UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# HOLOCENE SEDIMENTATION IN RICHARDSON BAY, CALIFORNIA

By

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This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards and stratigraphic nomenclature.

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Abstract: Examination of foraminifers, diatoms, ostracodes, clay mineralogy, and sediment-size variation from 9 borehole sites along the salt-marsh margins of Richardson Bay reveals a record of gradual infilling of fine-grained estuarine sediments. Over the past 10,000 years this area was transformed from a V-shaped Pleistocene stream valley to a flat-floored arm of the San Francisco Bay estuary.

A radiocarbon date obtained from a basal peat overlying nonmarine alluvial sand near the town of Mill Valley indicates that stable salt-marsh vegetation was present in the northwestern arm of Richardson Bay 4600 ± 165 years ago and agrees within error limits with a Holocene sea-level curve developed by Atwater, Hedel, and Helley in 1977 for southern San Francisco Bay. The average sedimentation rate over the last 4600 years is estimated to be 0.2 cm/yr for the inner part of the bay.

Comparison of early maps with updated versions as well as studies of marsh plant zonations in disturbed and nondisturbed areas shows that almost half of the marsh in Richardson Bay has been leveed or filled since 1899.

## INTRODUCTION

During the past few millennia, humans have found the environs of Richardson Bay, an arm of San Francisco Bay near the Golden Gate (Fig. 1, 2), to be an excellent place to live, gather food, recreate, and dump their refuse. The known history of human habitation in the area spans at least 2000 years, beginning with the Miwok Indians, whose shell-mound kitchen middens are found at Shelter Hill (Moratto, 1974), and continuing to today's houseboat and apartment dwellers of Sausalito and Mill Valley, California.

The creation of Richardson Bay by flooding of a V-shaped Pleistocene stream valley as the glaciers melted and sea level rose some 350 feet to its present level, epitomizes the latest period of Quaternary history in the San Francisco Bay area. This episode which took place over the past 10,000 years is recorded in sedimentologic, paleontologic, mineralogic, geomorphologic, and geochronologic evidence present in the bay.

## PHYSICAL SETTING

Richardson Bay is bounded on the southeast at its junction with San Francisco Bay by a submarine scarp that has a relief of 18 m (Carlson and others, 1970). This dropoff gives Richardson Bay the appearance in longitudinal section of a submarine hanging valley overlooking Raccoon Strait (Fig. 2) and tends to prevent coarse-grained sediments from being delivered into the mouth of Richardson Bay from San Francisco Bay. The exact depth to bedrock at the scarp edge is unknown, but a bedrock map of central San Francisco Bay (Carlson and McCulloch, 1970) suggests that the

Pleistocene valley floor at the site of Richardson Bay met the Central Valley drainage at a level that may have been as much as 60 m below the present bay floor.

Coyote and Widow Reed Creek enter the northwestern arm of Richardson Bay. These creeks have probably contributed only a small percentage of the sediment in the study area (Means, 1965), although no information on precise streamload capacities for these two drainage areas is available.

U.S. Coast and Geodetic Survey charts of San Francisco Bay indicate that the tidal currents moving through Raccoon Strait reach a maximum bayward velocity of 4 km/hr during floodtide and a maximum seaward velocity of 5 km/hr during ebbtide. During the same periods in the tidal cycle, currents flowing into Richardson Bay reach a maximum floodtide velocity of 0.7 km/hr and move toward the Golden Gate at a maximum rate of 0.9 km/hr during ebbtide. Thus suspended sediments are introduced into the outer parts of Richardson Bay and transported to its interior by floodtides, where quiet waters allow settling to take place (Means, 1965).

## SEDIMENTATION AND PALEOENVIRONMENTAL DATA

Before the post-Wisconsin rise in sea level, "Richardson Valley" drained the rugged and steeply sloping hillsides of the Marin Peninsula. A profile of this Pleistocene stream channel (approximated by the bedrock surface encountered in boreholes and by acoustical reflection data, (Fig. 3) indicates a thalweg slope of between 20 to 25 m/km in Richardson Bay. The modern channelway gradient for Richardson Bay varies from 1 to 13 m/km (Means, 1965). Gravel and cobbles cored by engineers of the

California Department of Highways from strata directly overlying bedrock indicate the presence of buried stream-channel deposits. These deposits are now overlain by 37 m of estuarine sediments near station B (Figs. 1, 3).

The use of a piston coring device at 9 borehole sites (Connor, 1975) along the shoreline of Richardson Bay enabled recovery of 108 core samples (Fig. 1). The greatest percentage of sediment sizes fall into the silt and clay range (2 to 62 mm diameter, Table 1) which is characteristic of most San Francisco Bay sediment (Means, 1965). The Folk and Ward sorting values for each of the samples indicate extremely poorly sorted silt and clay particles. Pestrong (1965) attributes poor sorting in San Francisco Bay sediments to the very small diameters of the grains which, when they are finally deposited in tital flat and salt marsh environments, makes them uneffected by reworking via currents. Both estuarine and fluvial intervals encountered in 4 of the 9 borehole sites contain different suites of clay minerals. Estuarine sediments contain smectite, but no vermiculite in the intervals studied. Alluvial sediments, on the other hand, were vermiculite-rich but contained no component of smectite.

