendix Table 3. Wet weight and loss-on-ignition results for Roe Island samples.

Young, W. R. 1929. Report on salt water barrier below confluence of Sacramento and San Joaquin rivers, California. California Department of Public Works, Division of Water Resources, Bulletin No. 22.

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Appendix—Data tables

Depth	Pinus	Picea	TAXODIACEAE/ CUPRESSACEAE/ TAXACEAE	Sequoia	Ephedra	Quercus	Lithocarpus	Juglans	Rhamnaceae	Rosaceae	Cornus	Eucalyptus	Salix	Alnus	Artemisia	Liguliflorae	COMPOSITAE High Spine	COMPOSITAE Low Spine	CRUCIFERAE	Erigeronum	Polygonum	UMBELLIFERAE	Plantago
2	15	-	2	-	-	9	-	2	1	-	-	-	-	1	3	-	3	1	4	-	-	1	-
5	13	-	3	-	-	11	-	2	-	-	-	1	2	-	5	-	13	1	6	-	-	-	-
10	3	-	-	1	-	3	-	-	-	-	-	-	2	2	4	-	4	-	1	-	-	-	-
15	4	-	5	-	-	9	1	2	1	-	1	-	-	-	2	-	1	1	4	-	-	-	1
17	3	-	4	-	-	-	-	-	1	-	-	-	2	-	-	-	2	-	-	-	-	1	-
21	1	-	2	-	-	6	-	1	-	-	-	-	-	-	1	1	6	-	1	-	-	1	-
30	5	-	3	-	-	7	-	-	-	-	-	-	-	-	-	-	22	-	-	-	-	1	-
35	1	-	3	1	-	5	-	-	-	-	-	-	-	1	2	1	25	-	-	-	-	-	-
40	3	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-	22	-	-	-	-	-	-
50	4	1	1	-	1	5	-	-	-	-	-	-	-	-	2	-	23	-	1	-	-	1	-
60	2	-	1	-	-	8	-	-	-	-	-	-	-	1	3	-	46	-	-	-	2	-	-
70	2	-	5	-	-	5	1	-	-	-	-	-	2	-	4	-	40	1	-	-	-	2	-
90	6	-	3	-	-	11	-	-	-	-	-	-	1	2	-	-	17	-	-	-	-	-	-
105	2	-	3	-	-	4	-	-	-	-	-	-	-	4	-	-	29	1	-	-	-	1	-
120	2	-	1	-	-	3	-	-	-	-	-	1	1	1	-	-	5	-	-	-	-	-	-
130	4	-	11	-	-	5	1	1	-	1	-	-	-	-	3	-	28	-	-	-	-	1	-
140	4	-	3	-	-	4	-	-	1	-	-	1	2	-	-	-	12	1	-	-	-	-	-
150	3	-	4	-	-	5	1	1	-	-	-	-	-	-	2	-	16	-	-	-	-	-	-
160	2	-	9	-	-	3	-	-	-	-	-	-	-	-	2	-	28	-	-	-	-	1	-
180	3	-	2	-	-	6	-	-	-	-	-	-	-	-	1	-	17	-	-	-	-	-	-
210	2	-	1	-	-	4	1	-	1	-	-	1	-	1	-	13	-	-	-	-	-	1	1
220	4	-	3	-	-	14	-	-	-	1	-	-	-	3	-	1	35	-	-	-	-	-	-
240	3	-	4	-	-	8	-	1	2	-	1	-	2	1	1	-	31	-	-	1	1	-	-
271	9	-	4	-	-	17	-	-	1	-	-	-	3	-	1	-	36	-	1	-	-	-	-
294	4	-	5	-	-	6	-	-	-	-	-	-	1	1	2	-	22	-	-	-	-	-	-
321	1	-	2	-	-	5	-	-	1	-	-	-	-	-	-	-	33	-	-	-	-	-	-
330	1	-	2	-	-	5	-	-	-	-	-	-	-	2	-	-	10	-	-	-	-	-	-
345	3	-	3	-	-	8	-	-	-	-	-	-	-	1	-	1	21	-	1	-	-	-	-

Appendix Table 4 (1 of 2 parts). Browns Island pollen counts. Depth in centimeters.

