UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Distribution of seed plants with respect to tide levels and water salinity in the natural tidal marshes of the northern San Francisco Bay estuary, California

By

Brian F. Atwater and Charles W. Hedel

OPEN-FILE REPORT

76 - 389

NOTE: This report is preliminary and has not been reviewed for conformity with Geological Survey standards and nomenclature.

Menlo Park, California

May 3, 1976

CONTENTS

Page

TABLES

ILLUSTRATIONS

[Plates in separate folder]

ABSTRACT

Shoaling of subtidal and intertidal mud flats has permitted tidal marshes to spread across large marginal areas of the San Francisco Bay estuary during the past several thousand years. By 1850 A.D. the tidal marshes of the estuary, including those of the Sacramento - San Joaquin Delta, covered an area nearly twice as large as the area of open water. Nearly 95 percent of these marshes have been diked or filled during the past 125 years.

Species distributions along leveled transects at six tidal marshes indicate that elevation and water salinity are the principal ecological factors that control the distribution of seed plants in the remaining natural tidal marshes of the northern San Francisco Bay estuary. Marsh surfaces situated near mean tide level are populated by robust monocotyledons (e.g., *Spartina foliosa*, *Scirpus californicus*), whereas surfaces situated near high-tide levels support dicotyledons and a few small monocotyledonous species (e.g., *Salicornia virginica*, *Distichlis spicata*). Marshes near the seaward end of the estuary are typically occupied by 10-15 salt-tolerant species (e.g., *Spartina foliosa* *Salicornia virginica*), whereas marshes at the riverward end of the estuary are inhabited by as many as 30 species, most of which are known to tolerate moderate or small amounts of salt (e.g., *Scirpus* spp., *Phragmites communis*, *Typha latifolia*).

INTRODUCTION

Purpose

More than half of the remaining tidal marshes in California are situated in the San Francisco Bay estuary (MacDonald and Barbour, 1974, p. 212-213). Despite widespread concern for the preservation of these wetlands, published information about their flora is scanty. Quantitative data on the distribution of seed plants in natural tidal marshes has been gathered only in the southern arm of the estuary (Hinde, 1954; Rountree, 1973, p. 203-225). Published information about marshes fringing the northern part of the estuary is restricted to general descriptions of marshes in the lower reaches of the estuary (Howell, 1970; Felice, 1954), and to topical studies of diked marshes that are located in the upper reaches of the estuary and are subjected to seasonal inundation for duck clubs (George, Anderson, and McKinnie, 1965; Mall, 1969; Rollins, 1973). The purpose of this study is to make a reconnaissance of the distribution of the principal seed plants of natural tidal marshes of the northern San Francisco Bay estuary. This information has several applications:

(1) The regional distribution of the principal tidal marsh plants appears to be controlled by water salinity. Our records of the present plant distribution permit comparative studies at some future date, when water salinities may differ because of proposed reductions in the volume of fresh-water inflow to the estuary (California Dept. of Water Resources, 1960).

(2) The distribution of the principal seed plants within each marsh is mainly controlled by the elevation of the surface on which they grow. Knowledge of the elevation ranges of these plants permits detection of historic uplift or subsidence of marsh surfaces from changes in marsh flora (e.g., Gilbert, 1908, p. 81-87; Jepson, 1908; Harvey, 1966, p. 22).

(3) The elevation and salinity ranges of living tidal marsh plants can be used to interpret former sea levels and water salinities from plant fossils contained in core samples of tidal marsh deposits. These interpretations permit determination of shoreline changes and vertical crustal movement during the recent geologic past (e.g., Redfield, 1972; Atwater, Hedel, and Helley, unpub. data).

Acknowledgements

This study has been supported as part of the U.S. Geological Survey's efforts to identify earthquake hazards in the San Francisco Bay region. We are grateful to several private land-owners and the California Department of Parks and Recreation for granting access to their land. Steve Talco drafted plates 3-8, and Virgil Frizzell reviewed the manuscript.

METHODS OF STUDY

The elevation ranges of tidal marsh angiosperms were investigated by noting the distribution of seed plants along leveled transects across six tidal marshes. These marshes were chosen to range in location from the lower to upper reaches of the estuary (fig. 1) in order to determine the effect of water salinity on floral populations. None of the marshes are pristine because all have undergone changes during the past 125 years that can be attributed to the activities of man. As much as possible, however, we visited marshes that have changed very little according to the following criteria (table 1): (1) minimal disruption of natural water circulation by levees and ditches, particularly at the landward edge of the marsh; (2) existence of at least part of the marsh surface prior to 1850; and (3) minimal historic land subsidence due to withdrawal of ground water or natural gas. In addition, we tried to investigate tidal marshes that displayed transitions from high-marsh to low-marsh flora and from low-marsh flora to barren mudflats. These transitions were poorly represented at the marshes near Petaluma, Fairfield, and Bethel Island, where the marsh surfaces drop abruptly into natural and man-made sloughs (table 1; plates 5, 7, 8).

A topographic profile of each of the six tidal marshes was constructed from spot elevations located at horizontal intervals of 30 m or less (plates 3-8). Elevations were referenced to the nearest bench mark of the National Geodetic Survey (formerly, the U.S. Coast and Geodetic Survey). We used the most recent leveling data for these monuments, obtained from the early 1950's to the late 1960's, to minimize errors due to historic land subsidence (see explanatory notes on plates 3-8). The bench-mark elevations were transferred across each

Figure 1.--The northern San Francisco Bay estuary, where fresh water from about 25 percent of California, including most of the Sierra Nevada (snow-capped range at top), meets sea water from the Pacific Ocean. As used in this report, northern San Francisco Bay estuary refers to the open-water and tidal-marsh areas between the Golden Gate and the eastern edge of the Sacramento-San Joaquin Delta, thereby including San Pablo Bay, Carquinez Strait, Suisun Bay, and the Sacramento-San Joaquin Delta (see index map). Triangles on the index map show the approximate locations of the natural tidal marshes at which we have studied the elevation ranges of seed plants (plates 3-8). Infrared photograph courtesy of National Aeronautics and Space Administration (Ames Research Center, Moffett Field, Calif.), taken April 14, 1972, at an altitude of 20,000 m(65,000 ft) from a U-2 aircraft.

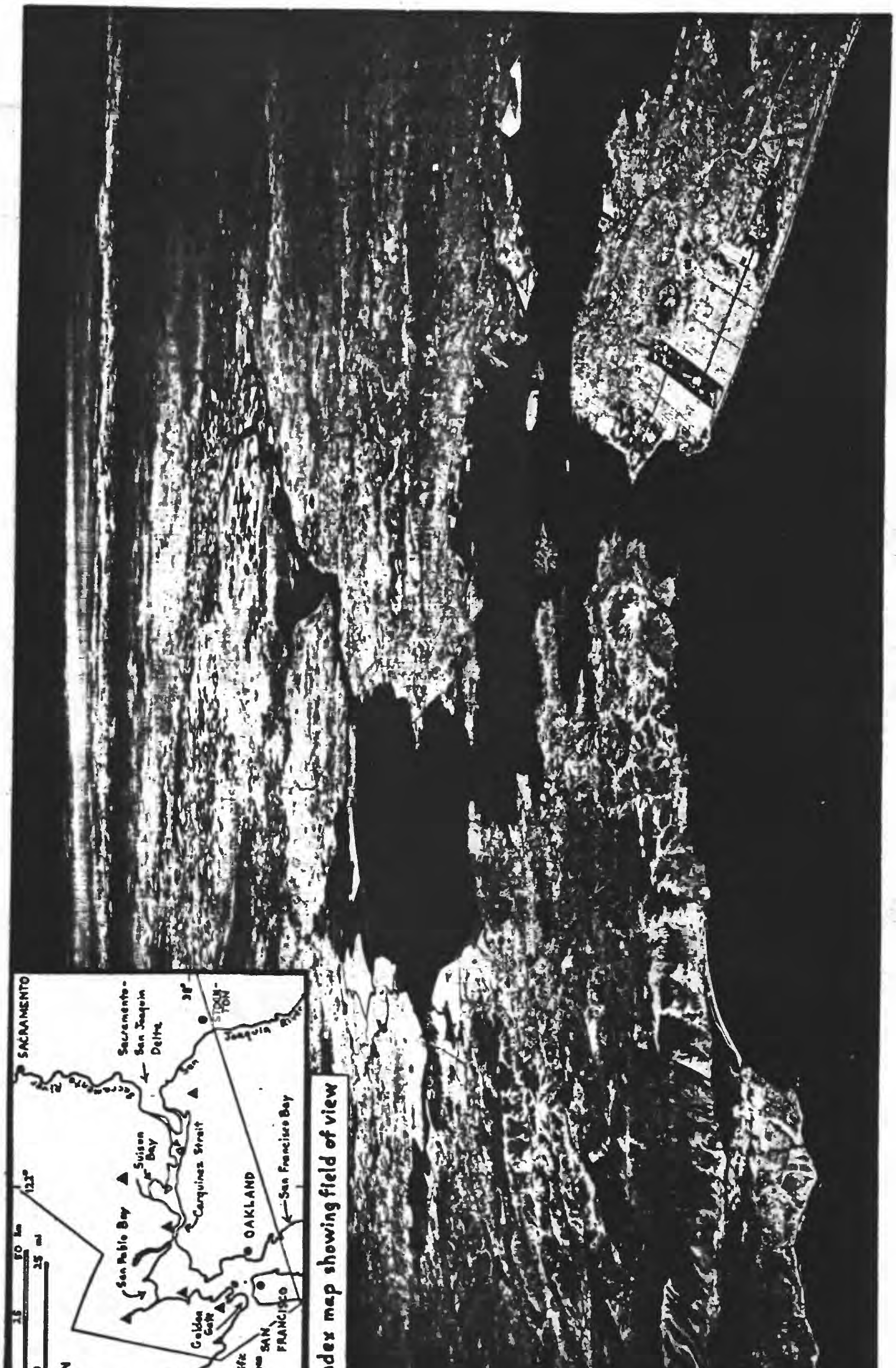

Index map showing field of view
SACRAMENTO
Sacramento-San Joaquin Delta
Suisun Bay
Carquinez Strait
San Pablo Bay
OAKLAND
San Francisco Bay
Golden Gate
SAN FRANCISCO
Pacific Ocean
Joaquin River
122°
38°
N

Table 1.--Natural and man-made features along levelled transects at six tidal marshes

Feature	Richardson Bay (plate 3)	Point San Pedro (plate 4)	Petaluma (plate 5)	Benicia (plate 6)	Fairfield (plate 7)	Bethel Island (plate 8)
Landward edge	Railroad embankment	Natural hillside	Natural hillside	Natural hillside, slightly damaged by dumping of concrete blocks	Levee (north end of transect); natural hillside (south end transect)	None
Bayward edge	Gentle slope into tidal mud flat	Gentle slope into tidal mud flat	Steep slopes into man-made and natural channels	Gentle slope into tidal mud flat	Steep slopes into natural channels	Steep slopes into man-made and natural channels
Age (Nichols and Wright, 1971)						
Present ca. 1850	No	Yes	Yes	Yes	Yes	Not known
Growth since 1850	Entire marsh younger than ca. 1900 (Connor, 1975)	≤300 meters horizontal, ≤2 meters vertical	Negligible except 0.2 meters vertical at northeast end of transect	≤100 meters horizontal, ≤1.5 meters vertical	Negligible	Not known
Historic land subsidence (unpub. data from U.S. Coast and Geodetic Survey)	None known	None known	None known	None known	0.1 m (1934-1964)	0.1 m (1951-1964)
Man-related features on marsh surface near transect	None	Several drainage ditches	Anomalously high surface near northeast end of transect, probably caused by sediment accumulation due to construction of artificial channel and duck ponds	Power transmission lines	Cattle several levees and drainage ditches	None

tidal marsh with a tripod-mounted self-aligning level and a stadia rod. Individual readings had a maximum uncertainty of ± 1 cm. Closure of the leveling surveys at the Point San Pedro and Petaluma marshes (plates 4, 5) indicated cumulative errors of about 5 cm.

The percentage abundance of seed plants was visually estimated at each point of known elevation within a circle having a radius of about 1 m. Most species distributions were determined along a single transect line at each marsh, but the elevation ranges of some plants were investigated elsewhere if these plants were represented inadequately along the transect.

Identification and nomenclature follow Mason (1957) with the exception of nomenclature for *Salicornia virginica*, which follows Munz (1959). Voucher specimens of the principal seed plants in each marsh have been submitted to the herbarium of San Jose State University. Additional specimens will be collected during the summer of 1976.

HISTORICAL AND ENVIRONMENTAL SETTING

OF THE TIDAL MARSHES

History of the estuary and its tidal marshes

Events prior to the arrival of European settlers

Ice ages and sea-level changes.--About 20,000 years ago the site of the San Francisco Bay estuary was roamed by bison, horses, ground sloths, and camels. The combined San Joaquin and Sacramento Rivers flowed through the Golden Gate and met the Pacific Ocean near the Farallon Islands, about 50 km (30 mi) west of San Francisco. There was no San Francisco Bay estuary.

The absence of an estuary 20,000 years ago can be attributed to glacial ice. Between 15,000 and 25,000 years ago, sheets of ice up to several kilometres in thickness covered large land areas in northern latitudes, including most of Canada and the northernmost United States (e.g., New England and the Puget Sound area). In addition, smaller alpine glaciers occupied many high mountain areas. The volume of this land ice in excess of what ice remains today was about 50 million km^3 (Flint, 1971, p. 76-79), equal to enough water to change the level of the ocean surface by at least 100 m (330 ft.).[1/] Thus, sea level 20,000 years ago was significantly lower than present levels because of the large quantity of water that was locked into land ice. This low stand of the sea left the entire site of the San Francisco Bay estuary above sea level, so the estuary did not exist.

[1/] 50 million km^3 is also enough ice to make a solid cylinder with a length equal to the distance from the earth to the moon and with a diameter equal to the length of the San Mateo-Hayward bridge.

About 15,000 years ago the ice in northern latitudes began to melt. Sea level rose as the melt water returned to the oceans, and by 10,000 years ago the rising sea entered the Golden Gate and began to spread inland (plate 1). During the next 2,000 years the shoreline advanced across gently sloping areas as rapidly as 35 m (116 ft) per year in response to a sea-level rise of about 2 cm (0.8 in) per year. This rate of sea-level rise decreased as the ice sheets disappeared, and has averaged only 0.1-0.2 cm (0.04-0.08 in) per year during the past 6,000 years (fig. 2).

The inception of the present San Francisco Bay estuary coincides in time with the first widespread human habitation of the western hemisphere (table 2), but other estuaries occupied the vicinity of the present one long before man settled in the Americas. Study of core samples collected by the California Division of Bay Toll Crossings suggests that estuaries and stream valleys have alternately occupied the vicinity of the present estuary during the past one million years (Atwater, Hedel, and Helley, unpub. data; Bruce Ross, oral commun., 1976). Presumably the stream valleys record seaward migrations of the shoreline accompanying low stands of the sea, and the estuaries indicate landward migrations of the shoreline accompanying high stands of the sea, such as we have today. Like the sea-level rise of the past 15,000 years, these sea-level fluctuations were probably related to waxing or waning of glacial ice.

Figure 2.--Sea-level changes during the past 10,000 years at the site of the southern arm of the San Francisco Bay estuary. The thick line shows that sea level has risen more than 50 m (164 ft) during the past 10,000 years. Most of this change in water level occurred between 8,000 and 10,000 years ago, when sea level rose about 2 cm (0.8 in) per year in response to melting of large continental ice sheets in northern latitudes. The rate of sea-level rise decreased more than ten-fold as these ice sheets disappeared, and has averaged only 0.1-0.2 cm (0.04-0.08 in) per year during the past 6,000 years. The boxes represent uncertainties in the ages and elevations of former sea levels. Most of this sea-level data is based on the radiocarbon ages and elevations of fossil tidal marsh plants. Like their modern counterparts, these plants probably grew very close to coeval sea levels. The plant fossils were collected from core samples that were originally obtained by the California Division of Bay Toll Crossings for bridge foundation studies. This illustration is adapted from the sea-level curve of Atwater, Hedel, and Helley (unpub. data).