A distinct Holocene fauna composed of foraminifers, diatoms, ostracodes, and other invertebrates found in the cored sediment was divisible into three biofacies: Marsh (brackish water conditions), Upper Tidal Flat to Intertidal (fully marine conditions), and Neritic (fully marine deeper water conditions) (Table III). Most foraminifers representative of brackish water conditions in San Francisco Bay have arenacaous tests formed by the agglutination of sand grains onto a chitinous external covering. The low pH, in this organic-rich reducing environment, discriminates against the preservation of foraminifers with calcareous tests. Environments with increasing water depth and salinity are characterized by species of foraminifers with hyaline calcareous tests such as Elphidium incertum obscurum and Ammonia beccari.

## Sedimentation Rates

Since the time of the sea's initial encroachment into the Golden Gate approximately 10,000 years ago (Atwater and others, 1977), sediment has been accumulating at the southeast end of Richardson Bay at an estimated average rate of 0.4 cm/yr based on the present thickness of sediment overlying the bedrock near station C (Figs. 1, 3) and on a postulated time for the advancing shoreline in this locality. Using the sea-level curve reported by Atwater and others (1977), the estimated time for the onset of estuarine conditions at station B (Fig. 1) near the present site of Richardson Bay Bridge is roughly 9000 years ago. The sedimentation rate at station B since then has averaged 0.4 cm/yr based on subsurface data from the California Department of Highways. A 4600-year-old, 31-cm-thick basal peat horizon at station A (Fig. 1) indicates that sedimentation rates in the inner part of the bay near Mill Valley, California have averaged 0.2 cm/yr over the last 4600 years. The lower sedimentation rate for station A relative to the sedimentation rates for stations B and C for 9000 and 10,000 years ago to the present respectively, reflects in part the constraints placed on the amount of sediment accumulation that is possible, given the changing sea level. At station A, the average sea-level rise has been approximately 0.15 to 0.2 cm/yr over the past 4600 years allowing an accumulation of approximately 9.5 m of sediment. At station B, the average sea-level change has been roughly 40 m over a 9000 year period, an amount that agrees with the 0.4 cm/yr sedimentation rate (Table 4). Using $^{137}Cs$ levels in surface samples collected from central Richardson Bay, historic sedimentation rates as high as 0.4 cm/yr have been estimated by Doug Hammond (Geology Department, University Southern California, oral communication, 1979). These rates may reflect the onset of landfill projects with the increase of major town developments around Richardson Bay in the late 1800s, which provide an additional sediment source to the bay proper.

## An Early Holocene Shifting Sediment Site

The amount of silt and clay that was available for deposition in Richardson Bay during early Holocene time may have been affected by changes in the location of the arrested saline wedge or so-called bottom-current density null zone. The null zone is defined as the area within the estuarine system where the saline wedge of seawater directed into the estuary and seaward moving river surface currents have equal and opposite effects, so that the mean nearbottom current velocity is zero (Hansen, 1965, and Keulegan, 1966). Because of the density difference between river water and seawater in estuaries, the seawater constantly tends to flow landward beneath the net seaward flow of less dense, lower salinity surface water (Fig. 4). Postma (1967) found that high concentrations of suspended matter of "turbidity maxima" were often located near the saltwater-freshwater interface or null zone. Simmons (1955) found the null zone to be the area in an estuary of most rapid sediment accumulation.

Historically floods on the Sacramento River, one of the main tributaries to San Francisco Bay, have pushed the null zone seaward (Peterson and others, 1975). The flood of 1862 was an extreme example. River currents at the Golden Gate were not reversed by the tides for 10 days, and the surface water there was entirely fresh (Young, 1929). During this flood, the location of the null zone may have been near the mouth of Richardson Bay. Conversely, during the drought of 1976-1977 in California, the volume of fresh water flowing seaward via the Sacramento River was greatly reduced, thereby allowing the null zone to penetrate further upestuary (Matthai, 1979). Sediment accumulation sites are thus created or abandoned as a result of this migrating saline wedge.

A post-Pleistocene sea-level rise undoubtedly caused the null zone to migrate from its Pleistocene position west of the Golden Gate to the mouth of Richardson Bay and then further upestuary to the San Pablo Bay region (Fig. 2). In early Holocene time, the mouth of Richardson Bay probably bordered the winter and (or) summer site of the null zone where sediment accumulating near Raccoon Strait may have been transferred into outer Richardson Bay by tidal currents.

The 30 m thickness of estuarine mud in outer Richardson Bay as seen between stations B and C (Fig. 3, Table IV) may be linked to the position of the system's saline wedge sediment source 7000 to 9000 years ago. As sea level continued to rise, the null zone migrated into San Francisco Bay proper toward San Pablo Bay, which effectively transferred the sediment accumulation site so that its silts and clays no longer had direct access into Richardson Bay.

## Historic Sedimentation

In order to understand historic changes in the areal extent of marshland in Richardson Bay, the elevations and zonations of three marsh plants were measured so that modern distributions could be compared with data collected by the U.S. Coast and Geodetic Survey in the 1850's. California cordgrass (Spartina foliosa), perennial pickleweed (Salicornia virginica), and annual pickleweed (Salicornia europaea)* each have different tolerances to the amount of daily submersion time produced by the tides (Hind, 1952). Each tend to grow at elevations within the salt marsh that are most suitable to their individual limitations; Salicornia virginica and Spartina foliosa preferring the lowermost elevations within the marsh.

