SEDIMENT ACCUMULATION IN SAN LEANDRO BAY, ALAMEDA COUNTY, CALIFORNIA, DURING THE 20th CENTURY--A PRELIMINARY REPORT

by K.M. Nolan and C.C. Fuller

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 86-4057

Prepared in cooperation with the
ALAMEDA COUNTY FLOOD CONTROL AND
WATER CONSERVATION DISTRICT

Sacramento, California
August 1986

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Federal Building, Room W-2234
2800 Cottage Way
Sacramento, CA 95825

Copies of this report
may be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, CO 80225
Telephone: (303) 236-7476

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

The metric system of units is used in this report. For readers who prefer inch-pound units, the conversion factors for the terms used in this report are listed below.

Metric (SI)	Multiply by	Inch-pound
cm (centimeter)	0.03280	feet
cm/a (centimeter per annum)	0.03280	feet per annum
cm^3 (cubic centimeter)	0.00003531	cubic feet
cm^3/g (cubic centimeter per gram)	0.001602	cubic feet per pound
dpm/a (disintegrations per minute per annum)		
g (gram)	0.002204	pounds
g/cm^2 (grams per square centimeter)	2.047	pounds per square feet
$(g/cm^2)/a$ (grams per square centimeter per annum)	2.047	pounds per square feet per annum
g/cm^3 (grams per cubic centimeter)	62.46	pounds per cubic feet
hm (hectometer)	2.471	acres
km^2 (square kilometer)	0.3861	square miles
m (meter)	3.281	feet
m^3 (cubic meter)	1.308	cubic yards
Mg (megagram)	1.102	tons
Mg/a (megagram per annum)	1.102	tons per annum
Mg/km^2 (megagram per square kilometer)	2.855	tons per square miles
mm (millimeter)	0.03937	inches
pCi/g (picocuries per gram)	0.002204	picocuries per pound

SEDIMENT ACCUMULATION IN SAN LEANDRO BAY, ALAMEDA COUNTY, CALIFORNIA, DURING THE 20th CENTURY: A PRELIMINARY REPORT

---

by K.M. Nolan and C.C. Fuller

ABSTRACT

Major changes made in the configuration of San Leandro Bay, Alameda County, California, during the 20th century have caused rapid sedimentation within parts of the bay. Opening of the Oakland tidal channel and removal of 97 percent of the marshlands formerly surrounding the bay have decreased tidal velocities and volumes. Marshland removal has decreased the tidal prism by about 25 percent. Comparison of bathymetric surveys indicates that sedimentation in the vicinity of the San Leandro Bay channel averaged 0.7 centimeter per annum between 1856 and 1984.

Lead-210 data collected at four shallow water sites east of the San Leandro Bay channel indicate that sedimentation rates have averaged between 0.06 and 0.28 centimeter per annum. Because bioturbation of bottom sediments cannot be discounted, better definition of this range in sedimentation rates would require measuring the activity of lead-210 on incoming sediments.

In addition to sediment deposited in the vicinity of the San Leandro Bay channel and open, shallow areas to the east, 850,740 cubic meters of sediment was deposited between 1948 and 1983 in an area dredged at the mouth of San Leandro Creek. All available data indicate that between 1,213,000 and 1,364,000 cubic meters of sediment was deposited in San Leandro Bay between 1948 and 1983.

Sediment-yield data from an adjacent drainage basin, when combined with inventories of lead-210 and cesium-137, indicate that most of the sediment deposited in San Leandro Bay is coming from resuspension of bottom sediments or from erosion of marshes or shorelines of San Leandro or San Francisco Bay.

INTRODUCTION

San Leandro Bay is a small shallow arm of southern San Francisco Bay near Oakland, Alameda County, California (figs. 1 and 2). Configuration of this bay, as well as that of the surrounding marshes and mudflats, has changed greatly since the early 1900's. The hydrographic survey of 1896 depicted San Leandro Bay as a shallow body of water surrounded by marshes and mudflats and connected to San Francisco Bay by the San Leandro Bay channel. In 1902, the Oakland tidal channel was dredged to connect San Leandro Bay with the Oakland Harbor. By 1972, landfilling had decreased marshland and associated mudflats adjacent to the bay by more than 96 percent--from about 810 hm in 1922 to 28.4 hm by 1977 (U.S. Army Corps of Engineers, 1980).

The Alameda County Flood Control and Water Conservation District is concerned that recent changes in the configuration of the bay have increased sedimentation rates and that this sedimentation has decreased the capacity of flood-control channels draining into San Leandro Bay. This report was prepared in cooperation with the Alameda County Flood Control and Water Conservation District to provide a preliminary assessment of rates and causes of sedimentation in San Leandro Bay. Sediment-accumulation rates were estimated by comparing bathymetric surveys made in 1856 and 1984, and by measuring the activity of the isotopes lead-210 and cesium-137 in four sediment cores taken from the bay. Sediment accumulation between 1948 and 1983 in an area dredged at the mouth of San Leandro Channel was determined by comparing bathymetric data from 1948 with data collected in 1983. The causes of sedimentation were assessed by comparing excess lead-210 and cesium-137 activity with fallout of these isotopes on the bay surface and by interpreting sedimentation rates within San Leandro Bay in light of the physical processes controlling sediment deposition within the bay, manmade changes in bay configuration, and the potential for direct input of sediment from upland drainages.

DESCRIPTION OF STUDY AREA

San Leandro Bay covers about 2.59 km^2 and averages only 1.6 m deep at mean tide level. At mean lower-low water, extensive mudflats are exposed, and open water is limited to about 15 percent of the bay. Nearly all parts of San Leandro Bay deeper than 0.9 m at mean higher-high water have been dredged. Dredging was concentrated in three areas: the Oakland tidal channel, the Airport Channel, and a distinct rectangular area at the mouth of San Leandro Channel (fig. 2). The Airport Channel was dredged in 1928 to provide docking facilities for the U.S. Navy Supply Center (U.S. Army Corps of Engineers, 1980). The area at the mouth of San Leandro Channel was dredged to a depth of 10.7 m in 1948 and was intended as a docking area for deep-water ships.

Streamflow enters San Leandro Bay through four major channels: East Creek, Damon, Elmhurst, and San Leandro. According to the U.S. Army Corps of Engineers (1980), the East Creek channel drains 14.5 km^2 and streamflow is from Courtland, Peralta, and Seminary Creeks; Damon Channel drains 26.4 km^2 and streamflow is from Lion Creek and Arroyo Viejo; and the Elmhurst and San Leandro Channels drain 6.0 and 124 km^2, respectively, and streamflow is from Elmhurst and San Leandro Creeks (figs. 1 and 2).

The drainage basins of all streams draining into San Leandro Bay contain large areas of gently sloping urban, suburban, and industrial land. The headwaters of Arroyo Viejo and San Leandro Creek drain steep nonurbanized land. Flow in the upper 11.1 km^2 of the San Leandro Creek drainage basin is controlled by reservoirs operated by the East Bay Municipal Utilities District.

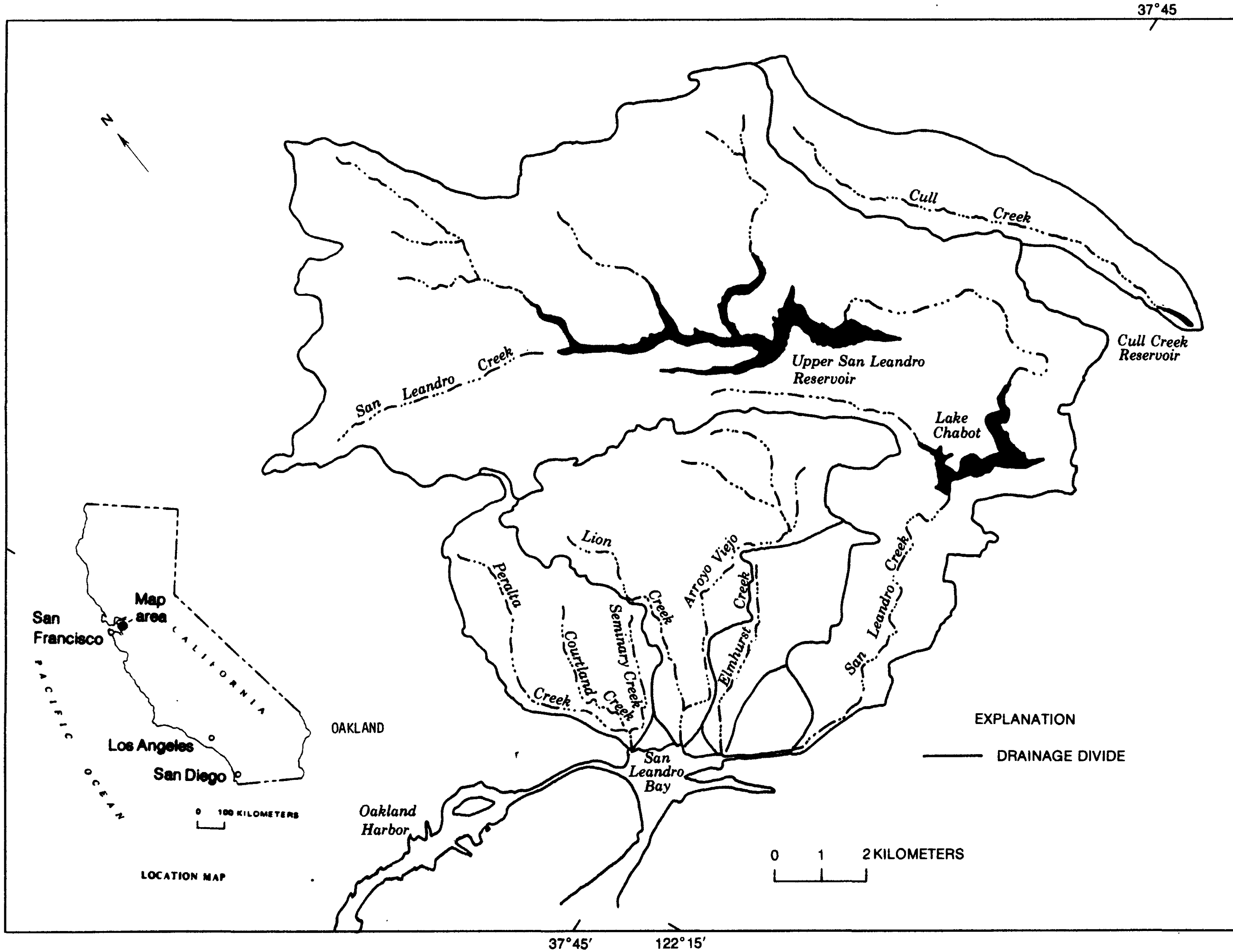


FIGURE 1.— Location of San Leandro Bay and nearby drainage basins.

