A 2000 yr record of Sacramento–San Joaquin river inflow to San Francisco Bay estuary, California

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ABSTRACT

Oxygen and carbon isotopic measurements of fossil bivalves (*Macoma nasuta*) contained in estuarine sediment are used to reconstruct a late Holocene record of salinity and stream flow in San Francisco Bay. Discharge into the bay is a particularly good indicator of paleoclimate in California because the bay's influent streams drain 40% of the state. The isotopic record suggests that between about 1670 and 1900 calendar years (yr cal) B.P. inflow to the bay was substantially greater than the estimated prediversion inflow of 1100 m^3/s. An unconformity representing a 900 yr hiatus is present in the core between 1670 and 750 yr cal B.P., possibly caused by a major hydrological event. Over the past 750 yr, stream flow to San Francisco Bay has varied with a period of 200 yr; alternate wet and dry (drought) intervals typically have lasted 40 to 160 yr.

INTRODUCTION

San Francisco Bay is the largest estuarine system in the western United States, with a watershed covering ~40% of California (Conomos, 1979). The bay, located at the mouth of the San Joaquin–Sacramento river system, receives river discharge from a drainage basin that integrates precipitation and runoff over an area of 162 000 km^2 (Peterson et al., 1989; Cayan and Peterson, 1989) (Fig. 1). In the estuary, mixing of river (~0‰ salinity) and ocean water (33‰ salinity) produces a horizontal salinity gradient (Conomos, 1979), and the resulting salinity at any location varies as a function of the volume of freshwater inflow (Peterson et al., 1989). Thus, reconstruction of salinity in San Francisco Bay estuarine sediments can be used as a proxy for paleorunoff and paleoprecipitation over a large area of California (Peterson et al., 1989; Cayan and Peterson, 1989).

Over the period of instrumental record (the past 80 yr), interannual stream flow appears to have varied on a decadal basis (Peterson et al., 1989) in response to atmospheric anomalies over the eastern North Pacific (Peterson et al., 1989; Cayan and Peterson, 1989). However, during this period the bay and its watershed have also undergone major changes caused by damming and diversion of its major tributaries, filling and diking of surrounding wetlands, and other land-use changes (Nichols et al., 1986). As a result, the natural river flow into San Francisco Bay is unknown. Nichols et al. (1986) estimated that modern inflow to the bay is about 60% of the historic (1850) natural level. A long-term record of salinity and stream flow to the bay provides a context in which to evaluate recent natural and anthropogenic changes.

Previous studies have shown that paleosalinity of San Francisco Bay estuarine water is recorded by the strontium isotopic composition of fossil shell carbonate preserved in estuarine sediments (Ingram and Sloan, 1992; Ingram and DePaolo, 1993). Here we report a 1900-yr-long record of salinity (and, by inference, river inflow and climate) based on the stable isotopic compositions of oxygen and carbon in molluskan fossils from the northern part of San Francisco Bay (i.e., San Pablo Bay).

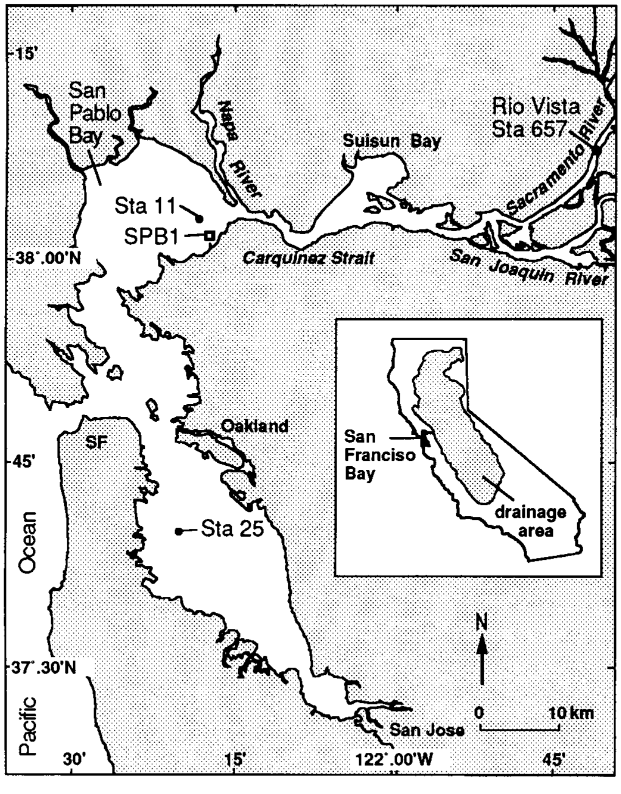


Figure 1. Map of San Francisco Bay, showing location of San Pablo Bay core (SPB1), and water sampling stations (sta 657, 25, and 11, filled circles).