Three sites located within two different saltmarsh areas were selected for study. In Manzanita Marsh (Fig. 1), sites 1 and 2 occur in an area that was established after 1850 (Nichols and Wright, 1971). Bayward portions of this section of marsh are the most recent as indicated by 1968 USGS air photographs (GS-VBZJ, 1-19 and 1-20). Nichols and Wright's compilation map of work done by the U.S. Coast and Geodetic Survey in the 1850s indicates that Manzanita Marsh encompasses an area of roughly 0.27 $km^2$ (Table V). This marsh expanded further after 1968 in the vicinity of Richardson Bay Bridge, when the bridge was widened to accommodate the increasing flow of commuter traffic from Marin County into San Francisco. This addition of concrete support piers and readjustment of California State Highway 1 under the bridge disturbed the marshland in this area

*Taxonomy follows Munz and Keck (1959).

and provided new unvegetated surfaces for the saltmarsh community to colonize.

Alto Marsh (site 3, Fig. 1) has remained largely pristine since the 1850s. The log of a borehole into Alto Marsh (Fig. 6) shows a buried tidal-marsh peat about 9.5 m beneath the present marshland surface which indicates the existence of a salt marsh at this site 4600 ± 165 years ago (R. M. Pardi, Radiocarbon Laboratory, Queens College, New York, written communication, 1978).

The principal landform in both Manzanita and Alto marshes (Fig. 5) is a planar surface near high-tide level between mean-tide level and mean higher high water. At Alto marsh this planar surface is at the same elevation as mean higher high water and is colonized almost exclusively by perennial pickleweed (*Salicornia virginica*). At Manzanita marsh the planar surface is much closer to the elevation of mean-tide level and is colonized by both species of *Salicornia* as well as *Spartina foliosa*.

Despite possible leveling errors, which can include the natural settling of benchmark sites and errors in extrapolating tidal datums from the nearest tidal gauging station (Atwater and others, 1979), a 0.4 m difference in the elevation between the planar surfaces in Manzanita and Alto marshes can be measured (Fig. 5). This difference can be attributed to the contrast in age and difference in the amount of human disturbance between the two marshes.

Alto Marsh has had more than 120 years for its topographic features and plants to adjust to the daily effects of the tides. On newly emergent tidal flats the stems of *Spartina foliosa* act as a series of baffles which effectively slow oncoming tidal waters, inducing sedimentation. The near high-tide planar surface now occupied by Salicornia virginica was created in this way, resulting in a bayward migration of the Spartina foliosa to new tidal flat surfaces.

Landfill and construction projects along bayward portions of Manzanita Marsh on the other hand, have created disturbances in sedimentation and plant colonization. Not enough time has elapsed at sites 1 and 2 in Manzanita Marsh for the three plant species present to trap and redistribute sediment to create the different elevational zones most favorable for their growth. Their zonation pattern is thus quite different from that of Alto Marsh.

## CONCLUSIONS

Rising sea level 10,000 years ago created a migrating null zone and caused the transformation of a Pleistocene steep-sided sand and gravel-bottomed stream valley into the mud-filled shallow estuary now known as Richardson Bay. Estuarine sedimentation, controlled by rising sea level, reached initial rates of 0.4 cm/yr. As the rate of sea level rise declined approximately 7500 years ago, this sedimentation rate decreased to 0.2 cm/yr.

The gradient of "Richardson Valley" changed with increasing encroachment of sea water from a late Pleistocene incline of 20 to 25 m/km to the present gradient of 1 to 13 m/km. Pleistocene alluvial sediments at the present estuarine/terrestrial boundary near Mill Valley, are overlain by marsh peats and tidally deposited clays which mark the arrival of sea water at this northwestern arm of Richardson Bay 4600 $\pm$ 165 years b.p.

Landfill projects in Richardson Bay after 1850 resulted in localized patches of disturbed marsh. Salt marsh plant species, tolerant of limited submersion periods during daily innundation by tides, have not yet re-adjusted to their optimum zonal distributions in these disturbed areas which can be located in transect surveys of the marshlands.

