Carbon-Isotope, Diatom, and Pollen Evidence for Late Holocene Salinity Change in a Brackish Marsh in the San Francisco Estuary

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Analysis of diatoms, pollen, and the carbon-isotopic composition of a sediment core from a brackish marsh in the northern part of the San Francisco Estuary has provided a paleosalinity record that covers the past 3000 yr. Changes in marsh composition and diatom frequencies are assumed to represent variations in freshwater inflow to the estuary. Three periods of relatively high salinity (low freshwater inflow) are indicated, 3000 to 2500 cal yr B.P., 1700 to 730 cal yr B.P., and ca. A.D. 1930 to the present. The most recent period of high salinity is primarily due to upstream storage and water diversion within the Sacramento–San Joaquin watershed, although drought may also have been a factor. The two earlier high-salinity periods are likely the result of reduced precipitation. Low salinity (high freshwater flow) is indicated for the period 750 cal yr B.P. to A.D. 1930. © 2001 University of Washington.

Key Words: San Francisco Estuary; Holocene; paleosalinity; pollen; diatoms; carbon isotopes.

INTRODUCTION

Brackish marshes in the San Francisco Estuary exist at the interface of freshwater inflow from rivers and salt water entering the Golden Gate from the Pacific Ocean. Prior to reclamation in the late 19th century, brackish marshes were especially extensive in Suisun Bay in the northern section of the estuary (Fig. 1). Brackish marshes are floristically distinctive and contain a greater diversity of plant species than either the salt marshes of San Francisco Bay or the freshwater marshes of the Sacramento–San Joaquin Delta (Atwater *et al.*, 1979).

The mean annual salinity in San Francisco Bay ranges from 33‰ at the Golden Gate to 0–1‰ in the Sacramento–San

Joaquin Delta (Fig. 2). The slope of the salinity gradient changes daily with the tidal cycle and seasonally with the marked variation in freshwater inflow between winter and summer (Fox *et al.*, 1991; Peterson *et al.*, 1995). The plants of the brackish marshes are well adapted to these cyclical variations and under normal conditions survive in place without significant mortality. However, if winters are moderately dry for several years in a row, as they were between A.D. 1986 and 1992, or extremely dry for even shorter intervals, such as in A.D. 1975–1976 and 1976–1977, the reduced freshwater inflow and resulting increase in salinity causes an up-estuary expansion of salt-tolerant species (e.g., *Spartina foliosa*) and a corresponding retreat of freshwater taxa (e.g., *Scirpus* spp.). In contrast, unusually wet winters, such as 1982–1983 and 1983–1984 have the opposite effect, with freshwater-adapted species extending their ranges toward the Golden Gate (Atwater and Hedel, 1976; Collins and Foin, 1993).

On longer time scales, changes in salinity may be caused by sea-level changes, resulting in an impact on both the location and composition of estuarine marshes. During the past century, estuarine salinity has been affected by human activities. The construction of reservoirs and water diversion systems has significantly changed the amount and timing of freshwater input (Nichols *et al.*, 1986). The volume of the tidal prism has been reduced by sediment accretion resulting from hydraulic mining and tidal marsh reclamation. The ecological consequences of these changes on the surviving areas of brackish marsh are not well understood.

In A.D. 1850, the fringes of Suisun Bay constituted the most extensive area of brackish marsh on the west coast of North America. Since then, over 90% of Suisun Marsh has been reclaimed. Our study site, Rush Ranch, in the northern part of Suisun Bay, is a small, unreclaimed relict of the Suisun tidal marsh (Fig. 1). The marsh is not pristine. During the early 20th

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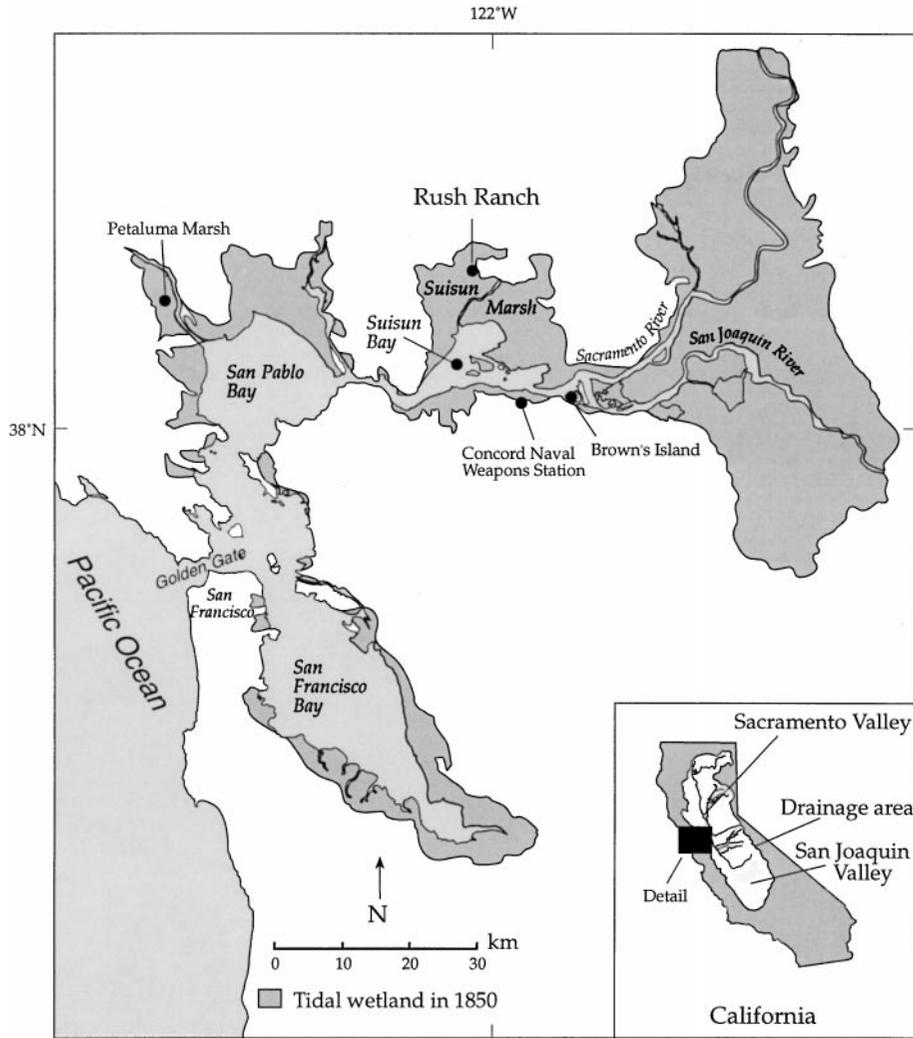
FIG. 1. Map of the study area showing the location of Rush Ranch Marsh in the San Francisco Estuary and the extent of tidal wetland in A.D. 1850.
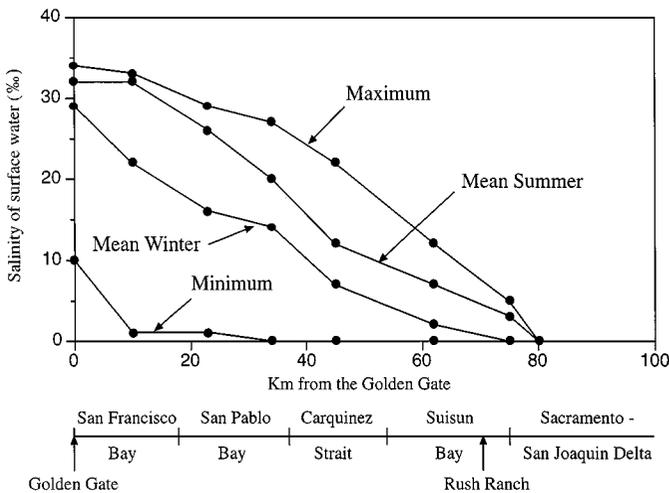