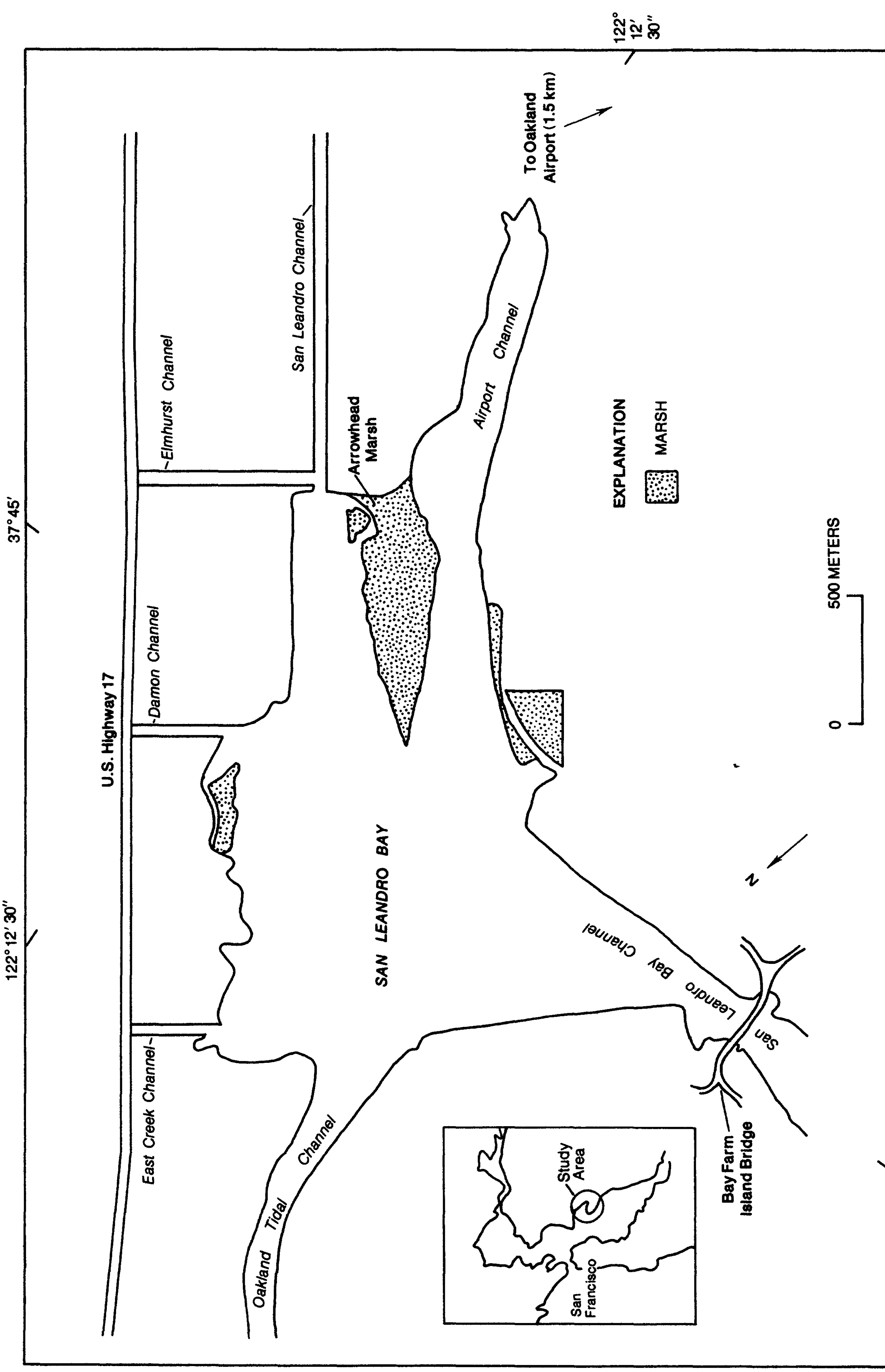


FIGURE 2.-- Location of San Leandro Bay.

Circulation of water within San Leandro Bay with water in San Francisco Bay is limited to flow through the Oakland tidal and San Leandro Bay channels. The Oakland tidal channel is 83.5 m wide and about 5.5 m deep (U.S. Army Corps of Engineers, 1980). The San Leandro Channel is about 200 m wide and, based on a recent bathymetric survey (Alameda County Flood Control and Water Conservation District, 1983), the average depth is 3.1 m where it enters San Leandro Bay.

PREVIOUS STUDIES

San Leandro Bay

The most notable sedimentation previously reported occurred where the San Leandro Bay channel enters San Francisco Bay. The U.S. Army Corps of Engineers (1980) reported that this area has become progressively more shallow since the early 1900's. Before 1900, this channel was 3 to 4.5 m deep, but, by the mid-1950's, parts of the channel west of Bay Farm Island were filled to the level of the surrounding mudflats. The U.S. Army Corps of Engineers (1980) indicated that this period of sedimentation corresponded to opening the Oakland tidal channel. They suggested that decreased flushing velocities, caused by opening this additional connection to San Francisco Bay, promoted deposition of sediment transported to this area by littoral drift along the shore of San Francisco Bay.

The U.S. Army Corps of Engineers (1980) suggested that opening the Oakland tidal channel decreased tidal-flushing velocities, particularly in the San Leandro Bay channel. This theory was partially based on a preliminary hydrodynamic survey conducted by Brown and Caldwell Consultants (1979). Drogue releases indicated that tidal flow from San Leandro Bay occurred primarily through the Oakland tidal channel (Brown and Caldwell Consultants, 1979). During a one-half tidal cycle, flow out of San Leandro Bay occurred for 7 hours through the Oakland tidal channel but for only 3.5 to 4 hours through the San Leandro Bay channel.

As previously mentioned, this theory was based partially on the study of Brown and Caldwell Consultants (1979). The decrease in tidal flow discussed by Brown and Caldwell Consultants (1979) is particularly significant when the work of Van Straaten and Kuenen (1958) is considered. Van Straaten and Kuenen (1958) showed that under calm conditions, the ebb current (flow out of a bay or tidal flat) is not able to remove all particles deposited by flood currents (flow into a bay or tidal flat). Particles deposited by flood currents settle so far inland that ebbtides are not always able to remove them. Van Straaten and Kuenen (1958) stressed that this situation occurs only during periods of calm, and storms play a major, but unclear, role in determining long-term sedimentation. The work of Van Straaten and Kuenen (1958) is mentioned to demonstrate that there may be a tendency for net sedimentation within embayments, such as San Leandro Bay, even without the effects of manmade changes in bay configuration.

San Francisco Bay

Sedimentation in San Francisco Bay has been the subject of numerous investigations. Findings of several of these reports are summarized below because they also are relevant to understanding processes responsible for controlling sedimentation in San Leandro Bay and present sedimentation data with which to compare data collected in San Leandro Bay.

Gilbert (1917, p. 86-88) recognized that large inputs of terrestrial sediment could promote sedimentation and cause expansion of marshland within the San Francisco Bay system. Most of the increased sediment supply noted by Gilbert (1917) came from hydraulic mining activities in the Sierra Nevada foothills during the mid-1800's. Rapid marsh expansion occurred during the late 19th century as a result of large quantities of sediment released by mining. Gilbert (1917, p. 102-103) also noted that when levees prevented exchange of water with surrounding marshes, sediment accumulated in tidal sloughs because tidal currents were slackened.

Atwater and others (1979) demonstrated that the distribution of marshes is strongly controlled by rates of sedimentation and land submergence. They illustrated that when submergence, the rise of sea level relative to the land surface, exceeded sedimentation rates, the extent of tidal marshes decreased. Conversely, when sedimentation rates exceeded submergence rates, marsh area increased. Historic rises in mean sea level averaged about 0.2 cm/a (Atwater and others, 1979, fig. 1).

Processes controlling sediment circulation and sediment deposition in San Francisco Bay are outlined by Conomos and Peterson (1977) and Krone (1979). Sediment entering the bay from tributary drainages consist mainly of silt- and clay-size material. Most of this sediment enters the bay during high streamflow in winter months. This sediment is resuspended by waves generated by onshore winds during spring and summer and is redistributed throughout the bay by tidal- and wind-driven currents. The effectiveness of winds in suspending deposited sediment decreases rapidly with water depth. In shallow areas, wind-generated waves generally exert sufficient shear stress to resuspend silt and clay. As water depth increases, bed-shear stress decreases and waves lose the force necessary to overcome shear strength of the deposit.

Fuller (1982, p. 174) compiled a sediment budget for South San Francisco Bay based on inventories of lead-210 and cesium-137. This budget indicates that South San Francisco Bay retains $1.0 \pm 0.4 \times 10^{11}$ grams of sediment per year. This accounts for one-third of the estimated fine-grained input from local streams (Porterfield, 1980). Fuller (1982) estimated that sediment accumulation in South San Francisco Bay averages 0.03 $(g/cm^2)/a$ (about 0.04 cm/a) but that sedimentation rates in deep-water areas exceed those in shallow areas.

STUDY METHODS

Isotope Studies

Lead-210

Recent sediment-accumulation rates in San Leandro Bay were investigated using the radioisotope lead-210. Lead-210 as well as radioisotopes of thorium are used to estimate sedimentation rates in various depositional environments because these elements are strongly bound to sediment particles and their precursors in the process of radioactive decay are relatively soluble. Lead-210 is particularly well suited for determining recent sediment-accumulation rates because of its short half-life of 22.3 years. Lead-210 is used to estimate sediment-accumulation rates in lakes (Robbins and Edgington, 1975; Schroeder, 1985, Domonik and others, 1981; and Davis and others, 1984) and in coastal marine environments (Bruland and others, 1974; Benninger, 1976; and Fuller, 1982). The maximum dating range using lead-210 is generally about 100 years.

