

Reconstructing sediment age profiles from historical bathymetry changes in San Pablo Bay, California

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Received 20 July 2006; accepted 28 December 2006

Available online 6 March 2007

Abstract

Sediment age profiles reconstructed from a sequence of historical bathymetry changes are used to investigate the subsurface distribution of historical sediments in a subembayment of the San Francisco Estuary. Profiles are created in a grid-based GIS modeling program that stratifies historical deposition into temporal horizons. The model's reconstructions are supported by comparisons to profiles of ¹³⁷Cs and excess ²¹⁰Pb at 12 core sites. The predicted depth of the 1951 sediment horizon is positively correlated to the depth of the first occurrence of ¹³⁷Cs at sites that have been depositional between recent surveys. Reconstructions at sites that have been erosional since the 1951 survey are supported by a lack of detectable ¹³⁷Cs and excess ²¹⁰Pb below the upper 6–16 cm of the core. A new data set of predicted near-surface sediment ages was created to illustrate an application of this approach. Results demonstrate other potential applications such as guiding the spatial positioning of future core sites for contaminant measurements.

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Keywords: sedimentation; historical bathymetry; GIS; San Francisco Estuary

1. Introduction

Concerns for the declining environmental health of many estuarine systems have focused attention toward the impacts of human activities on water and sediment quality. Understanding how estuaries have responded to past modifications is necessary to prevent further degradation in response to future environmental pressures. This paper presents a modeling approach used to investigate the subsurface distribution of historical sediments in a subembayment of the San Francisco Estuary in western North America. The San Francisco Estuary has been greatly altered by human activities over the past 150 years and these modifications have triggered changes in the estuary's sediment dynamics (Nichols et al., 1986; Foxgrover et al., 2004). The supply of sediment to the estuary increased rapidly during the hydraulic mining period of the 19th century (Gilbert,

1917) and later decreased due to a reduction in the pulse of mining-induced sediment, the trapping of sediment behind dams, and bank stabilization measures (Wright and Schoellhamer, 2004). Sediments deposited during the historical period are associated with elevated levels of environmental contaminants (Hornberger et al., 1999; Venkatesan et al., 1999).

Since the establishment of a comprehensive monitoring program in 1993, environmental levels of a few problem contaminants have persistently exceeded water quality guidelines (Thompson et al., 2000). Many of the contaminants causing concern, including polychlorinated biphenyls (PCBs) and mercury, are primarily stored in the bay's sediments (Hornberger et al., 1999; Pereira et al., 1999; Ritson et al., 1999; van Geen and Luoma, 1999; Venkatesan et al., 1999). As such, sediment dynamics play an important role in determining the long term fate of contamination (Fuller et al., 1999; Schoellhamer et al., 2003). Improved understanding of sediment age distributions within the bay can therefore assist in the prediction of potential movement and location of contaminants as

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well as guide the positioning of future cores for contaminant profile measurements.

Previous studies have used radioisotope dating methods to reconstruct sediment chronologies at select sites within the bay (Fuller, 1982; Fuller et al., 1999). Such techniques produce profiles of sediment ages over the past 100 years within a core, however, results are limited to the localized area for which sedimentation has been homogenous. An alternative approach to examining sediment dynamics within the bay has attempted to capture the spatial variability of sediment deposition and erosion by analyzing historical changes in bathymetry (e.g. Jaffe et al., 2007). This paper presents an extension of the bathymetric change technique that generates sediment age profiles based on the sequence of historical changes. The objective of this study is to reconstruct sediment age profiles from an existing data set of historical bathymetry in the San Francisco Estuary and evaluate the results by comparing the reconstructions to sediment ages derived from profiles of ^{137}Cs and ^{210}Pb measured in sediment cores. A secondary objective of the study is to demonstrate a potential application of this approach that allows the spatial distribution of historical sediments to be explored.

2. Setting

The sediment age profiles reconstructed in this study are located in San Pablo Bay, a subembayment in the northern part of the San Francisco Estuary (Fig. 1). San Pablo Bay's surface covers approximately 280 km² and is roughly circular in shape. Water depth is predominantly shallow (two thirds of it is less than 2 m deep) but is bisected by a deep channel connecting Central San Francisco Bay with Carquinez Strait and Suisun Bay. Sediment supplied to San Pablo Bay is primarily clay and silt sized particles that are delivered as suspended load from the Sacramento and San Joaquin Rivers (Krone, 1979).

Sediment deposited in San Pablo Bay is subsequently resuspended and transported by wind-wave and tidal currents resulting in a complex pattern of deposition and erosion. For example, active deposition is observed on the mudflats near river mouths where highly turbid water masses move into and out of the bay with each tide (Ganju et al., 2004). Wind-wave and tidal current resuspension erodes and transports sediment from the shallow subtidal to the mudflats, flanks of the main channel, and, during the summer months when gravitational circulation creates up-estuary current, into Suisun Bay (Ganju and Schoellhamer, 2006). As a result of the spatially variable distribution of erosion and deposition, sediment age profiles are expected to reflect these general patterns of variability in different parts of San Pablo Bay.

3. Methods

3.1. Historical bathymetry GIS

Reconstructions of sediment age profiles are based on a sequence of historical bathymetry changes within the bay. Changes were assessed by querying a temporal series of bathymetric surfaces (grids) in a Geographic Information System

(GIS). The National Ocean Service and its predecessor agencies have completed six bathymetric surveys of San Pablo Bay: 1856, 1887, 1898, 1922, 1951, and 1983. A temporal series of bathymetry was created by generating a 50-m resolution grid from each survey (series described in Jaffe et al., 2007). The bathymetric grids are interpolated from hydrographic survey data and adjusted to a common vertical datum to remove the effects of sea level rise. The spatial extent of each grid is confined by the Mean High Water line as mapped on historical surveys. Tributary channels less than 150 m wide are excluded from the study because the morphology of such channels is not well represented by the resolution of the bathymetric surface models (50 m).