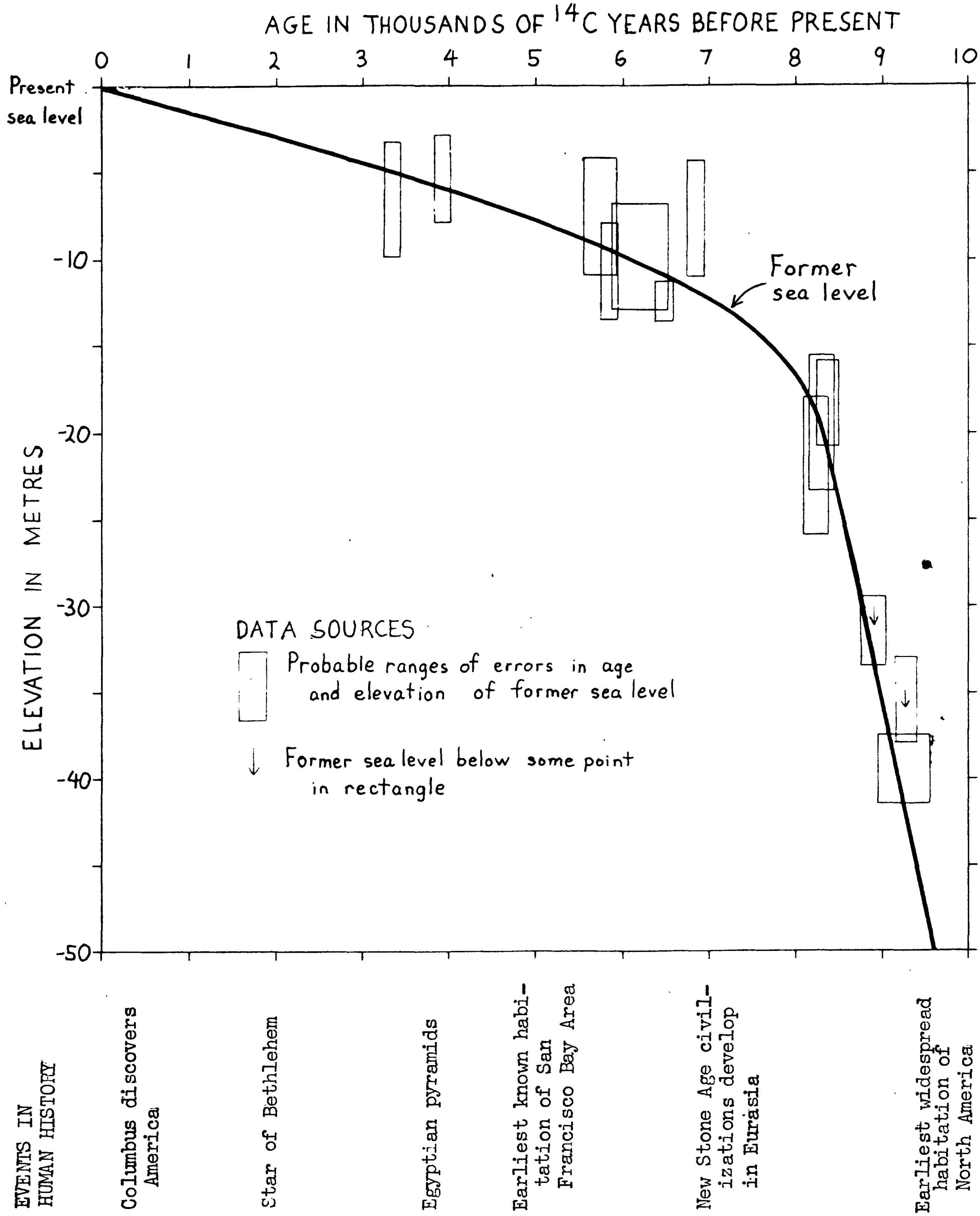

AGE IN THOUSANDS OF 14C YEARS BEFORE PRESENT
0
1
2
3
4
5
6
7
8
9
10
Present sea level
-10
-20
-30
-40
-50
ELEVATION IN METRES
Former sea level
DATA SOURCES
Probable ranges of errors in age and elevation of former sea level
Former sea level below some point in rectangle
EVENTS IN HUMAN HISTORY
Columbus discovers America
Star of Bethlehem
Egyptian pyramids
Earliest known habitation of San Francisco Bay Area
New Stone Age civilizations develop in Eurasia
Earliest widespread habitation of North America

Table 2.--A time scale for the history of the earth and for the history of the San Francisco Bay area

Time		Historical event	
Years before present	Date in calendar year[1/]	Events of global significance	Events in the San Francisco Bay area
4,500,000,000	January 1	Formation of the earth	
600,000,000	November 12	First abundant life	
225,000,000 - 65,000,000	December 13-26	Age of dinosours	Formation of oldest rocks in bay area
65,000,000 - present	December 26-31	Age of mammals	
4,000,000 - 2,000,000	December 31 4-8 p.m.	First hominids (man-like creatures) appear in East Africa	
1,000,000 - present	December 31, 10-12 p.m.	Man continues to evolve Global climatic fluctuations cause numerous ice ages	Estuaries situated in the vicinity of San Francisco Bay during warm intervals between ice ages
100,000	December 31 11:47 p.m.	Appearance of our species, _Homo Sapiens_	Large estuary at the site of San Francisco Bay (Atwater, Hedel, and Helley, in preparation)
25,000 - 15,000	December 31 11:57-11:58 p.m.	Most recent major ice covers Canada, New England, Seattle, Yosemite Valley; sea level is about 100 m (330 ft) below its present elevation	Site of San Francisco Bay is a broad valley populated by incense cedar, ground sloths, bison, and native horses; the combined San Joaquin and Sacramento Rivers flow through the Golden Gate and meet the Pacific Ocean about 50 km (30 mi) west of San Francisco
10,000	December 31	Ice sheets melt in	The present San

	11:59 p.m.	northern latitudes and water returns to ocean basins, causing a rapid rise in sea level First widespread human habitation of North America	Francisco Bay estuary begins to form as the rising ocean enters the Golden Gate (plate 1)
0 - 3,000	December 31 last 36 seconds	Most of recorded human history	Tidal marshes spread across tidal mud flats (fig. 3; table 1)
200	December 31 1 1/2 seconds before midnight	American revolution	Spaniards arrive
0 - 125	December 31 last 3/4 second	Birth of present generations	95 percent of historic tidal marshes diked or filled (plate 2, fig. 4)

1/ The time span of the earth's history, 4.5 billion years, is converted into a single calendar year starting January 1 (4.5 billion years ago) and ending at the last moment of New Year's Eve (today).

Growth of tidal marshes.--Rates of submergence (sea-level rise; see fig. 2) and rates of sediment accumulation have largely controlled the areal extent of the tidal marshes of the modern San Francisco Bay estuary since its inception 10,000 years ago (Atwater, Hedel, and Helley, unpub. data). Borehole investigations near San Francisco suggest that tidal marshes 8,000-10,000 years ago were restricted to narrow, discontinuous bands at the margins of the expanding estuary. Probably the sea-level rise of 2 cm (0.8 in) per year exceeded the long-term rate of sediment accumulation on the marsh surfaces, so the marshes were ultimately submerged and relocated toward newly inundated land areas.

The rate of sediment accumulation began to equal or exceed the rate of submergence in many parts of the estuary as the rate of sea-level rise decreased more than ten-fold between 8,000 and 6,000 years ago. This shift created conditions more favorable to growth and maintenance of tidal marshes. For example, the thickness and radiocarbon ages of peat in the western part of the San Joaquin - Sacramento Delta indicate that tidal marshes have persisted in this area for the past 6,000 years (Schlemon and Begg, 1973, p. 262), the marsh surfaces building vertically to keep pace with slowly rising sea levels. Nevertheless, most of the extensive modern marshes around the lower reaches of the estuary did not become established until several thousand years after the inception of a slow rate of sea-level rise. The youth of these marshes is indicated by the thinness of tidal-marsh deposits immediately beneath their surfaces. Mud flat sediments typically underlie the veneer of tidal-marsh deposits, suggesting that the marshes grew by spreading across tidal mud flats (fig. 3). The lag between the inception of a slow rate of sea-level rise and the growth of these marshes probably represents the time required for accumulating sediments to construct mud flat surfaces that were high enough to support tidal-marsh vegetation.

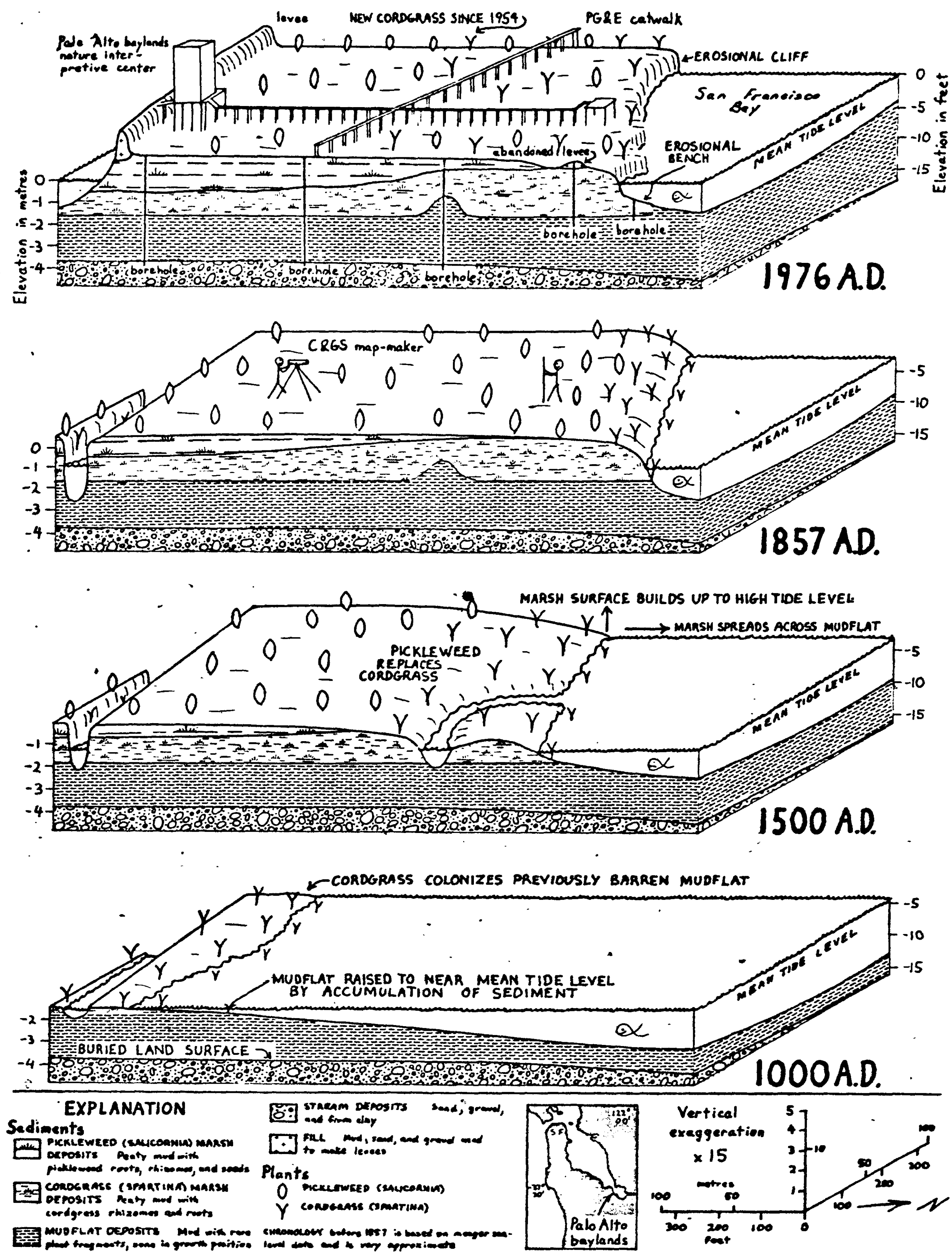
Events subsequent to the arrival of European settlers

Topographic surveys by the U.S. Coast Survey in the 1850's portray the San Francisco Bay estuary as it must have appeared during the California Gold Rush (plate 2). Collectively, the tidal marshes and open-water bays covered an area slightly larger than the state of Rhode Island (fig. 4). The area of tidal marsh was much greater than the area of open water, with the Delta marshes comprising about 40 percent of the total area and the marshes of San Francisco, San Pablo, and Suisun bays accounting for another 25 percent.

About 95 percent of the historic tidal marshes of the San Francisco Bay estuary have been diked or filled since the California Gold Rush (fig. 4; plate 2). Most of the Delta marshes have been leveed for farming. Crops have also been raised on many diked marshes fringing Suisun Bay, but most of the diked wetlands in this area are now used for duck-hunting and livestock-grazing (Mall, 1969, p. 8). The majority of the marshes of San Pablo and San Francisco bays have been converted into grazing and farming lands, salt evaporation ponds, sites for residential and industrial structures, garbage dumps, and transportation facilities.

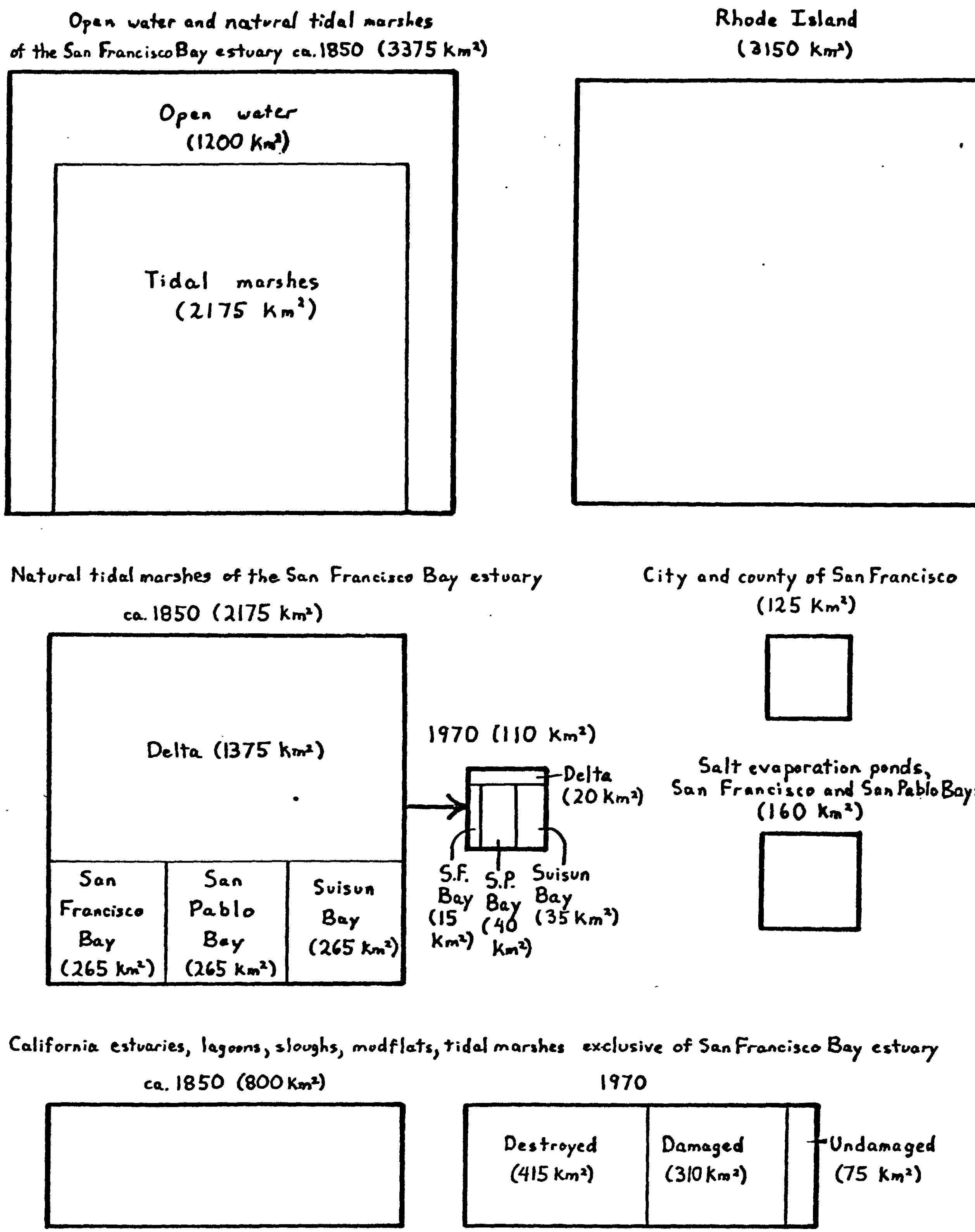
Figure 3.--History of a tidal marsh near Palo Alto. Many of the tidal marshes fringing the southern arm of the San Francisco Bay estuary have spread across previously barren mud flats during the past several thousand years. This horizontal growth is evidenced by the presence of mud-flat sediments beneath a cap of marsh deposits. Within the cap of marsh deposits, cordgrass-marsh deposits commonly underlie pickleweed-marsh deposits, so the marsh surfaces have also grown vertically from about mean tide level (cordgrass-marsh deposits) to high tide level (pickleweed-marsh deposits). Both horizontal and vertical marsh growth are recorded by sediments beneath a tidal marsh near Palo Alto (top diagram). The earliest estuarine sediments at the site of this marsh cover a fossil land surface that was inundated by the bay about 2,000-3,000 years ago. These sediments lack roots in growth position and appear to represent a mud-flat environment. Sediments ultimately accumulated on the mud flat more rapidly than sea level rose, so that by about 1,000 A.D. the mud-flat surface began to reach the level at which cordgrass can grow (bottom diagram). By 1500 A.D. the cordgrass had probably advanced across additional mud-flat areas. Concurrently, the cordgrass trapped enough sediment to build the early-formed parts of the marsh surface to near the average level of the higher of the daily tides, and pickleweed replaced cordgrass in these high-marsh areas. Horizontal and vertical growth probably continued in this manner and produced the tidal marsh that was mapped by the Coast and Geodetic Survey in 1857. Marsh growth has been arrested and even reversed