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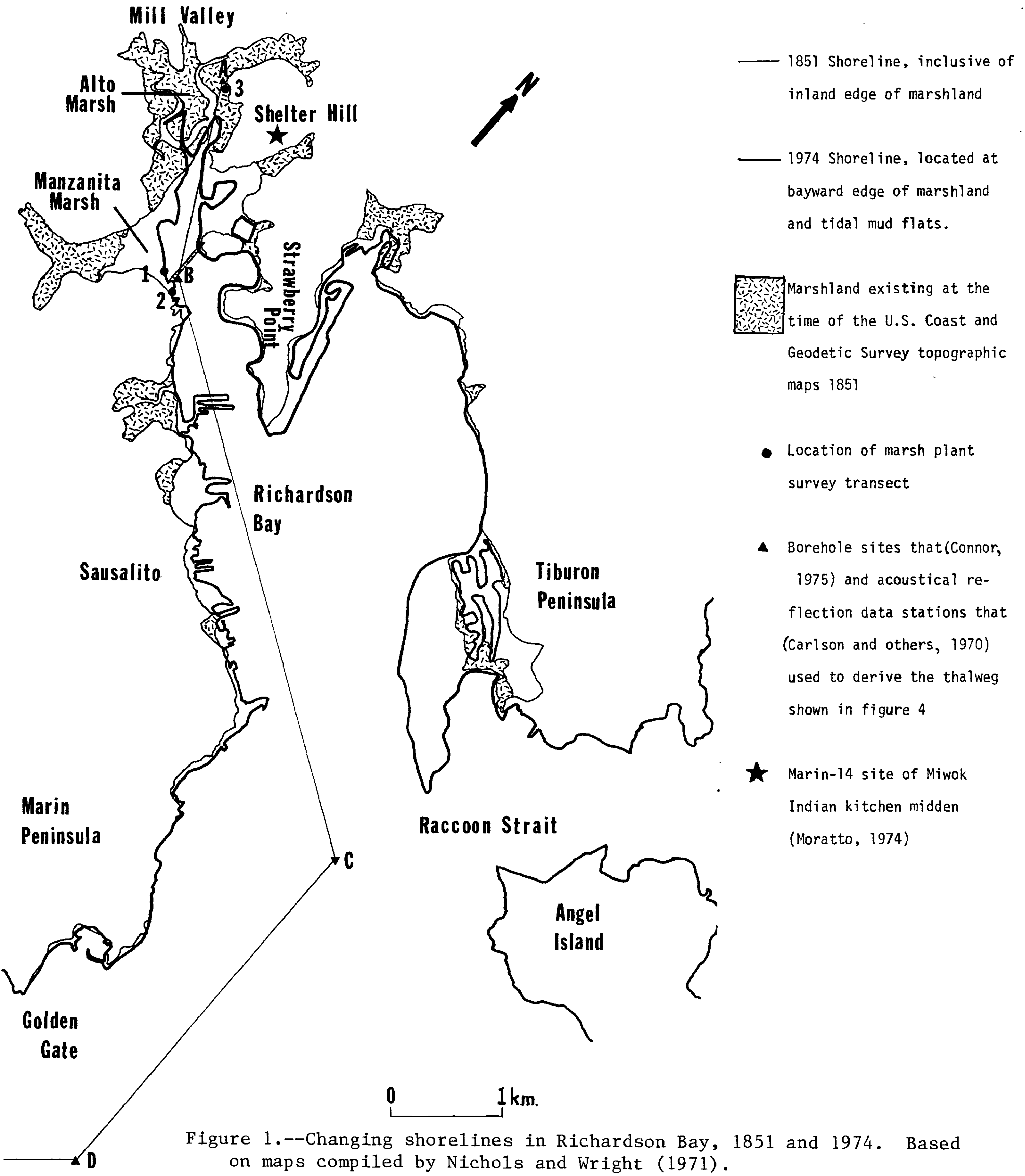



Figure 1.--Changing shorelines in Richardson Bay, 1851 and 1974. Based on maps compiled by Nichols and Wright (1971).