3.2. Modeling sediment age profiles with Bathychronology

Profiles of sediment age were reconstructed based on the temporal sequence of bathymetric changes in the bay between 1856 and 1983. A GIS model called Bathychronology (described in Higgins et al., 2005) automates the reconstruction procedure and allows for a rapid and easily repeatable analysis. The model assumes that changes in bathymetry result from sediment dynamics in the bay. A decrease in water depth between surveys is interpreted as a depositional horizon and an increase in water depth between surveys is interpreted as erosion that has removed previously deposited sediments. A tabular array of bathymetric changes is produced by querying the temporal series of bathymetric grids at a specific geographic location.

The Bathychronology model tracks the chronological sequence of bathymetric changes at a given location and stacks more recent depositional horizons on top of earlier units. During the reconstruction the upper and lower boundaries of each horizon are dated with the survey years that correspond to the bathymetric change being represented. When the model encounters an erosional period in the sequence it assumes that the uppermost horizon is truncated and removes sediment from the top of the profile. If the magnitude of erosion exceeds the thickness of the uppermost horizon, then the horizon is removed from the profile and the remainder of erosion is used to truncate the horizon below. Following an erosional period the sediment age at the upper boundary of the truncated horizon is adjusted by linearly interpolating between the survey years. A constant rate of change is assumed between grids in the temporal sequence. For example, if a 20 cm depositional horizon from the period 1920–1940 was truncated by 10 cm, then the sediment age at the upper boundary of the horizon would be adjusted from 1940 to 1930.

For this paper, sediment age profiles were first created for a sample of geographic coordinates that represent locations of known core sites within the bay. The Bathychronology model was then applied to the entire gridded surface to generate new spatial data sets representing the distribution of historical sediments. Assigning the sediment age at the top of each grid cell's reconstructed profile to a new grid produced a data set of predicted near-surface sediment ages.

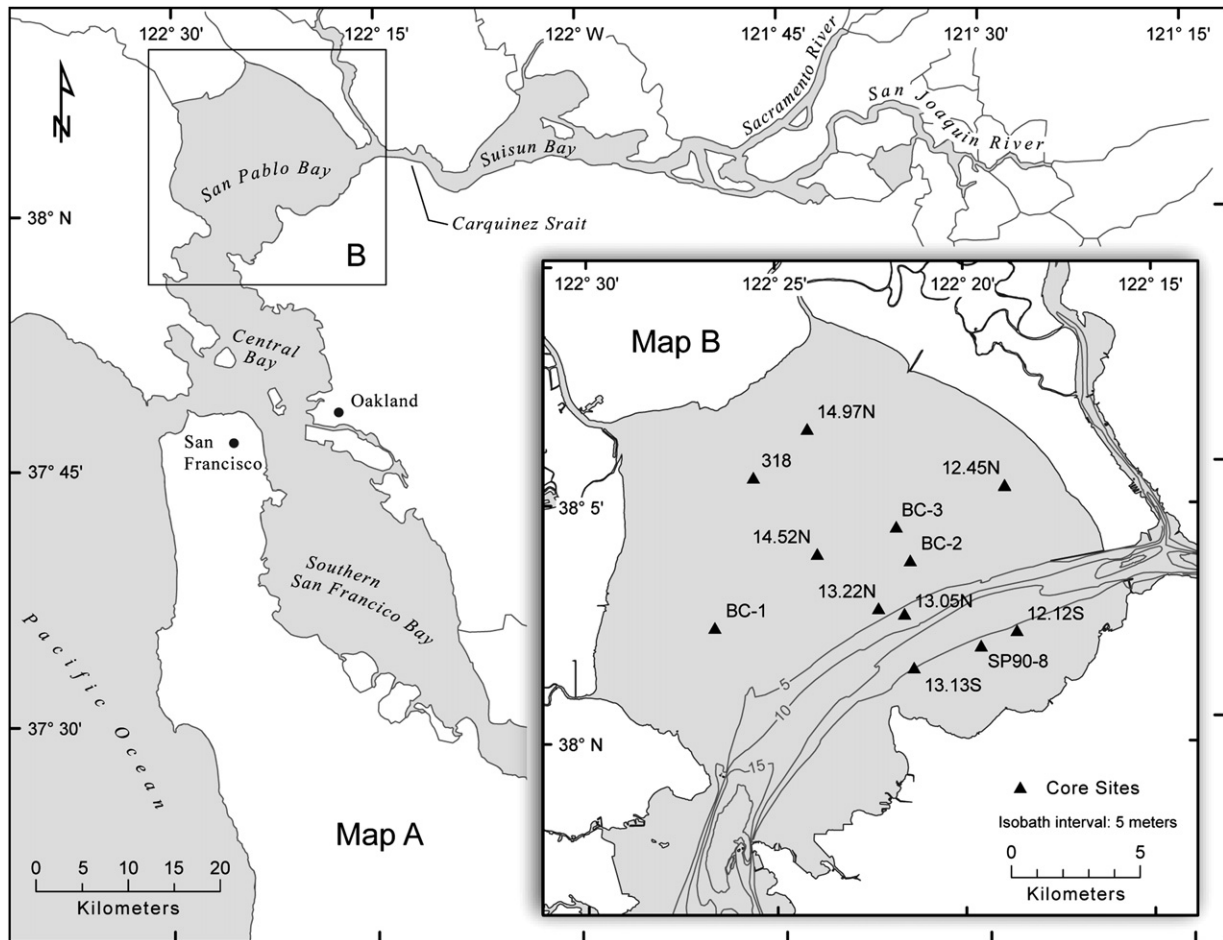


Fig. 1. Map showing the location of San Pablo Bay in the San Francisco Estuary (Map A) and the locations of core sites within San Pablo Bay (Map B).