Depth	GRAMINEAE	CHENOPODIACEAE/ AMARANTHACEAE	Typha spp	CYPERACEAE	Triglochin	Pteridium	Botrychium	Indeterminate	Unknown	Lycopodium (Control)	Total Pollen and Spores	Subtotal : Marsh Pollen	lycopodium/test tube	grains/test tube	grains/cm ³
2	11	24	4	24	64	-	-	40	3	123	212	126	27822	47953	36055
5	25	123	3	68	39	-	1	44	5	73	365	268	27822	139110	104594
10	10	10	3	77	5	-	1	31	24	150	181	106	41733	50358	37863
15	39	17	-	119	59	1	-	35	16	103	318	235	41733	128846	96876
17	18	10	2	137	33	-	-	45	1	101	259	200	27822	71346	53643
21	25	1	1	117	9	1	-	36	2	274	212	158	27822	21527	16185
30	12	16	-	128	51	-	1	27	4	116	277	229	41733	99656	74929
35	10	12	-	137	28	-	-	31	4	100	261	212	27822	72615	54598
40	3	10	1	201	14	-	-	8	2	105	266	250	41733	105724	79491
50	21	33	-	295	9	-	-	40	2	105	439	381	27822	116322	87460
60	10	2	-	200	9	-	-	30	10	184	324	267	41733	73486	55253
70	22	10	-	260	43	-	-	46	8	67	451	375	27822	187279	140812
90	12	12	-	153	29	-	-	3	10	84	259	223	41733	128677	96749
105	19	4	-	142	20	-	-	20	1	63	250	214	27822	110405	83011
120	12	1	-	198	12	-	-	19	2	106	257	228	41733	101183	76077
130	8	6	-	144	75	-	-	35	10	71	333	261	27822	130489	98112
140	8	2	1	205	8	-	-	27	1	78	280	235	27822	99874	75093
150	12	3	1	110	4	-	-	52	8	146	222	145	41733	63457	47712
160	4	3	-	148	1	-	-	55	-	71	256	184	27822	100316	75426
180	4	-	1	156	3	-	-	29	4	130	226	180	41733	72551	54550
210	6	3	-	40	5	-	-	21	7	168	108	67	41733	26828	20172
220	27	6	-	73	1	-	-	42	2	139	212	142	27822	42434	31905
240	18	5	1	110	2	-	-	31	7	199	230	165	41733	48234	36266
271	21	1	-	68	-	-	-	43	11	223	216	126	41733	40423	30393
294	16	4	1	136	-	-	-	43	9	115	250	178	41733	90724	68213
321	24	4	-	65	2	-	-	64	1	122	202	128	27822	46066	34636
330	6	5	-	44	2	-	-	24	16	104	117	67	41733	46950	35300
345	16	5	-	117	4	-	-	44	1	112	225	163	27822	55892	42024

Appendix Table 4 (2 of 2 parts). Browns Island pollen counts. Depth in centimeters.

Depth	Pinus	Abies	TAXODIACEAE/ CUPRESSACEAE/ TAXACEAE	Sequoia	Quercus	Ericaceae	Lithocarpus	Fraxinus	Juglans	Rhamnaceae	Rosaceae	Cornus	Corylus	Eucalyptus	Salix	Alnus	Artemisia	Liguliflorae	COMPOSITAE High Spine	COMPOSITAE Low Spine	CRUCIFERAE	Polygonum	UMBELLIFERAE
2	7	-	10	-	15	-	-	-	-	-	-	-	-	-	1	2	-	-	9	-	-	-	-
4	7	-	3	-	5	-	-	-	-	-	-	-	-	-	2	-	2	-	7	-	1	-	-
5	5	-	-	2	5	-	-	1	-	-	-	-	-	-	-	-	2	-	4	-	-	-	-
8	5	-	-	-	5	-	-	-	2	1	-	-	-	-	-	1	1	-	-	-	-	-	-
10	18	-	3	-	21	-	-	-	-	-	1	-	-	-	-	6	-	1	8	3	3	-	-
12	12	-	6	-	9	-	-	-	-	4	-	-	-	1	2	6	3	-	22	-	1	-	-
14	9	-	3	-	6	-	-	-	-	-	-	-	-	-	-	2	4	-	29	-	1	-	-
15	6	-	4	-	8	-	-	-	-	-	-	-	-	-	-	3	-	2	2	-	-	-	-
17	7	-	3	-	5	-	-	-	-	4	-	-	1	-	-	4	3	-	27	-	1	-	-
20	8	-	6	-	5	1	-	-	-	-	1	-	-	-	-	2	3	-	7	1	-	-	-
25	4	-	2	-	11	-	-	-	-	-	-	-	1	-	-	3	4	-	11	-	1	-	-
29	2	-	3	-	9	-	-	-	-	2	-	1	-	-	-	-	5	-	6	1	2	-	-
30	6	-	-	-	4	-	2	-	-	2	-	-	-	-	-	2	2	-	12	-	1	-	-
35	4	-	7	-	9	-	-	-	-	1	-	-	-	-	-	3	5	-	7	-	-	-	-
40	8	-	2	-	7	-	-	-	-	1	1	-	-	-	-	3	4	1	15	-	-	-	-
60	2	-	2	-	7	-	-	-	-	1	-	-	-	-	-	2	-	1	11	-	1	-	-
80	6	-	6	-	13	-	-	-	-	-	1	-	-	-	-	1	1	-	28	-	-	-	-
101	3	-	6	-	7	-	-	-	-	-	-	-	-	-	-	1	1	-	15	-	-	-	-
120	4	-	6	-	15	-	-	-	-	1	-	-	-	-	-	1	1	-	15	-	-	-	-
130	3	-	-	-	3	-	-	-	-	-	-	-	-	-	-	2	2	-	24	-	-	-	-
140	6	-	3	-	11	-	-	-	-	1	-	-	-	-	-	-	5	-	29	-	-	-	-
150	9	2	8	-	11	-	-	-	-	1	-	-	1	-	-	-	3	-	36	-	-	-	-
160	3	-	1	-	4	-	-	-	-	-	-	-	-	1	1	-	-	-	51	-	-	-	-
180	-	-	2	-	2	-	-	-	-	1	-	-	-	-	1	1	1	-	56	-	-	-	-
200	3	-	5	-	13	-	-	-	-	-	1	-	1	-	1	9	5	-	3	-	-	-	-
220	7	-	6	-	12	-	-	-	-	-	-	-	-	-	2	1	2	1	17	-	-	-	1
230	6	-	7	-	10	-	-	-	-	2	-	-	-	-	-	8	4	-	23	-	-	-	-
250	5	-	2	-	5	-	-	-	-	1	-	-	-	-	-	3	2	-	20	1	-	-	-
280	5	-	6	-	4	-	-	-	-	-	-	-	-	1	2	1	1	-	43	-	-	2	-
310	7	-	2	1	4	-	-	-	-	1	-	-	-	-	1	2	-	-	11	-	-	-	-
345	5	-	3	-	7	-	-	-	-	1	-	-	-	-	2	4	4	-	12	-	-	-	-