Lead-210 is produced in the atmosphere by decay of radon-222, which emanates primarily from continental sources (Turekian and others, 1977). Lead-210 is rapidly removed from the atmosphere by rain, snow, and dry fallout. Once in the water column, lead-210 is rapidly attached to sediment particles. These particles settle, along with particles bearing excess lead-210 from surrounding land surfaces, in depositional sites. In addition to direct fallout, lead-210 is produced by decay of radium-226 in the sediment column. In sediment deposited within about the last 100 years, the activity of lead-210 is greater than the activity of radium-226 because of the additional atmospheric input of lead-210. Lead-210 is also supplied by stream runoff and by decay of radium-226 in the water column (Benninger, 1976). Input of radium-226 is negligible in San Francisco Bay due to its shallow depth (Fuller, 1982). The activity, which is unsupported by direct decay of radium-226 and represents primarily atmospheric input, is termed excess lead-210 activity. The quantity of excess activity is a function of the half-life of lead-210 and length of time since burial.

Three general conditions must be met to successfully use lead-210 to estimate rates of sediment accumulation:

1) The flux of lead-210 to the sediments must be constant,

2) The sedimentation rate must be constant during the dating period, and

3) Lead-210 must not be mobile in the sediment column.

Thompson and others (1975) determined that lead-210 is immobile in marine sediment. Fuller (1982) determined this to be true also for sediment in San Francisco Bay. Assuming that excess lead-210 on incoming particles is constant, sedimentation rates are calculated from the exponential decrease of lead-210 activity with depth. Sedimentation rates are calculated from the slope of this profile using the following relationship:

$$C_z = C_o e^{-(Y/S)Z} \qquad (1)$$

where

C_z is activity of excess lead-210, in disintegrations per minute per gram;

Y is decay constant for lead-210, in years;

S is sedimentation rate, in centimeters per annum;

Z is depth in sediment column, in centimeters; and

C_o is excess lead-210 activity of surface sediment, in disintegrations per minute per gram.

The natural log (ln) of this expression,

$$\ln C_z = \ln C_o - (Y/S)Z \qquad (2)$$

is used to determine the slope (Y/S) by linear regression. The resulting sedimentation rate, S, does not account for sediment compaction. The accumulation rate [$(g/cm^2)/a$] can be calculated by multiplying S by the mass of dry sediment per cubic centimeters of wet sediment, P . P is assumed to be equivalent to values measured by Fuller (1982) (0.6 g/cm^3 for the upper 4 cm of sediment and 0.75 g/cm^3 for sediment below the upper 4 cm).

The above procedure assumes that post-depositional reworking of sediment by biologic or physical processes has not occurred. Such downward mixing of surface sediment results in calculated sedimentation rates that are anomalously high (Benninger and others, 1979 and Peng and others, 1979). In addition, resuspension of surface sediment may cause an exchange of older particles in the sediment column with younger particles. This may result in an activity profile that indicates sediment accumulation when in fact no sedimentation is occurring (Fuller, 1982). In systems where these processes are possibly operating, such as in shallow water embayments like San Leandro Bay, the use of equation 1 may overestimate sedimentation rates.

As an alternative to equation 1, the sediment-accumulation rate can be determined using the mass-balance method. This method calculates the sediment-accumulation rate by integrating excess lead-210 activity over depth by the following equation:

$$C_w W = Y \int C_z \, dz \qquad (3)$$

where

C_w is excess lead-210 activity of incoming particles, in disintegrations per minute per gram; and

W is sediment-accumulation rate, in grams per square centimeter per annum.

The integral term in equation 3 is equal to the integrated excess lead-210 activity, or flux of lead-210 to the sediment (atoms per square centimeter per minute). Integrated excess lead-210 activity therefore represents the summation of activity per cubic centimeter over depth. The activity per volume of wet sediment was calculated by multiplying activity per gram of dry sediment by the mass of dry sediment per cubic centimeter of wet sediment, P_{eff}. Intervals not analyzed were assumed to have an activity equal to the average of adjacent intervals. The use of equation 3, as does use of equation 1, assumes that excess activity of incoming particles is constant. If the lead-210 activity of incoming particles is known, the accumulation rate determined using equation 3, unlike equation 1, is independent of sediment mixing and compaction (Fuller, 1982, p. 96).

Cesium-137

The distribution of cesium-137 in sediment of San Leandro Bay was determined in an attempt to verify sedimentation rates estimated using lead-210 and to estimate the extent of reworking or mixing of sediments. Cesium-137 was introduced to the atmosphere by aboveground nuclear detonations. This man-made fission product is deposited on the Earth's surface by processes similar to those that deposit lead-210. Cesium-137 was first recorded as fallout in the San Francisco Bay area in 1954 and reached peak fallout in 1963 (HASL, 1977). Assuming that sediments were not disturbed and that cesium-137 is immobile in the sediment column, the maximum depth of cesium-137 activity marks surfaces deposited in the mid-1950's and the location of maximum cesium-137 activity marks surfaces of the mid-1960's. Cesium-137 has been used as a marker to determine sedimentation rates in lakes (Robbins and Edgington, 1975 and Dominik and others, 1981) and estuaries (Olsen and others, 1981 and Donoghue, 1981). Cesium-137 is associated with fine-grained sediments and is generally attached to clay-sized particles by ion exchange. The use of cesium-137, as does use of lead-210, depends on the assumption that cesium-137 is immobile in the sediment column.

Field Methods

Ten sediment core samples were taken from San Leandro Bay during January and February 1984. These cores were taken by pushing 7.6-cm diameter clear plastic core liners into the bottom sediments by hand, capping the top of the core liner, and extracting the core liner and core by hand. Cores were taken from a boat during periods of changing tide. Water depths during sampling ranged from 0.15 to 0.91 m. Following extraction, cores were examined for completeness and for evidence of bioturbation as indicated by the presence of macrofauna and their burrows. Evidence of excessive bioturbation was not found on the outside of any core.

Following extraction, cores were extruded from the core liner and subdivided into 4 cm sections. The outside edges of these subsamples were discarded to avoid material that may have been dragged down sides of the core liner during insertion or core extrusion.

Subsamples were further examined for evidence of bioturbation and nonhomogeneous composition. Some small worms were noted at a depth of 12 cm in core SLB06 with one small worm at a depth of 22 cm. Shell fragments were in several cores to a depth of 12 cm but live mollusks were not found. The top 4 cm of all cores contained a light brown noncompacted flocculated material. This material was interpreted to represent the upper layer of bottom sediment and indicated that cores were undisturbed during collection. Most material below this upper layer consisted of homogeneous gray-green mud intermixed with small quantities of shell fragments.

Analytical Methods

A total of 24 subsamples from four cores (SLB01, SLB05, SLB08, and SLB09; fig. 3) were analyzed by the Denver Central Laboratory of the U.S. Geological Survey for lead-210, radium-226, and cesium-137 activity by gamma spectrometry. These cores were chosen for analysis because they were collected from widely spaced locations within the bay. Analyses of these cores were performed on intervals of 4 cm depth which were air dried, ground, and well mixed. Shell fragments greater than 1 mm were removed before analysis.

Bathymetric Surveys

The bathymetry of San Leandro Bay was surveyed in August 1983 for the Alameda County Flood Control and Water Conservation District. This survey was conducted using a fathometer and reported bathymetry at a contour interval of 0.03 m. In addition to the bathymetric survey done in 1983, bathymetric data are available for all or part of San Leandro Bay from surveys conducted in 1856, 1929, 1954, and 1981. The 1856 survey includes data from 14 survey lines across the bay and is available from the California State Lands Commission, Sacramento, as Hydrographic Survey H-628. The 1929 and 1956 surveys were conducted by the U.S. Coast and Geodetic Survey. The 1929 survey contains data for only dredged areas of the bay and the 1956 survey contains only a small quantity of data immediately west of the Bay Farm Island Bridge. The 1981 survey was done by the National Oceanic and Atmospheric Administration (1981) and contains a high density of data points within San Leandro Bay. In addition to these general surveys, detailed bathymetric data were collected before and after dredging of the rectangular channel at the mouth of San Leandro Creek (William E. Hanvenor, Port of Oakland, written commun., 1984).

RESULTS OF INVESTIGATION

Isotope Studies

Results of isotope analyses are summarized in table 1 and activity of lead-210, radium-226, and cesium-137 versus depth are plotted in figure 4. Excess lead-210 activity was determined for individual samples by subtracting the core average activity of radium-226 from lead-210 activity for individual samples. Lead-210 activity at sites of the four cores analyzed seems to decrease exponentially with depth. Lead-210 activity reaches the level of activity supported by radium-226 between depths of 16 and 24 cm. Cesium-137 activity for these cores extends as deep or deeper than the maximum depth of excess lead-210 activity. A maximum in cesium-137 activity, which would mark the period around 1963, was found only in core SLB01. This peak, however, was too broad to be used to estimate a sedimentation rate.

Sediment-accumulation rates were calculated from lead-210 profiles using equations 1 and 3 at sites SLB01 and SLB08 (table 1, columns 4, 5, and 6). Data were insufficient at the other two sites to fit an exponential profile.