3.3. Determining apparent sediment ages from ^{137}Cs and excess ^{210}Pb

Apparent sediment ages determined from core profiles of ^{137}Cs and ^{210}Pb were used to evaluate the sediment age profiles reconstructed with the Bathychronology model. Use of ^{137}Cs and ^{210}Pb to determine sediment accumulation rates and construct sediment chronologies is a commonly used methodology (e.g. Robbins and Edgington, 1976; Appleby and Oldfield, 1992; Fuller et al., 1999). Briefly, ^{137}Cs (half life 30.1 years), a man-made radionuclide, provides time horizons related to the first occurrence (1952) and maximum input (1963) of atmospheric fallout of this radionuclide from above-ground atomic weapons testing. Use of ^{137}Cs as a sediment geochronometer assumes that sediment cores have not been significantly modified by bioturbation and resuspension. Apparent sediment accumulation rates were also determined from profiles of ^{210}Pb (half life 22.3 years), a naturally occurring isotope in the ^{238}U decay series. Unsupported (excess) ^{210}Pb results from decay of radon in the atmosphere and subsequent fallout yields a near continuous input. Radioactive decay of the excess ^{210}Pb activity in sediments provides a measure of sediment age as a function of depth. In many environments, ^{210}Pb provides indication of sedimentation occurring

over the past 100 years. However, because of low atmospheric fallout rates and dilution of suspended sediments by older sediments, the effective detection limit of excess ^{210}Pb was determined to correspond to an age of 60 years for San Pablo Bay sediments (Fuller et al., 1999).

3.4. Evaluating model output

Radioisotope profiles were analyzed by methods described in Fuller (1982) for the eight cores collected in 1978–1979, and in Fuller et al. (1999) for four sediment cores collected in San Pablo Bay in 1990 and 2000 (Fig. 1; Table 1). Geographic coordinates of the core sites were input to the Bathychronology model to reconstruct sediment age profiles for each location. To account for the difference between the most recent bathymetric survey in the temporal series (1983) and the year that the cores were collected, the modeled 1951–1983 sedimentation rates were linearly interpolated or extrapolated to the core collection date. For the four cores collected after 1983, the reconstructed profiles were adjusted by the extrapolated amount of deposition or erosion. For the cores collected in 1978–1979, 26/32 of the observed erosion or deposition from the 1951–1983 period was used in the reconstructions. The Bathychronology reconstructions were first

Table 1

Descriptions of sediment cores used to evaluate the reconstructed sediment age profiles. Cores and radioisotope profiles from 1978–1979 are described in Fuller (1982), core SP90-8 and radioisotope profiles are described in Fuller et al. (1999), and cores from 2000 are described in Allison et al. (2003). Depths of ^{137}Cs and excess ^{210}Pb refer to depth in core. Excess ^{210}Pb was not measured in all cores. The range of uncertainty following the modeled 1951 depths is the standard deviations of the post-1951 deposition for the adjacent grid cells and reflects the spatial variability of deposition around each site

Site	Core date	Latitude	Longitude	Water depth (m)	^{137}Cs depth (cm)	Excess ^{210}Pb depth (cm)	Modeled 1951 depth (cm)
12.12S	1978	–122° 18.616'	38° 2.222'	5.0	112	n.a.	71 ± 14
12.45N	1978	–122° 18.917'	38° 5.272'	1.0	20	28	14 ± 4
13.05N	1978	–122° 21.600'	38° 2.589'	9.0	>85	>85	60 ± 28
13.13S	1978	–122° 21.350'	38° 1.455'	6.0	110	120	74 ± 12
13.22N	1978	–122° 22.283'	38° 2.705'	8.0	>95	n.a.	79 ± 12
14.52N	1978	–122° 23.900'	38° 3.855'	2.0	8	n.a.	n.a.
14.97N	1978	–122° 24.150'	38° 6.472'	1.0	16	n.a.	n.a.
318	1979	–122° 25.584'	38° 5.455'	1.0	10	15	5 ± 9
SP90-8	1990	–122° 19.570'	38° 1.908'	3.8	119	117	106 ± 10
BC-1	2000	–122° 26.629'	38° 2.314'	2.4	6	8	n.a.
BC-2	2000	–122° 21.437'	38° 3.706'	2.6	10	10	n.a.
BC-3	2000	–122° 21.800'	38° 4.412'	2.2	12	14	n.a.

evaluated by comparing the predicted depth of sediment from 1951 (top of the 1922–1951 depositional horizon) to the first occurrence of ^{137}Cs at the core sites. If deposition were occurring when fallout of ^{137}Cs began in 1952, the first occurrence of ^{137}Cs should occur near the predicted depth of 1951 sediments.

Two core sites were selected to present a more detailed evaluation of the Bathychronology reconstructions. The model output was evaluated for both sites with comparisons to apparent sediment ages derived from profiles of ^{137}Cs and excess ^{210}Pb in the cores. Core site SP90-8 (Fig. 1) is representative of locations where the model predicts recent (post-1951) deposition at the surface. A description of this core and radioisotope profiles was presented in Fuller et al. (1999). Core site BC-2 (Fig. 1), described in Allison et al. (2003), is representative of locations where the model predicts older (1877) sediments at the surface. Radioisotope profiles and core descriptions for the eight cores collected in 1978–1979 were presented in Fuller (1982).

4. Results

4.1. Bathychronology reconstructions

The sediment age profiles reconstructed for this study illustrate a variety of depositional histories within the bay. Historical deposition (post-1856) is present in all 12 profiles with a range of 22–411 cm (Fig. 2). The profiles can be broadly classified into two groups based on the sign of bathymetric change between the two most recent surveys. Seven of the reconstructed profiles include recent (post-1951) deposition in the near-surface layer. The reconstructed profiles at the other five sites predict erosion during the most recent survey interval and indicate the presence of older (pre-1951) sediment in the near-surface layer. The profiles from core sites SP90-8 and BC-2 are further described to represent the contrasting depositional histories between the two groups.