FIG. 2. Surface water salinity (1969–1975) from the Golden Gate to the Sacramento–San Joaquin Delta (Atwater *et al.*, 1979; original data from Conomos and Peterson, 1977).

century it was used for cattle grazing, and since 1940 its hydrology has been significantly influenced by reservoir construction and water diversion (Nichols *et al.*, 1986).

Previous work on stable-isotope variations in cores from San Francisco and San Pablo bays has shown that significant changes in salinity occurred in the estuary throughout the late Holocene (Ingram and Sloan, 1992; Ingram and DePaolo, 1993; Ingram *et al.*, 1996a, 1996b). However, uncertainties in radiocarbon dating of carbonate shells from these cores have made detailed interpretation difficult. In this paper, we establish a secure chronology with a series of AMS dated based almost entirely on *Scirpus* seeds. The record indicates that significant long-term changes in salinity have occurred in the estuary during the last 3000 years.

CARBON ISOTOPES, DIATOMS, AND POLLEN AS PALEOSALINITY PROXIES

Rush Ranch (RR) was selected as a study site because of its central location on the estuary's salinity gradient. We assumed

that changes in salinity regimes would be more easily detected here than in San Francisco Bay or the Sacramento–San Joaquin Delta. The composition of marsh vegetation at any given location in the San Francisco Estuary is primarily controlled by distance from the Golden Gate, the magnitude of freshwater input, and the duration of tidal submergence (Atwater *et al.*, 1979; Josselyn, 1983). The latter effect is a primary control of the elevational ranges of tidal marsh species, which in turn have been used to define zonal patterns (Hinde, 1954; Macdonald, 1988; Atwater *et al.*, 1979).

Spartina foliosa and *Salicornia virginica* dominate the tidal marshes in the more saline sectors of the estuary, such as San Francisco Bay (Atwater *et al.*, 1979). *Spartina* is important in low marsh areas (0.25 m below to 0.75 m above msl) where mean winter surface-water salinities exceed 15‰ and mean summer salinities are >20‰. *Salicornia* is the dominant species on the less frequently flooded high-marsh plain (ca. 1 m altitude). The seasonal range in salinity is much greater here than in the low marsh because of evaporation. The winter–summer range in salinity in *Salicornia*-dominated areas in Suisun Marsh is from 18.5 to 81‰ (Mall, 1969).

Mean summer salinities range from 8 to 12‰ and winter salinities from 2 to 8‰ in brackish marshes. *Scirpus californicus* replaces *Spartina* in the low marsh, and a diverse mixture of species is typically found in the high marsh (e.g., *Distchlis spicata*, *Salicornia virginica*, *Juncus* spp., *Scirpus maritimus*, and *Scirpus americanus*). In the freshwater marshes of the Sacramento–San Joaquin Delta, *Scirpus acutus* and *Typha* spp. dominate the low marsh and *Scirpus americanus* and a diverse assemblage of herbaceous species are important on the high marsh (Atwater *et al.*, 1979).

Taxa utilizing the C_4 pathway (Table 1) have substantially higher $\delta^{13}C$ values ($\sim -14‰$) than those utilizing the C_3 pathway ($\sim -29‰$), due to fractionation during carbon fixation within the plant leaf (Smith and Epstein, 1970; O'Leary *et al.*, 1992). *Salicornia* uses the CAM photosynthetic pathway and has $\delta^{13}C$ values similar to those of the C_3 species ($\sim -27‰$). The $\delta^{13}C$ value of peat samples can serve as a proxy for changes in

TABLE 1
Carbon Isotope Ratios ($\delta^{13}C$) of Plant Species in the San Francisco Estuary

Species	Photosynthetic pathway	$\delta^{13}C$ (‰)
Distichlis spicata	C4	−13.5
Spartina foliosa	C4	−12.7
Cuscuta salina	C3	−29.8
Frankenia grandifolia	C3	−30.2
Grindelia stricta	C3	−26.4
Jaumea carnosa	C3	−27.2
Juncus balticus	C3	−28.4
Lepidium latifolium	C3	−26.6
Scirpus californicus	C3	−27.5
Scirpus maritimus	C3	−25.5
Typha latifolia	C3	−27.8
Salicornia virginica	CAM	−27.2

vegetation because the carbon isotopic composition of the vegetation is preserved in marsh peat (Ember *et al.*, 1987; Malamud-Roam and Ingram, in press). In particular, the presence or absence of C_4 plants, such as *Spartina* and *Distichlis*, can be detected easily.

The use of carbon isotopes for reconstructing changes in marsh composition in the eastern United States is facilitated because (1) eastern C_4 taxa tend to dominate in more saline areas, and (2) C_3 taxa prefer freshwater environments (DeLaune, 1986; Chmura and Aharon, 1995). A parallel dichotomy exists in San Francisco Bay marshes, except that salt-tolerant *Salicornia* is isotopically indistinguishable from the C_3 plants that dominate the freshwater marshes. Fortunately, this complication can be overcome by pollen analysis, because *Salicornia* pollen is easily distinguished from the pollen produced by *Scirpus*, *Typha*, and other freshwater taxa.

Several studies have documented the diatom flora of San Francisco Bay (Wong and Cloern, 1981; Mahood *et al.*, 1986; Laws, 1988), but none have described the flora in detail or utilized diatom assemblages to understand the ecology of this complex ecosystem. The present study represents the first attempt to use diatom assemblages for interpreting regional climate change.

A Diatom Salinity Index (DSI) was developed for the northern San Francisco estuary marshes. The DSI summarizes the proportions of taxa that prefer freshwater, brackish, and marine salinities. These preferences are freshwater (F; 0–2‰), both freshwater and brackish (FB; 0–30‰), brackish (B; 2–30‰), brackish and marine (BM; 2–35‰), and marine (M; 30–35‰): $DSI = (F + FB + 0.5B)/(F + FB + B + BM + M)$. The value for taxa with brackish preference receives reduced weight in the numerator in order to treat the brackish salinities as transitional between freshwater and normal marine salinity values. The index ranges from 0.00 to 0.30 for samples dominated by marine taxa, 0.31 to 0.70 for samples dominated by a mixture of taxa, and 0.71 to 1.00 for samples dominated by freshwater taxa. At Rush Ranch, the DSI corresponds closely to the abundance of freshwater taxa.