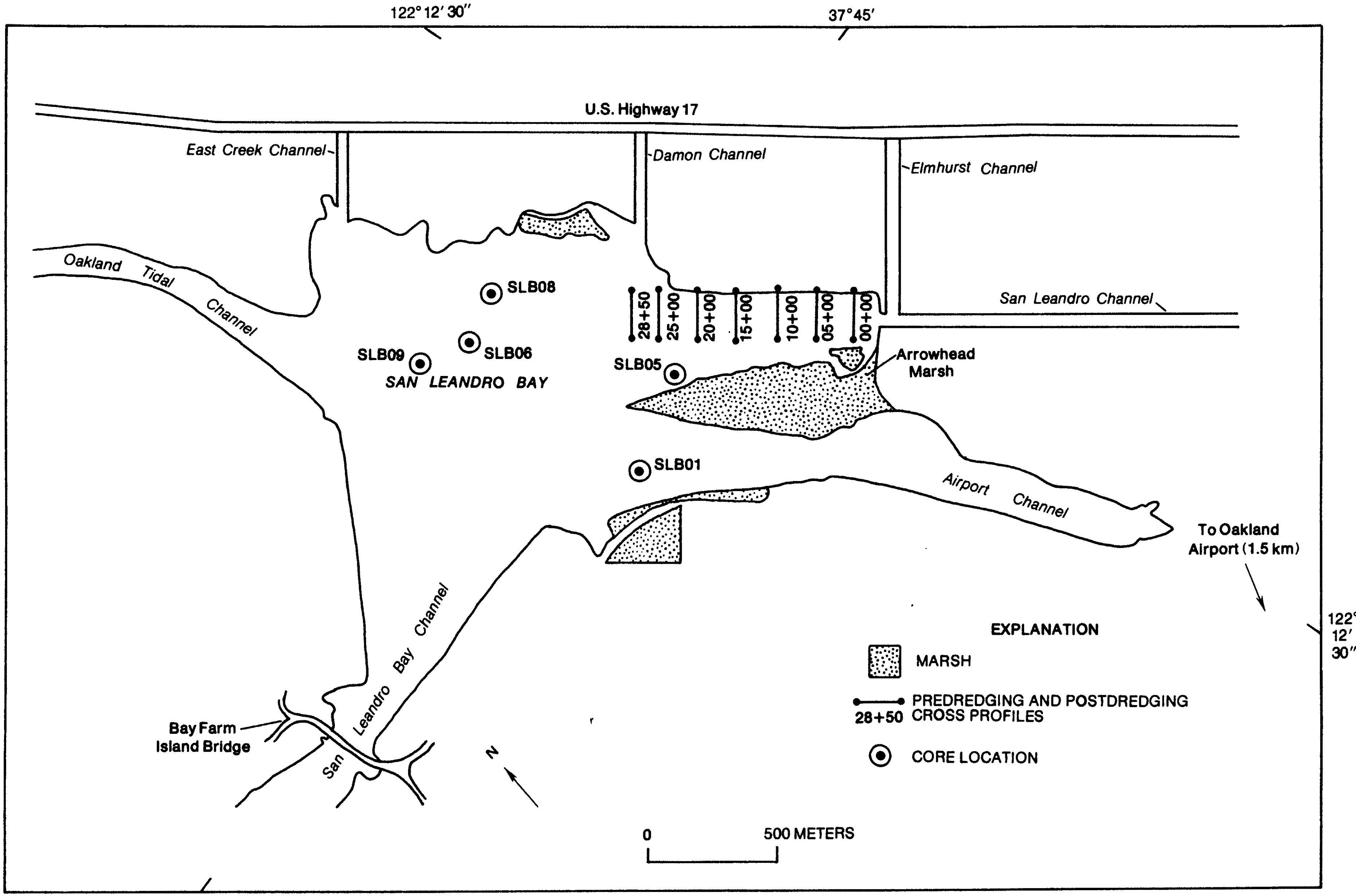


FIGURE 3.— Location of cores analyzed for radioisotopes and location of cross profiles used in bathymetric comparison.

TABLE 1.--Summary of radioisotope data from San Leandro Bay sediment cores

[Errors shown are relative errors associated with counting isotope activity]

W in column 4 and S in column 7 are calculated from equation 3 using C_w equal to baywide yearly average for San Francisco Bay of 2.3±0.4 dpm/g (Fuller, 1982).
W in column 5 and S in column 8 are calculated from equation 3 using C_w equal to average excess activity of surface (0 to 4 cm) sediment (0.6 dpm/g).
W in column 6 and S in column 9 are calculated from equation 1 (see text).

Core	Integrated excess lead-210 activity (dpm/cm²)	Ratio integrated lead-210 activity / Fallout	Sediment-accumulation rate (W), in (gm/cm²)/a			Sedimentation rate (S), in cm/a			Integrated cesium-137 activity (pCi/cm)	Ratio integrated cesium-137 activity / Fallout[1]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
SLB01	5.6±1.0	1.2±0.3	0.07±0.01	0.29±0.07	0.30±0.07	0.09±0.01	0.39±0.07	0.40±0.07	4.6±0.1	1.6±0.2
SLB05	5.3±0.9	1.1±0.2	0.06±0.01	0.27±0.06	--	0.08±0.01	0.36±0.06	([2])	2.6±0.1	0.9±0.1
SLB08	2.9±0.7	0.6±0.2	0.03±0.01	0.15±0.04	0.11±0.04	0.04±0.01	0.20±0.04	0.15±0.04	3.2±0.1	1.1±0.1
SLB09	2.8±0.7	0.6±0.2	0.03±0.01	0.15±0.05	--	0.04±0.01	0.20±0.05	([2])	2.3±0.1	0.8±0.1

[1]Fallout cesium-137 activity from HASL (1977) records; decay corrected (see Fuller, 1982).
[2]Insufficient data to fit profile using equation (1).

Sediment-accumulation rates at these two sites were determined using only equation 3, the mass-balance method. The mass-balance method yielded accumulation rates ranging from 0.03 to 0.07 (g/cm²)/a (table 1, column 4) when the excess activity of incoming particles (C_W) was assumed to equal the baywide yearly average for southern San Francisco Bay (Fuller, 1982). Accumulation rates of 0.15 to 0.30 g/cm² were obtained when incoming particle activity (C_W) was assumed equivalent to the average surface (0-4 cm) excess lead-210 activity for all four cores. By assigning this surface interval activity to C_W in equation 3, the calculated accumulation rate should be equivalent to that obtained by equation 1. This equivalence can be seen from the agreement of rates calculated by both methods for cores SLB01 and SLB08. Therefore, the accumulation and sedimentation rates for cores SLB05 and SLB09 in columns 5 and 8 (table 1) can be substituted for those in columns 6 and 9 since the exponential method could not be used at those sites. Sediment-accumulation rates (grams per square centimeter per annum) in table 1, columns 4-6 were converted to sedimentation rates (centimeter per annum) by dividing by P_{eff} (0.75) to yield the values in columns 7-9.

The discrepancy between the mass-balance method (table 1, columns 4 and 7) and the exponential method (columns 6 and 9) may be the result of several factors. The value of C_W from South San Francisco Bay may be an overestimate of the actual incoming particle activity of deposited sediments if there is significant input of lower activity sediments derived from shoreline erosion and terrestrial runoff. Thus, the rate calculated by this method would be a lower limit of the net-accumulation rate. Alternatively, physical and biological reworking of the sediment column may mix higher activity particles downward, thus modifying the shape of the activity profile. These mixing processes result in an overestimate of the accumulation rate by the exponential method (Peng and others, 1979; Benninger and others, 1979; and Fuller, 1982). The possibility of sediment reworking cannot be eliminated because some small worms

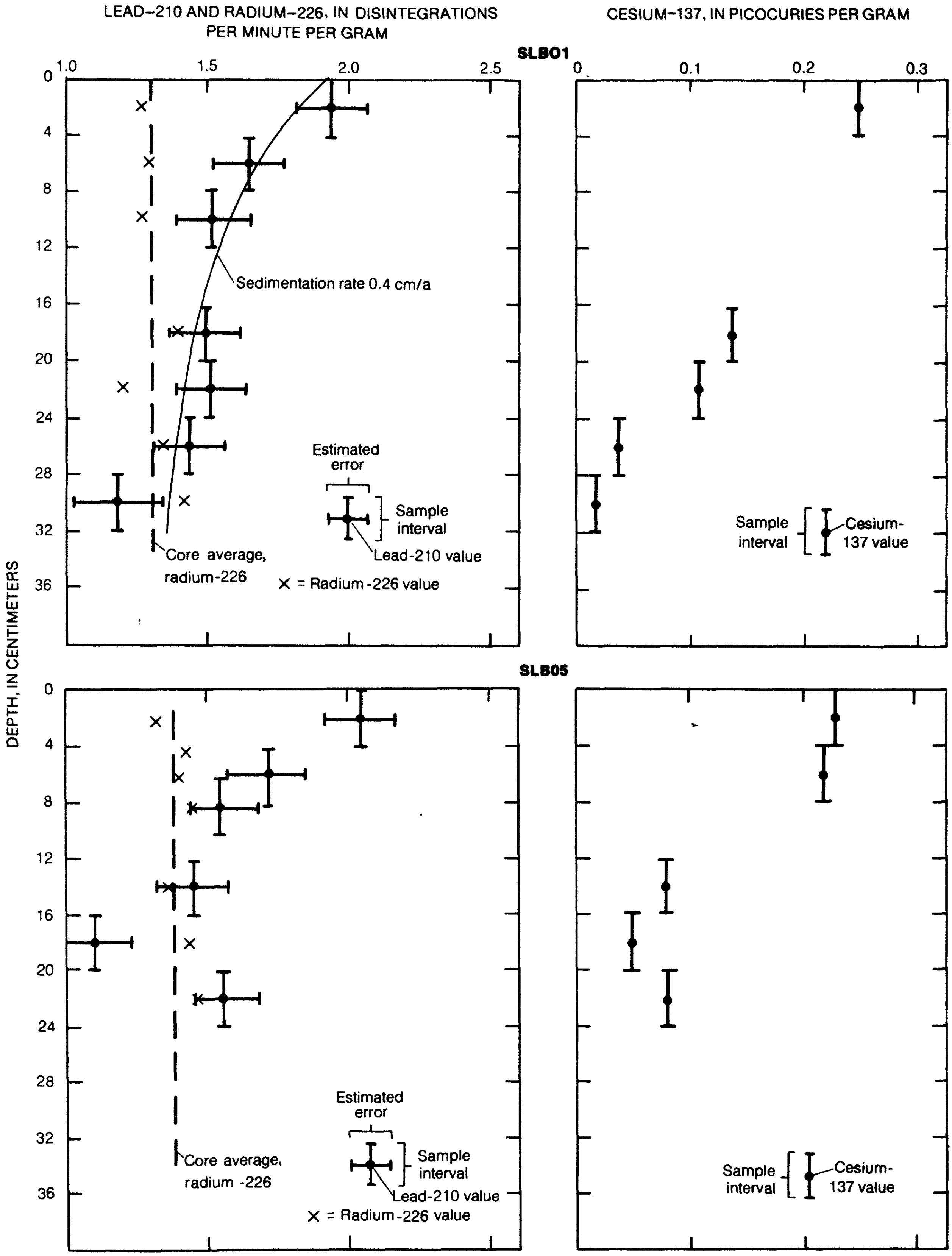


FIGURE 4.— Plot of lead-210, radium-226, and cesium-137 activity versus depth for cores SLB01, SLB05, SLB08, and SLB09. Estimated error is that associated with counting isotope activity. Sedimentation rates shown were determined using equation 1.