The chronology of bathymetric changes at core site SP90-8 shows an interesting sequence of sediment deposition and erosion. A 248 cm decrease in water depth between 1856 and 1983

(Fig. 3a) indicates net deposition during the historical period. This deposition, however, was interrupted by an erosional period between 1922 and 1951. The reconstructed sediment age profile divides historical sediments into three depositional horizons. Rapid sedimentation during the period of hydraulic gold mining deposited 186 cm of sediment between 1856 and 1887. Deposition continued between the 1887 and 1898 surveys and then diminished to nearly zero during the following period 1898–1922. Erosion of 106 cm between 1922 and 1951 removed all of the 1887–1922 sediments and truncated the upper portion of the 1856–1887 horizon by 25 cm. Of the initial 186 cm deposited between 1856 and 1887, 161 cm remained. Following the erosional period, the predicted sediment age at the upper boundary of the truncated 1856–1887 horizon was adjusted to 1883 assuming a constant accumulation rate for this period. Subsequent to the hiatus in sedimentation, a second depositional horizon was added to the profile from the deposition of 87 cm between the 1951 and 1983 surveys. Extrapolation of the 1951–1983 sedimentation rate to the year that the core was collected (1990) added a third horizon of 19 cm to the sediment chronology. The resulting sediment age profile shows 106 cm of deposition since the 1951 survey overlying a 161 cm horizon from the period 1856–1883 (Fig. 3a).

The chronology of bathymetric changes at core site BC-2 shows a different sequence of deposition and erosion. An overall 162 cm decrease in water depth between 1856 and 1983 indicates a net depositional environment (Fig. 3b). Similar to site SP90-8, there was a rapid influx of sediment to site BC-2 during the hydraulic mining period 1856–1887. In contrast to site SP90-8, however, the interval between the most recent surveys (1951–1983) was erosional at site BC-2. The 48 cm of erosion between 1951 and 1983 exceeded the total amount of deposition following the 1887 survey. As a result, the reconstructed sediment age profile is limited to deposition from the period 1856–1887. Extrapolating the 1951–1983 erosion rate to the year that core BC-2 was collected (2000) reduced the 1856–1887 horizon to a thickness of 136 cm and the predicted age of the exhumed sediment at the upper boundary to 1878 (Fig. 3b).

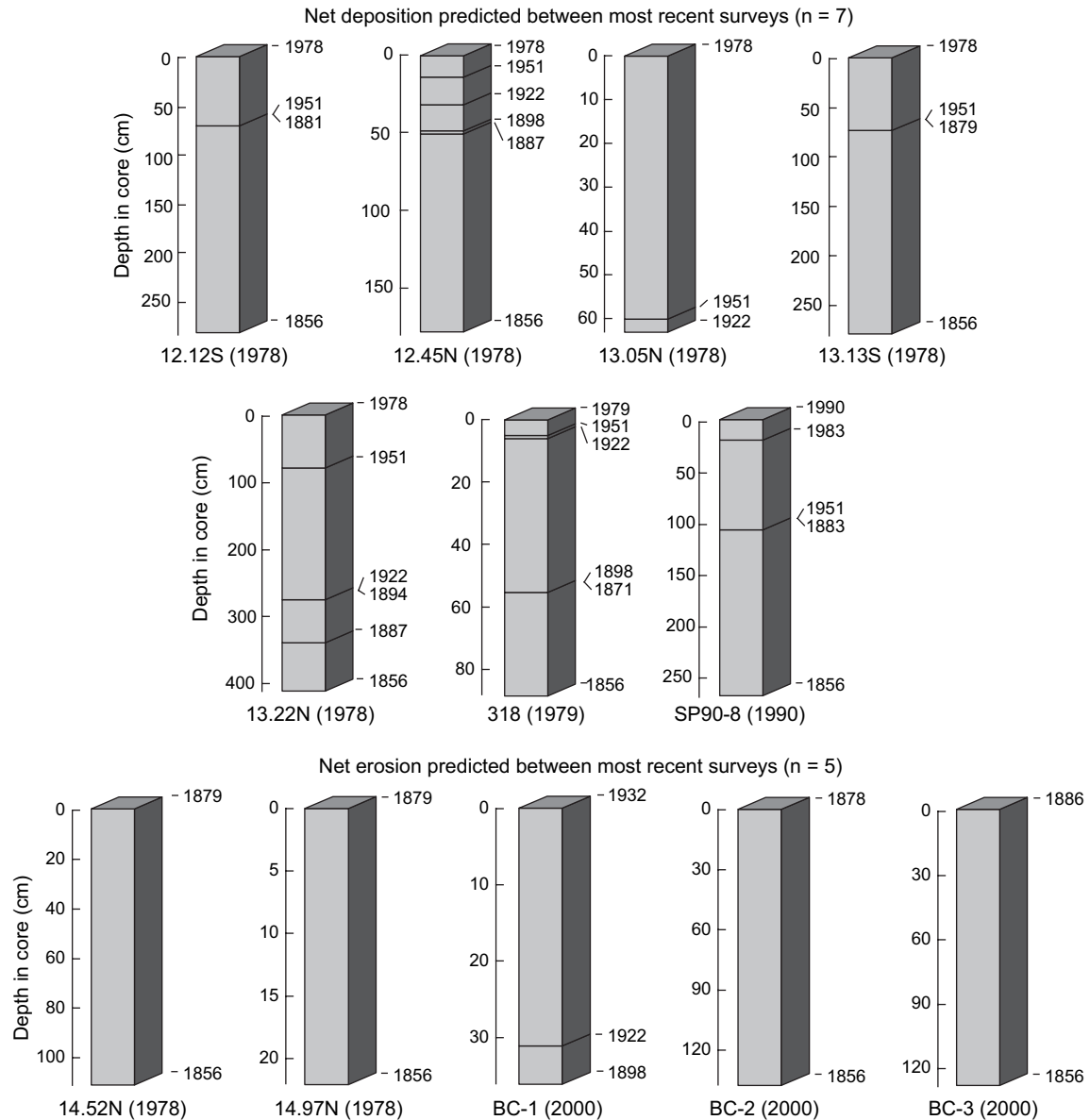


Fig. 2. Sediment age profiles at core locations reconstructed from historical changes in bathymetry. The predicted year of deposition is listed for the upper and lower boundaries of each horizon. Note the vertical axis differences that make the profiles of equal size on the page.