during the past 125 years (top diagram): cordgrass has replaced pickleweed on much of the high marsh surface (Harvey, 1966, p. 22), and the bayward edge of the marsh has been eroded as much as 100 feet (30 metres) (Nichols and Wright, 1971). These changes can be partly explained by a 3-foot (1 metre) relative rise in sea level at the Palo Alto baylands during the past 50 years, most of which was caused by land subsidence due to excessive pumping of groundwater (Poland, 1971).



levee
NEW CORDGRASS SINCE 1954
PG&E catwalk
Palo Alto baylands nature interpretive center
EROSIONAL CLIFF
San Francisco Bay
abandoned levee
EROSIONAL BENCH
MEAN TIDE LEVEL
borehole
1976 A.D.
Elevation in metres
Elevation in feet
CRGS map-maker
1857 A.D.
MARSH SURFACE BUILDS UP TO HIGH TIDE LEVEL
MARSH SPREADS ACROSS MUDFLAT
PICKLEWEED REPLACES CORDGRASS
1500 A.D.
CORDGRASS COLONIZES PREVIOUSLY BARREN MUDFLAT
MUDFLAT RAISED TO NEAR MEAN TIDE LEVEL BY ACCUMULATION OF SEDIMENT
BURIED LAND SURFACE
1000 A.D.
EXPLANATION
Sediments
PICKLEWEED (SALICORNIA) MARSH DEPOSITS Peaty mud with pickleweed roots, rhizomes, and seeds
CORDGRASS (SPARTINA) MARSH DEPOSITS Peaty mud with cordgrass rhizomes and roots
MUDFLAT DEPOSITS Mud with rare plant fragments, none in growth position
STREAM DEPOSITS Sand, gravel, and from clay
FILL Mud, sand, and gravel used to make levees
Plants
PICKLEWEED (SALICORNIA)
CORDGRASS (SPARTINA)
CHRONOLOGY before 1857 is based on meager sea-level data and is very approximate
Palo Alto baylands
Vertical exaggeration x 15
metres
feet

Figure 4.--Historic changes in the area of natural tidal marshes of the San Francisco Bay estuary, and comparisons with the areas of other natural features and jurisdictions. Data sources: marshes and open water of San Francisco Bay estuary ca. 1850 after Gilbert (1917, p. 75, 78); marshes of San Francisco Bay estuary ca. 1970 from grid measurements of a 1:125,000-scale compilation of natural tidal marshes based on a slightly smaller scale map by San Francisco Bay Conservation and Development Commission (1969) and on 1:24,000 topographic maps; salt ponds after Jackson (1969, p. 152); and California wetlands exclusive of San Francisco Bay estuary after California Coastal Zone Conservation Commissions (1975, p. 39). See plate 2 for a map that shows historic changes in area and distribution of natural tidal marshes.


Open water and natural tidal marshes of the San Francisco Bay estuary ca. 1850 (3375 Km²)
Open water (1200 Km²)
Tidal marshes (2175 Km²)
Rhode Island (3150 Km²)
Natural tidal marshes of the San Francisco Bay estuary ca. 1850 (2175 Km²)
Delta (1375 Km²)
San Francisco Bay (265 Km²)
San Pablo Bay (265 Km²)
Suisun Bay (265 Km²)
1970 (110 Km²)
Delta (20 Km²)
S.F. Bay (15 Km²)
S.P. Bay (40 Km²)
Suisun Bay (35 Km²)
City and county of San Francisco (125 Km²)
Salt evaporation ponds, San Francisco and San Pablo Bays (160 Km²)
California estuaries, lagoons, sloughs, mudflats, tidal marshes exclusive of San Francisco Bay estuary
ca. 1850 (800 Km²)
1970
Destroyed (415 Km²)
Damaged (310 Km²)
Undamaged (75 Km²)

Many of the remaining natural tidal marshes have probably been altered by man-induced changes of sea level, sedimentation, and water salinity. A man-induced rise in sea level relative to land has affected a large part of the southern arm of the estuary during the past 50 years. This sea-level rise has been caused by subsidence of the land surface accompanying excessive withdrawal of ground water, and it measures about 1 m (3 ft.) near Palo Alto and 2 m (6 ft.) near Alviso (Poland, 1971) (By comparison, tide records at San Francisco indicate that sea level has risen only 0.15 m (0.5 ft.) during the past 125 years (James Dowden, oral commun., 1975), apparently because of natural land subsidence or world-wide sea-level changes). Land subsidence near Palo Alto and Alviso due to ground-water withdrawal may be partly responsible for erosion of the bayward edges of marshes in these areas and for local replacement of pickleweed (Salicornia; a high-marsh plant) by cordgrass (Spartina; a low-marsh plant) (fig. 3; Harvey, 1966, p. 22). However, the bayward edges of many of these same marshes also sustained considerable erosion during the last half of the nineteenth century (Gilbert, 1917, p. 21-22), prior to known overdraft of ground water.

Unnaturally large amounts of sediment have been supplied to the San Francisco Bay estuary during the past 125 years because of hydraulic gold mining in the Sierra Nevada (Gilbert, 1917), urbanization (Knott, 1973), and dumping of dredge spoils. Accumulation of sediments derived from these sources may largely account for rapid historic growth of many marshes in the northern part of the estuary, such as a marsh near Point San Pedro which has advanced as much as 300 m (1,000 ft.) across previously barren mud flats since the California Gold Rush (plate 4; Nichols and Wright, 1971).

Historic changes in the water salinity of the San Francisco Bay estuary are likely because the fresh-water inflow from the Sacramento - San Joaquin drainage has been cut in half since 1900 by water-diversion projects (California Dept. of Water Resources, 1960). The response of plant communities in tidal marshes to this diversion of fresh water is unknown.

Native vegetation of the tidal marshes

Most of the major plants of the modern tidal marshes of the San Francisco Bay estuary appear to be native. Table 3 is a partial list of these plants. A more complete and better documented list could be prepared following a careful study of plant fossils from prehistoric tidal marsh deposits. As far as we know, this kind of investigation has not yet been attempted.

Table 3.--Some tidal marsh plants believed to be native to the San Francisco Bay estuary.

Plant	Evidence	Authority
Spartina foliosa (cordgrass)	(1) Described in California in 1840	(1) Mobberley (1956, p. 500) Beetle (1947, p. 336)
	(2) Borehole investigations indicate that a robust salt-marsh grass colonized mud flats near Palo Alto 125-1,000 years ago (fig. 3)	(2) Atwater and Hedel (this report)
Distichlis spicata (saltgrass)	Widespread in coastal California	Beetle (1947, p. 336)
Phragmites communis	(1) Widespread in coastal and central California and throughout the world	(1) Beetle (1947, p. 336)
	(2) Fossil remains are possibly present in peats of the San Joaquin-Sacramento Delta	(2) Wier (1950, p. 39)
Scirpus spp. (bulrushes and tules)	(1) *S. robustus*, *S. Olneyi*, *S. californicus*, and *S. acutus* are widespread in coastal and/or central California	(1) Mason (1957, p. 309, 317, 323)
	(2) Fossil achenes of *Scirpus* spp. are present in 9,000-year-old tidal-marsh deposits near San Francisco	(2) Atwater, Hedel, and Helley (unpub. data)
Salicornia spp. (pickleweed)	(1) Widespread in coastal California	(1) MacDonald and Barbour (1974, p. 193-196)
	(2) Fossil seeds of *Salicornia* spp. are present in 4,000-year-old tidal-marsh deposits near Hayward	(2) Atwater, Hedel, and Helley (unpub. data)
Unidentified trees and shrubs (Delta marshes only)	Sketches and maps made ca. 1850 show tall trees and shrubs along the banks of the major channels of the San Joaquin-Sacramento Delta. The same documents do not show trees in the tidal marshes around Suisun, San Pablo, and San Francisco Bays.	Ringgold (1852)

Physical environment of the modern tidal marshes

Climate

The climate of the San Francisco Bay region is characterized by mild, wet winters and warm, dry summers. Precipitation is distinctly seasonal, with most occurring from November to March and very little occurring between June and September. Almost all precipitation is in the form of rain.

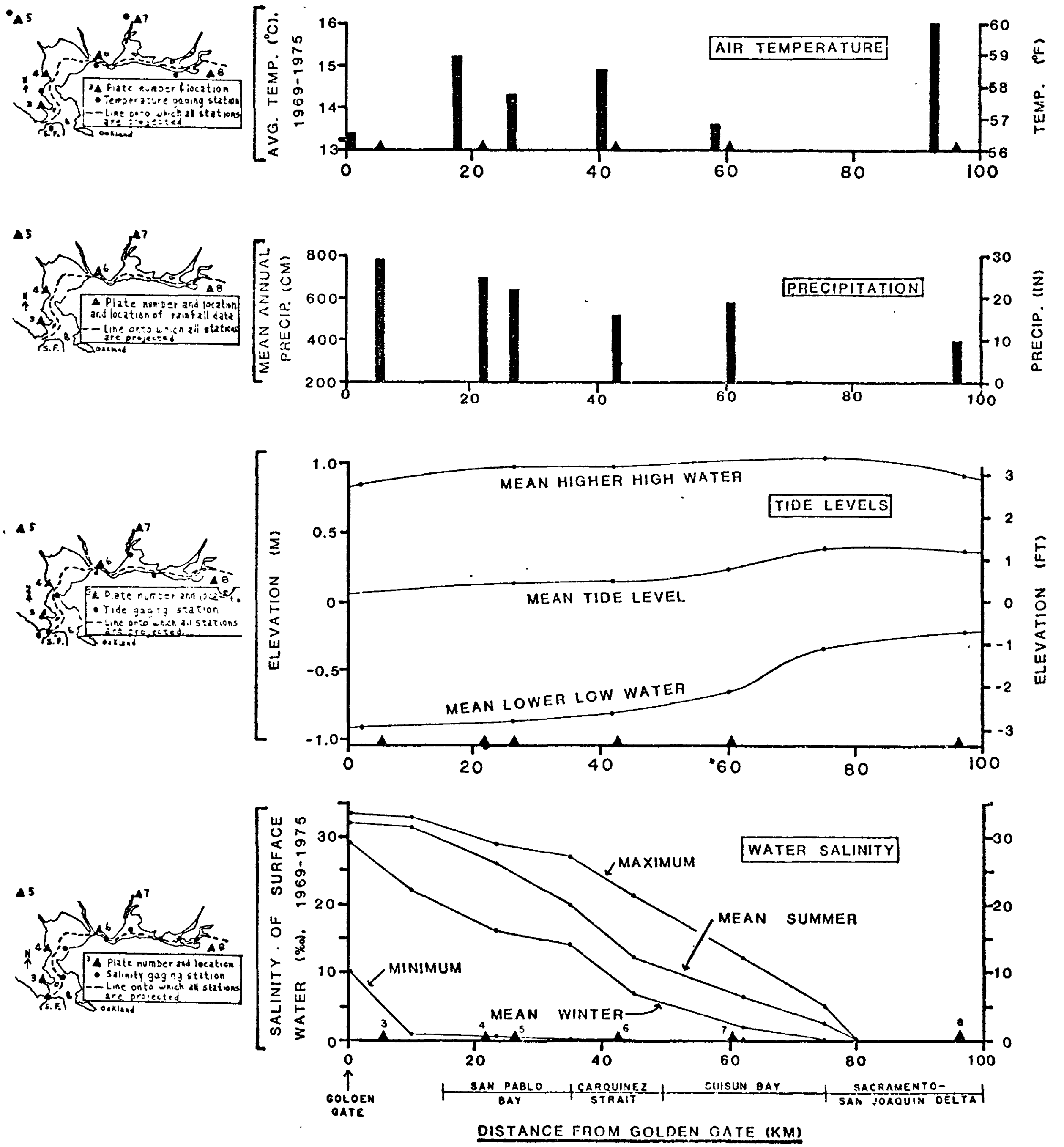
Precipitation and temperature are influenced by elevation, local topography, and proximity to the Pacific Ocean. In general, these factors create slightly cooler and wetter conditions near the Golden Gate than in the Delta region (fig. 5).

Tides

The surface of the San Francisco Bay estuary rises and falls twice daily in response to tides. Successive tides have unequal heights because they include a large diurnal component, which produces a single daily cycle, as well as a semi-diurnal component, which causes two complete cycles each day.

Tide levels within the estuary are influenced mostly by the geometry of the water bodies and by the fresh-water inflow from the Sacramento and San Joaquin Rivers. The effect of geometry is most pronounced in the southern arm of the estuary, where the tidal range varies by nearly two-fold (Homan and Schultz, 1963, p. 712). Fresh-water inflow appears to increase tide levels in the northern part of the estuary because, with respect to a constant datum, the principal

Figure 5.--Variations in water salinity, tide levels, precipitation, and air temperature (y-axes) along a longitudinal profile of the northern San Francisco Bay estuary, extending from the Golden Gate to the western Sacramento - San Joaquin Delta (x-axes). Salinity, tidal, and climatic data from the margins of the estuary are projected onto the longitudinal profile (see index maps). Triangles along the x-axes show the projected locations of tidal marshes at which we have studied the elevation ranges and distribution of tidal-marsh plants. Numbers accompanying the triangles refer to plates 3-8, which show detailed information about these marshes. Data sources: surface-water salinities from Conomos and Peterson (in press); tide levels from National Ocean Survey (1974, and R. Smith, written commun., 1975-1976), given with respect to NGVD (see table 4 for explanation of datums for heights and tide levels); precipitation values at locations of plates 3-8 interpolated from an isoheytal map of the San Francisco Bay region (Rantz, 1971); and air temperature data from U.S. National Climatic Center (1969-1975).