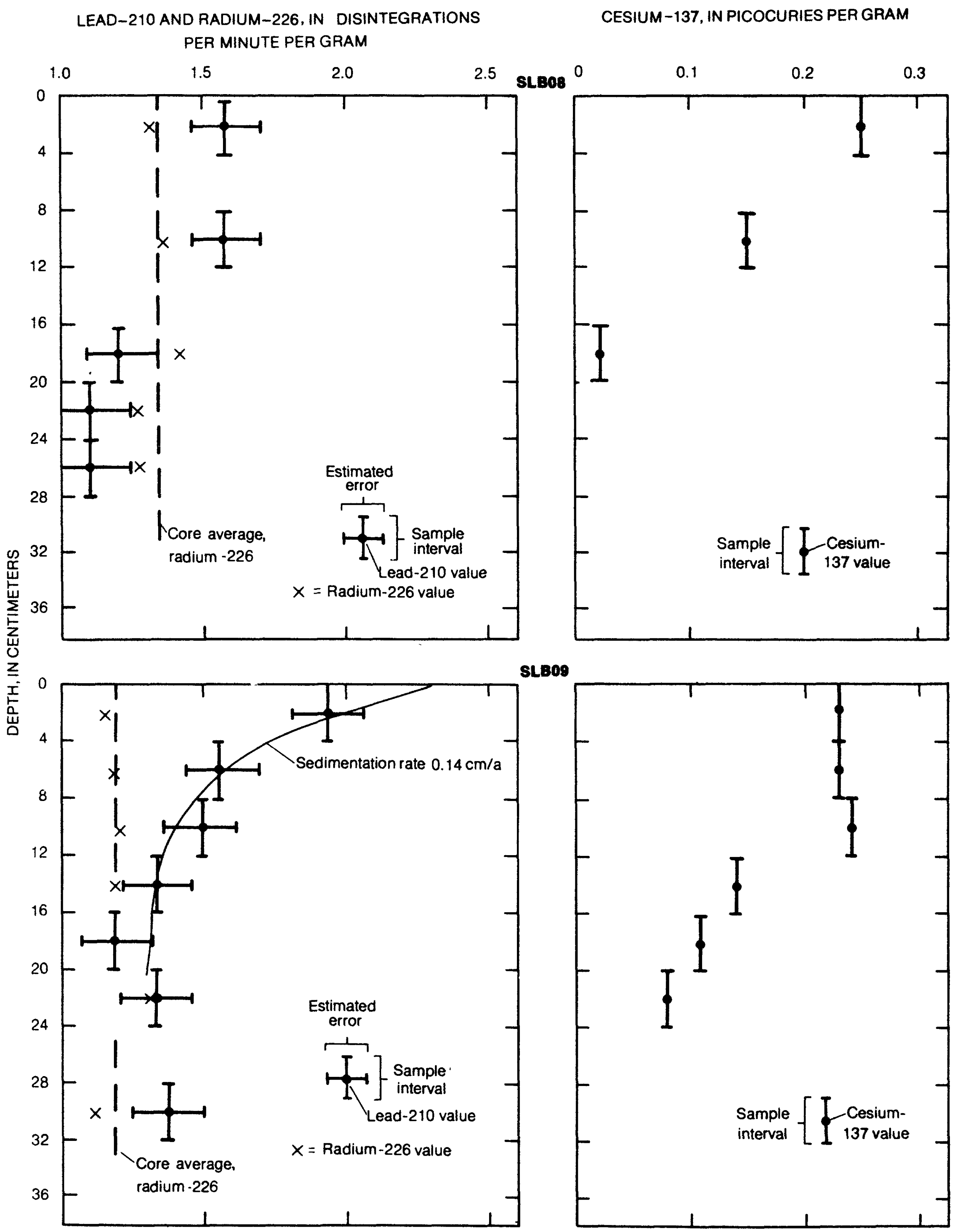


FIGURE 4.—Continued.

were noted in core SLB06 to a depth of 22 cm and because X-radiographs were not taken of cores to confirm the presence of laminations. Therefore, the rates calculated by the exponential method must be assumed to be upper limits of the true rates. Conversely, since the activity of depositing particles in San Leandro Bay is not well established, the use of the South San Francisco Bay yearly average value for C_w measured by Fuller (1982) must result in a lower limit for the calculated accumulation rates. The use of a radioisotope with a much shorter half-life or with a different input history for comparison to the lead-210 activity profile would allow estimation of the magnitude of sediment reworking and correction for this effect (Peng and others, 1979 and Robbins and Edgington, 1975). Activity profiles of cesium-137 were measured on the San Leandro Bay cores for this purpose, but those data are of limited use.

Sediment-accumulation rates estimated from the maximum depth of cesium-137 penetration are unrealistically high when compared with values determined from the lead-210 profiles. If the depth of maximum cesium-137 penetration represents sediment deposited in 1954, estimates of sediment-accumulation rates range between 0.6 and 1.0 cm/a. Such a contrast in rates estimated using the cesium-137 and lead-210 data was not unexpected after examining the depth profiles of these isotopes. The depth of maximum penetration of cesium-137 (which should represent 1954 surfaces) is at least as deep as the maximum excess lead-210 depth (which should represent about 100 years of accumulation). As an alternative to assuming that the 1952 horizon is represented by the maximum depth of cesium-137, this horizon could be assumed to equal the point were cesium-137 activity begins to decrease exponentially (12 cm at sites SLB01 and SLB08). This method yields accumulation rates of 0.4 cm/a and agrees well with the lead-210 derived rate for SLB01 but is a factor of two greater than the rate estimated for SLB08. The unrealistic high rates indicated by the cesium-137 data result because there has been significant postdepositional migration of cesium-137 in the sediment column.

Measurements of distribution coefficients indicate that cesium-137 is more likely than lead-210 to be mobile within the sediment column. Distribution coefficients are a measure of the equilibrium concentration of the isotope per gram of solid (concentration per gram) relative to concentration per milliliter (or cubic centimeter) in solution. Distribution coefficients of lead-210 in San Francisco Bay were determined by Fuller (1982) to be on the order of 10^5 cm^3/g while values of distribution coefficients for cesium-137 were several orders of magnitude lower than those for lead-210. Duursma and Eisma (1973) found cesium-137 distribution coefficients on the order of 10^3 cm^3/g; more recent studies by Sholkovitz and others (1983) and Santschi and others (1984) found distribution coefficients for cesium-137 in marine systems of 5×10^1 to 7×10^2 cm^3/g. Sholkovitz and others (1983) and Santschi and others (1984) noted that their results indicated that transport of cesium-137 in pore waters is a potentially significant process. The much lower distribution coefficients for cesium-137 imply that cesium-137 is at least two orders of magnitude more soluble than lead-210.

The work of Duursma and Eisma (1973) indicated that cesium-137 distribution is largely controlled by ion exchange for potassium and stable cesium on clays. Because partitioning by ion exchange is an equilibrium (that is, reversible) process, cesium-137 dissolved in pore waters migrates away from zones of higher total activity following deposition. This causes a shift in equilibrium and results in release of cesium-137 from the particles to the pore water and causes equilibrium to be reestablished.

As the dissolved cesium-137 migrates, it also reequilibrates with the particles it contacts. These processes occur concurrently to maintain a concentration gradient in the pore water and thus cause the cesium-137 to be redistributed away from zones of higher activity. For a distribution coefficient of 10^2 cm^3/g, a mean diffusional distance of about 8 cm is estimated for a 30-year period (Fuller, 1982, p. 139). Therefore, postdepositional migration of cesium-137 accounts in part for the differences observed in the activity profiles of cesium-137 and lead-210. This result indicates that the use of cesium-137 as an indicator of sediment-accumulation rates in marine systems is not reliable in systems with low-accumulation rates. Mobility of cesium-137 in such environments would produce apparent sedimentation rates in excess of true rates.

Since the possibility of sediment reworking cannot be eliminated, or compensated for, and since postdepositional migration of cesium-137 independent of sediment particles is likely, better estimates of sediment-accumulation rates cannot be established. From the arguments presented in the preceding paragraphs, we conclude that only a range of sediment-accumulation rates can be derived from this data set. The range for each core are shown as grams per square centimeter per annum in columns 4 and 6 of table 1 and as centimeters per annum in columns 7 and 9.

Ratios of integrated excess lead-210 activity to integrated excess activity expected from delivery by direct fallout (Fuller and Hammond, 1983) are less than 1--ranging from 0.6 to 1.0 (table 1). Ratios of integrated cesium-137 activity to direct fallout delivery (Fuller, 1982 p. 139) are also low (table 1). These low ratios indicate that inventories of excess lead-210 and cesium-137 can be supported by direct fallout to the surface of San Leandro Bay and that net input of excess lead-210 or cesium-137 by sediment entering San Leandro Bay, from either adjacent drainages or open water of San Francisco Bay, is minimal.

Bathymetric Surveys

Changes in bathymetry of San Leandro Bay were assessed by comparing the survey of 1856 with the survey of 1983. These two surveys were compared because they provide the longest and most detailed record available. Results of comparing the 1856 and 1983 surveys are shown in figure 5. Because the survey done in August 1983 (Alameda County Flood Control and Water Conservation District, 1984) was referenced to NGVD of 1929, the 1983 data were converted to a datum of mean lower-low water before comparison could be made. A survey of tidal datums done in 1983 by the U.S. National Oceanic and Atmospheric Administration shows that NGVD of 1929 is 0.896 m above mean lower-low water at the Oakland Airport. The 1983 data were converted to a datum of mean lower-low water by subtracting 0.896 m from depths shown on the 1984 survey. Because the 1856 survey reported depths only to the nearest 0.30 m, the 1983 data also were rounded to the same precision. The 1856 survey was presumably done using a lead-sounding weight as opposed to the fathometer used in 1984. This variation in collection methods probably introduced some discrepancy in the two data sets because the lead weight probably sank into the soft bottom sediment to some unknown depth. Such discrepancies have not been compensated for because the depth to which the lead-sounding weight may have sunk into the sediment is unknown.