4.2. Evaluation of Bathychronology reconstructions

Evaluation of the reconstructed sediment age profiles for the 12 core sites began with comparisons of the predicted depth for the 1951 sediment horizon to the first occurrence of ^{137}Cs in the core profiles. Plotting the two variables illustrates a positive correlation ($r = 0.98$, $p < 0.0001$) for the seven depositional sites (Fig. 4). Interestingly, the first occurrence of ^{137}Cs was consistently deeper in the sediment profiles than the depth of the 1951 sediment horizon predicted by the model. The predicted depth for the 1951 sediment horizon averaged 70% of the depth to the first occurrence of ^{137}Cs at the seven depositional sites. At the remaining five core sites the model predicted sediments older than 1951 to be exposed at the surface due to erosion between the two most recent surveys. Based on the predicted ages one would not expect to

detect ^{137}Cs in the core profiles. Instead, ^{137}Cs was detected in the upper 6–16 cm at the five sites (Fig. 4). However, in all cases the Cs penetration is shallow, no peak is observed in the profiles, and excess ^{210}Pb goes to a similar depth to ^{137}Cs , when it was measured (Table 1).

Comparing the profiles of ^{137}Cs and excess ^{210}Pb from core SP90-8 to the reconstructed sediment age profile presents a more detailed evaluation of the Bathychronology model (Fig. 5). Excess ^{210}Pb activity decreases with depth to the supported activity at 119 cm yielding an apparent linear sedimentation rate of 4.5 ± 1.5 cm/yr using a constant flux—constant accumulation model (Fuller et al., 1999). The ^{137}Cs profile has maximum activity at 105 cm and decreases to undetectable activity below 119 cm. Assigning a date of 1963 to the ^{137}Cs maximum yields an apparent sedimentation rate of 3.9 cm/yr. Based on the sedimentation rates derived from ^{137}Cs and

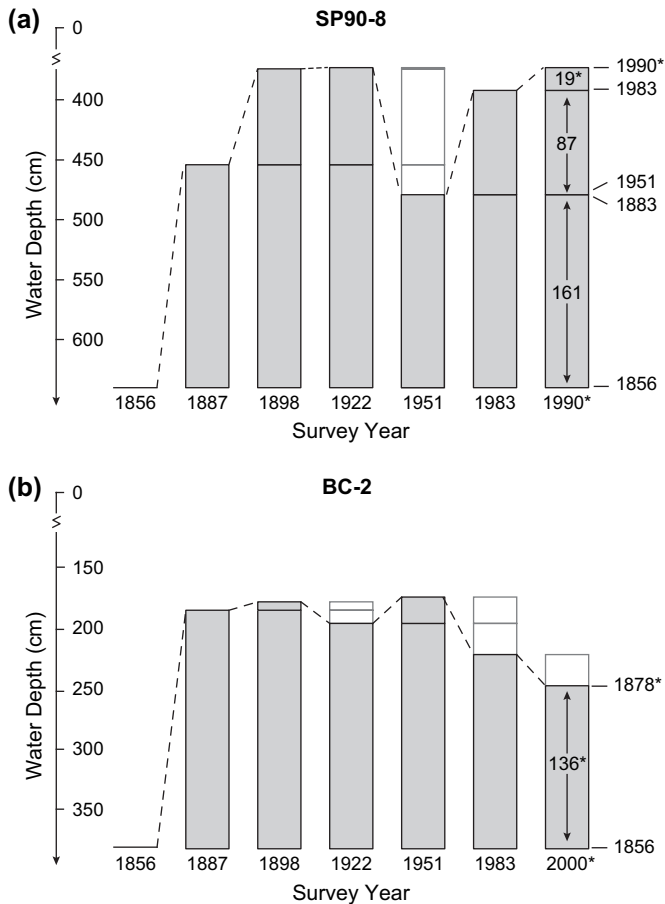


Fig. 3. Changes in water depth between bathymetric surveys and the chronological reconstruction of sediment age profiles for core sites SP90-8 and BC-2. Dashed line connects bathymetric surface of consecutive grids in the historic time series. Shaded boxes denote depositional horizons. Hollow boxes represent depositional units removed by erosion. Horizon thickness is labeled in profiles on far right. Predicted year of deposition is noted for the upper and lower boundaries of horizons. * indicates the water depth was extrapolated from the 1983 value to the core collection date based on the 1951–1983 sedimentation rate.

excess ^{210}Pb , the maximum depth of ^{137}Cs penetration corresponding to its first occurrence in 1952 should occur between 148 and 170 ± 52 cm, respectively. The lack of detectable excess ^{210}Pb and ^{137}Cs below 119 cm suggests that sediments below this depth were deposited more than 60 years before the core date of 1990. The two radioisotope profiles indicate a discontinuity between sediments from the 1950s and sediments older than 1930 at approximately 119 cm depth. The discontinuity in the radioisotope profiles is 14 cm deeper than the predicted hiatus in sedimentation at 106 cm in the Bathychronology reconstruction (Fig. 5).