AIR TEMPERATURE
AVG. TEMP. (°C), 1969-1975
TEMP. (°F)
Plate number & location
Temperature gaging station
Line onto which all stations are projected
PRECIPITATION
MEAN ANNUAL PRECIP. (CM)
PRECIP. (IN)
Plate number and location and location of rainfall data
Line onto which all stations are projected
TIDE LEVELS
MEAN HIGHER HIGH WATER
MEAN TIDE LEVEL
MEAN LOWER LOW WATER
ELEVATION (M)
ELEVATION (FT)
Tide gaging station
WATER SALINITY
SALINITY OF SURFACE WATER (‰), 1969-1975
MAXIMUM
MEAN SUMMER
MINIMUM
MEAN WINTER
Plate number and location
Salinity gaging station
Line onto which all stations are projected
S.F.
Oakland
GOLDEN GATE
SAN PABLO BAY
CARQUINEZ STRAIT
SUISUN BAY
SACRAMENTO-SAN JOAQUIN DELTA
DISTANCE FROM GOLDEN GATE (KM)

tidal datums rise 0.2-0.7 m (0.6-2.2 ft) between the Pacific Ocean the Sacramento - San Joaquin Delta (fig. 5; see table 4 for a description of datums for tide levels and heights).

Water salinity

The salinity of water throughout the San Francisco Bay estuary is controlled mainly by the fresh-water discharge of the Sacramento and San Joaquin Rivers (McCulloch, Peterson, Carlson, and Conomos, 1970, p. 3). This fresh-water inflow causes the salinity of the surface water of the estuary to decrease from the Golden Gate to the Sacramento - San Joaquin Delta (fig. 5). Salinity gradients are more complex in the southern arm of the estuary because there is no large fresh-water discharge at its head near San Jose (McCulloch, Peterson, Carlson, and Conomos, 1970, p. 12).

Pronounced seasonal variations in the fresh-water discharge from the Sacramento and San Joaquin Rivers cause migration of the salinity gradient for surface water in the northern part of the estuary (fig. 5; Conomos and Peterson, in press). Peak discharges typically occur between December and June because of rainfall runoff during the winter and melting of the snow pack in the Sierra Nevada during the spring (McCulloch, Peterson, Carlson, and Conomos, 1970, p. 5). Fresh-water inflows are much lower during summer and autumn months.

Table 4.--Datums for tide levels and heights. Sources: National Ocean Survey (1974, p. 164-165) and Shalowitz (1964, p. 48, 62)

Datum	Abbreviation	Definition
Mean higher high water	MHHW	Average height of the higher of the two daily high tides during a 19-year period.
Mean high water	MHW	Average height of all high tides during a 19-year period.
Mean tide level	MTL	Plane halfway between mean high water and mean low water. Also called half-tide level.
Mean low water	MLW	Average height of all low tides during a 19-year period.
Mean lower low water	MLLW	Average height of the lower of the two daily low tides during a 19-year period
Mean sea level	MSL	Average height of the water surface for all stages of the tide during a 19-year period, usually determined from hourly height readings.
National Geodetic Vertical Datum	NGVD	The standard datum for heights across the nation. Formerly called the "U.S. Coast and Geodetic Survey sea-level datum of 1929," and originally determined from sea-level heights at 26 tide stations in the United States and Canada. May differ from local mean sea level, so it is best regarded as an arbitrary datum that happens to be close to sea level.

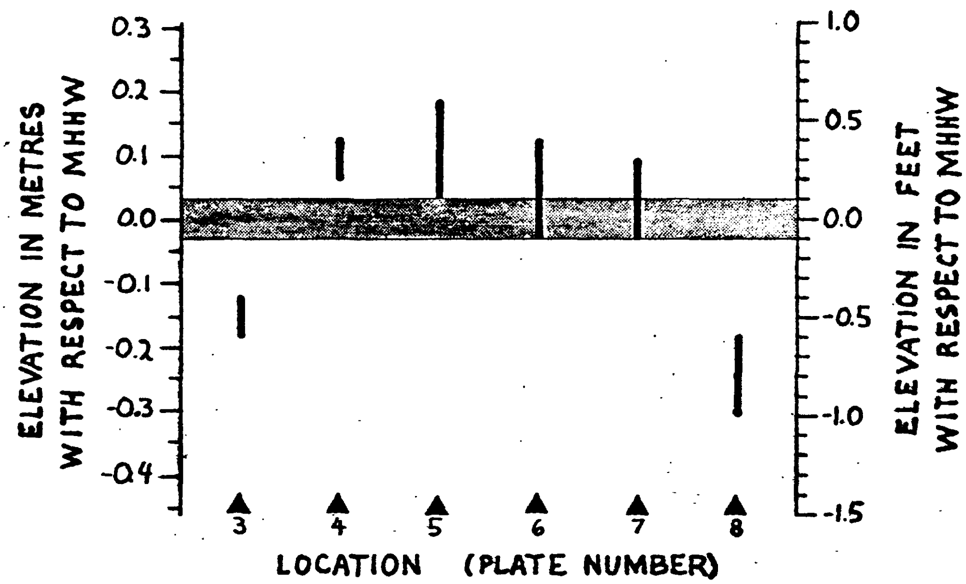
Natural landforms of the tidal marshes

High-marsh surfaces.--The most extensive landforms of the tidal marshes of the San Francisco Bay estuary are flat surfaces situated near high tide levels. Excepting the channels that trench them, these high-marsh surfaces have so little relief (plates 4, 7) that they were used as elevation datums for topographic surveys by the U.S. Coast and Geodetic Survey in the late nineteenth century.

Mature, natural high-marsh surfaces are generally situated 0.0-0.15 m (0.0-0.5 ft) above mean higher high water (MHHW) (fig. 6; plates 4, 6, 7). Higher surfaces (plate 5) are probably due to man-induced sedimentation. Some marsh surfaces formed during this century are characterized by elevations lower than mean higher high water (plate 3), but others have reached mature heights within the past 125 years (plate 4).

The narrow elevation range of the mature, natural high-marsh surfaces with respect to MHHW (fig. 6) suggests that tide levels control the ultimate heights of high-marsh surfaces. The rate of sediment accumulation on marsh surfaces probably declines as the surface builds up to high-water levels because the added height causes a decrease in the frequency of inundation by sediment-laden water. Ultimately the high-marsh surface may reach a stable elevation with respect to tide levels if the reduced sedimentation rate equals the combined rates of erosion (Pestrong, 1972, p. 40) and sea-level rise.

Figure 6.--Elevations of high-marsh surfaces with respect to mean higher high water. Mean higher high water (MHHW) is shown as a band about 6 cm (2.4 in) wide to account for uncertainties in its elevation. The marsh surfaces that are known to have existed ca. 1850 (plates 4-7) are situated at or slightly above MHHW. Some younger surfaces have also reached these levels (plate 4), but others are considerably lower (plate 3). The age of the marsh shown on plate 8 is not known. Parts of the marsh surface portrayed on plate 5 may be anomalously high due to accumulation of sediments dredged from ship channels and duck ponds. See plates 3-8 for the topographic profiles and tide-level data on which this figure is based.



ELEVATION IN METRES WITH RESPECT TO MHHW
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
ELEVATION IN FEET WITH RESPECT TO MHHW
1.0
0.5
0.0
-0.5
-1.0
-1.5
3
4
5
6
7
8
LOCATION (PLATE NUMBER)

Low-marsh surfaces.--The parts of tidal marshes that slope from high-marsh surfaces into tidal mud flats are much less extensive than the high-marsh surfaces (plates 4, 6). The slopes of these low-marsh surfaces in the northern part of the estuary are generally gradual. However, many low-marsh areas in the subsiding parts of the southern arm of the estuary have been reduced to wave-cut cliffs up to 1 m high (fig. 3).

Narrow low-marsh surfaces are also present along the banks of sloughs. Most of these surfaces have been formed by slumping of adjacent high-marsh areas into the sloughs (Pestrong, 1972, p. 33).

Sloughs.--Sloughs provide access for the tidal waters as they flood and drain the marshes. In addition, some sloughs carry the discharges from rivers and creeks. See Pestrong (1965) for discussion of the sloughs in the southern arm of the estuary.

Levees.--Natural levees once lined the major channels of the Sacramento - San Joaquin Delta (Gilbert, 1917, plates 28, 29A). The effect of these levees on tidal inundation of adjacent marshes is unknown, but probably was inhibitory. Some of the trees and shrubs sketched by Ringgold (1852) may have grown on these raised surfaces.

DISTRIBUTION OF SEED PLANTS

Ecological factors

Elevation and water salinity are the principal ecological factors that control the distribution of seed plants in the natural tidal marshes of the northern San Francisco Bay estuary. The elevation of marsh surfaces with respect to tide levels governs the local distribution of marsh plants. In general, robust monocotyledons populate the lowest marsh surfaces, which are submerged by most high tides, whereas dicotyledons and a few species of small monocotyledons inhabit surfaces situated at or above the reach of high tides. The salinity of the water that inundates the marshes determines the regional distribution of plant species and communities. Marshes flooded by nearly undiluted sea water are typically occupied by a small number of salt-tolerant species, whereas marshes served by fresh or brackish water are inhabited by a more diverse community that is dominated by species that typically tolerate moderate to small amounts of salt (table 5; fig 7).

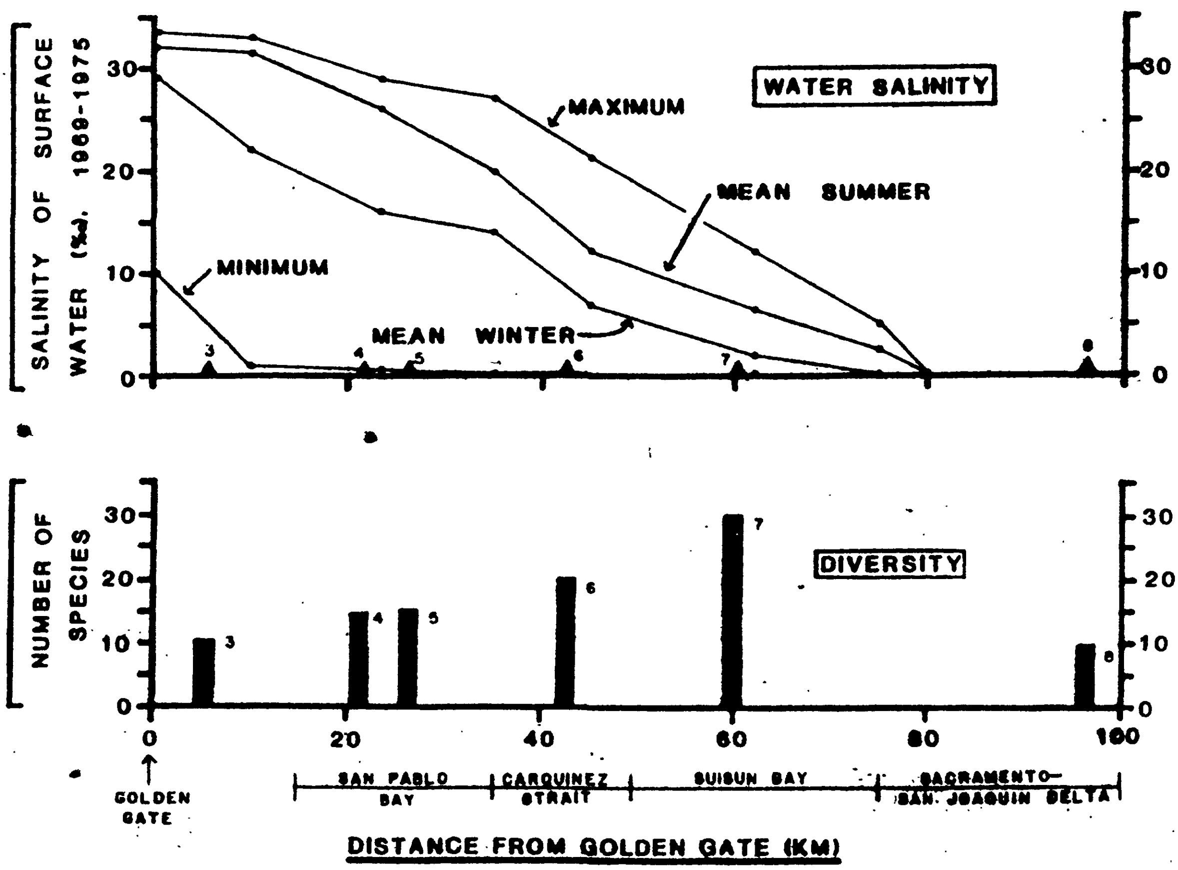
Table 5.--Seed plants found at natural tidal marshes. This list is compiled from field notes as well as from plates 3-8, so it is more complete than the latter. Underlined X's indicate that voucher specimens have been submitted to the herbarium of San José State University, San José, Calif.

Plant name	Richard-son Bay (Plate 3)	Pt. San Pedro (Pl. 4)	Peta-luma (Pl. 5)	Benicia Rec. Area (Pl. 6)	Fair-field (Pl. 7)	Bethel Is. (Pl. 8)
Monocotyledons						
TYPHACEAE						
Typha latifolia				X	X	X
GRAMINEAE						
Distichlis spicata	X	X	X	X	X	
Phragmites communis				X	X	X
Spartina foliosa	X	X	X			
CYPERACEAE						
Scirpus acutus			X			
Scirpus californicus				X	X	
Scirpus californicus?						X
Scirpus Olneyi			X	X	X	X
Scirpus robustus		X	X	X		
JUNCACEAE						
Juncus balticus		X	X	X	X	X

Dicotyledons (see next page)

Plant name	Richard-son Bay (Plate 3)	Pt. San Pedro (Pl. 4)	Peta-luma (Pl. 5)	Benicia Rec. Area (Pl. 6)	Fairfield (Pl. 7)	Bethel Is. (Pl. 8)
CHENOPODIACEAE						
Atriplex patula	X	X	X	X	X	
Atriplex sp.				X		
Salicornia rubra		X				
Salicornia virginica	X	X	X	X	X	
CARYOPHYLLACEAE						
Spergularia sp.	X					
POLYGONACEAE						
Rumex crispus	X	X	X	X	X	
FRANKENIACEAE						
Frankenia grandifolia	X	X	X	X	X	
PLUMBAGINACEAE						
Limonium commune var. *californicum*	X	X		X		
CONVOLVULACEAE						
Cuscata salina	X	X	X	X	X	
COMPOSITAE						
Cirsium sp.					X	
Cotula coronopifolia					X	
Grindelia cuneifolia	X	X	X	X		
Jaumea carnosa		X		X	X	
Unidentified species	1	1/1	3/3	5/4	18/18	5/4
Total species	11	14/10	15/13	21/14	32/30	10/9

Figure 7.--Comparison of the diversity of tidal-marsh seed plants with water salinity along a longitudinal profile of the northern San Francisco Bay estuary. The plant diversity is inversely related to water salinity: as salinity decreases with distance from the Golden Gate, the number of species present at tidal marshes (plates 3-7) increases. High-marsh plants account for most of this increase in diversity. Diversity is low in our Delta marsh (plate 8) because no high-marsh surface is present.



SALINITY OF SURFACE WATER (‰), 1969-1975
WATER SALINITY
MAXIMUM
MEAN SUMMER
MINIMUM
MEAN WINTER
NUMBER OF SPECIES
DIVERSITY
GOLDEN GATE
SAN PABLO BAY
CARQUINEZ STRAIT
SUISUN BAY
SACRAMENTO-SAN JOAQUIN DELTA
DISTANCE FROM GOLDEN GATE (KM)

Other potentially important variables derive from elevation and water salinity: the soil moisture content and the frequency, duration, and depth of submergence depend on the elevation of the marsh surface with respect to tide levels; the amount of soil salt depends on the salinity of the water inundating the marsh (Rollins, 1973); and soil-water salinity depends in turn on soil moisture and salt. Additional variables seem to have a negligible effect. For example, the trends of precipitation and air temperature (fig. 5) indicate that the low-diversity, salt-tolerant marsh communities near the Golden Gate are subjected to a wetter and cooler climate than the mere heterogeneous, nearly salt-intolerant communities of the Delta region.