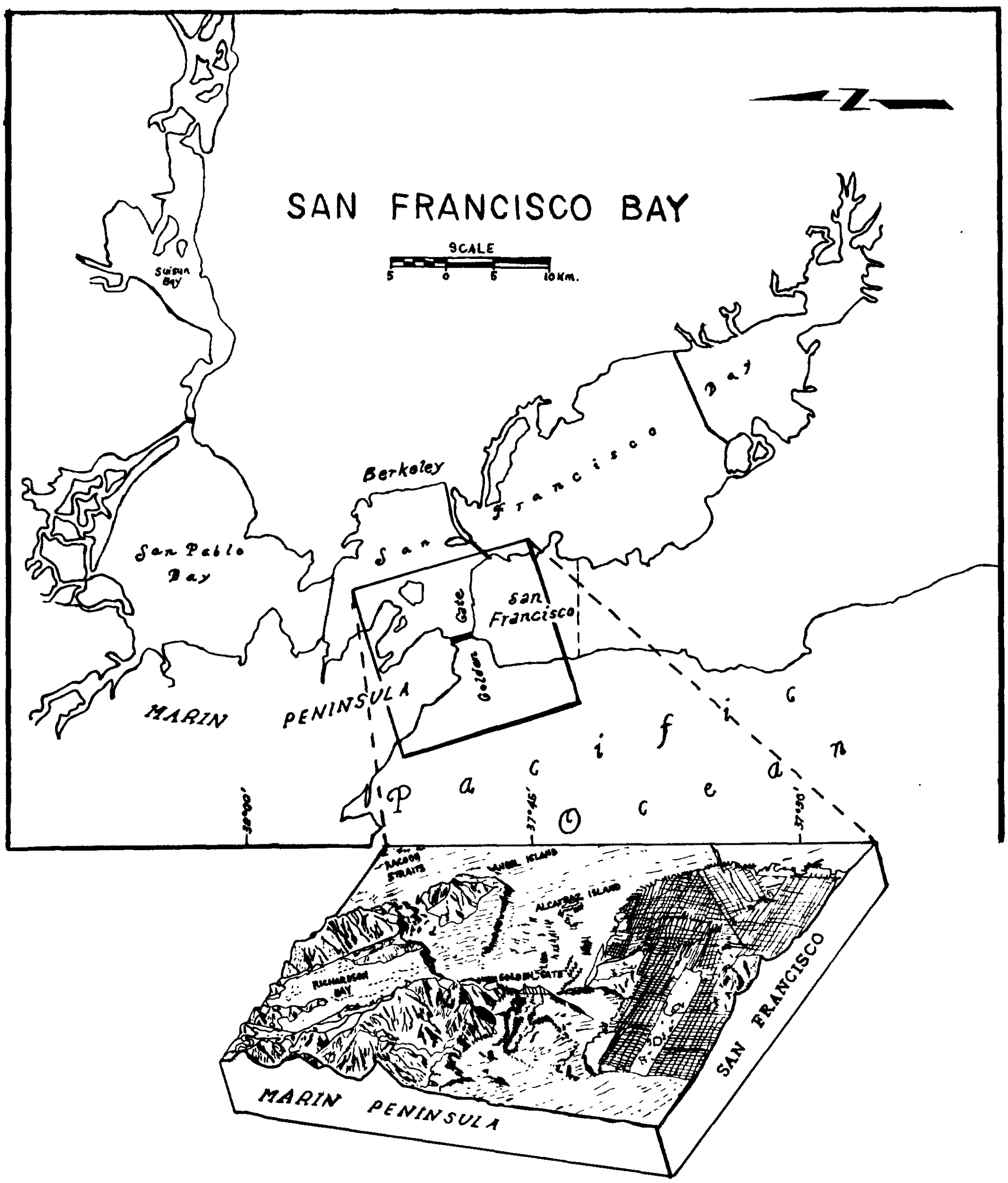



Figure 2.--Index map of the San Francisco Bay region with a block diagram showing the prominent scarp that borders the southeast end of Richardson Bay (after Carlson and others, 1970).