Geology; April 1996; v. 24; no. 4; p. 331–334; 7 figures.

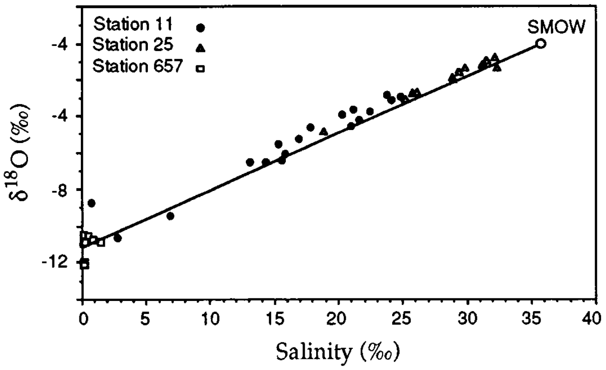


Figure 2. Oxygen isotopic composition of San Francisco Bay estuarine waters collected over three-year period (1991 to 1993, from three stations: sta 11, 25, and 657; see Fig. 1). SMOW = standard mean ocean water.

METHODS

Oxygen and carbon isotopes can be used to determine paleosalinity because seawater and freshwater entering San Francisco Bay have markedly different isotopic compositions. The $\delta^{18}O$ value of freshwater entering the estuary is an average value of precipitation and runoff over the drainage basin, which varies between -5.5‰ along the coast to -16.5‰ in the eastern Sierra Nevada (Ingraham and Taylor, 1991). Measurements of oxygen isotopic compositions and salinities of San Francisco Bay waters collected over a three yr period (Fig. 2) indicate a simple linear mixing relation between seawater ($\delta^{18}O = 0$‰, salinity = 33‰) and river water ($\delta^{18}O = -11.6$‰, salinity = 0.1‰), expressed as $\delta^{18}O_{\text{water}} = 0.34$ (salinity) $- 11.6$. Measurements of modern bivalves collected live from the bay indicate that the isotopic variations in the ambient water are accurately recorded in the shells (Ingram et al., 1996). To determine paleosalinity from $\delta^{18}O$ values in carbonate bivalve shells, the following equation is used (McCrea, 1950; Epstein et al., 1953): salinity $= 2.94\ \delta^{18}O_{\text{carbonate}} - \{(T - 16.9)/-1.43\} + 34.12$, where T (temperature) is in °C. In calculating salinity from $\delta^{18}O_{\text{carbonate}}$, we assume an average T of 15.7 °C in San Pablo Bay (Conomos et al., 1979). The carbon isotopic composition in river water ($\delta^{13}C \sim -9$‰) is also low relative to seawater ($\delta^{13}C \sim 1$‰), producing the following near-linear mixing relation (Spiker, 1980): salinity = 2.94 ($\delta^{13}C + 9.2$).

CORING AND SEDIMENT SAMPLES

The sediments analyzed in this study were cored from the southeastern side of San Pablo Bay (northern San Francisco Bay; Fig. 1). The coring site is located about 1.25 km due south of the main ship channel in San Pablo Bay (lat 38°2′30″N, long 122°18′29″), in a water depth of 5.6 m. Cores were extracted by means of a modified Osterberg vacuum piston corer with a core barrel 1.15 m long and an inside diameter of 10 cm. The 6.7-m-long core was X-ray radiographed for examination of sedimentary structures prior to sampling. The sediments are composed of laminated clay and silt, fine sand, detrital organic carbon and charcoal, calcareous and agglutinated foraminifers, diatoms, ostracodes, mollusk shells, and fish remains (Fig. 3). The dominant bivalve in the upper part of the core (0 to 125 cm) is the bent-nose clam *Macoma nasuta. Macoma* is present, but less abundant, between 125 and 279 cm, and absent below 279 cm depth. Below 279 cm, the mussel *Mytilus edulis* is the dominant bivalve. The shift in the relative abundance from *Mytilus* to *Macoma* has been noted in shell mounds distributed through San Francisco Bay (Cook, 1946), although it is not known whether this shift is due to a natural environmental change or due to over-harvesting by people (Nichols and Pamatmat, 1988).