Inspection of figure 5 shows that the greatest changes in bathymetry occurred in the vicinity of the San Leandro Bay Channel. Deposition up to 2.75 m occurred in this area. Changes farther back in San Leandro Bay were much less. Water depths were generally the same during both surveys with a few readings differing by 0.3 m. One set of readings in the middle of the bay showed 1.2 m of fill and another showed 0.6 m of fill. In general, however, bathymetric changes between 1856 and 1984, in the interior and eastern parts

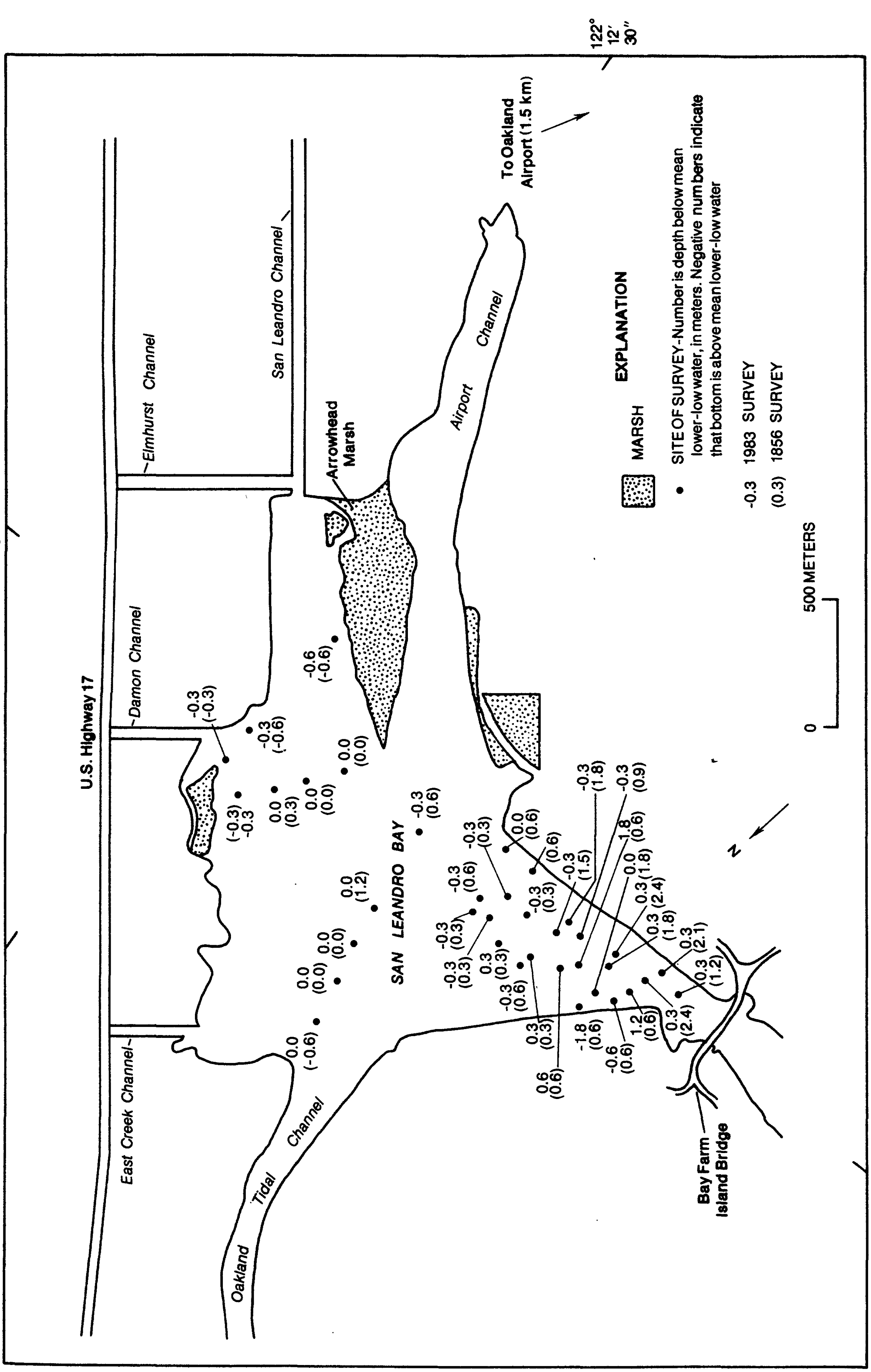


FIGURE 5.— Water depths below mean lower-low water in San Leandro Bay in 1856 and 1983.

of San Leandro Bay, were not large enough to be measured by the two surveys.

Sedimentation in the channel dredged at the mouth of San Leandro Creek between 1948 and 1983 was determined by comparing bathymetry presented in the 1948 postdredging survey and in the 1983 bathymetric map. Volumes of sediment that accumulated between 1948 and 1983 are shown in table 2. Examples of filling that occurred along cross profiles of the channel are shown in figure 6. The volumes of fill shown in table 2 were calculated by applying the fill measured at cross profiles, which were generally spaced 152 m apart, and applying that fill to one-half the length of channel between individual cross profiles. Average depths of fill ranged from 4.9 to 10.4 m for the 35-year period. These values represent average annual sedimentation rates of between 14 and 30 cm/a. The greatest filling occurred on the bayward (or northern) end of the channel, away from the mouth of San Leandro Creek.

TABLE 2.--Sedimentation in channel dredged at mouth of San Leandro Creek, September 1948 to August 1983

(See figure 3 for location of cross profile)

Cross profile No.	Fill at cross profiles: Average depth (m)	Fill at cross profiles: Total (m^2)	Distance between cross profiles (m)	Volume of fill between cross profiles (m^3)
00+00	5.2	889.1		
			152.4	132,314
05+00	4.9	847.3		
			152.4	136,276
10+00	5.6	941.1		
			152.4	138,112
15+00	5.3	871.4		
			152.4	147,249
20+00	6.5	1,061.0		
			152.4	167,922
25+00	6.9	1,142.7		
			106.7	128,867
28+50	10.4	1,272.8		
	Total fill	-----------		850,740

DISCUSSION OF RESULTS

Sedimentation Rates and Submergence

Sedimentation rates in San Leandro Bay, in the vicinity of the San Leandro Bay channel, are much higher than can be explained from submergence rates measured in South San Francisco Bay. Atwater and others (1979, table 2) showed that historic submergence rates have averaged 0.1 to 0.2 cm/a. During the 128 years between 1856 and 1984, such submergence would yield a total of 12.8 to 25.6 cm, whereas deposition of as much as 275 cm was recorded in the vicinity of the San Leandro Bay channel. The range of sedimentation rates determined for cores SLB01, SLB05, SLB08, and SLB09 are, depending upon the activity of incoming lead-210 used in calculation, within or slightly more than the range of submergence rates reported by Atwater and others (1979). When C is assumed equal to values found by Fuller (1982) throughout San Francisco Bay, sedimentation rates (table 1, columns 4 and 7) are below submergence rates. When C is assumed equal to average excess activity of surface sediment, sedimentation rates (table 1, columns 5, 6, 8, and 9) are equal to or higher than submergence rates. Available data do not allow better resolution of the range of rates. The bathymetric data in figure 5 tend to indicate that a rate of 0.4 cm/a probably did not persist for the 128-year period between 1856 and 1984.

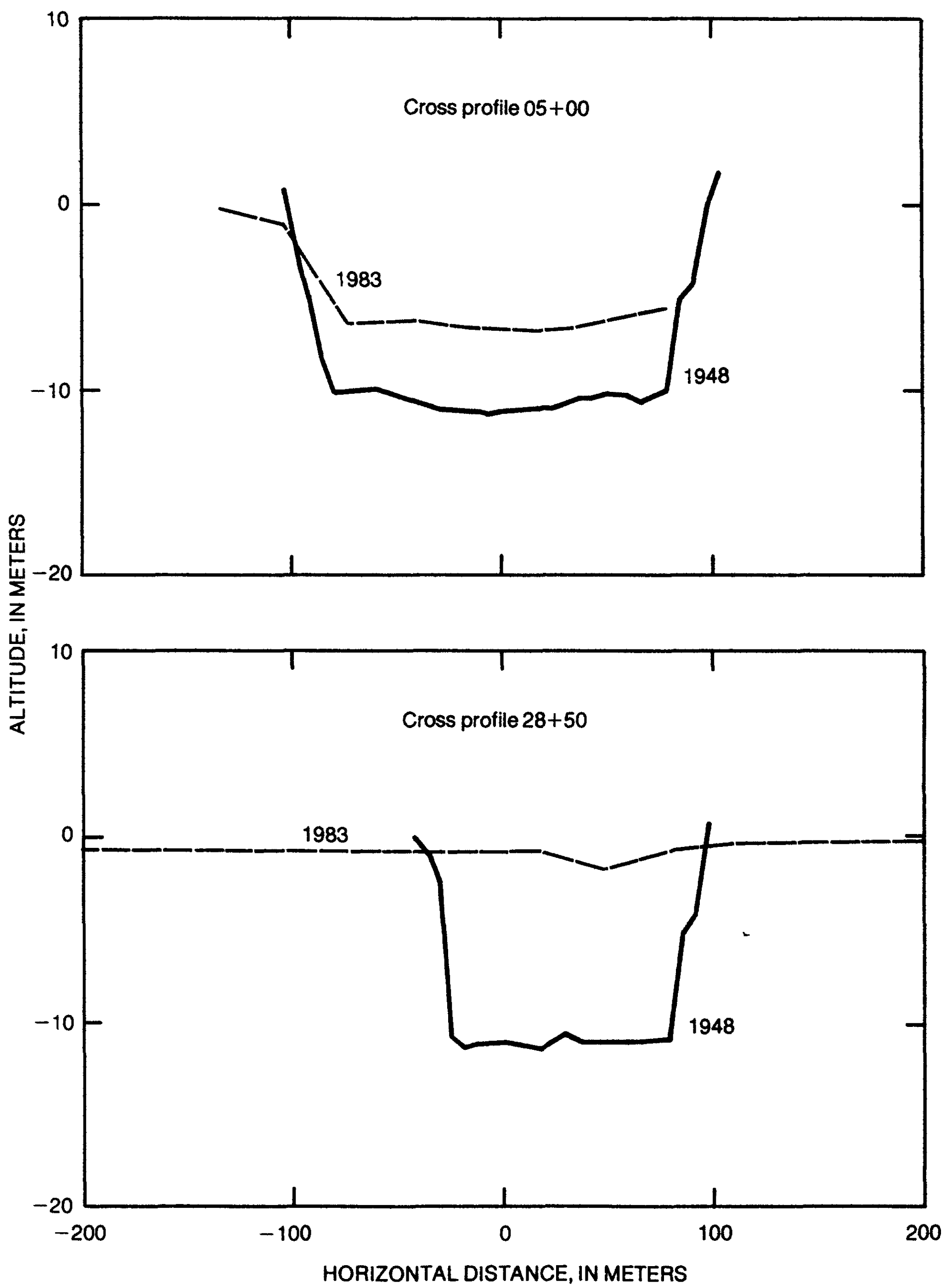


FIGURE 6.— Examples of postdredging and 1983 cross profiles at the mouth of San Leandro Creek. Datum for postdredging profiles was originally mean lower-low water but was corrected to National Geodetic Vertical Datum of 1929 to agree with 1983 data. See figure 3 for location of cross profile.

Such rates probably would have produced filling of more than 50 cm and therefore would have been discernible from data presented in figure 5.

Sedimentation rates in the deeper dredged areas were much higher than those in the more common, shallow areas. In shallow areas, shear stress applied by tidal currents and wind-generated waves keep sediment in suspension and inhibit deposition [see summary of Krone (1979) in "Previous Studies" section]. At sites of cores SLB08 and SLB09, shear stress applied by tidal currents and wind-generated waves is apparently greater or sediment supply is less than at sites of SLB01 and SLB05. Sedimentation rates at SLB01 and SLB05 are about twice those at SLB08 and SLB09.