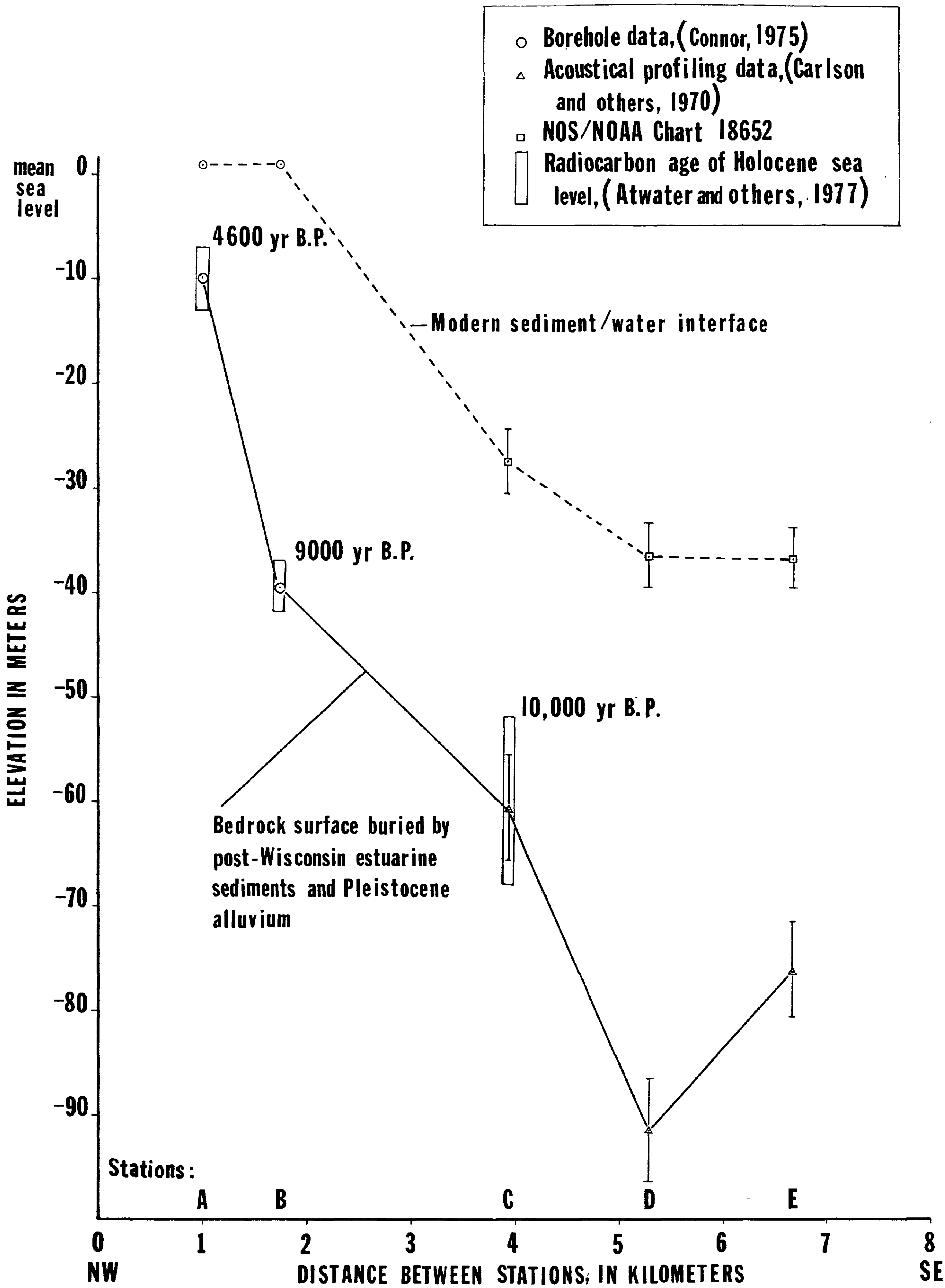



Figure 3.--Profile of the Pleistocene stream channel surface, now buried by post-Wisconsin estuarine sediments in Richardson Bay. All vertical error bars show approximate uncertainties in the elevation of the thalweg.

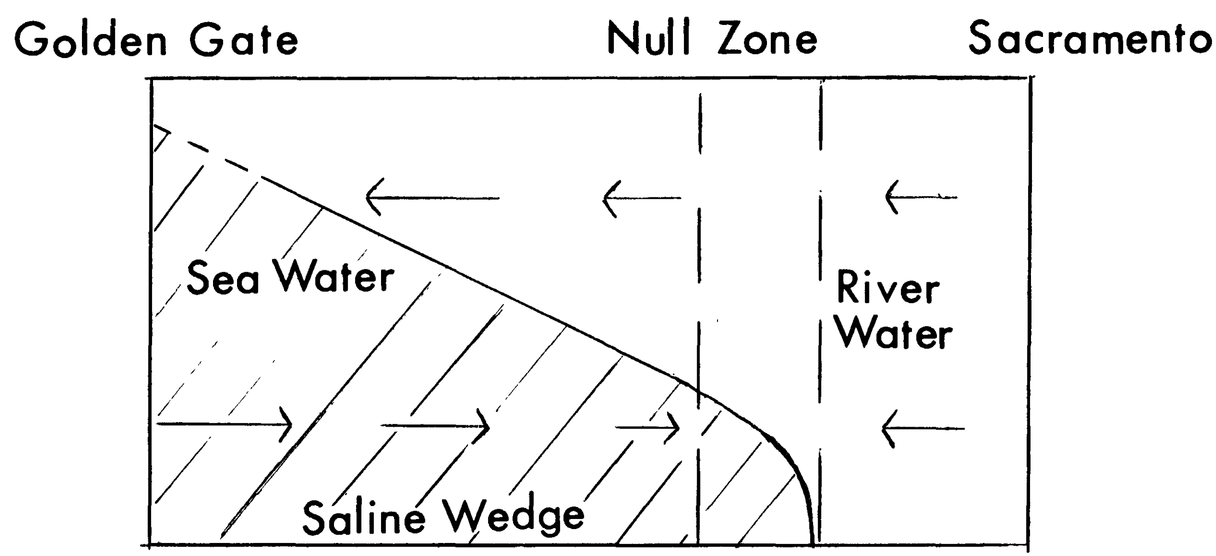



Figure 4.--Schematic representation of the relative position of the null zone within an estuary system; arrow lengths indicate relative current strength. After Peterson and others (1975) and Keulegan (1966).