Appendix Table 5 (1 of 2 parts). Roe Island pollen counts. Depth in centimeters.

Depth	Plantago	GRAMINEAE	CHENOPODIACEAE/ AMARANTHACEAE	Sarcobatus	Typha latifolia	Typha spp	CYPERACEAE	Triglochin	Pteridium	Indeterminate	Unknown	Lycopodium (Control)	Total Pollen and Spore	Subtotal: Marsh Pollen	Lycopodium/test tube	grains/test tube	grains/cm3
2	-	22	63	-	6	1	4	28	-	33	8	127	212	126	27822	46443	34920
4	-	16	120	-	1	5	7	6	-	20	7	49	209	156	27822	118669	89225
5	-	17	134	-	1	-	3	2	-	14	5	177	205	160	27822	32223	24228
8	-	26	143	-	-	-	7	15	-	19	4	58	229	191	27822	109849	82593
10	-	26	307	-	1	-	12	12	-	30	18	62	470	365	27822	210909	158578
12	-	10	313	-	-	2	80	54	3	18	1	89	547	479	27822	170996	128568
14	-	15	142	-	1	-	108	70	-	36	3	148	429	364	27822	80646	60636
15	-	9	79	-	-	-	35	39	-	27	2	84	214	164	27822	70880	53293
17	-	4	98	-	-	-	48	40	1	14	3	84	263	217	27822	87109	65496
20	-	7	297	-	-	-	46	182	1	13	3	81	583	539	27822	200250	150564
25	-	10	105	-	-	1	50	108	-	12	3	100	326	284	27822	90700	68195
29	1	9	90	-	-	-	47	102	-	14	-	103	294	254	27822	79414	59710
30	-	7	188	-	1	1	33	53	-	13	3	82	330	293	27822	111967	84185
35	-	4	143	-	-	-	39	70	2	22	-	102	316	263	27822	86194	64807
40	-	4	48	-	-	-	72	45	-	11	3	111	225	184	27822	56396	42403
60	1	6	15	1	-	-	99	47	-	31	2	86	229	178	27822	74084	55702
80	-	15	52	-	-	-	70	10	-	31	8	184	242	175	27822	36592	27513
101	-	4	30	-	-	-	119	27	-	13	-	139	226	195	27822	45236	34012
120	-	12	57	-	-	1	79	105	-	7	2	124	306	268	27822	68658	51622
130	-	14	207	-	-	-	119	83	3	32	6	48	498	447	27822	288653	217033
140	-	17	304	-	-	1	86	54	-	16	5	57	538	490	27822	262601	197444
150	1	21	307	-	1	-	142	97	-	31	5	79	676	603	27822	238072	179001
160	-	7	44	-	-	-	103	12	-	43	1	168	271	217	27822	44880	33744
180	-	11	17	-	-	-	95	40	-	34	9	77	269	219	27822	97196	73080
200	-	5	9	-	-	-	243	92	-	22	6	102	418	352	27822	114016	85726
220	-	11	136	-	6	-	103	50	-	37	2	79	394	317	27822	138758	104329
230	-	3	98	-	-	-	85	73	-	13	2	99	334	282	27822	93864	70575
250	-	18	12	-	-	-	95	84	-	22	5	75	275	229	27822	102014	76702
280	-	3	10	-	1	-	314	2	-	37	1	87	432	372	27822	138151	103873
310	-	7	24	-	-	-	75	50	-	31	2	88	218	167	27822	68923	51822
345	-	16	91	-	-	-	71	115	-	24	7	52	362	305	27822	193684	145627

Appendix Table 5 (2 of 2 parts). Roe Island pollen counts. Depth in centimeters.