Pollen has been used as a paleosalinity proxy in several previous studies (Meyerson, 1972; Mudie, 1975; Davis, 1992). In the San Francisco Estuary, changes in marsh composition along the salinity gradient are easily detected in pollen samples taken from the marsh surface. Chenopodiaceae pollen typically accounts for more than 80% of the aquatic pollen sum in salt marshes. This pollen type is assumed to represent *Salicornia* and *Atriplex*, although the latter is a relatively minor component of the modern marsh. Chenopodiaceae pollen is rare in surface pollen samples taken in upland sites in coastal California (Mudie, 1975). In freshwater marshes, Cyperaceae dominates, being 50 to 80% of the aquatic pollen sum. The Cyperaceae pollen type is probably mostly from *Scirpus*, although *Juncus* and *Cyperus* may also be present. The modern pollen-rain of brackish marshes, with high percentages of Asteraceae, Poaceae, Chenopodiaceae, and Cyperaceae pollen types, is more diverse than that of either the salt marshes or the freshwater marshes.

METHODS

Field Techniques

Plant specimens and sediment samples were collected from marshes at the Concord Naval Weapons Station (Fig. 1) in the spring of 1997 to measure their carbon isotopic composition for calibration purposes. The specimens have been vouchered and deposited in the herbarium of the University of California Museum of Paleontology Pollen Laboratory.

In February 1996, a 3.5-m core was recovered from an area of high marsh (1 m altitude) at RR in northern Suisun Bay (Fig. 1). The core site is located between a tidal channel and the adjacent upland area. The core was raised with a modified 5-cm-diameter Livingston piston corer equipped with plastic (butyrate) liners. The high clay content of the marsh sediments prevented full recovery of meter-length sections, so cores were taken at overlapping 50-cm depths. The cores were X-radiographed and then split lengthwise for stratigraphic description and subsampling.

Laboratory Techniques

The core was subsampled for carbon-isotope analysis of sedimentary organic-carbon at 5-cm (0–35 cm) and 10-cm (35–355 cm) intervals. Sediment samples were wet-sieved into coarse (>2 mm) and fine (>125 μm, <2 mm) size fractions. The coarse fraction consists of mostly undecomposed plant roots and rhizomes, whereas the fine fraction represents decomposed plant matter and occasional foraminifera.

Thirty-seven samples were analyzed from the coarse fraction and fourteen samples were analyzed from the fine fraction. Samples were pretreated with 1 N hydrochloric acid to remove carbonate material and were combusted to yield CO_2 for isotopic analysis using standard techniques (Boutton, 1991).

Carbon-isotopic ratios ($^{13}C/^{12}C$) were measured on a Fisons Instruments Prism Series II mass spectrometer at the Lawrence Berkeley National Laboratory's Center for Isotope Geochemistry (CIG). Carbon-isotope ratios of modern marsh sediments and plants were measured on a 20/20 Europa Scientific mass spectrometer connected to a Europa Scientific SL carbon–nitrogen analyzer. All carbon-isotopic data ($^{13}C/^{12}C$) are reported in the δ notation relative to the PeeDee Belemnite standard (PDB), where $\delta^{13}C = [(^{13}C/^{12}C_{sample}/^{13}C/^{12}C_{std}) - 1] \times 1000$. The precision is ± 0.05‰ for the $\delta^{13}C$ value.

Twenty-five samples were taken at $\sim$10-cm intervals for pollen analysis. Standard extraction procedures were followed (Faegri and Iversen, 1975), with the addition of sieving through a 125-μm mesh after the KOH treatment. *Lycopodium* spores were added to each sample to permit calculation of absolute concentrations (Stockmarr, 1971). Pollen counting was done with a Leitz Laborlux Microscope at $400\times$ magnification. The mean count, excluding *Lycopodium*, was 389 pollen and spores.

Seventy-one samples were analyzed for diatoms. Sampling intervals varied among 1 cm (0–25 cm), 5 cm (25–150 cm), and 10 cm (150–350 cm). Samples were processed using standard techniques and were pretreated with 30% H_2O_2, 36% HCl, and 16 N HNO_3. Prepared material was mounted on standard microscope slides using Hyrax, and identifications were made using an Olympus BH-2 microscope equipped with $50\times$ and $100\times$ oil immersion lenses. A minimum of 300 specimens were counted on each slide.

The chronology for the RR core is based on four AMS radiocarbon dates (Table 2). Three of these dates are on *Scirpus* seeds picked from the 2-mm sieved fractions. The fourth, from a section of the cores that lacked seeds, is on a *Distichlis spicatum* rhizome. These rhizomes do not penetrate deeply ($\sim$10 cm) and are therefore reliable indicators of the age of the marsh surface. The chronology was developed using linear interpolation between calibrated dates. Calibrated ages were chosen using the midpoint of the range given in the CALIB program (MacCalib Rev 3.03c; Stuiver and Reimer, 1993).

RESULTS

Chronology

The radiocarbon dates (Table 2) indicate that the base of the core has an extrapolated age of ca. 3000 cal yr B.P. This is generally consistent with other radiocarbon dates from the estuary, which indicate that marshes began expanding 3000 to 2000 cal yr B.P. (Atwater *et al.*, 1979). The accretion rate at the core site has varied between 0.6 and 1.6 mm/yr over the past 3000 yr.

Stratigraphy

Significant variations in the paleosalinity proxies (the DSI, pollen frequencies, and carbon isotope ratios) occur in the RR core (Fig. 4). Pollen preservation was poor in the lowest 25 cm of the core, and results are therefore only shown from the surface to a depth of 325 cm. For purposes of discussion five stratigraphic units are recognized.

Unit RR-5 (325–275 cm, ca. 2700–ca. 2500 cal yr B.P.)

Unit RR-5 consists of alternating sections of coarsely laminated clayey silt and peaty clay. The organic content ranges from 30 to 60% of the dry bulk density. Ostracods and gastropods are present in the relatively inorganic sediments, but not in the peaty clay. The DSI oscillates around 0.5. Chenopodiaceae pollen is the dominant pollen type in this unit and Cyperaceae pollen is virtually absent. The $\delta^{13}C$ values are highly variable, ranging from -25 to -14‰. The high $\delta^{13}C$ values are positively correlated with peaks in the Poaceae pollen curve.

Unit RR-4 (275–175 cm, ca. 2500–ca. 1750 cal yr B.P.)