Replacement of salt-tolerant plants by those that tolerate little salt is controlled largely by competition for space. Competition is inevitable because most salt-tolerant plants appear to tolerate or prefer fresh water (Penfound and Hathaway, 1938; Taylor, 1939; Barbour, 1970; Phleger, 1971).

Grouping of species by elevation range

Most of the major seed plants in the natural tidal marshes of the northern San Francisco Bay estuary can be grouped into one of the following communities: (1) a low-marsh community, composed of plants that grow at the lowest elevations in the marsh (MTL or lower); (2) a middle-marsh community, composed of plants that are generally restricted to intermediate elevations (MTL to MHHW); and (3) a high-marsh community, composed of plants that grow mainly at high elevations (at or above MHHW). These communities typically overlap within a given marsh, and they vary greatly in kinds, numbers, and vertical ranges of constituent species along a longitudinal profile of the estuary. Nevertheless, the persistence of vertical zonation throughout the estuary indicates that elevation with respect to tide levels controls vertical plant distribution not only in salt-water tidal marshes, as has been demonstrated by Johnson and York (1915, p. 136-143), Purer (1942), Hinde (1954), Vogl (1966), and many others, but also in brackish- and fresh-water tidal marshes.

The following discussion of plant distribution is divided into sections on low-, middle-, and high-marsh communities. Each section contains a summary of the species composition and ecology of each community, followed by notes on principal species.

Low-marsh plants

Description of the community

Only two or three species of seed plants grow on the lowest marsh surfaces: *Spartina foliosa*, *Scirpus californicus*, and possibly *Scirpus* acutus. Other plants probably cannot tolerate the prolonged submergence endured by these species under certain salinity conditions. Water salinity and competition restrict *Spartina foliosa* to the lower reaches of the estuary and *Scirpus californicus* and *Scirpus acutus* to the upper reaches (fig. 9). Consequently, *Spartina foliosa* shares only a few tidal marshes in the middle of the estuary with these species of *Scirpus* (compare figs. 14 and 15).

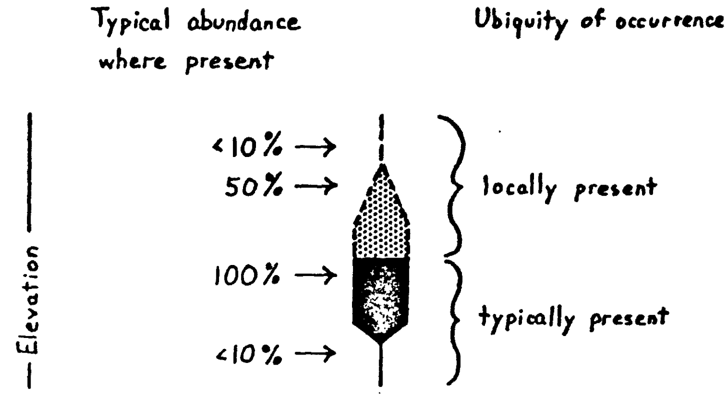
Spartina foliosa Trin. 1840

Spartina foliosa ranges in elevation from 0.0-0.3 m (0.0-1.0 ft) below MTL to 0.2-0.5 m (0.7-1.6 ft) below MHHW (fig. 9). The upper limit falls from west to east at San Pablo Bay because of progressive replacement of *Spartina foliosa* by competitive species of *Scirpus* (figs. 9, 10).

Individual plants of *Spartina foliosa* growing near MHHW are typically half as tall as plants growing near MTL. Similar height differences are displayed in North Carolina marshes by a closely related species, *Spartina alterniflora*, and have been attributed to greater salinities in high-marsh soils (Mooring, Cooper, and Seneca, 1971, p. 54).

Figure 8.--Explanation of symbols used in figures 9-13 to show occurrence and abundance of tidal-marsh seed plants. Solid lines and black shading indicate widespread occurrence at a given elevation; dashed lines and stippled shading show relatively sparse occurrence. The width of each figure represents percentage abundance and ranges continuously from 1-10 percent (one line-width) to 100 percent (broadest part of figure). This representation of occurrence and abundance is more refined than the symbols used in plates 3-8. Data comes from field notes on percentage abundances of plant species at known elevations.

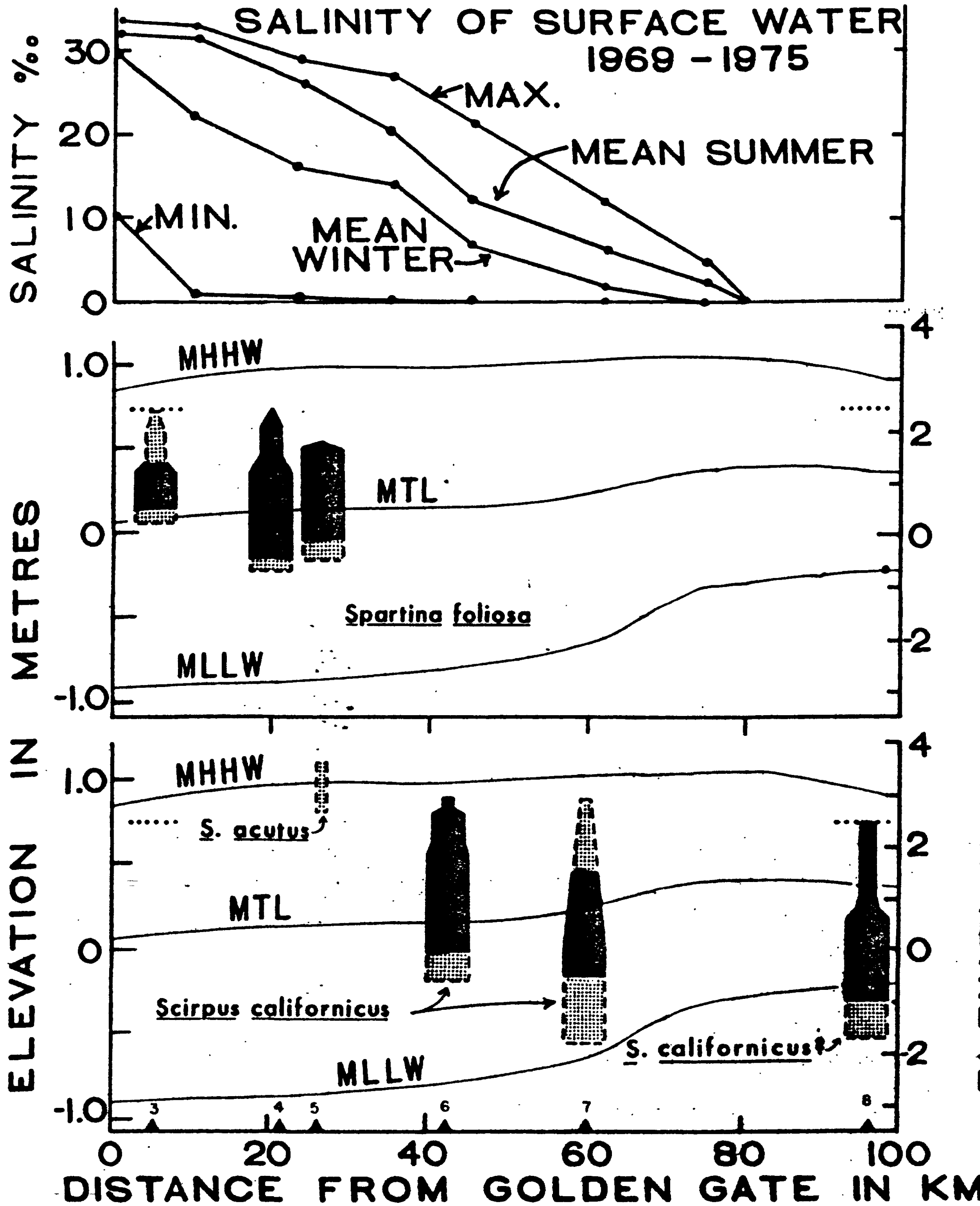
OCCURRENCE OF PLANT SPECIES AT EACH MARSH



ADEQUACY OF LEVELLING DATA

...... Levelling data above this elevation inadequate for determination of plant distribution

Figure 9.--Regional and vertical distribution of the principal low-marsh plants in the natural tidal marshes of the northern San Francisco Bay estuary. Symbols showing the occurrence and abundance of plants are explained in fig. 8. Projection of data from the margins of the estuary to the longitudinal profile is the same as in fig. 5. Also see fig. 5 for sources of data on water salinity and tide levels. The triangles along the bottom line show the projected locations of the tidal marshes at which we have studied the elevation ranges of seed plants. Numbers accompanying the triangles refer to plates 3-8, which present species distributions along leveled transects across these marshes.


SALINITY OF SURFACE WATER
1969 - 1975
MAX.
MEAN SUMMER
MEAN WINTER
MIN.
SALINITY ‰
30
20
10
0
MHHW
MTL
MLLW
Spartina foliosa
1.0
0
-1.0
4
2
0
-2
MHHW
S. acutus
MTL
Scirpus californicus
S. californicus
MLLW
3
4
5
6
7
8
ELEVATION IN METRES
ELEVATION IN FEET
0
20
40
60
80
100
DISTANCE FROM GOLDEN GATE IN KM

Despite its preference for fresh water, as shown by greenhouse experiments (Phleger, 1971), Spartina foliosa is restricted to areas with mean winter surface-water salinities greater than 15 o/oo and mean summer salinities greater than 20 o/oo (fig. 9). Spartina foliosa is absent in fresher-water areas, where conditions for growth should be more favorable, because it is replaced by Scirpus spp., Typha latifolia and Phragmites communis (figs. 9, 10). Apparently, these species compete successfully against Spartina foliosa in the upper reaches of the estuary. Spartina foliosa's areas of competitive advantage are confined to the lower reaches of the estuary (fig. 14), perhaps because potential competitors are physiologically excluded by high water salinities.

Scirpus acutus Muhl. ex Bigel 1814 and Scirpus californicus (C. A. Mey) Steud. 1841.

Similarities between Scirpus acutus and Scirpus californicus lead to uncertainties in our identifications of these species. Some of the specimens that we collected are readily identified by the nature of the bristles subtending flowers and achenes and by the cross-sectional shapes of the upper parts of the culms (Mason, 1957, p. 319, 321-323). Other specimens, however, were not chosen and preserved with sufficient care to include diagnostic bristles, and they are called Scirpus californicus? only because the upper parts of the culms are subterete. In addition, our collections are insufficient to rule out the presence of Scirpus acutus in marshes where only Scirpus californicus is listed on table 5.

While it may be locally joined by Scirpus acutus, Scirpus californicus is probably the principal low-marsh replacement of Spartina foliosa in the fresh- and brackish-water parts of the estuary (figs. 9, 15). The upper limit of Scirpus californicus varies little with respect to MHHW. The lower limit, however, drops from 0.3 m (1.0 ft) below MTL at Carquinez Strait to 0.3 m (1.0 ft) below MLLW in the Delta (fig. 9), suggesting that Scirpus californicus tolerates more submergence by fresh water than by brackish water.

The only occurrence of Scirpus acutus that we can document is at a marsh near Petaluma (plate 5; fig. 9). The plants appear to be anomalous in elevation (near MHHW) and size (1.5-2.0 m tall; elsewhere Scirpus acutus can grow as tall as 5 m (Mason, 1957, p. 323)), perhaps because they are situated near the seaward limit of the distribution of tall bulrushes and tules.

Middle-marsh plants

Description of the community

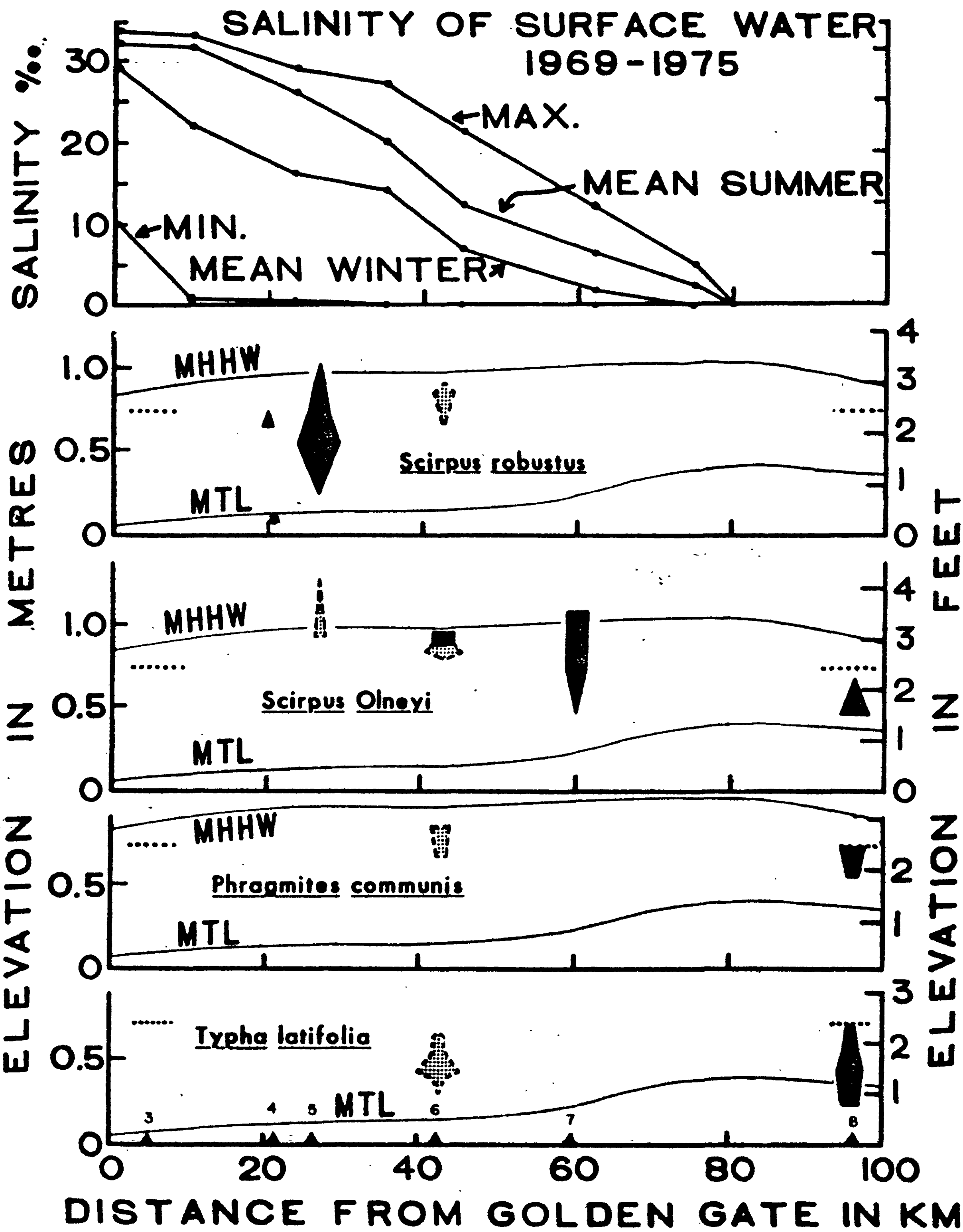
The tidal marshes near Point San Pedro, Petaluma, Benicia, Fairfield, and Bethel Island (plates 4-8) contain plants that generally grow between high-marsh surfaces and the lowest marsh surfaces. This middle-marsh community includes Scirpus robustus, Scirpus Olneyi, Phragmites communis, Typha latifolia, Cotula coronopofolia, Salicornia rubra, and several unidentified species (table 5, figs. 10, 11). No distinct middle-marsh plants are recognized at Richardson Bay (plate 3) because Spartina foliosa, a low-marsh species, and Salicornia virginica, a high-marsh species, occupy the intermediate elevations.