Effects of Changes in Bay Configuration

The high rates of sedimentation in the vicinity of the San Leandro Bay channel can be explained by considering the major changes that occurred historically in the configuration of San Leandro Bay and surrounding marshes. Effects of opening the Oakland tidal channel are shown by the U.S. Army Corps of Engineers (1980) and Brown and Caldwell Consultants (1980). These two studies indicate that opening the Oakland tidal channel has dispersed the flow of water entering and leaving San Leandro Bay during changing tides and therefore decreased tidal-flushing velocities. This in turn has caused rapid sedimentation in the vicinity of the San Leandro Bay channel. Tidal velocities undoubtedly are decreased in other parts of San Leandro Bay due to opening the Oakland tidal channel, but effects in these areas are probably less than in the constriction formed by the San Leandro Bay channel.

Another factor probably responsible for the high sedimentation rates in San Leandro Bay is the vast reduction of marsh areas during the 1900's. Gilbert (1917, p. 75-79 and 123-138) recognized that tidal marshes are important in storing water in the tidal prism. Marshes receive water during rising tide and release it through sloughs during falling tide. When water is prevented from entering marsh areas, tidal flow through sloughs serving those areas is shut off and sedimentation results (Gilbert, 1917, p. 102-103). Prior to the time when manmade modification removed most of the marsh adjacent to San Leandro Bay, much of the open bay water consisted of sloughs serving these marshes. Airport Channel drained a large marsh at the present site of the Oakland Airport; the rectangular area at the mouth of San Leandro Channel drained marshes on the south side of the bay; and the East Creek and Damon Channels drained small marsh areas on the east side of the bay.

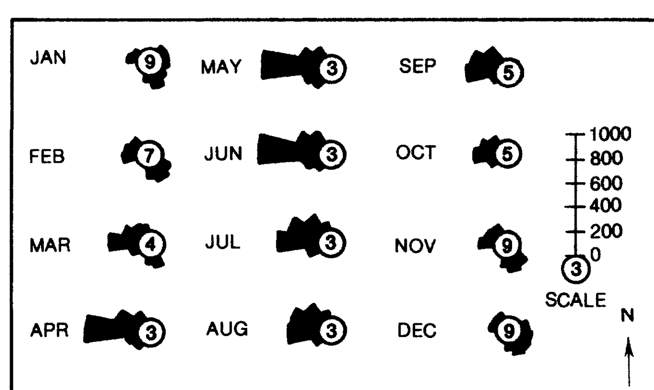
The magnitude of the effect of decreased marsh area on the tidal prism can be estimated using data provided by Gilbert (1917). He estimated that marshes bordering the east side of San Francisco Bay had an effective depth of storage of 0.16 m. The U.S. Army Corps of Engineers (1980) indicated that marsh area in San Leandro Bay decreased by 782 hm between 1922 and 1977. Applying Gilbert's (1917) figures indicates that the tidal prism in San Leandro Bay has decreased by 1.25×10^6 m^3. The remaining 28 hm of marsh would have an effective tidal prism of 0.04×10^6 m^3. The range between mean high water and mean low water at the Oakland Airport is 1.46 m (John Monser, Alameda County Flood Control and Water Conservation District, oral commun., 1984). This is very close to the 1.43 m estimated by Gilbert (1917) for the mean depth of the effective tidal prism in southern San Francisco Bay. Applying the 1.46 m mean tidal range measured at the Oakland Airport to the 2.59 km^2 of open water in San Leandro Bay indicates an effective tidal prism of 3.78×10^6 m^3. The present tidal prism can be estimated as 3.82×10^6 m^3. Using these figures, the loss of marshland in San Leandro Bay has decreased the quantity of the tidal prism by 25 percent. It should be stressed that Gilbert's data are for the main body of San Francisco Bay and that flow into and out of San Leandro Bay may cause variation in these figures. The data used should, however, provide a reasonable approximation of the effects of the decrease in marshlands on the tidal prism. Given the large effect indicated by this estimate, it seems reasonable to expect increased sedimentation in what used to be sloughs serving marshland of San Leandro Bay.

As mentioned above, sedimentation rates at sites of cores SLB01 and SLB05 were about twice those at sites of SLB08 and SLB09. Sites SLB01 and SLB05 drained large areas of marshland prior to changes in bay configuration. In addition to being sites that drained preexisting marshland, these sites are sheltered from prevailing winds. Wind direction and frequency at the Oakland Airport are shown in figure 7. This figure illustrates the dominance of westerly winds. Sites SLB01 and SLB05 are sheltered from westerly winds and have little open water to the west which means that wind-generated waves in those areas should be small when compared with locations of cores SLB08 and SLB09.

Sediment Sources

Sediment deposited in San Leandro Bay may come from (1) resuspension of bottom sediments within San Leandro Bay, (2) erosion of shorelines and marshes adjacent to San Leandro Bay, (3) water circulating from San Francisco Bay, or (4) direct input from drainage basins draining into San Leandro Bay. The quantity of sediment available from the first three of these sources is particularly difficult to estimate. There are some data, however, that can be used to determine the role of sediment from the fourth source, terrestrial drainages, in contributing sediment to San Leandro Bay. For this reason, the quantity of sediment deposited in San Leandro Bay between 1948 and 1983 was estimated and the degree to which sediment coming directly from terrestrial drainages could be expected to account for that volume of sediment was assessed.

The total volume of sediment deposited in San Leandro Bay between 1948 and 1983 is estimated to be between 1,213,000 and 1,364,000 m^3. Fill in the 0.20 km area dredged at the mouth of San Leandro Channel was to 850,740 m^3 (table 2). Because sedimentation rates in the vicinity of the San Leandro Bay channel were so high, rates in that area were calculated separately from rates in the remaining shallow areas. Using data from figure 5, sedimentation rates in the 0.40 km^2 to the east of the Bay Farm Island Bridge averaged 0.7 cm/a. Because much of this rapid sedimentation probably occurred after 1922, the average of 0.7 cm/a probably represents a conservative estimate. Rates since 1922



EXPLANATION

SCALE, IN MILES PER HOUR TIMES PERCENTAGE OF FREQUENCY.
NUMBER IN CIRCLE INDICATES PERCENTAGE OF TIME OF CALM

FIGURE 7.– Cross product of wind direction and frequency at the Oakland International Airport (from Conomos, 1979).

were probably much higher. If a sedimentation rate of 0.7 cm/a existed between 1948 and 1983, 321,000 m^3 of sediment would have been deposited in this 0.40 km^2 area. Assuming sedimentation rates in the remaining shallow parts of San Leandro Bay averaged between 0.06 and 0.28 cm/a (the average of values in column 7 and columns 8 and 9, table 1), total sedimentation for the 35-year period in the 1.96 km^2 of remaining open water would have been between 41,160 m^3 and 192,080 m^3.

Because postdredging bathymetry is not available for the Airport Channel, fill in this area was estimated only as shallow water deposition. Combining values for the area east of Bay Farm Island Bridge, the dredged channel, and shallow water deposition yields an estimated total deposition between 1948 and 1983 of between 1,213,000 and 1,364,000 m^3. Using an average bulk density value of 0.75 g/cm^3 measured by Fuller (1982, p. 200) for a shallow sediment core in San Francisco Bay, yields average annual deposition of between 26,000 and 29,200 Mg/a. An average annual sediment yield would require between 153 and 173 Mg/km^2 of silt- and clay-size material from the 169 km^2 drainage area to account for this estimated deposition.

Sediment yields from streams entering San Leandro Bay were not measured. Some data exist for Cull Creek which drains relatively erosive terrain adjacent to the southern end of the San Leandro Creek basin. These data indicate that, although high sediment yields are possible from steep upland areas, much of this sediment can be trapped by reservoirs downstream of these rapidly eroding areas. Sediment-discharge data for two gaging stations on Cull Creek are shown in table 3. Sediment data were collected downstream of the reservoir only in 1979. Although sediment yields of more than 2,800 Mg/km^2 (greater than the values needed to maintain sedimentation) are possible upstream of the reservoir, the reservoir was quite affective in trapping sediment in 1979--decreasing the yield by 96 percent.

TABLE 3.--Total sediment yield for Cull Creek

Station name and No.	Water year	Total sediment yield Mg	Total sediment yield Mg/km^2
Cull Creek above Cull Creek Reservoir 11180960	1979	8,474	470
	1980	43,038	2,869
	1981	1,294	19.6
Cull Creek below Cull Creek Reservoir 11180965	1979	338	20.3

Sediment yield from the Cull Creek drainage basin should be used only to place limits on potential yields from drainages entering San Leandro Bay. Data from Cull Creek represent an upper limit of yields to be expected from terrain draining into San Leandro Bay because terrain in the upper reaches of Cull Creek seems to be eroding at least as rapidly, and probably more rapidly than, terrain in San Leandro Creek or Arroyo Viejo drainage basins (Jack Lindley, Alameda County Flood Control and Water Conservation District, oral commun., 1984).

The effectiveness of the Cull Creek Reservoir in trapping sediment indicates that sediment yields from upper reaches of San Leandro Creek can only be expected to be a fraction of values needed to produce the estimated sedimentation in San Leandro Bay. Reservoirs in the San Leandro Creek basin control flow in 89 percent of that drainage basin which represents 65 percent of the total area draining into San Leandro Bay. The Arroyo Viejo drainage basin drains some upland areas, and could conceivably have an average annual sediment yield as high as 152 to 173 Mg/km^2, but drains only 10 percent of the area draining into San Leandro Bay.

Sediment yields from the more gently sloping, suburban and urban land along downstream reaches are unknown but are assumed to be low due to the gentle slopes and highly engineered nature of channels in that area. In addition, total sediment yields listed in table 3 represent all size fractions of sediment. Sediment deposited in San Leandro Bay is dominated by only silt- and clay-size material (table 4). To completely estimate the role of drainage-basin sediment in supplying sediment to San Leandro Bay would require information on the size distribution of supplied sediment and some estimate of the length of time necessary to weather coarse material to silt and clay sizes.