Unit RR-4 is characterized by a high organic content (typically, $>60\%$), the organic fraction consisting primarily of decomposed *Scirpus* stems and rhizomes with lesser amounts of *Distichlis* rhizomes. The DSI and pollen frequencies are variable, with the dominant diatom taxa being freshwater taxa. Cyperaceae and Chenopodiaceae pollen both average about 40% of the pollen sum, and Poaceae pollen has a prominent peak at

TABLE 2
Radiocarbon Dates from Rush Ranch, Browns Island, and Petaluma Marsh

Site—Core	Depth (cm)	Material dated	Laboratory number[a]	Age (^{14}C yr B.P.)	One-sigma age range (cal yr B.P.)[b]
Browns Island—97A	60–61	*Scirpus* seeds	CAMS-46627	240 ± 80	420–0
Browns Island—97A	89–90	*Scirpus* seeds	CAMS-40777	810 ± 80	780–660
Browns Island—97A	129–30	*Scirpus* seeds	CAMS-40778	1060 ± 40	970–930
Browns Island—97A	149–150	*Scirpus* seeds	CAMS-46624	1210 ± 50	1170–1060
Browns Island—97A	179–180	*Scirpus* seeds	CAMS-46625	1270 ± 80	1280–1070
Browns Island—97A	209–210	*Scirpus* seeds	CAMS-46626	1560 ± 50	1520–1360
Browns Island—97A	240–241	*Scirpus* seeds	CAMS-40780	1780 ± 80	1810–1570
Browns Island—97A	322–333	*Scirpus* seeds	CAMS-40781	2330 ± 70	2360–2320
Petaluma Marsh—90.1	42–48	Bulk peat	Beta-53860	200 ± 60	296–0
Petaluma Marsh—90.1	52–58	Bulk peat	Beta-53861	280 ± 60	430–0
Petaluma Marsh—90.1	60–70	Bulk peat	Beta-46829	590 ± 70	648–529
Petaluma Marsh—90.1	80–90	Bulk peat	Beta-52696	480 ± 50	536–501
Petaluma Marsh—90.1	90–100	Bulk peat	Beta-46830	520 ± 50	548–511
Petaluma Marsh—90.1	105–115	Bulk peat	Beta-52697	790 ± 60	733–664
Petaluma Marsh—90.1	120–130	Bulk peat	Beta-46831	880 ± 50	889–724
Petaluma Marsh—87.2	148	Rhizome	AA-2735	1000 ± 50	946–800
Petaluma Marsh—90.1	150–160	Bulk peat	Beta-46832	1220 ± 50	1223–1064
Petaluma Marsh—90.1	180–190	Bulk peat	Beta-46833	1740 ± 70	1716–1544
Petaluma Marsh—90.1	210–220	Bulk peat	Beta-46834	1900 ± 80	1925–1720
Rush Ranch—96A	114–115	*Scirpus* seeds	CAMS-27555	840 ± 60	785–674
Rush Ranch—96A	175–176	*Scirpus* seeds	CAMS-27556	1840 ± 50	1826–1706
Rush Ranch—96A	259–260	*Scirpus* seeds	CAMS-27557	2390 ± 50	2461–2344
Rush Ranch—96A	299–300	*Distichlis* rhizome	CAMS-27558	2400 ± 60[c]	2748–2492

[a] The Beta numbers are conventional ^{14}C dates. The CAMS and AA numbers are AMS-dates.

[b] All radiocarbon dates were calibrated with the bidecadal dataset of MacCALIB Rev. 3.03c (Stuiver and Pearson, 1993).

[c] The calibrated age of this sample was corrected for C4 fractionation by adding 144 years to its radiocarbon age, which represents 16 years for each ‰ difference between its δ^{13}C value of −16‰ and a δ^{13}C value of −25‰.

about 225 cm (ca. 2150 cal yr B.P.). The δ^{13}C values are highly negative in the lower and upper levels of this unit and less negative in levels with high Poaceae pollen percentages.

Unit RR-3 (175–115 cm, ca. 1750–ca. 750 cal yr B.P.)

The organic content is generally near 50% but drops slightly in the upper part of this unit to 40% dry weight. The DSI is generally low, with a minimum of 0.1 at 140 cm (ca. 1250 cal yr B.P.). The brackish to marine taxon *Navicula peregrina* comprises as much as 80% of the total assemblage. At 170 cm (ca. 1750 cal yr B.P.) Cyperaceae frequencies decrease to <5% and Chenopodiaceae increase to >70%. Chenopodiaceae pollen is less important in the upper part of the unit, where Poaceae pollen is >25% of the pollen sum. As in the previous unit, the δ^{13}C values generally parallel the trends in Poaceae pollen, although the lowest δ^{13}C values occur 10 cm below the Poaceae peak.

Unit RR-2 (115–10 cm, ca. 750 cal yr B.P.–ca. A.D. 1930)

The organic content of this unit varies from 30 to 50% of the dry bulk density. In the lower part of the unit, the peat consists primarily of *Scirpus* stems in vertical growth position. The DSI averages ca. 0.9 and shows little variability throughout the unit. *Denticula subtilis*, a freshwater diatom, comprises as much

as 80% of the assemblage in this interval. Cyperaceae pollen averages ca. 60% of the pollen sum, and Asteraceae pollen is between 10 and 20%. Chenopodiaceae pollen is rare, typically <5%. Poaceae pollen also is also relatively unimportant, especially in the upper part of the unit. The fine-fraction δ^{13}C samples show little intersample variation and are all highly negative at ca. −27‰. The coarse-fraction samples are more variable but, with the exception of the three youngest samples, are also highly negative, with δ^{13}C values of ca. −26‰.

Unit RR-1 (10 cm–surface, ca. A.D. 1930–Present)

The lower part of Unit RR-1 (20–7 cm) has a low organic content (25–40%). The inorganic fraction consists of clay and silt. All three salinity proxies change abruptly within this unit. The DSI drops from 0.90 at 20 cm to 0.10 at the surface, and *Denticula subtilis* is replaced by a number of taxa that tolerate a greater range of salinities. Cyperaceae and Asteraceae pollen decrease from 50 and 15%, respectively, to <5%. Chenopodiaceae pollen increases from <5 to 70%. Poaceae pollen also increases from <5% at 10 cm to 15% at the surface. The δ^{13}C of both the coarse and fine fractions increase toward the present, although the latter lags the former by about 15 cm.
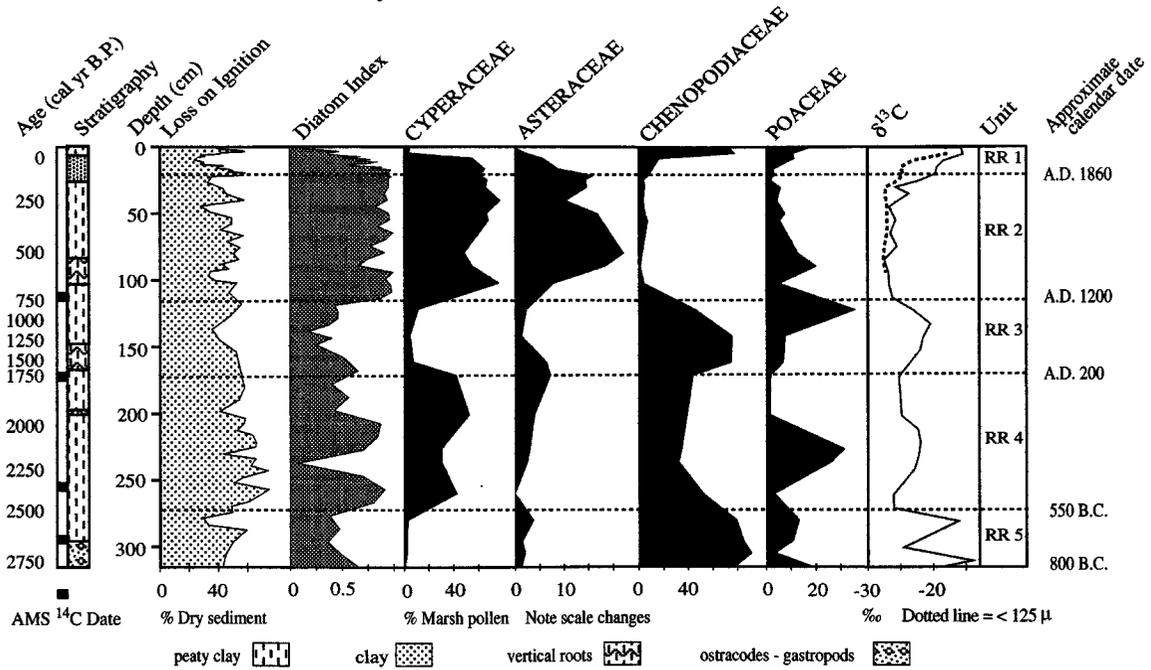
Rush Ranch, Solano County, California