Scirpus robustus Pursh 1814

Scirpus robustus flourishes between MTL and MHHW at San Pablo Bay and Carquinez Strait but is generally absent elsewhere in the estuary (figs. 10, 16). The elevation range and abundance of Scirpus robustus appear to be greatest where salinities are low enough to allow it to grow and reproduce but high enough to preclude competition by Scirpus Olneyi, Scirpus californicus, and Typha latifolia.

Surface-water salinities at San Pablo Bay are similar to soil salinities at dominant stands of Scirpus robustus in the diked marshes of Suisun Bay. The most favorable mean annual soil salinities for Scirpus robustus in the diked marshes of Suisun Bay are 7-32 o/oo, with an optimal salinity of 22 o/oo (Mall, 1969, p. 35). In comparison, the mean summer (summer and autumn) salinity of surface water at San Pablo Bay between 1969 and 1975 was 18-29 o/oo, and the mean winter (winter and spring) salinity was 13-18 o/oo (figs. 5, 10). These water

Figure 10.--Regional and vertical distribution of the principal middle-marsh plants in the natural tidal marshes of the northern San Francisco Bay estuary. Symbols showing the occurrence and abundance of plants are explained in fig. 8. Projection of data from the margins of the estuary to the longitudinal profile is the same as in fig. 5. Also see fig. 5 for sources of data on water salinity and tide levels. The triangles along the bottom line show the projected locations of the tidal marshes at which we have studied the elevation ranges of seed plants. Numbers accompanying the triangles refer to plates 3-8, which present species distributions along leveled transects across these marshes.



SALINITY OF SURFACE WATER
1969-1975
SALINITY ‰
MAX.
MEAN SUMMER
MIN.
MEAN WINTER
MHHW
Scirpus robustus
MTL
Scirpus Olneyi
Phragmites communis
Typha latifolia
ELEVATION IN METRES
ELEVATION IN FEET
DISTANCE FROM GOLDEN GATE IN KM

salinities probably create similar salinities in the marsh soils (e.g., Rollins, 1973), and therefore may provide a competitive advantage for Scirpus robustus in the natural tidal marshes around San Pablo Bay.

The scarcity or absence of Scirpus robustus in natural marshes of Suisun Bay (plate 7) is noteworthy because this plant covers about six percent of the diked marsh areas of Suisun Bay (George, Anderson, and McKinnie, 1965, p. 10). In addition, its seeds provide the major food for nearly 90 percent of the ducks that winter at Suisun Bay (Mall, 1969, p. 15). Soil salinities are high in the diked marshes because gun clubs flood these marshes at the start of the hunting season when water salinities are high (George, Anderson, and McKinnie, 1965, p. 11). Year-round water circulation in the natural marshes of Suisun Bay, on the other hand, permits leaching of soil salts when the applied water is nearly fresh. Resulting soil salinities in these natural marshes are probably low enough to give Scirpus Olneyi and Typha latifolia a competitive advantage over Scirpus robustus (fig. 10; Mall, 1969, p. 35).

Scirpus Olneyi Gray 1845

Scirpus Olneyi is most abundant in the natural marshes of Suisun Bay and the Delta, where mean annual water salinities do not exceed 10 o/oo. However, it is also present as far west as western San Pablo Bay (fig. 17), where water salinities are typically near 20 o/oo. According to Mall (1969, p. 35), Scirpus Olneyi competes best at soil salinities between 8 and 21 o/oo.

Typha latifolia Linné 1753

We have not attempted to distinguish Typha latifolia from possible hybrids between it and Typha augustiolia (see Mason,1957, p. 37). Typha latifolia or a hybrid species of Typha tolerates greater submergence than other middle-marsh plants (fig. 10). Distribution is restricted to the marshes of Carquinez Strait, Suisun Bay, and the Sacramento-San Joaquin Delta (fig. 18).

Phragmites communis Trin. 1820

Phragmites communis is generally restricted to the Delta region. However, it does grow locally with Scirpus californicus as far west as Carquinez Strait (fig. 19, plate 6).

High-marsh plants

Description of the community

The most diverse group of tidal marsh plants inhabits high-marsh surfaces. These nearly flat surfaces are typically situated 0.0-0.15 m (0.0-0.5 ft) above MHHW (fig. 6). Plants that grow on them include Salicornia virginica, Distichlis spicata, Frankenia grandifolia, Atriplex patula, Jaumea carnosa, Grindelia cuneifolia, Limonium commune, and some unidentified species that are confined to brackish- and fresh-water marshes. Juncus balticus, a plant with a large and varied elevation range, also grows high in some marshes and is discussed along with these plants.

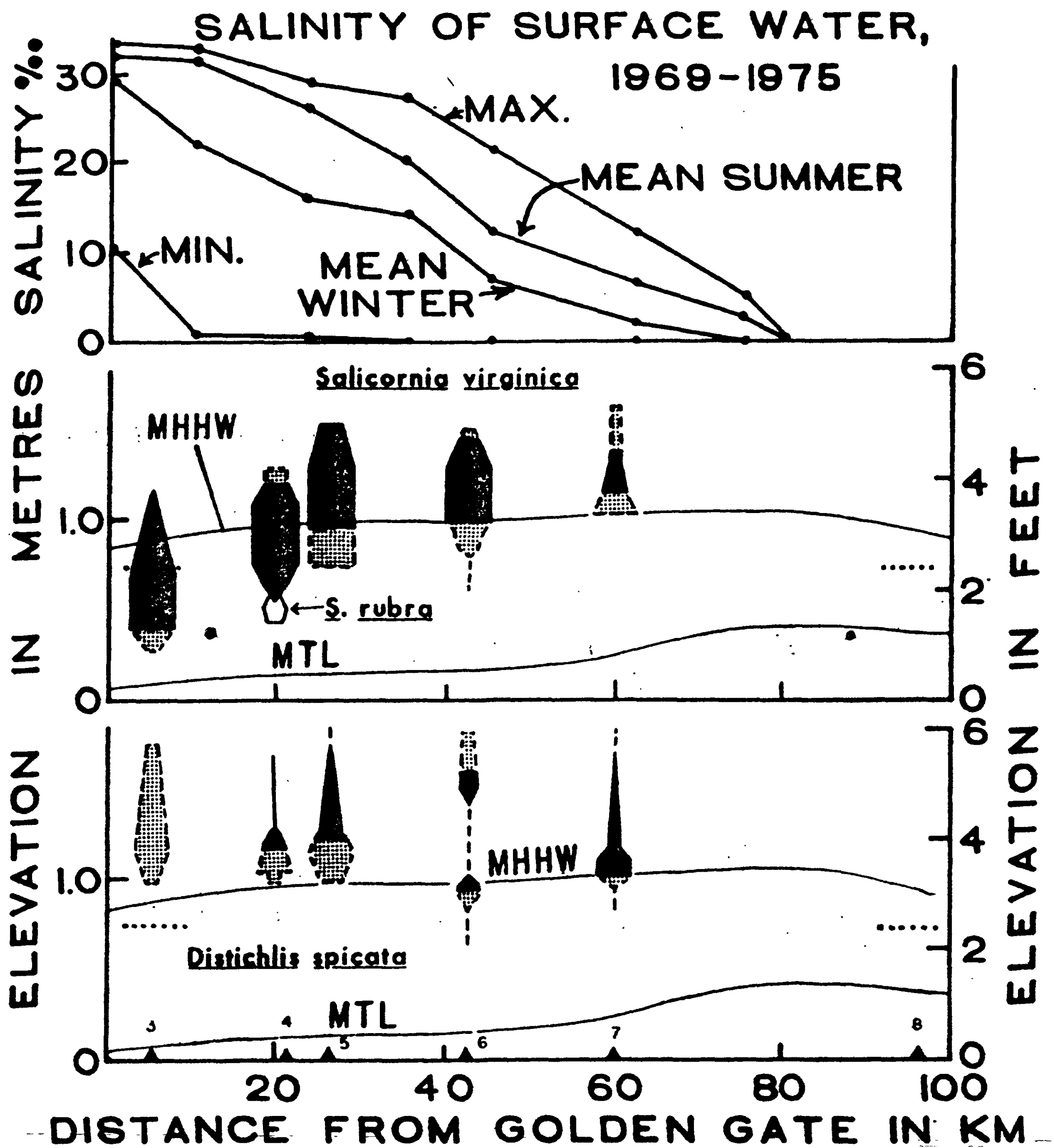
Salicornia virginica Linné 1753

The elevation range of Salicornia virginica progressively shrinks toward the fresh-water end of the estuary because of competition from middle-marsh plants (figs. 10, 11). In addition, the percentage abundance of Salicornia virginica is reduced as water salinity falls because of successful competition by other high-marsh species, particularly Distichlis spicata, which is a better competitor than Salicornia virginica where soil salinity is less than 35 o/oo (Mall, 1969, p. 42-43). Despite these changes in vertical distribution due to water salinity, Salicornia is present on every high-marsh surface we have studied (fig. 20; open circles on fig. 20 only refer to tidal marshes that lack high-marsh surfaces).

Distichlis spicata (Linné) Greene 1887

Distichlis spicata typically grows above MHHW. Its uppermost occurrences create a band at the landward edge of many marshes, the

Figure 11.--Regional and vertical distribution of the principal high-marsh plants in the natural tidal marshes of the northern San Francisco Bay estuary. Symbols showing the occurrence and abundance of plants are explained in fig. 8. Projection of data from the margins of the estuary to the longitudinal profile is the same as in fig. 5. Also see fig. 5 for sources of data on water salinity and tide levels. The triangles along the bottom line show the projected locations of the tidal marshes at which we have studied the elevation ranges of seed plants. Numbers accompanying the triangles refer to plates 3-8, which present species distributions along levelled transects across these marshes.


SALINITY OF SURFACE WATER,
1969-1975
MAX.
MEAN SUMMER
MIN.
MEAN
WINTER
SALINITY ‰
30
20
10
0
Salicornia virginica
MHHW
S. rubra
MTL
Distichlis spicata
MHHW
MTL
ELEVATION IN METRES
ELEVATION IN FEET
1.0
0
6
4
2
0
3
4
5
6
7
8
20
40
60
80
100
DISTANCE FROM GOLDEN GATE IN KM

plants growing on relatively dry soils and situated above the other major high-marsh plants (plates 3-6). Some of these occurrences are characterized by stunted, sparsely distributed individuals. The lower occurrences of Distichlis spicata at San Pablo Bay are restricted to sparse patches among stands of Salicornia virginica or along the edges of channels. However, Distichlis spicata is much more widespread and abundant around Suisun Bay because it replaces Salicornia virginica as the principal high-marsh plant (fig. 11). Like Salicornia virginica, Distichlis spicata is present on all high-marsh surfaces that we have visited (fig. 21).

Frankenia grandifolia (Cham. & Schl., Linné 1826), Atriplex patula (Linné 1753) and Jaumea carnosa (Less.) Gray in Torr. 1874

These plants are subordinate constituents of the high-marsh community. They grow sparsely above MHHW (fig. 12) throughout the estuary (figs. 22-24).

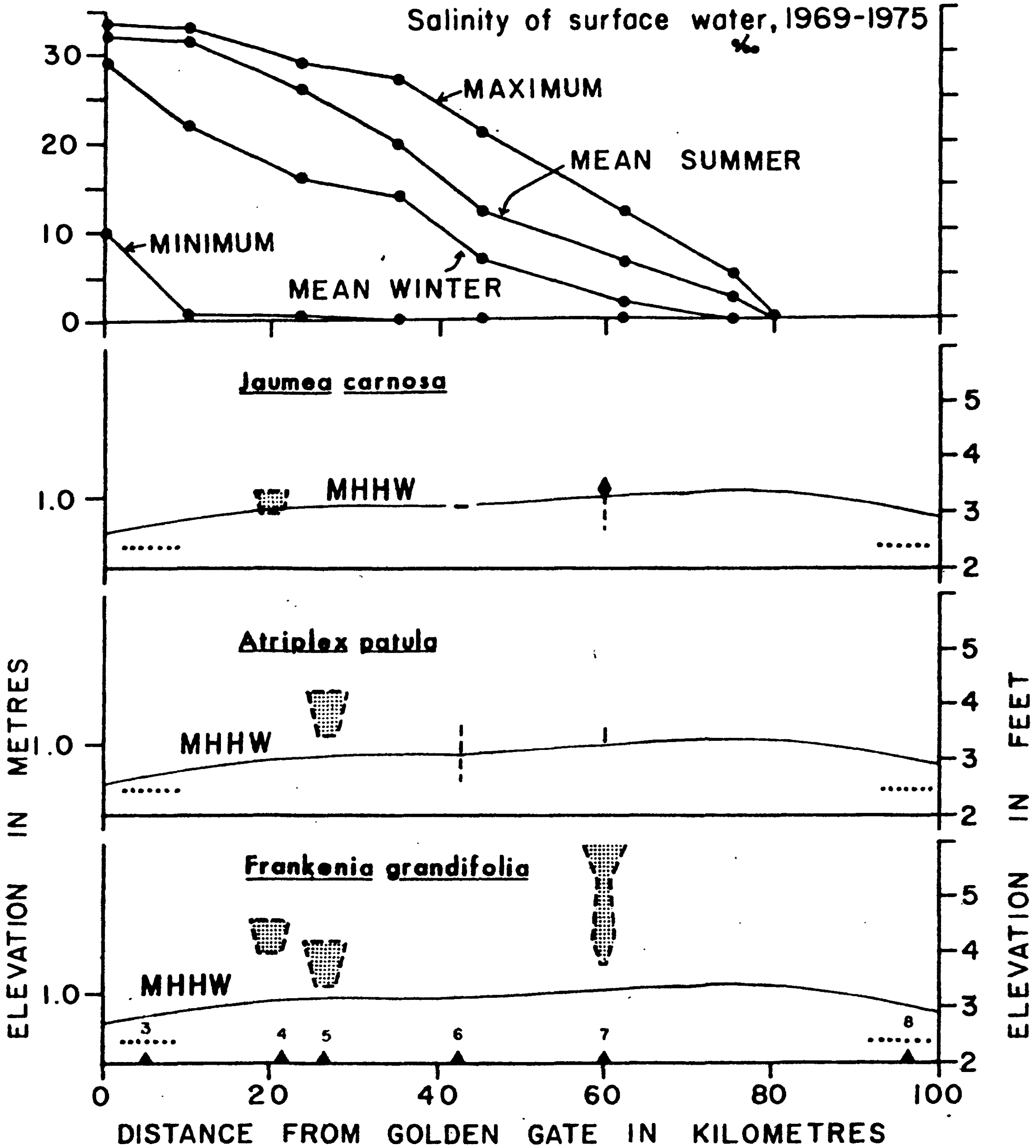
Grindelia cuneifolia Nutt 1841

Grindelia cuneifolia typically grows on high-marsh surfaces bordering channels and also inhabits high-marsh soils that have been disturbed by man. Grindelia cuneifolia appears to be restriced to marshes fringing Carquinez Strait, San Pablo Bay, and San Francisco Bay (fig. 25).