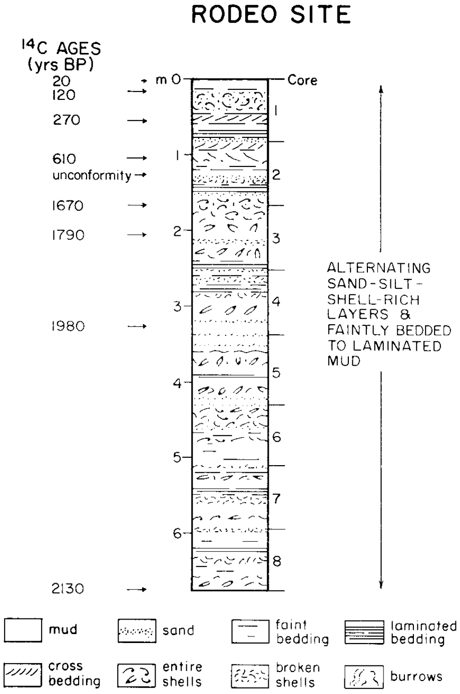


Figure 3. Stratigraphic column of San Pablo Bay core showing lithologic and sedimentary structures. Calibrated ^{14}C ages are indicated and location of unconformity in core is shown.

The core was subsampled sequentially every 2 cm, and *Macoma nasuta* shells (whole shells or fragments) from the upper 279 cm of core were separated for isotopic analyses and radiocarbon dating. Only the portion of the core containing *Macoma* was subsampled, in order to avoid comparing stable isotope data from two different molluskan groups. To ensure that the salinity record is not skewed by the large seasonal variations in inflow and salinity that naturally characterize San Francisco Bay, several well-preserved shells were homogenized from each sample. Shell surfaces were cleaned ultrasonically in distilled water, dried, and powdered for isotopic analyses. Sample $\delta^{13}C$ and $\delta^{18}O$ values were determined using six to nine analyses of a carbonate standard CM-1 per sample run of 24 to 36 unkowns, and reported relative to the VPDB (Peedee belemnite) carbonate standard. The analytical precision is ±0.05‰ for carbon and ±0.01‰ for oxygen.

The core was dated with ^{14}C by accelerator mass spectrometry at the Lawrence Livermore National Laboratory. Powdered shell samples were graphitized by means of standard methods (Vogel et al., 1987), and radiocarbon ages were calculated following standard conventions (Stuiver and Polach, 1977; Donohue et al., 1990). The radiocarbon ages were corrected for reservoir effects from coastal upwelling of ^{14}C-depleted water off northern California; an average reservoir age of 625 yr and the marine calibration curve of Stuiver and Braziunas (1993) were used. Because of the relatively large corrections applied to the data, we consider the age uncertainties to be at least ±100 yr.

RESULTS

The calibrated radiocarbon age for the base of the San Pablo Bay core is 2130 yr cal B.P. The sedimentation rate is significantly greater between 1670 and 2130 yr cal B.P. (6.8 mm/yr) than over the past 750 yr (1.8 mm/yr; Fig. 4). An unconformity representing a

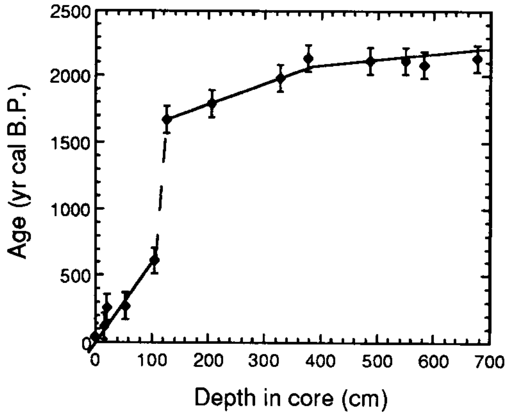
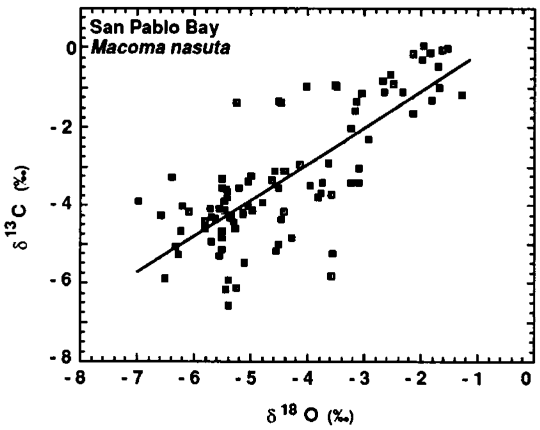


Figure 4. Sediment thickness plotted against corrected radiocarbon ages (yr cal B.P.). Dashed line indicates location of presumed unconformity in sediments.