The radioisotope profiles from core BC-2 are markedly different from those of core SP90-8. Excess ^{210}Pb and ^{137}Cs are detected only to 10 cm (Fig. 5). ^{137}Cs activity decreases slightly with depth and does not reflect the well-known fallout deposition history evident by the lack of a subsurface activity maximum corresponding to 1963. Excess ^{210}Pb similarly decreases with depth over the upper 10 cm. A linear sedimentation rate of 0.16 cm/yr was determined from this profile

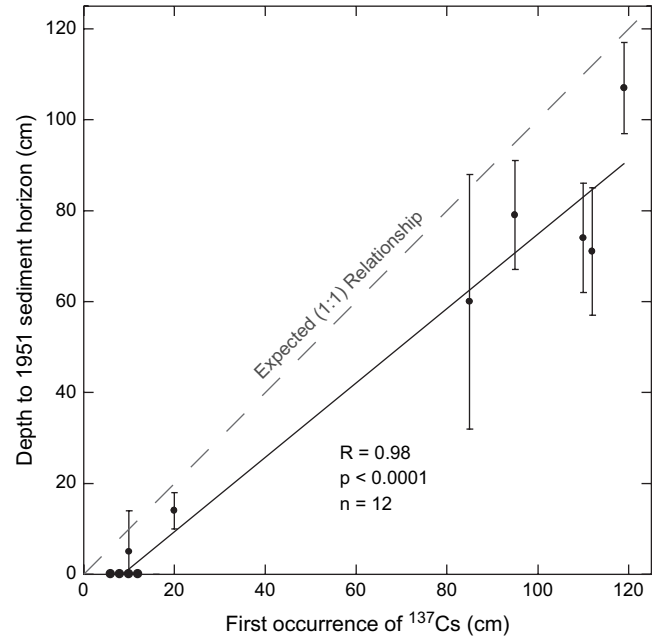


Fig. 4. Correlation between the depth to the first occurrence of ^{137}Cs and the predicted depth to the 1951 sediment horizon ($r = 0.98$, $p < 0.0001$, $n = 12$). Error bars represent the standard deviation of bathymetric change between 1951 and 1983 surveys for the 3×3 grid cell neighborhood around the core location.

using a constant flux—constant accumulation model (see Fuller et al., 1999). The 1951 horizon is estimated at 7 cm using this apparent linear sedimentation rate. Whereas the presence of excess ^{210}Pb and ^{137}Cs in the upper 10 cm does not support the Bathychronology reconstruction of sediments from 1878 at the surface, the lack of detectable excess ^{210}Pb and ^{137}Cs below 10 cm suggests that sediments below this depth were deposited more than 60 years before the core collection date of 2000.

4.3. Spatial distribution of historical sediments

The advantage of deriving sediment age profiles from the Bathychronology model rather than directly from sediment cores is that the model can be easily repeated anywhere a time series of bathymetric data are available. Another advantage is that output from the model can be captured to explore the spatial variability of historical sediment surfaces (or horizons). To demonstrate a potential application of this approach, a GIS grid was generated to map the distribution of near-surface sediment ages across the surface. The map shows the distribution of sediments that were deposited during the most recent period (1951–1983), sediments that were deposited earlier in the historical record but exhumed by recent erosion, and exhumed sediments that pre-date the 1856 survey (Fig. 6). All areas identified as depositional between the 1951 and 1983 surveys by Jaffe et al. (2007) are similarly mapped here. These areas are concentrated along the margins of the main channel and the shallows of the northeastern shore. The remaining 70% of the bay was erosional during the most

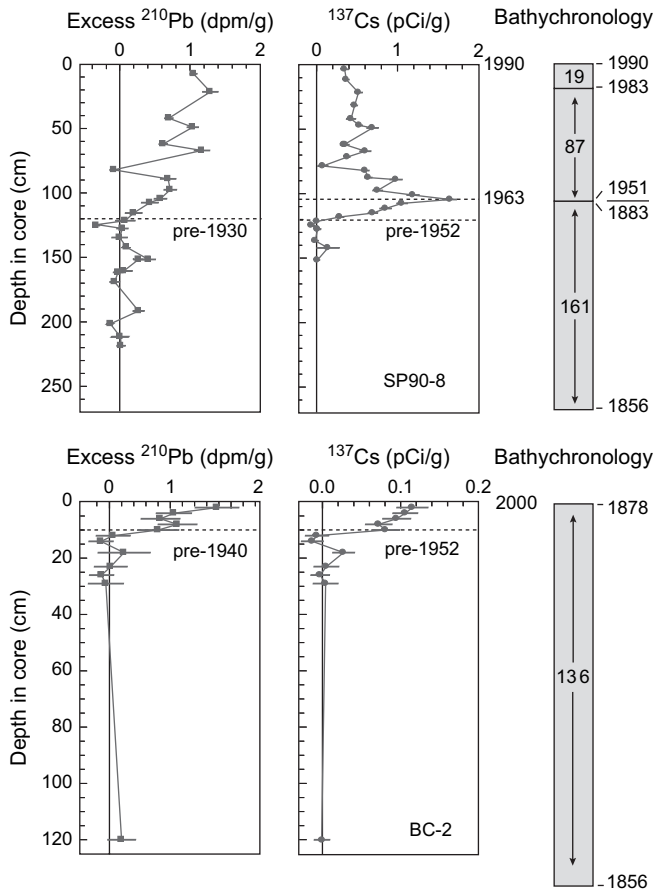


Fig. 5. Profiles of ^{137}Cs and ^{210}Pb measured from core SP90-8 (Fuller et al., 1999) and core BC-2 (analyzed using methods from Fuller et al., 1999) and the corresponding sediment age profiles reconstructed from historical bathymetry changes.

recent survey interval. In these areas, the Bathychronology model predicts sediment older than 1951 to be exhumed by erosion and exposed at the surface. On the broad slopes north and south of the channel, the model predicts sediment ages that range between 1856 and 1950 at the surface. Along the center of the main channel and on the western shallows, the model predicts erosion of any historical sediments. Thus, the age of near-surface sediments at these locations is predicted to pre-date 1856.