Juncus balticus Willd 1809

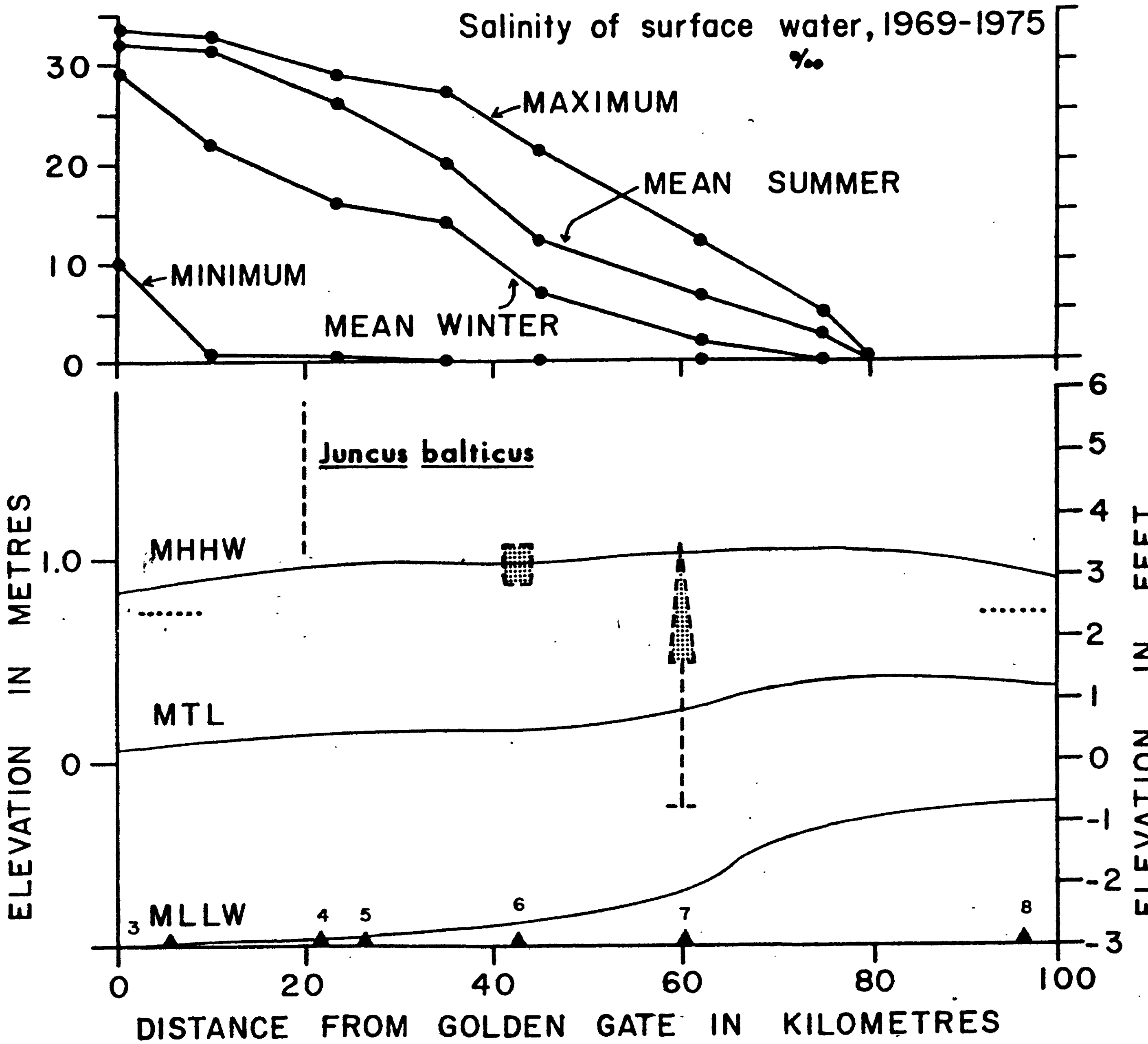
Juncus balticus responds to water salinity by growing at progressively lower elevations from the salt-water to fresh-water reaches of the estuary (fig. 13). Like Scirpus californicus (fig. 9), it

Figure 12.--Regional and vertical distribution of the subordinate high-marsh plants in the natural tidal marshes of the northern San Francisco Bay estuary. Symbols showing the occurrence and abundance of plants are explained in fig. 8. Projection of data from the margins of the estuary to the longitudinal profile is the same as in fig. 5. Also see fig. 5 for sources of data on water salinity and tide levels. The triangles along the bottom line show the projected locations of the tidal marshes at which we have studied the elevation ranges of seed plants. Numbers accompanying the triangles refer to plates 3-8, which present species distributions along levelled transects across these marshes.



Salinity of surface water, 1969-1975 ‰
MAXIMUM
MEAN SUMMER
MINIMUM
MEAN WINTER
30
20
10
0
Jaumea carnosa
MHHW
1.0
Atriplex patula
MHHW
1.0
Frankenia grandifolia
MHHW
1.0
ELEVATION IN METRES
ELEVATION IN FEET
5
4
3
2
3
4
5
6
7
8
0
20
40
60
80
100
DISTANCE FROM GOLDEN GATE IN KILOMETRES

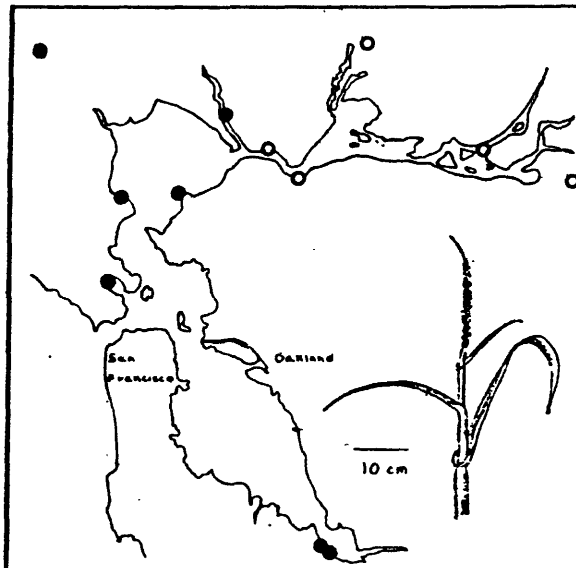
Figure 13.--Regional and vertical distribution of _Juncus balticus_ in the natural tidal marshes of the northern San Francisco Bay estuary. Symbols showing the occurrence and abundance of plants are explained in fig. 8. Projection of data from the margins of the estuary to the longitudinal profile is the same as in fig. 5. Also see fig. 5 for sources of data on water salinity and tide levels. The triangles along the bottom line show the projected locations of the tidal marshes at which we have studied the elevation ranges of seed plants. Numbers accompanying the triangles refer to plates 3-8 which present species distributions along leveled transects across these marshes.



Salinity of surface water, 1969-1975
‰
MAXIMUM
MEAN SUMMER
MINIMUM
MEAN WINTER
30
20
10
0
Juncus balticus
MHHW
MTL
MLLW
1.0
0
ELEVATION IN METRES
ELEVATION IN FEET
6
5
4
3
2
1
0
-1
-2
-3
3
4
5
6
7
8
0
20
40
60
80
100
DISTANCE FROM GOLDEN GATE IN KILOMETRES

appears to tolerate greater submergences as water salinity decreases. A preference for fresh water is also suggested by the absence of _Juncus balticus_ in the marshes of San Francisco Bay (fig. 26). Elsewhere in California this species grows as high as 3,000 m (10,000 ft) above sea level (Mason, 1957, p. 351).

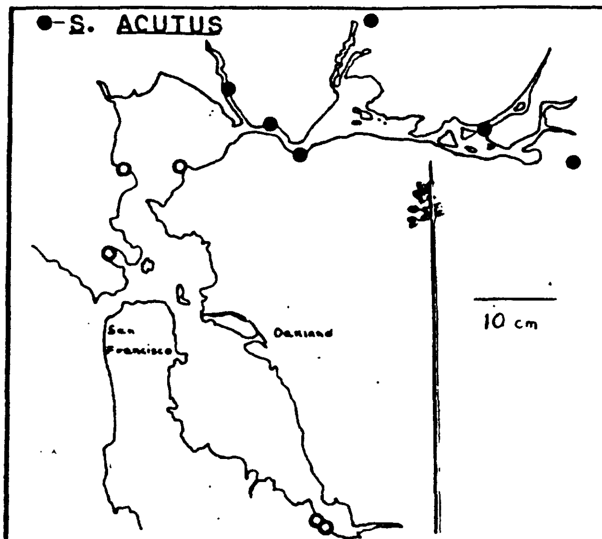
Figure 14.--Distribution of _Spartina foliosa_ Trin. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by Hylton Mayne from a specimen collected near Palo Alto, Calif.



DISTRIBUTION OF SPARTINA FOLIOSA IN NATURAL TIDAL MARSHES

- ● PRESENT
- ○ ABSENT OR PROBABLY ABSENT

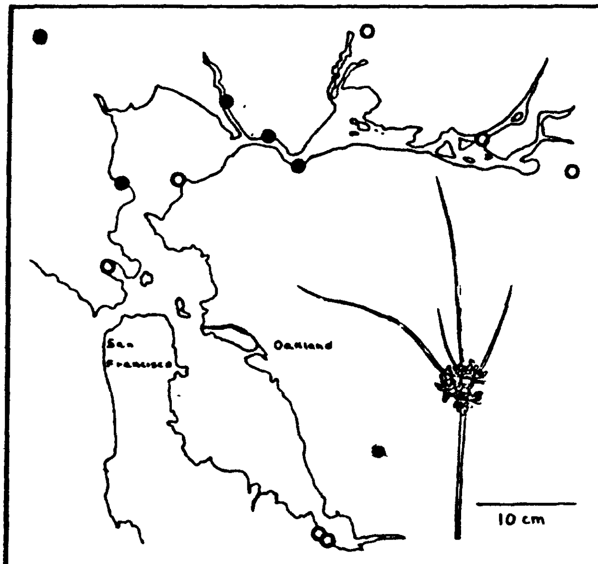
Figure 15.--Distribution of _Scirpus_ _acutus_ Muhl. ex Bigel., and _Scirpus californicus_ (C. A. Mey) Steud. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by M. B. Pomeroy (Mason, 1957, p. 322) and illustrates the upper one-third of the culm of a specimen of _S_. _acutus_.



DISTRIBUTION OF {SCIRPUS ACUTUS AND SCIRPUS CALIFORNICUS} IN NATURAL TIDAL MARSHES

● PRESENT
o ABSENT OR PROBABLY ABSENT

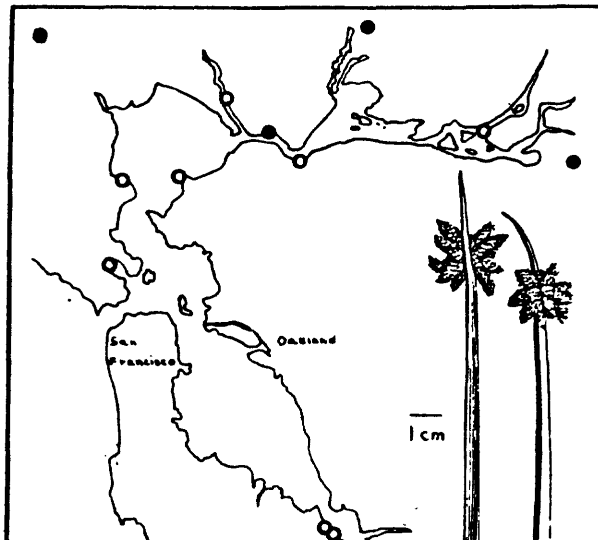
Figure 16.--Distribution of _Scirpus robustus_ Pursh in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by M. B. Pomeroy (Mason, 1957, p. 311).



DISTRIBUTION OF <u>SCIRPUS</u> <u>ROBUSTUS</u> IN NATURAL TIDAL MARSHES

● PRESENT
○ ABSENT OR PROBABLY ABSENT

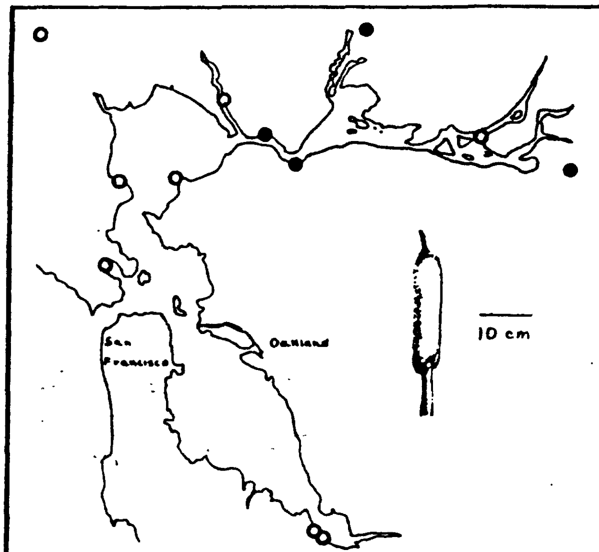
Figure 17.--Distribution of Scirpus Olneyi Gray in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by M. B. Pomeroy (Mason, 1957, p. 316).



DISTRIBUTION OF *SCIRPUS OLNEYI*
IN NATURAL TIDAL MARSHES

● PRESENT
o ABSENT OR PROBABLY ABSENT

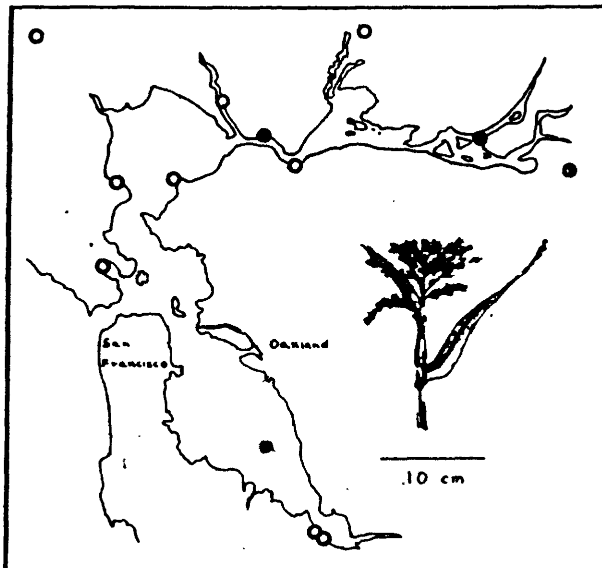
Figure 18.--Distribution of *Typha latifolia* L. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by Hylton Mayne from an illustration by M. B. Pomeroy (Mason, 1957, p. 40).



DISTRIBUTION OF *TYPHA LATIFOLIA* IN NATURAL TIDAL MARSHES

● PRESENT
○ ABSENT OR PROBABLY ABSENT

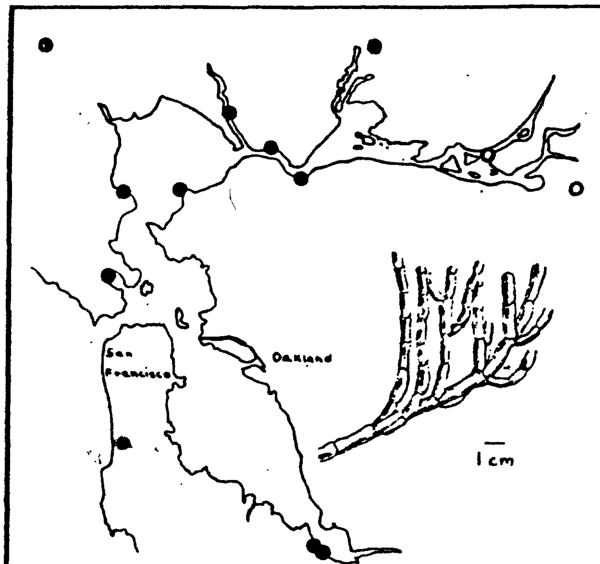
Figure 19.--Distribution of _Phragmites communis_ Trin. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by Hylton Mayne from an illustration by M. B. Pomeroy (Mason, 1957, p. 191).



DISTRIBUTION OF PHRAGMITES COMMUNIS IN NATURAL TIDAL MARSHES

● PRESENT
o ABSENT OR PROBABLY ABSENT

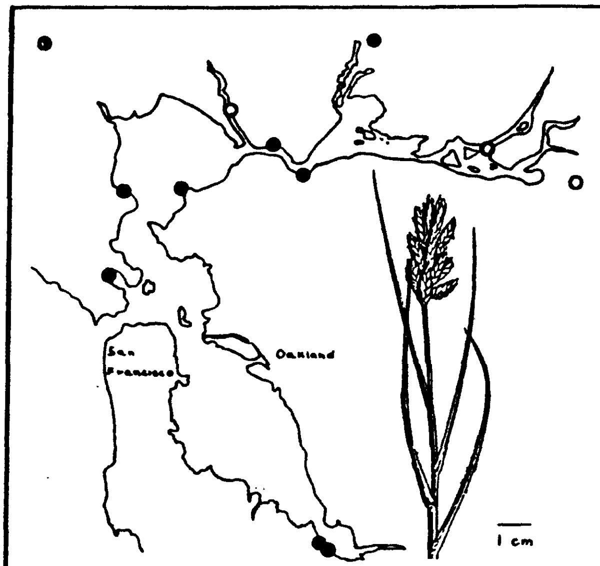
Figure 20.--Distribution of Salicornia virginica L. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by M. B. Pomeroy (Mason, 1957, p. 468) and illustrates S. pacifica Standley, which is included in S. virginica L. by Munz (1959).