VERTICAL DISTRIBUTION OF MARSH PLANTS

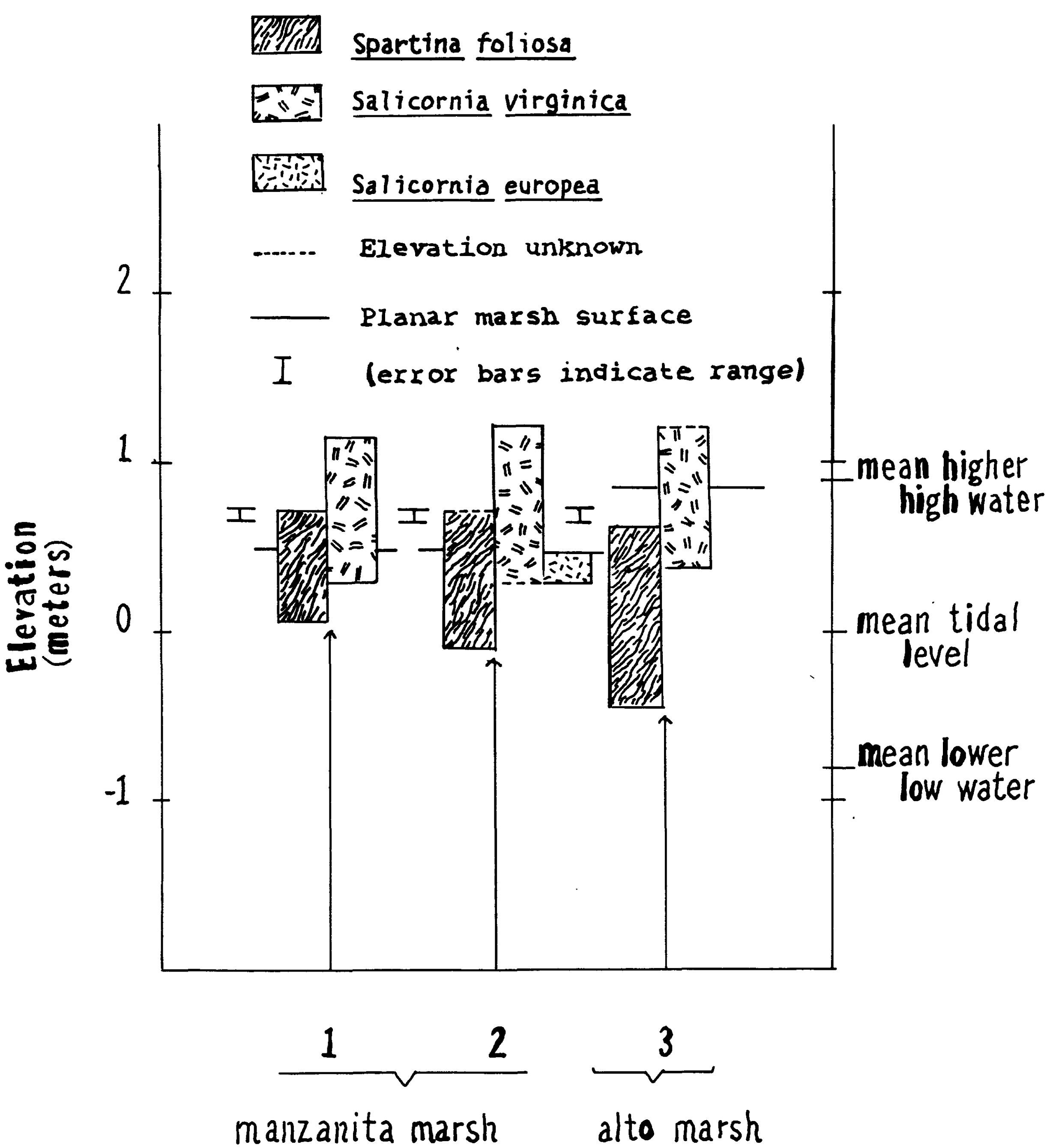
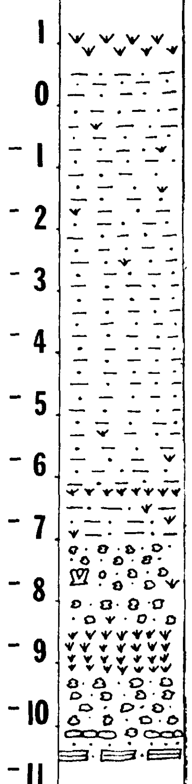



Figure 5.--Leveling for profile 1 by Atwater and Hedel (1976, pl. 3). Atwater and Kilpatrick leveled profile 2 (Atwater and others, 1979). The bench mark for both of these profiles was R 481, with an established leveling error of ± 0.05 m. Profile 3 was leveled by Atwater and the author using RV 223. This bench mark was located on a concrete pier adjacent to the Northwestern Pacific Railroad tracks and may have changed elevation by as much as 0.1 m owing to shifting or settlement of the gravel supporting the tracks.

LOG OF BOREHOLE C-9

(Located near the intersection of the Northwestern Pacific Railroad tracks with East Blithedale Avenue in Mill Valley, California, Station A, Fig. )



| Elevation m | Color (Munsell System) | Particle Size | Microfossils | Plant Fragments | Probable Environment of Deposition |
|---|---|---|---|---|---|
| 1 to 0 | Top -N2/0<br>Middle -2.5Y4/2<br>Bottom -5Y4/1 | Silty clay | Trochammina inflata<br>Haplophragmoides subinvolutum<br>Miliammina fusca<br>Haplophragmoides columbiensis e.<br>Elphidium clavatum | Surface plants<br>Salicornia v.<br>Abundant roots in place | Salicornia Marsh |
| -1 to -2 | | | | Scarce detrital plant fragments < 2mm | Mud flat |
| -3 to -4 | 5Y4/1 | | Trochammina inflata<br>ostracodes | very rare detrital plant fragments < 2mm | |
| -6 to -7 | | Sandy clay<br>Silty clay | ostracodes<br>Trochammina inflata<br>molluscan fragment | rare to locally common detrital plant fragments ≤ 4mm | |
| -8 to -9 | 25Y4/2 | Sandy clay with small pebbles(3 mm) | Spartina seed<br>Trochammina inflata<br>Salicornia calyx | Very abundant in-place roots incl. large ribbed Spartina rhizome | Tidal marsh |
| -10 to -11 | 5Y3/1<br>5Y4/1 | Pebbly sandy clay with some lithic fragments (graywacke?) | | Very rare roots<br>No roots | Upland Creek |

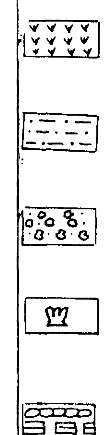



Figure 6.--Log of Borehole C-9 from Alto Marsh.

Figure 7.--Alto Marsh at the northwest end of Richardson Bay. Mount Tamalpais and the city of Mill Valley, Calif., lie just to the right of center.