5. Model uncertainty

Assessments of bathymetric change from historical surveys have been discussed for a range of marine and estuarine environments (Sallenger et al., 1975; List et al., 1994; Jaffe et al., 1997, 1998, 2007; Cappiella et al., 1999; Gibbs and Gelfenbaum, 1999; Foxgrover et al., 2004). Interpreting results from such studies is complicated by potential measurement error in the survey data. Translating these errors into an uncertainty for the reconstructed sediment age profiles is complicated by the fact that survey errors are dependent on water depth. An acceptable accuracy for the earliest surveys was 3% of the measured water depth (Shalowitz, 1964) and

is less for more recent data. The relatively shallow depths for most of San Pablo Bay tend to minimize this error and reduce uncertainty in the reconstructed profiles.

Adjusting vertical datums to account for sea level rise introduces further uncertainty to the comparison between bathymetric surveys. As discussed by Jaffe et al. (2007), the method used to adjust the most recent surveys (1951 and 1983) to a common datum employs a well-constrained calculation that does not introduce significant error. Comparing these recent surveys to the earlier historical surveys such as 1858, however, requires some assumptions that could introduce as much as 4 cm of uncertainty in the calculation (Jaffe et al., 2007). As a result, datum adjustment is not a significant factor affecting the comparisons of the 1951 sediment horizon to the radioisotope profiles, however, it must be considered when interpreting the model results that incorporate sediment horizons based on the earliest surveys.

An additional component of uncertainty for this study is related to the precision with which the core sites are located. The geographic positions of cores collected in 1990 and 2000 are known within approximately 10 m. The positions of cores collected in 1978–1979, however, are less constrained. Variability of bathymetric changes in the area adjacent to the grid cell being reconstructed could thus influence the resulting sediment age profiles if the actual core site is located outside of the grid cell being analyzed by the model. This component of uncertainty in the analysis is dependent on the gradient of bathymetric changes in the surrounding area. In areas undergoing a uniform bathymetric change (or no change at all), an imprecise location of the core site would have little effect on the comparisons used to evaluate the model output. In areas of a strong spatial gradient of bathymetric change, however, an imprecise location of the core site could have a large influence on the results. To address the issue of spatial positioning, the standard deviations of bathymetric change were calculated for a 3×3 cell neighborhood around the grid cell being processed. The deviations were then included as an estimate of uncertainty around the predicted depths for the 1951 sediment horizon in the comparison to radioisotope profiles. These uncertainties range from 4 to 28 cm and average 13 cm (Table 1; Fig. 4).

6. Discussion and conclusions

The 12 sediment age profiles reconstructed for this study depict a variety of depositional histories within San Pablo Bay. The general patterns of sediment ages from Bathychronology reconstructions are consistent with what is known about sediment transport processes and directions in San Pablo Bay (Ganju et al., 2004; Ganju and Schoellhamer, 2006; Jaffe et al., 2007). After the large influx of sediment from hydraulic gold mining in the middle to late 1800s (Gilbert, 1917), wind-waves and tidal currents redistributed sediments resulting in regions of deposition and erosion. Erosion in the shallow subtidal zone from wind-wave resuspension has exposed sediments from the hydraulic mining period. The sediment removed from this region, combined with new sediment supplied from the Sacramento and San Joaquin Rivers and local

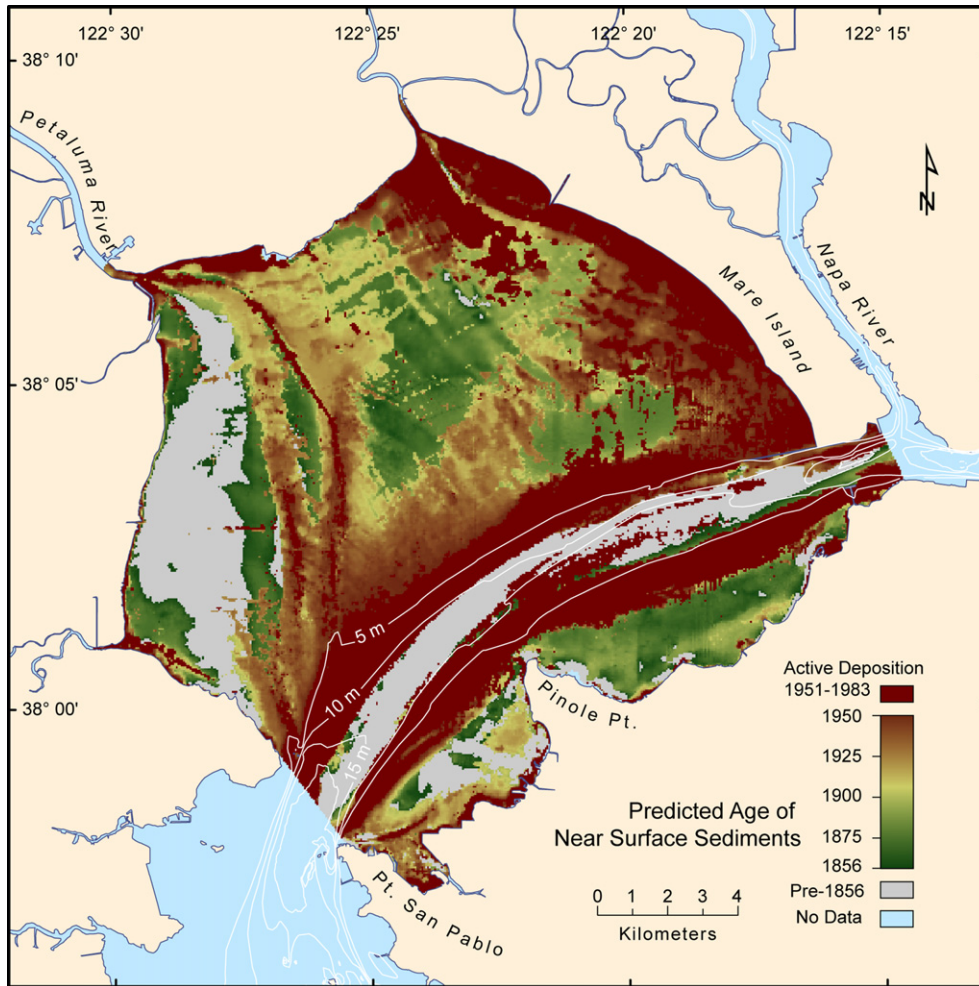


Fig. 6. Spatial distribution of historical sediments in San Pablo Bay predicted using the Bathychronology methodology. Sediment ages represent the predicted year of deposition at the top of each reconstructed sediment age profile.

tributaries, likely was moved by tidal currents and deposited on intertidal mudflats and on the flanks of the main channel. The Bathychronology reconstructions show this general pattern of older sediment in the shallow subtidal zone and recent sediment on the mudflats and main channel flanks.