Figure 5. Values of $\delta^{18}O$ plotted against $\delta^{13}C$ values (relative to VPDB [Peedee belemnite] standard) for San Pablo Bay core (*Macoma nasuta*).



hiatus of about 900 yr (ca 750 to 1670 yr cal B.P.) occurs in the core at a depth of 125 cm (Fig. 4). The hiatus is coincident with a prominent reflector in San Pablo Bay, suggesting it may be attributable to an extreme hydrological event.

Oxygen and carbon isotopic compositions are positively correlated within the core, suggesting that both $\delta^{18}O$ and $\delta^{13}C$ variations are responding to changes in salinity in the ambient water (Fig. 5). In a plot of the $\delta^{18}O$ and $\delta^{13}C$ values of 94 analyses of *Macoma nasuta* fossils (Fig. 6), the average values below the hiatus (125 to 279 cm) are −5.20‰ and −4.37‰, respectively. Above the hiatus (0 to 125 cm), both values vary over a larger range; the average $\delta^{18}O$ is −2.24‰ and the average $\delta^{13}C$ is −3.66‰ (Fig. 6).

Salinity values above the hiatus (0–750 yr cal B.P.) averaged 22.4‰ (Fig. 6). Below the hiatus (1670 to about 1900 yr cal B.P.), salinity averaged 18.2‰. The paleosalinity data indicate that the average natural salinity during the past 750 yr was 1.5‰ lower than the artificially increased modern value of 24‰ (Conomos et al., 1979), and that average salinity during the period 1670 to 1900 yr cal B.P. was ~6‰ lower than this modern value. A similar result is obtained using the $\delta^{13}C$—salinity relation. The salinity recorded in the sediments represents an average over several decades, because of bioturbation.

Paleoinflow can be estimated from paleosalinity values using the salinity-delta flow relation for San Pablo Bay: $S(Q) = 33e^{-0.35Q}$, where S(Q) is the salinity for a given river discharge, and Q is river discharge (Peterson et al., 1989). Although the absolute values of the calculated flows are subject to considerable uncertainty, the relative highs and lows and the appropriate magnitude of the changes are usefully represented. We assume here that the volume of the bay has remained constant over the past 2000 yr. Although sea level has risen ~3 m over the past 2000 yr (Atwater et al., 1977), about 3 m of sediment has been deposited over the same time period. The average delta flow over the past 750 yr is 1250 m^3/s, close to the estimated prediversion, or natural, value of 1100 m^3/s (Nichols et al., 1986). In the interval from 124 to 279 cm (1670 to 1900 yr B.P.), the calculated average annual discharge is 1840 m^3/s.

Over the past 750 yr the periods of lowest salinity correspond to average annual delta flow of 1680 m^3/s, one and one-half times larger than the modern "prediversion" value. The periods of high salinity correspond to an average annual delta flow of 660 m^3/s, or 60% of the modern value (Fig. 7). The periods of high inflow relative to modern occurred at 90–150, 220–275, and 570–680 yr cal B.P. (Fig. 7). Periods of low inflow relative to modern occurred at 160–220, 290–460, 500–540, and 710–750 yr cal B.P. The data suggest that average annual salinity and river inflow to San Francisco Bay deviated from the long-term average for periods of 40 and 160 yr (Fig. 7).

The $\delta^{18}O$ values in the upper part of the core (0 to 125 cm) indicate a 200 yr periodicity in river discharge. A 200 yr period is also evident in other paleoclimate proxy records (Stine, 1990; Anderson, 1991) and in the radiocarbon production rate, and is thought to be linked to fluctuations in solar activity (Stuiver and Braziunas, 1992; Stuiver and Quay, 1980).