FIG. 3. Stratigraphy, chronology, Diatom Salinity Index, Selected pollen taxa, and $\delta^{13}C$ values from the Rush Ranch core. Pollen represent percentages of total marsh pollen.

DISCUSSION

The three paleosalinity proxies from the RR core all show the same basic trends (Fig. 3). Changes in salinity occurred relatively rapidly, e.g., at 2500, 1750, and 750 cal yr B.P., and at A.D. 1930. Salinity conditions remained relatively stable during the intervening periods. The following discussion explores methodological implications of the evidence presented and the extent to which the RR paleosalinity record reflects effects of climatic change (e.g., changes in freshwater flow into the estuary) or nonclimatic factors (e.g., plant succession, changes in sea level, and human impacts). We also compare RR and other paleosalinity records from coastal California.

Methodological Implications

The Rush Ranch carbon-isotope and pollen data are complementary in that they permit a more detailed reconstruction of salinity change than would be the case with either record alone. For example, the positive correlation between Poaceae pollen percentages and $\delta^{13}C$ variations (Fig. 3) strongly supports the idea that the Poaceae pollen was derived from either *Distichlis* or *Spartina*. *Distichlis spicata* is locally important in high-marsh environments from San Pablo Bay to Suisum Bay, whereas *Spartina foliosa* is a low-marsh species, whose contemporary range barely extends eastward into Suisun Bay. The correlation also indicates that Poaceae species, which in central California are C_3 taxa, are an unimportant component. This multiproxy approach can distinguish taxa that are isotopically similar but
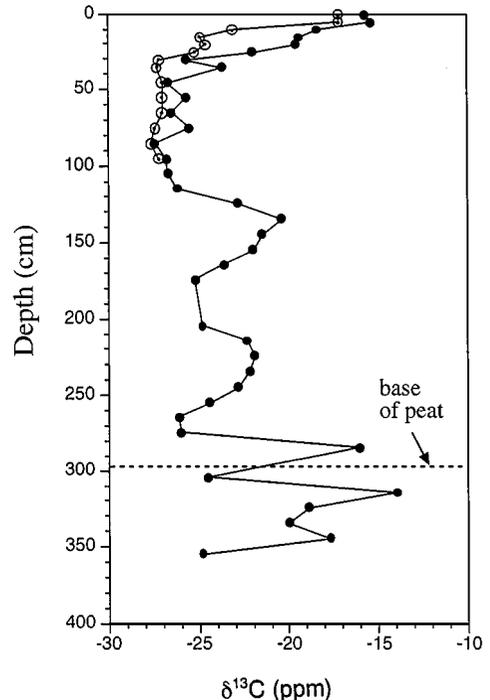

FIG. 4. Carbon isotopes ($\delta^{13}C$) plotted against depth (cm) for the Rush Ranch core. The coarse fraction (>2 mm) is plotted with closed circles and the fine fraction (>125 μm, <2 mm) is plotted using open circles.

TABLE 3
Sample Depth and Carbon Isotopic Composition of Coarse
and Fine Fractions from the Rush Ranch Core

Depth (cm)	$\delta^{13}C$ coarse (>2 mm)	$\delta^{13}C$ fine (>125 μm, <2 mm)
0.5	−15.7	−17.2
5.5	−15.4	−17.2
10.5	−18.4	−23.1
15.5	−19.4	−24.9
20.5	−19.6	−24.6
25.5	−22.0	−25.2
30.5	−25.7	−27.2
35.5	−23.7	−27.3
45.5	−26.7	−27.0
55.5	−25.7	−27.0
65.5	−26.5	−27.0
75.5	−25.5	−27.4
85.5	−27.4	−27.6
95.5	−26.8	−27.2
104.5	−26.7	
114.5	−26.2	
124.5	−22.8	
134.5	−20.4	
144.5	−21.5	
154.5	−22.0	
164.5	−23.6	
174.5	−25.2	
204.5	−24.8	
214.5	−22.3	
224.5	−21.9	
234.5	−22.2	
244.5	−22.8	
254.5	−24.4	
264.5	−26.1	
274.5	−26.0	
284.5	−16.1	
304.5	−24.5	
314.5	−14.0	
324.5	−18.9	
334.5	−20.0	
344.5	−17.7	
354.5	−24.8	

ecologically different. For example, *Salicornia* and *Scirpus* have similar $\delta^{13}C$ values but very different salinity tolerances.

The depth of vertical penetration of roots at Rush Ranch can be inferred from differences between the $\delta^{13}C$ values of the fine (>125 μm, <2 mm)- and coarse (>2 mm)-fraction samples (Fig. 6 and Table 3). The two size fractions show the same trends, but the coarse samples are offset vertically by 10 to 15 cm. *Distichlis*, a C_4 taxon, has resistant roots that are included in the coarse-fraction samples. Thus, the displacement of grain size probably reflects *Distichlis* root penetration.

The Paleosalinity Record: Nonclimatic Effects

Plant succession is an important nonclimatic influence on marsh salinity. The RR stratigraphy indicates that the late Holocene marsh was permanently established ca. 2500 cal yr

B.P. Prior to this (Unit RR-5, Fig. 3), alternating periods of marsh and low-energy tidal flat characterized the core site. The Poaceae pollen peaks and corresponding low $\delta^{13}C$ values in RR-5 most likely represent *Spartina foliosa*. The species indicates that mean seasonal salinity perhaps was 15–20‰ as compared with 2–7‰ today. The Chenopodiaceae pollen is probably nonlocal in origin, having been washed or blown into the tidal flat from nearby marshes fringing the eastern upland area (Fig. 1).

Given the ecology of local marsh plants, the initial period of marsh formation, as represented by the lower part of Unit RR-4, involved growth of low-marsh taxa (e.g., *Spartina foliosa* and *Scirpus californicus*). The radiocarbon chronology indicates that a gradual accumulation of marsh peat (ca. 1.3 mm/yr) culminated in the development of a mature high-marsh by 1750 cal yr B.P. (i.e., at the end of Unit RR-4). The reduced frequency of tidal flooding and increased evaporation on the high-marsh plain would have increased the local importance of salt-tolerant taxa, such as *Salicornia* and *Distichlis*. The marsh surface was close to the upper limit of tidal action, which would also have slowed the rate of accretion, as is indicated in the radiocarbon chronology.