Evidence From Isotope Studies

The low ratios of integrated excess lead-210 activity and cesium-137 activity to fallout (table 1, columns 3 and 11) imply that sediment particles deposited in San Leandro Bay have a low component of particles recently derived from terrestrial drainage systems or from the open part of San Francisco Bay. This does not preclude input of sediment from these outside sources but indicates that net sediment input from such areas is not particularly voluminous. This conclusion is based on the reported excess lead-210 activity of suspended sediment in South San Francisco Bay and in the Sacramento-San Joaquin River delta, which are 1.9 to 3.8 dpm/g and 3.7 dpm/g, respectively (Fuller, 1982), and on the assumption that particles entering San Leandro Bay from terrestrial drainage systems or San Francisco Bay have similar activities to these measured values. In addition, data presented by Fuller (1982) indicate that there is no reason to believe that the lead-210 activity of sediment recently deposited in San Leandro Bay is any less than the activity of incoming sediment. Fuller (1982) found that the lead-210 activity of recent sediment was independent of sediment size (in the fraction less than 0.062 mm). This means that there should be no tendency for the somewhat coarser sediment, which should settle out first in San Leandro Bay, to be any different, isotopically, from the sediment measured by Fuller.

TABLE 4.--Size distribution of sediment in core SLB06

(Core was analyzed using sieve and pipet analysis outline by Guy, 1969)

Core interval (cm)	Percent finer than, in millimeters								
	0.002 clay	0.004	0.008 silt	0.016	0.031	0.062	0.125 sand	0.25	0.5
0-4	38	42	50	58	69	84	94	99	100
8-12	41	48	54	63	74	85	94	98	100
16-20	44	51	60	74	89	97	99	100	100
24-28	61	72	86	95	98	100	100	100	100

SUMMARY AND ADDITIONAL STUDIES

Data discussed in this report indicate that sedimentation rates in parts of San Leandro Bay near the San Leandro Bay channel are high when viewed in light of submergence rates, and that changes in configuration of the bay have been the likely cause of these high rates. Opening the Oakland tidal channel decreased tidal-flushing velocities, and removal of 97 percent of marshland surrounding the bay has decreased the tidal prism by about 25 percent. In shallow areas away from the San Leandro Bay channel, highest rates of sedimentation were in areas that are protected from prevailing winds and formerly received tidal flow from marshlands.

Inventories of lead-210 and cesium-137 indicate that little of the sediment deposited in San Leandro Bay during the 20th century came from drainage basins adjacent to the bay or was recently delivered to San Francisco Bay. Low sediment yields from drainages adjacent to San Leandro Bay also are indicated by data available for 1979 from upstream and downstream of the reservoir on Cull Creek. Combining the isotope inventories with the sediment-yield data indicates that much of the sediment deposited within San Leandro Bay is coming from resuspension of bottom material or from erosion of marshes and(or) shorelines of San Leandro Bay and(or) San Francisco Bay.

The present data base was collected for a preliminary analysis of rates and causes of sedimentation in San Leandro Bay and leaves some questions about the exact sedimentation rates in shallow areas and the source of sediment being deposited. The activity of lead-210 on sediment suspended in the water column was not measured, nor were sediment yields of streams draining into San Leandro Bay. Measurement of lead-210 activity on incoming sediment would allow better estimates of sedimentation rates using the mass-balance method and therefore correct for uncertainties caused by possible bioturbation.

Sediment-yield data are available only for Cull Creek, which drains land adjacent to basins that drain into San Leandro Bay. Even data from this basin are available only for 1979. The role of tributary streams in supplying sediment to San Leandro Bay could be better defined by direct measurement of sediment entering the bay. Isotope inventories indicate that little recently deposited sediment is entering San Leandro Bay. Although this tends to indicate that net sediment input from outside San Leandro Bay is minimal, it does not preclude the possibility that older sediment is being resuspended from the bottom of San Francisco Bay or eroded from shores or marshes of San Francisco Bay and transported into San Leandro Bay by tidal flow. Measurement of flow and sediment concentrations of tidal currents would better define the role of tidal flow from San Francisco Bay in supplying sediment to San Leandro Bay. Finally, estimates of sedimentation rates in shallow areas of San Leandro Bay are based on data from only four widely spaced sediment cores. Better definition of the spatial variability of sedimentation rates could be obtained if additional cores were collected and analyzed.

REFERENCES CITED

Alameda County Flood Control and Water Conservation District, 1983, Bathymetric chart of San Leandro Bay: scale 1 inch = 200 feet, 1 map.

Atwater, B.F., 1979, Ancient processes at the site of southern San Francisco Bay, *in* Conomos, T.J., ed., San Francisco Bay: The urbanized estuary, Pacific Division of The American Association for the Advancement of Science, San Francisco, p. 31-46.

Atwater, B.F., Conrad, S.G., Dowden, J.N., Hedel, C.W., MacDonal, R.L., and Savage, W., 1979, History, landforms, and vegetation of the estuary's tidal marshes, *in* Conomos, T.J., ed., San Francisco Bay: The urbanized estuary, Pacific Division of the Association for the Advancement of Science, San Francisco, p. 347-386.

Benninger, L.K., 1976, The uranium series radionuclides as tracers of geochemical processes in Long Island Sound: New Haven, Connecticut, Yale University, Ph.D. dissertation, 151 p.

Benninger, L.K., Aller, R.C., Cochran, J.K., and Turekian, K.K., 1979, Effects of biological sediment mixing on the Pb-210 chronology and trace metal distribution in a Long Island Sound sediment core: Earth and Planetary Science Letters, v. 43, p. 241-259.

Brown and Caldwell Consultants, 1979, Preliminary hydrodynamics survey: Study conducted for East Bay Municipal Utility District by Brown and Caldwell Consultants, Environmental Sciences Division, Walnut Creek, California, p. 3-12 - 3-16.

Bruland, K.W., Bertine, K., Kide, M., and Golderg, E.D., 1974, The history of trace metal pollution in the Southern California Coastal Zone: Environmental Science and Technology, v. 8, p. 425-432.

Conomos, T.J., 1979, Properties and circulation of San Francisco Bay waters, in Conomos, T.J., ed., San Francisco Bay: The urbanized estuary, Pacific Division of the American Association for the Advancement of Science, San Francisco, p. 47-84.

Conomos, T.J., and Peterson, D.H., 1977, Suspended-particle transport and circulation in San Francisco Bay: An Overview, *in* Wiley, M., ed., Estuarine processes: v. 2, New York, Academic Press, p. 82-97.

Davis, R.B., Hess, C.T., Norton, S.A., Hanson, D.W., Hoagland, K.D., and Anderson, D.S., 1984, Cs-137 and Pb-210 dating of sediments from soft-water lakes in New England (U.S.A.) and Scandinavia, a failure of Cs-137 dating: Chemical Geology, v. 44, p. 151-185.

Dominik, J.A., Mangini, A., and Muller, G., 1981, Determination of recent deposition rates in Lake Constance with radioisotopic methods: Sedimentology, v. 28, p. 653-677.

Donoghue, J.F., 1981, Estuarine sediment transport and Holocene depositional, Upper Chesapeake Bay, Maryland: Los Angeles, California, University of Southern California, Ph.D dissertation, 328 p.

Duursma, E.K. and Eisma, D., 1973, Theoretical, experimental and field studies concerning diffusion of radioisotopes in sediments and suspended particles in the sea, Part C: Field Studies: Netherlands, Journal of Sea Research, v. 6, p. 265-324.

Fuller, C.C., 1982, The use of Pb-210, Th-234, and Cs-137 as tracers of sedimentary processes in San Francisco Bay, California: Los Angeles, California, University of Southern California, unpublished M.S. thesis, 251 p.

Fuller, C.C., and Hammond, D.E., 1983, The fall-out rate of Pb-210 on the western coast of the United States: Geophysical Research Letter, v. 10, no. 12, p. 1164-1167.

Gilbert, G.K., 1917, Hydraulic-mining debris in the Sierra Nevada: U.S. Geological Survey Professional Paper 105, 154 p.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 5, Chapter C1, 58 p.

HASL, 1977, Final tabulation of monthly Sr-90 fall-out data: 1954-1976: Health and Safety Laboratory Environmental Quarterly, no. 329.

Krone, R.B., 1979, Sedimentation in the San Francisco Bay system in Conomos, T.J., ed., San Francisco Bay: The urbanized estuary, Pacific Division of the American Association for the Advancement of Science, San Francisco, p. 85-96.

National Oceanic and Atmospheric Administration, 1981, Hydrographic survey from Government Island to San Leandro Bay: Hydrographic Survey H-9927, scale 1:5,000, 1 map.

Olsen, C.R., Simpson, H.H., Peng, T.H., Bopp, R.F., and Trier, R.M., 1981, Sediment mixing and accumulation rate effects on radionuclide depth profiles in Hudson Estuary sediments: Journal of Geophysical Research, v. 86, p. 11020-11028.

Peng, T.H., Broecker, W.S., and Berger, W.H., 1979, Rates of benthic mixing in deep-sea sediments as determined by radioactive tracers: Quaternary Research, v. 11, p. 141-149.

Porterfield, George, 1980, Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909-66: U.S. Geological Survey Water-Resources Investigations 80-64, 92 p.

Robbins, J.A. and Edgington, D.N., 1975, Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137: Geochimica et Cosmochimica, v. 99, p. 285-304.

Santschi, P.H., Nyffeler, U.P., O'Hara, P., Buckholtz, M., and Broecker, W.S., 1984, Radio-tracer uptake on the seafloor: results from the MANOP chamber deployments in the eastern Pacific: Deep-Sea Research, v. 31, p. 451-468.

Schroeder, R.A., 1985, Sediment accumulation rates in Irondequoit Bay, New York, based on lead-210 and cesium-137 geochronology: Northeastern Environmental Science, v. 4, p. 23-29.

Sholkovitz, E.R., Cochran, J.K., and Carey, A.E., 1983, Laboratory studies of the diagenesis and mobility of Pu-239 and Cs-137 in nearshore sediments: Geochemical Cosmochimica Acta, v. 47, p. 1369-1379.

Thompson, J., Turekian, K.K., and McCaffrey, R.J., 1975, *in* Cronin, L.E., ed., Estuarine research: v. 1, New York, Academic Press, 28 p.

Turekian, K.K., Nozaki, Y., and Benninger, L.K., 1977, Geochemistry of atmospheric radon products: Annual Review of Earth and Planetary Science, v. 5, p. 227-255.

U.S. Army Corps of Engineers, 1980, General investigation study, San Leandro Bay, California--Reconnaissance report: San Francisco District, 36 p.

Van Straaten, J.M.J.V., and Kuenen, Ph.H., 1958, Tidal action as a cause of clay accumulation: Journal of Sedimentary Petrology, v. 28, no. 4, p. 406-413.