DISCUSSION

The paleosalinity record in San Francisco Bay is an important addition to existing paleoclimate records in California for several reasons. The paleosalinity signal in the bay is a function of the volume of stream flow, integrating precipitation over a large area of the state. Individual tree-ring and lake records, in contrast, repre-

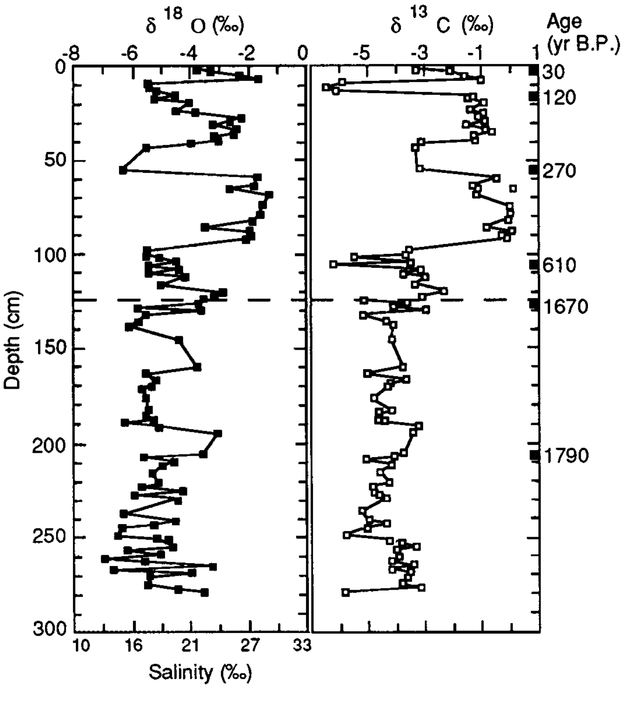


Figure 6. Values of $\delta^{18}O$ and $\delta^{13}C$ (relative to VPDB [Peedee belemnite] standard) for *Macoma nasuta* shells from San Pablo Bay core plotted against depth in core (cm). Calibrated radiocarbon ages are shown on right.

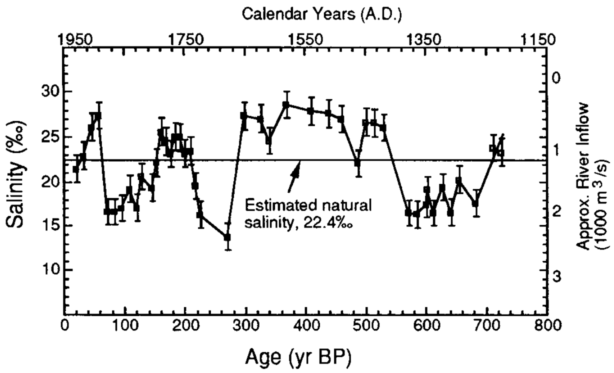


Figure 7. Calculated salinity and river inflow plotted against calibrated radiocarbon age for upper 125 cm of core. Line represents average "natural" salinity of 22.4‰ over past 750 yr.

sent more local conditions. In addition, the estuarine sedimentary record may provide a more continuous record than shoreline or submerged-tree-stump records in California, and thus can help to place these episodic records in perspective.

Paleohydrologic records from California spanning the past several thousand years reveal extended periods when climate was wetter, and other periods when it was drier, than those recorded during the twentieth century (Stine, 1990, 1994; Lamarche, 1973; Enzel et al., 1989; Fritts et al., 1979), similar to our record from San Francisco Bay. Tree-ring records from the western United States (Fritts et al., 1979) indicate a dry period from 140 to 210 yr cal B.P., coincident with low river discharge from 160 to 220 yr cal B.P. (A.D. 1730 to 1790). The low river inflow periods from 490 to 550 yr cal B.P. (A.D. 1400 to 1460) and 710 to 750 yr BP (A.D. 1190 to 1240) are of similar duration, and are supported by the ages of tree stumps submerged in lakes and rivers from the Sierra Nevada (A.D. 1200 to 1350 and A.D. 910 to 1110; Stine, 1994). The large uncertainties associated with radiocarbon dating the estuarine sediments may explain the imprecise correlation between the two records.

The paleo-stream-flow record in San Francisco Bay presented here indicates that the region has been much drier for as long as 150 yr. In contrast, the longest recorded drought in California is only six years (A.D. 1928 to 1934). The estuarine record presented here, in corroboration with other paleoclimate records in California, suggests that periods of drought could be more severe than is evident from the historical record, with important implications for water resource planning and policy decisions.

ACKNOWLEDGMENTS

Supported by the Interagency Ecological Program, California Department of Water Resources (grant B-58859) and the Office of Energy Research, Office of Basic Energy Sciences, Engineering and Geosciences Division of the U.S. Department of Energy (contract DE-AC03-76SF00098). We thank Brian Atwater and Scott Stine for thoughtful reviews.

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Manuscript received September 18, 1995
Revised manuscript received December 12, 1995
Manuscript accepted January 9, 1996