The distribution of marsh plants is strongly influenced by the frequency and duration of tidal submergence, so any vertical displacement of the marsh, caused for example by a tectonically induced change in sea level, has important ecological consequences. Perhaps the decline in Cyperaceae and rise in Chenopodiaceae pollen percentages at 1750 cal yr B.P. were caused by an upward displacement of the marsh surface. Similarly, the decrease in Chenopodiaceae and the increase in Cyperaceae pollen percentages at 750 cal yr B.P. may have been caused by a lowering of the marsh surface.

One means of testing these possibilities is to compare the RR radiocarbon chronology with chronologies developed for two other marsh sites in the estuary. Petaluma Marsh in San Pablo Bay and Brown's Island east of Suisun Bay are located on separate fault blocks (Fig. 5). If tectonic activity were the primary determinant of marsh stratigraphy, each marsh should show a somewhat different record of sediment accretion. The age–depth relationships for the three marshes are remarkably similar (Fig. 5). This finding suggests that tectonic activity has not played a major role in changing the floristic composition of the marshes. The three marshes are located close to three different faults, and it seems unlikely that a single earthquake event would affect all three areas in the same way. The average rate of marsh accretion over the last 750 yr has been close to 1.5 mm/yr at all three sites, close to the average rate of sea-level rise at San Francisco for the period A.D. 1855–1986 (Lyles *et al.*, 1988). All of this strongly suggests that the primary control on marsh elevation during the period of record has been eustatic and not isostatic sea-level change.

The final nonclimatic influence on marsh salinity is reduced freshwater flow into the estuary because of diversions for agricultural and urban use (Nichols *et al.*, 1986; Peterson *et al.*, 1995). Storage in reservoirs decreases winter inflow and
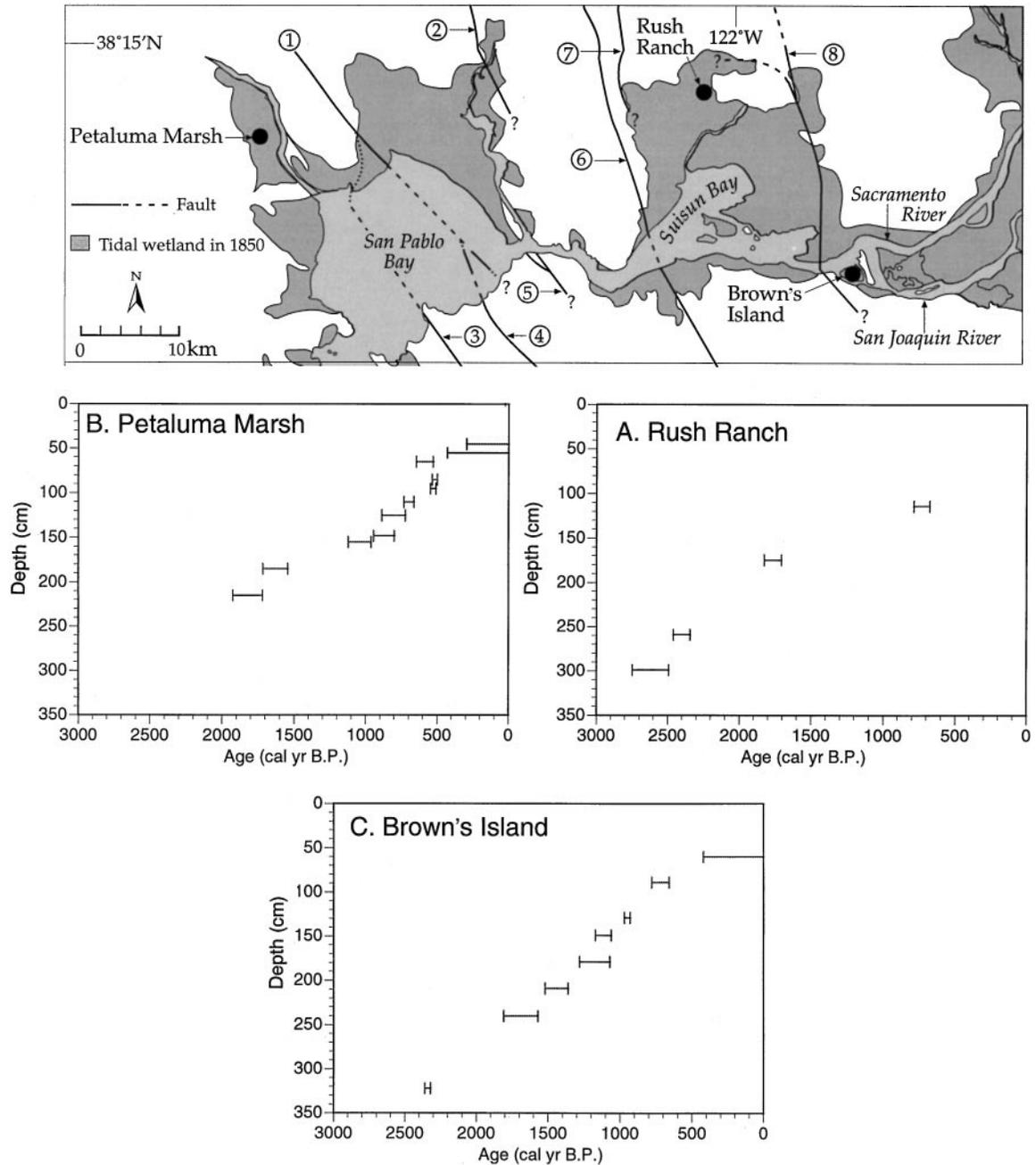
FIG. 5. Map showing the location of major faults and three marsh sites (Brown's Island, Rush Ranch, and Petaluma Marsh) cored in northern San Francisco Bay. Calibrated radiocarbon ages (cal yr B.P.), shown for three marsh locations, are plotted against depth in core. Faults are as follows: (1) Rodger's Creek; (2) West Napa; (3) Hayward; (4) Pinole; (5) Franklin Canyon; (6) Green Valley; (7) Cordelia; (8) Pittsburg–Kirby Hills.

increases summer flow. Russell *et al.* (1982) estimated that the pre-A.D. 1850 inflow to the estuary from the delta averaged 36 km³/yr and that by A.D. 1978 the flow had been reduced by 44% to 20 km³/yr. Significant diversion of water first occurred in the period A.D. 1920–1950 when numerous dams and aqueducts were constructed. The California Aqueduct, which diverts water from the delta to southern California, was constructed between A.D. 1960 and 1970.

We interpret the increase in salinity indicated in stratigraphic Unit RR-1 to be the result of water diversion and reduced freshwater flow into the estuary. All three paleosalinity proxies increase significantly at approximately the same depth in the core: we see a shift to isotopically less-negative $\delta^{13}C$ values in the fine-fraction between 10.5 and 5.5 cm, an increase in Chenopodiaceae and decrease in Cyperaceae pollen percentages between 8 and 5 cm, and a drop in the DSI at ca. 10 cm. If the mean

annual accretion rate for this part of the core is assumed to be 1.5 mm/yr and the increase in salinity is set to the 10 cm depth, the corresponding date would be A.D. 1930. The salinity increase indicated in Unit RR-1 may also be partially due to reduced precipitation in the Sacramento Basin watershed. Earle (1993) used tree-ring evidence to reconstruct Sacramento stream flow for the period A.D. 1560 to 1980 and found that A.D. 1917 to 1950 was the driest interval over the 420-yr period.