Figure 8.--Egrets stand along the boundary between newly colonizing California cordgrass (Spartina foliosa) and emergent pickleweed (Salicornia virginica).

Table 1.--Particle Size Distribution of Richardson Bay Sediment

| Sampling Interval (m below surface) | 62 m % Sand | 2-62 m % Silt | 2 m % Clay | Mean (Folk and Ward, 1957) | Sorting (Folk and Ward, 1957) | Station Location (see Connor, 1975) |
|---|---|---|---|---|---|---|
| 0.0-0.23 | 0.2 | 63.6 | 36.2 | 18.2 | 20.7 | Station 2 |
| 4.65-4.88 | 0.6 | 65.6 | 33.8 | 17.2 | 20.1 | Station 3 |
| 9.83-10.06 | 0.2 | 73.5 | 26.3 | 13.9 | 16.6 | Station 6 |
| 10.14-10.37 | 0.2 | 59.6 | 40.2 | 19.8 | 22.0 | Station 6 |
| 22.33-22.56 | 0.3 | 60.5 | 39.2 | 19.4 | 21.8 | Station 7 |

Analyzed samples from various intervals using a hydrophotometer (Connor, 1975)

Table 2.--Clay Mineralogy

| | Chlorite | Smectite | Vermiculite | Mica |
|---|---|---|---|---|
| Marine Samples (2) | 20% | 53% | 0% | 26% |
| Nonmarine Samples (4) | 26% | 0% | 27% | 27% |

The six samples reported in the table above were chosen as representatives of the fluvial-estuarine boundary in four different localities in Richardson Bay. They were glycolated and analyzed with the help of Julius Schlocker, U.S. Geological Survey. Clay mineral percentages were determined by calculating the areas under each peak on the X-ray diffractogram, as described by Pierce and Siegel (1969). Percentages were then averaged for each clay mineral for the marine and nonmarine samples respectively.

Table 3.--Faunal constituents of Holocene sediments in Richardson Bay

March Biofacies (brackish water conditions)

Foraminifera

*Ammotium salsus* (Cushman and Bronniman)

*Elphidium incertum obscurum* (Williamson)

*Jadamina polystoma*, Bartenstein and Brand

*Trochammina inflata* (Montagu)

*Trochammina inflata macresens*, Brady

Diatoms

*Campylodiscus noricus*

Marsh plant remains

*Distichilis spicata* -- seeds

*Salicornia virginica* -- seeds, calyx

*Spartina foliosa* -- rhizomes

Ostacodes

*Cyprideis beaconensis* (LeRoy)

(Table 3--continued)

| Upper tidal-flat to subtidal biofacies (fully marine conditions) |
| --- |
| Foraminifera |
| *Ammonia beccari tepida* (Cushman) |
| *Bigenerina irregularis* (Phelger and Parker) |
| *Elphidium clavatum*, Cushman |
| *Elphidium incertum obscurum* (Williamson) |
| *Haplophragmoides subinvolutum*, Cushman and McCulloch |
| |
| Diatoms |
| *Arachnoidiscus ehrenbergii*, Bailey |
| *Campylodiscus noricus* |
| *Pleurosigma normanii*, Ralfs |
| |
| Invertebrates |
| *Balanus sp.* -- barnacle |
| *Littorina scutalata*, Gould -- gastropod |
| *Macoma balthica* (Linne) -- bivalve |
| *Mytilus sp.* -- bivalve |
| *Psephidia lordi* (Baird) -- bivalve |
| *Ostrea sp.* -- bivalve |

(Table 3.--continued)

| Neritic biofacies (fully marine conditions) |
| --- |

Foraminifera

*Ammonia beccari tepida* (Cushman)

*Bigenerina irregularis* (Phelger and Parker)

*Elphidiella hannai* (Cushman and Grant)

*Elphidium poeyanum*, (d'Orbigny)

*Elphidium tumidum*, *Natland*

*Haplophragmoides Columbiensis evolutum*, Cushman

Diatoms

*Actinoptychus undulatus* (Bailey)

*Coscinodiscus sp.*, Ehrenberg

*Isthima nervosa*, Kutzing

*Surirella sp.*, Turpin

Table 4.--Sedimentation Rates for Three Stations in Richardson Bay

| STATION | ONSET OF ESTUARINE CONDITIONS (years b.p.) | AVERAGE SEDIMENTATION RATE (cm/yr) |
|---|---|---|
| C | 10,000 | 0.4 |
| B | 9,000 | 0.4 |
| A | 4,600 | 0.2 |

Table 5.--Changes in Marshland Area in Richardson Bay, 1851-1974

| | Area ($Km^2$) | | | Rate ($km^2$/yr) |
|---|---|---|---|---|
| | 1851 | 1974 | 1951-1974 | 1851-1974 |
| Total area of marshland in Richardson Bay | 2.31 | 1.37 | ......... | ......... |
| Net increase in marshland in Richardson Bay | .... | .... | ......... | 0.006 |
| Growth of new marshland in Manzanita Marsh | .... | .... | 0.27 | ......... |
| Average rate of marshland increase | .... | .... | ......... | 0.002 |
| Average rate of marshland decrease | .... | .... | ........ | 0.008 |