Comparing the Bathychronology reconstructions to sediment ages obtained from radioisotope profiles provides a quantitative way to validate the model and discuss its applicability to further studies of historical sedimentation patterns. Despite the potential for errors noted above, initial comparisons yielded encouraging results. The relative agreement between the predicted depth for the 1951 sediment horizon and the depth to the first occurrence of ^{137}Cs suggests that the Bathychronology model will be a useful tool for investigating the spatial extent of historical sedimentation. The consistent underprediction of the depth to the 1951 sediment horizon is particularly noteworthy in this regard. Currently, the assumptions built into the Bathychronology reconstructions disregard the role of sediment compaction. In reality, the porosity of sediments should decrease following a depositional event due to compaction from overlying sediments.

In the example presented above for core site SP90-8, the 106 cm difference between the 1951 and 1990 surfaces would be the amount of deposition without considering the effect of compaction. The actual depth to the 1951 sediment horizon should be greater than 106 cm due to compaction. The effect of compaction could be quantified using density measurements from sediment cores, however, density data were not available for the cores used in this paper. Assuming that the change in dry density with increasing depth follows the measured relationship obtained by Fuller et al. (1999) from a core in nearby Richardson Bay, we estimate approximately 17 cm of compaction at the predicted depth of the 1951 sediment horizon. Accounting for this 17 cm of compaction in the reconstructed sediment age profile increases the depth to the 1951 sediment horizon from 106 to 123 cm and decreases the difference between the model prediction and the expected value of 119 cm based on the maximum penetration of ^{137}Cs . Although sediment compaction is more complex than it is portrayed in the above example, our estimate demonstrates the effect and may explain some of the difference in the comparisons between the Bathychronology reconstructions and the radioisotope profiles.

Another observation to address is the presence of ^{137}Cs and excess ^{210}Pb in the upper 6–16 cm of the five erosional cores. The apparent contrast produced by the relatively older predicted ages for near-surface sediments at these sites may be the result of the low sedimentation rates derived from the radioisotope profiles (0.16 to 0.2 cm/yr) that are within the sensitivity of the Bathychronology model. Alternatively, the presence of both radioisotopes to 6–16 cm combined with the absence of a subsurface ^{137}Cs maximum may result from dynamic processes of sediment resuspension, transport and deposition coupled with downward mixing into the sediment column (e.g. bioturbation). These processes could result in the incorporation of “recent” material into the sediment column without net accumulation (see Fuller, 1982). In addition, mixing may account for the deeper penetration of ^{137}Cs in cores in comparison to the 1951 horizon predicted by the model for the depositional sites. In nearby Richardson Bay, rapid sediment mixing was evident from the presence of unsupported ^{234}Th (24.1 day half life) to depths ranging from 2 to greater than 10 cm at eight coring sites (Fuller et al., 1999). Sediment mixing was modeled as a diffusive process with the mixing rate decreasing with depth to zero by 33 cm at one of these sites. At this site, sediment mixing resulted in an increase in the maximum depth of ^{137}Cs of about 20 cm compared to sediment accumulation in the absence of mixing. More extensive mixing was observed in South San Francisco Bay where unsupported ^{234}Th was measured to depths up to 15 cm (Fuller, 1982).

Although ^{234}Th measurements were not made in the San Pablo Bay cores presented here, sediment mixing rates of similar magnitude to those measured in other parts of the San Francisco Estuary cannot be ruled out for San Pablo Bay. For example, X-radiographs of cores collected in 2000 from many locations in San Pablo Bay have worm burrows to depths of 10 cm or more (Allison et al., 2003), indicative of sediment mixing. Because of the similar maximum depth profile of ^{239}Pu , ^{240}Pu to the ^{137}Cs profile in SP90-8, remobilization of ^{137}Cs and downward diffusion likely does not occur (Fuller et al., 1999) and, thus, cannot account for its presence. As a result, sediment mixing may account for the observed penetration of ^{137}Cs to depths of 6–16 cm even in the absence of net accumulation at the erosional core sites.

Comparing the reconstructed sediment age profiles to profiles of ^{137}Cs and excess ^{210}Pb at 12 core sites in San Pablo Bay has demonstrated that the Bathychronology approach can be an effective methodology to investigate the subsurface distribution of historical sediments in an estuary. The model's predicted depth to the 1951 sediment horizon was reasonably close to the measured depth to the first occurrence of ^{137}Cs at the depositional sites. The relatively older ages predicted for near-surface sediments at the erosional sites were also supported by the lack of detectable ^{137}Cs and excess ^{210}Pb below the upper 6–16 cm. The relative congruence between the model results and the radioisotope profiles suggests that spatial distributions of the historical sediment horizons produced with the model can assist in locating core sites for future research or predicting contaminant fluxes from the sediment into the water.

Acknowledgements

This research was supported by the U.S. Geological Survey Priority Ecosystem Science, Water Resources Discipline National Research, Geologic Discipline Toxics, and Geologic Discipline Coastal Marine Geology programs. Richard Smith was instrumental in formulation of the techniques used to reconstruct sediment ages from bathymetry. Laura Zink Torresan digitized historical hydrographic and topographic surveys. Amy Foxgrover skillfully developed grids of San Pablo Bay bathymetry. The manuscript was improved by thoughtful comments from Noah Snyder, Peter VanMetre, and two anonymous reviewers.

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