The Paleosalinity Record: Climatic Effects

Loss-on-ignition, diatom, pollen, and carbon isotope data indicate that the RR marsh was permanently established by ca. 2500 cal yr B.P. (Fig. 3). This event was preceded by a period (Unit RR-5) of incipient marsh formation that periodically reverted to tidal flat, as indicated by high Chenopodiaceae pollen percentages, an absence of Cyperaceae pollen, high but fluctuating $\delta^{13}C$ values and Poaceae pollen percentages, and high DSI. The values of the paleosalinity proxies in Unit RR-5 are similar to those of Unit RR-1. However, a high marsh similar to that of the 20th century did not exist at the core site prior to 2500 cal yr B.P. An intermittent low marsh with *Spartina* is the more plausible interpretation, suggesting mean seasonal salinity values at the core site could have been 15–20‰ as compared with 2–7‰ today.

The paleosalinity proxies in units RR-1 (A.D. 1930 to the present) and RR-3 (1750 to 750 cal yr B.P.) also show convincing evidence of climatic influences, indicating that average freshwater-inflow levels during Unit RR-3 were as low as they have been during the present century. Russell *et al.* (1982) estimated that 20th century diversions had reduced the freshwater inflow to the estuary by 44% to 20 km^3/yr by A.D. 1978. This magnitude of flow probably was also typical of the period 750–1750 cal yr B.P. This interpretation suggests an equivalent reduction in precipitation for the watershed, since there were no prehistoric, artificial diversions.

Further evidence of climatic effects in the RR record is the marked decrease in all three paleosalinity proxies in Unit RR-2 (750 cal yr B.P. to A.D. 1930). Cyperaceae pollen dominates the records, indicating that tules (probably *Scirpus maritimus* and *Scirpus americanus*) covered most of the high marsh. According to Mall's (1969) data on the salinity tolerances of Suisun Marsh plants, these results imply mean annual salinities on the marsh surface of 7 to 33‰, which is significantly less than the modern 19 to 81‰ mean annual range for *Salicornia*. The mean annual salinity of the surface waters of Suisun Bay was probably proportionally reduced to less than 5‰.

Comparisons with Other California Paleosalinity Records

The relative importance of climate change as an influence on marsh salinity can be clarified by comparison with records from different areas. Relatively few paleosalinity studies have been carried out in coastal California, and even where data are available, chronological control generally is poor. However, a comparison of some of the available records shows several interesting trends (Fig. 6.) The RR and San Joaquin Marsh indices show similar trends for the last 1500 yr, although the low-salinity phases are more pronounced and more prolonged at RR than at San Joaquin Marsh. Both sites show increasing salinity during the last 100 yr.

The Petaluma Marsh and San Pablo Bay records only cover the last 700 yr. The former is based on the Mg/Ca ratios of ostracode valves and the latter on oxygen isotope ratios of *Macoma nasuta*. The Petaluma record shows the same basic trends as the pollen indices, with decreasing salinity from ca. 650 cal yr B.P. until about 200 cal yr B.P., followed by increasing salinity to the present. The San Pablo salinity curve shows little agreement with the other records. We attribute this discrepancy to uncertainties in radiocarbon dating at this site. The chronology was based on four AMS dates that were corrected for an assumed reservoir age of 625 yr. If this correction is too great, the core
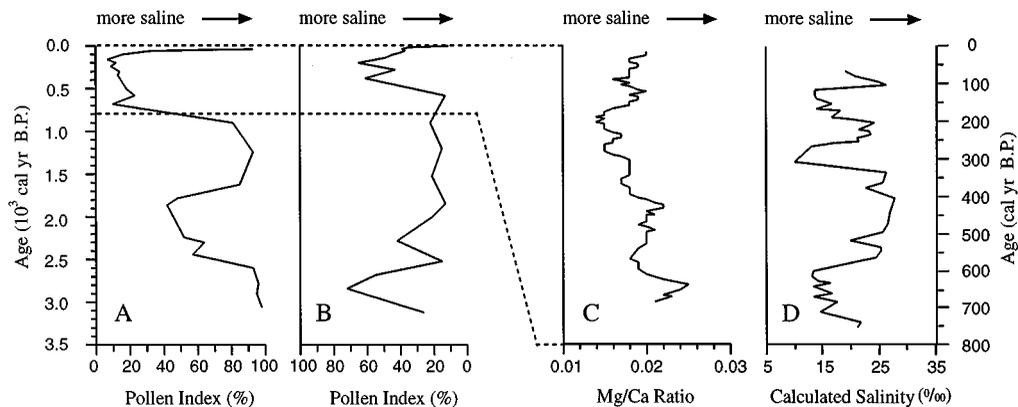

FIG. 6. Paleosalinity records from Coastal California. (A) Rush Ranch Pollen Index. The index represent Chenopodiaceae plus Poaceae pollen as a percentage of Chenopodiaceae, Poaceae, Cyperaceae, and Asteraceae. (B) San Joaquin Pollen Index from Davis (1992). The index represents the percentage of Asteraceae pollen. High percentages represent freshwater conditions. (C) Mg/Ca ratio from ostracods from a Petaluma marsh core. High Mg/Ca ratio indicates higher salinity (from Ingram *et al.*, 1998). (D) Salinity determined by $\delta^{18}O$ measured on fossil mollusk shells from San Pablo Bay (from Ingram *et al.*, 1996a).

will represent a proportionally longer time period than indicated (Fig. 6D).

CONCLUSIONS

This study documents the results of the analyses of diatoms, pollen, and stable carbon isotopes from a 3.5-m core from RR, a brackish tidal marsh in the northern sector of the San Francisco Estuary. The core spans the last 3000 yr and indicates that the marsh was established ca. 2500 cal yr B.P. The results also indicate that the salinity of water affecting the marsh has changed significantly during this period. These changes are due partially to climatic effects or, more specifically, changes in the magnitude of freshwater inflow into the estuary. Nonclimatic effects, such as plant succession and human impacts were also important. No obvious evidence of tectonic activity was encountered.

Reduced freshwater-flow into the estuary occurred at 3000 to 2500 cal yr B.P., 1750 to 750 cal yr B.P., and ca. A.D. 1930 to the present. During the first period the intermittent presence of the C_4 grass *Spartina foliosa* at the core site indicates that mean seasonal surface salinities may have been in the range of 15 to 20‰. In the second period, all three proxy records indicate salinity conditions similar to those of the present. These results imply a reduction of rainfall in the Sacramento–San Joaquin watershed, possibly by as much as 44% below 20th-century levels. The third period of reduced freshwater inflow coincides with, and is most likely due to, upstream storage and water diversion in the Sacramento–San Joaquin watershed. However, drought may also have been a factor, as the period A.D. 1970 to 1950 was extremely dry in the Sacramento Valley watershed. The period 750 cal yr B.P. to A.D. 1930 was characterized by unusually high freshwater-inflows to the estuary. Mean seasonal salinities during this period were probably analogous to those of the Sacramento–San Joaquin Delta prior to water diversions (i.e., 0‰) both in winter and summer.

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REFERENCES

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

Atwater, B. F., and Hedel, C. W. (1976). "Distribution of Seed Plants with Respect to Tide Levels and Water Salinity in the Natural Tidal Marshes of the Northern San Francisco Bay Estuary." U.S. Geological Survey Open-File Report 76–389.

Boutton, T. W. (1991). Stable carbon isotope ratios of natural materials: I. Sample preparation and mass spectrometer analysis. *In* "Carbon Isotope Techniques" (D. C. Coleman and B. Fry, Eds.), pp. 155–171. Academic Press, San Diego.

Byrne, R., Collins, J., and Esser, B. (1994). "Late Holocene Salt Marsh Formation at Petaluma, California." Abstract, Annual Meeting of the Geological Society of America, Seattle, Washington, Oct. 24–27, 1995.

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

Collins, J. N., and Foin, T. C. (1993). Evaluation of the impacts of aqueous salinity on the shoreline vegetation of tidal marshlands in the San Francisco estuary. *In* "Managing Freshwater Discharge to the San Francisco Bay/Sacramento–San Joaquin Delta Estuary: The Scientific Basis for an Estuarine Standard" (J. R. Schubel, Ed.), pp. C1–C34. San Francisco Estuary Project, San Francisco.

Conomos, T. J., and Peterson, D. H. (1977). Suspended-particle transport and circulation in San Francisco Bay: An overview. *In* "Estuarine Processes" (L. E. Cronin, Ed.), pp. 82–97. Academic Press, New York.

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

DeLaune, R. D. (1986). The use 13C signature of C-3 and C-4 plants in determining past depositional environments in rapidly accreting marshes of the Mississippi River deltaic plain, Louisiana. *Chemical Geology* **59,** 315–320.

Earle, C. J. (1993). Asynchronous droughts in California streamflow as reconstructed from tree rings. *Quaternary Research* **39,** 290–299.

Ember, L. M., Williams, D. F., and Morris, J. T. (1987). Processes that influence carbon isotope variations in salt marsh sediments. *Marine Ecology Progress Series* **36,** 33–42.

Faegri, K., and Iversen, J. (1975). "Textbook of Pollen Analysis." Hafner, New York.

Fox, J. P., Mongan, T. R., and Miller, W. J. (1991). Long-term, annual and seasonal trends in surface salinity of San Francisco Bay. *Journal of Hydrology* **122,** 93–117.

Hinde, H. P. (1954). The vertical distribution of salt marsh phanerogams in relation to tide levels. *Ecological Monographs* **24,** 209–225.

Ingram, B. L., De Deckker, P., Chivas, A. R., Conrad, M. E., and Byrne, A. R. (1998). Stable isotopes, Sr/Ca, and Mg/Ca in biogenic carbonates from Petaluma Marsh, northern California, USA. *Geochimica et Cosmochimica Acta* **62,** 3229–3237.

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

Ingram, B. L., Ingle, J. C., and Conrad, M. E. (1996a). A 2000 yr record of Sacramento San Joaquin River inflow to San Francisco Bay Estuary, California. *Geology* **24,** 331–334.

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

Ingram, B. L., Sloan, D. (1992). Strontium isotopic composition of estuarine sediments as paleosalinity–paleoclimate indicator. *Science* **255,** 68–72.

Josselyn, M. (1983). "The Ecology of San Francisco Bay Tidal Marshes: A Community Profile." FWS/OBS-83/23, U.S. Fish and Wildlife Service, Division of Biological Services, Washington, DC.

Laws, R. A. (1988). Diatoms (Bacillariophyceae) from surface sediments in the San Francisco Bay Estuary. *Proceedings of the California Academy of Science* **44,** 127–156.

Lyles, S. D., Hickman, L. E., and Debaugh, H. A. (1988). "Sea Level Variations for the United States 1855–1986." U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Rockville, MD.

Macdonald, K. B. (1988). Coastal salt marsh. *In* "Terrestrial Vegetation of California" (M. Barbour and J. Major, Eds.), pp. 263–294. California Native Plant Society, Davis.

Mahood, A. D., Fryxell, G. A., and McMillan, M. (1986). The diatom genus *Thalassiosira*: Species from the San Francisco Bay system. *Proceedings of the California Academy of Science* **44,** 127–156.

Malamud-Roam, F., and Ingram, B. L. (in press). Stable carbon isotopes in plants and sediments of tide marshes of the San Francisco Estuary. *Journal of Coastal Research*.

Mall, R. E. (1969). "Soil–Water–Salt Relationships of Waterfowl Food Plants in the Suisun Marsh of California." Wildlife Bulletin No. 1., California Department of Fish and Game, Sacramento.

Meyerson, A. L. (1972). Pollen and paleosalinity analyses from a Holocene tidal marsh sequence, Cape May County, New Jersey. *Marine Geology* **12,** 335–357.

Mudie, P. J. (1975). "Palynology of Recent Coastal Lagoon Sediments in Southern and Central California." Abstract, Annual Meeting of the Botanical Society of America, Corvallis, Oregon, Aug. 17–22, 1975.

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

Nichols, F. H., Coern, J. E., Luoma, S. N., and Peterson, D. H. (1986). The modification of an estuary. *Science* **231,** 525–528.

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

Peterson, D. H., Cayan, D. R. DiLeo, J., Noble, M., and Dettinger, M. (1995). The role of climate in estuarine variability. *American Scientist* **83,** 58–67.

Round, F. E., Crawford, R. M., and Mann, D. G. (1990). "The Diatoms." Cambridge Univ. Press, Cambridge.

Russell, P. P., Bursztynsky, T. A., Jackson, L. A., and Leong, E. Y. (1982). Water and waste inputs to San Francisco Bay—An historical perspective. *In* "San Francisco Bay: Use and Protection" (W. J. Kockelman, T. J. Conomos, and A. E. Leviton, Eds.), pp. 127–136. Pacific Division, American Association for the Advancement of Science, San Francisco.

Smith. B. N., and Epstein, S. (1970). Biogeochemistry of stable isotopes of hydrogen and carbon in salt marsh biota. *Plant Physiology* **46,** 738–742.

Stockmarr, J. (1971). Tablets with spores used in absolute pollen analysis. *Pollen et Spores* **13,** 615–621.

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

Wells, L. E., and Goman, M. (1994). Late Holocene environmental variability in the upper San Francisco Estuary as reconstructed from tidal marsh sediments. *In* "Proceedings of the Eleventh Annual Pacific Climate (PACLIM) Workshop, Asilomar, California, April 19–22," pp. 185–198. Technical Report 40, Interagency Ecological Program, California Department of Water Resources, Sacramento.

Wong, R. L. J., Cloern, J. E. (1981). "Plankton Studies in San Francisco Bay. II. Phytoplankton Abundance and Species Composition, January 1977–December 1979." U.S. Geological Survey Open-File Report 81–214.