DISTRIBUTION OF <u>SALICORNIA VIRGINICA</u> IN NATURAL TIDAL MARSHES

- ● PRESENT
- o ABSENT OR PROBABLY ABSENT

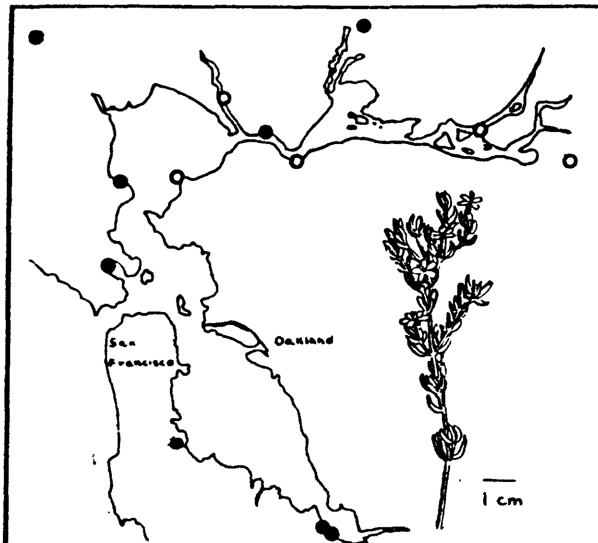
Figure 21.--Distribution of _Distichlis spicata_ (L) Green in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by M. B. Pomeroy (Mason, 1957, p. 146).



DISTRIBUTION OF <u>DISTICHLIS</u> <u>SPICATA</u> IN NATURAL TIDAL MARSHES

● PRESENT
○ ABSENT OR PROBABLY ABSENT

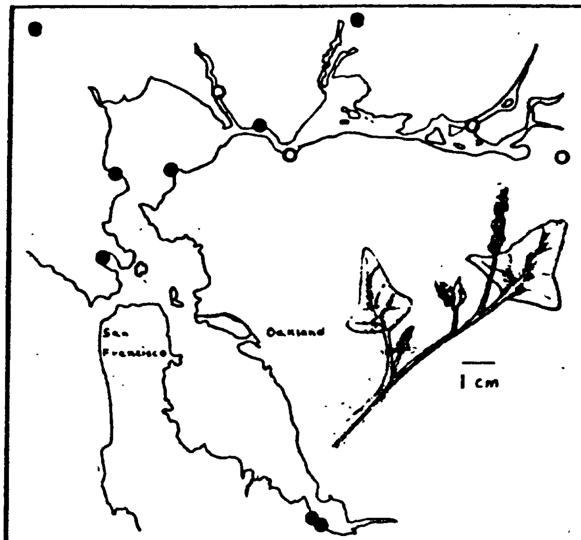
Figure 22.--Distribution of _Frankenia grandifolia_ Cham. & Schl. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by M. B. Pomeroy (Mason, 1957, p. 590).



DISTRIBUTION OF *FRANKENIA GRANDIFOLIA*
IN NATURAL TIDAL MARSHES

● PRESENT
○ ABSENT OR PROBABLY ABSENT

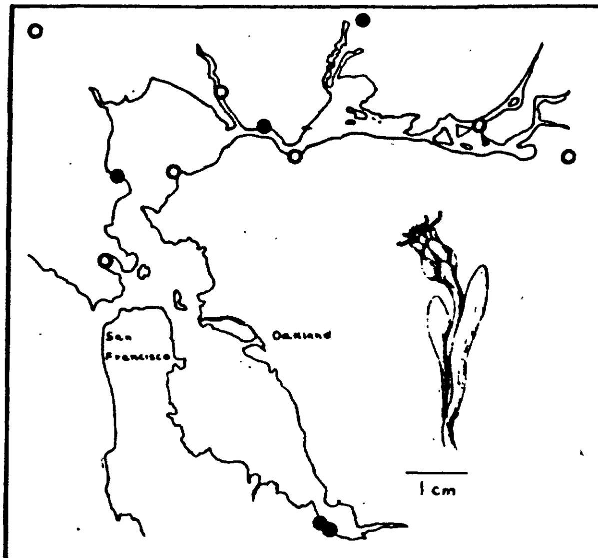
Figure 23.--Distribution of *Atriplex patula* L. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by Hylton Mayne from an illustration by M. B. Pomeroy (Mason, 1957, p. 454).



DISTRIBUTION OF <u>ATRIPLEX PATULA</u>
IN NATURAL TIDAL MARSHES

● PRESENT
○ ABSENT OR PROBABLY ABSENT

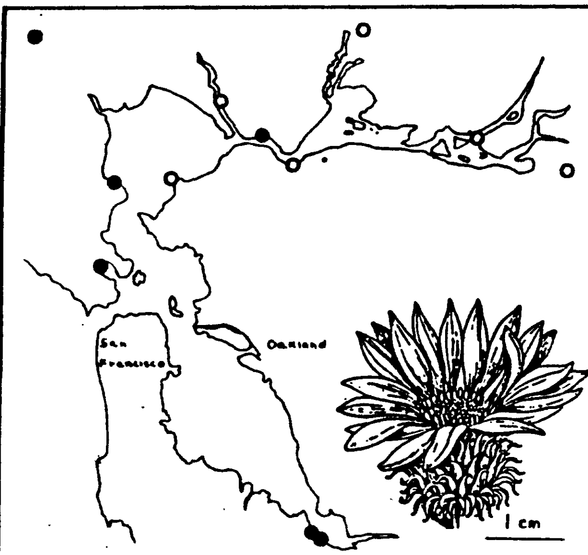
Figure 24.--Distribution of _Jaumea carnosa_ (Less.) Gray in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by Hylton Mayne from an illustration by an unknown artist in Mason (1957, p. 824).



DISTRIBUTION OF <u>JAUMEA CARNOSA</u>
IN NATURAL TIDAL MARSHES

● PRESENT
o ABSENT OR PROBABLY ABSENT

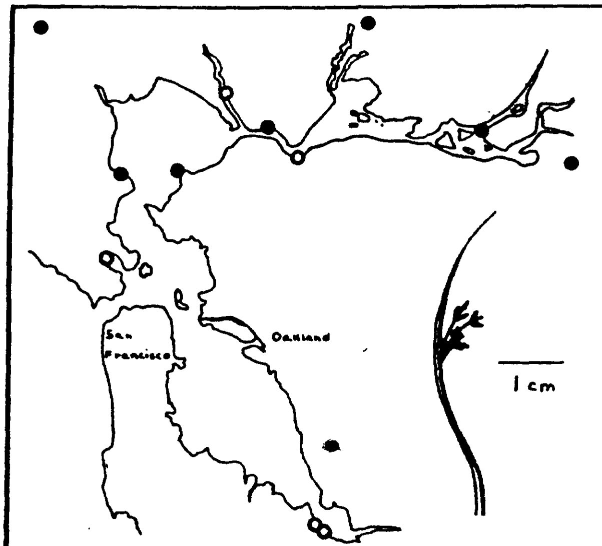
Figure 25.--Distribution of Grindelia cuneifolia Nutt. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by J. B. Sanders (Jepson, 1951, p. 1021) and illustrates G. camporum Green.



DISTRIBUTION OF *GRINDELIA CUNEIFOLIA* IN NATURAL TIDAL MARSHES

● PRESENT
o ABSENT OR PROBABLY ABSENT

Figure 26.--Distribution of *Juncus balticus* Willd. in natural tidal marshes of the San Francisco Bay estuary. The plant sketch was drawn by Hylton Mayne from an illustration by M. B. Pomeroy (Mason, 1957, p. 352).



DISTRIBUTION OF *JUNCUS BALTICUS* IN NATURAL TIDAL MARSHES

- ● PRESENT
- o ABSENT OR PROBABLY ABSENT

SUMMARY

(1) Estuaries and stream valleys have alternately occupied the vicinity of the present San Francisco Bay estuary during the past one million years. The changing environments record sea-level fluctuations that were probably related to waxing and waning of large ice sheets in northern latitudes. The most recent estuary began to form about 10,000 years ago (plate 1) in response to a rapid sea-level rise that accompanied the melting of some of these ice sheets.

(2) The rate of sea-level rise (fig. 2) has influenced the areal extent of tidal marshes since inception of the estuary 10,000 years ago. The rapid initial rise in sea level created conditions that were unfavorable to growth of tidal marshes. During the past 6,000 years, however, the rate of sea-level has been slow enough for accumulating sediments to shoal some of the margins of the estuary. These sediments constructed tidal mud flats, many of which have been colonized by seed plants during the past several thousand years (fig. 3) to produce extensive marshes around San Francisco, San Pablo, and Suisun Bays.

(3) By 1850 A.D. the tidal marshes of the bays and the Sacramento San Joaquin Delta covered an area nearly twice as large as the area of open water of the bays and about two-thirds as large as the state of Rhode Island. Nearly 95 percent of these marshes have been diked or filled during the past 125 years (plate 2, fig. 4). Many of the remaining natural tidal marshes have probably been altered by man-induced changes in sea level, sedimentation, and water salinity.

(4) Natural high-marsh surfaces that existed ca. 1850 A.D. form a flat plain that is presently situated 0.0-0.15 m (0.0-0.5 ft) above mean higher high water fig. 6; plates 4-7). The narrow elevation range of these surfaces with respect to mean higher high water suggests that tide levels control the ultimate heights of high-marsh surfaces.

(5) Species distributions along leveled transects at six tidal marshes (plates 3-8) indicate that elevation and water salinity are the principal ecological factors that control the distribution of seed plants in the natural tidal marshes of the northern San Francisco Bay estuary (figs. 7-13). Marsh surfaces situated near mean tide level are populated by robust monocotyledons (e.g. Spartina foliosa, Scirpus californicus), whereas surfaces situated near high-tide levels support dicotyledons and a few species of small monocotyledons (e.g., Salicornia virginica, Distichlis spicata). Marshes near the seaward end of the estuary are typically occupied by 10-15 salt-tolerant species (e.g., Spartina foliosa, Salicornia virginica), whereas marshes at the riverward end of the estuary are inhabited by as many as 30 species, most of which are known to tolerate moderate or small amounts of salt (e.g., Scirpus spp., Phragmites communis, Typha latifolia).

REFERENCES

Barbour, M. G., 1970, Is any angiosperm an obligate halophyte?: Amer. Midl. Natur., v. 84, p. 105-120.

Beetle, A. A., 1947, Distribution of the native grasses of California: Hilgardia, v. 17, p. 309-357.

California Coastal Zone Conservation Commissions, 1975, California Coastal Plan: State of California, 443 p.

California Dept. of Water Resources, 1960, The Delta and the Delta Water Project: Calif. Dept. Water Resources, 22 p.

Connor, C. L., 1975, Holocene sedimentation history of Richardson Bay, California: Stanford Univ., unpub. M.S. thesis, 112 p.

Conomos, T. J., and Peterson, D. H., (in press), Suspended particle transport and circulation in San Francisco Bay--An overview: Proc. of the Third Meeting of the International Estuarine Research Federation.

Filice, F. P., 1954, An ecological survey of the Castro Creek area in San Pablo Bay: Wasmann Jour. Biol., v. 12, p. 1-24.

Flint, R. F., 1971, Glacial and Quaternary geology: John Wiley and Sons, New York, 892 p.

George, H. A., Anderson, William, and McKinnie, Harold, 1965, An evaluation of the Suisun Marsh as a waterfowl area: Calif. Dept. of Fish and Game, administrative report, 20 p.

Gilbert, G.K., 1908, Tomales Bay to Bolinas Lagoon, p. 66-91 in Lawson, A.C., ed., The California earthquake of April 18, 1906 - Report of the State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, v. 1.

_____ 1917, Hydraulic-mining débris in the Sierra Nevada: U.S. Geol. Survey Prof. Paper 105, 154 p.

Goldman, H. B., 1969, Geology of San Francisco Bay, p. 9-29 in Goldman, H. B., ed., Geologic and engineering aspects of San Francisco Bay fill: Calif. Div. Mines and Geology, Spec. Rept. 97, 130 p.

Harvey, H. T., 1966, Some ecological aspects of San Francisco Bay: San Francisco Bay Conservation and Development Commission, 31 p.

Hinde, H. P., 1954, Vertical distribution of salt marsh phanerogams in relation to tide levels: Ecol. Monog., v. 24, p. 209-225.

Homan, W. J., and Schultz, E. A., 1963, Model tests of shoaling and of dredge spoil disposal in San Francisco Bay, p. 708-730 in Proceedings of the Federal Inter-agency Sedimentation Conference: U.S. Dept. of Agriculture, Misc. Pub. 970, 933 p.

Howell, J. T., 1970, Marin flora, second edition: Univ. California Press, Berkeley, 366 p.

Jackson, H. A., 1969, Prepared statement of Leslie Salt Co., presented by Harry A. Jackson, Jr., Secretary and Counsel: U.S. House of Representatives, Committee on Government Operations, Hearings--The nation's estuaries, San Francisco Bay and Delta, Calif., part 2, p. 151-154.

Jepson, W. L., 1908, Report on an examination of plants on Pepper Island, Bolinas Lagoon, April 9, 1907, p. 91 in Lawson, A.C., ed., The California earthquake of April 18, 1906--Report of the State Earthquake Investigation Commission: Carnegie Inst. Washington Pub. 87, v. 1.

______ 1951, Manual of the flowering plants of California: Univ. Calif. Press, Berkeley, 1238 p.

Johnson, D. S., and York, H. H., 1915, The relations of plants to tide levels: Carnegie Inst. Washington Pub. 206.

Knott, J. M., 1973, Effects of urbanization on sedimentation and floodflows in Colma Creek basin, California: U.S. Geol. Survey Open-file report, 54 p.

McDonald, K. B., and Barbour, M. G., 1974, Beach and salt marsh vegetation of the North Pacific Coast, p. 175-234 in Reimold, R. J., and Queen, W. H., eds., Ecology of halophytes: New York, Academic Press, 605 p.

Mall, R. E., 1969, Soil-water-salt relationships of waterfowl food plants in the Suisun marsh of California: California Dept. of Fish and Game, Wildlife Bull. 1, 59 p.

Mason, H. L., 1957, A flora of the marshes of California: Berkeley, Univ. of Calif. Press, 878 p.

McCulloch, D. S., Peterson, D. H., Carlson, P. R., and Conomos, T. J., 1970, Some effects of fresh-water inflow on the flushing of south San Francisco Bay: U.S. Geol. Survey Circ. 637-A, 27 p.

Mobberley, D. G., 1956, Taxonomy and distribution of the genus Spartina: Iowa State College Jour. of Science, v. 30, p. 471-574.

Mooring, M. T., Cooper, A. W., and Seneca, E. D., 1971, Seed germination response and evidence for height ecophenes in Spartina alterniflora from North Carolina: Amer. Jour. Bot., v. 58 p. 48-55.

Munz, P. A., 1959, A California flora: Univ. Calif. Press, Berkeley, 1681 p.

National Ocean Survey, 1974, Tide tables, 1974--Pacific Coast of North and South America, 222 p.

Nichols, D. R., and Wright, N. A., 1971, Preliminary map of historic margins of marshland, San Francisco Bay, California: U.S. Geol. Survey Open-file map (scale 1:125,000).

Penfound, W. T., and Hathaway, E. S., 1938, Plant communities in the marshlands of southeastern Louisiana: Ecol. Monogr., v. 8, p. 1-56.

Pestrong, Raymond, 1965, The development of drainage patterns on tidal marshes: Stanford Univ. Pub. Geol. Sci., v. 10, no. 2, 87 p.

_____ 1972, San Francisco Bay tidelands: California Geology, v. 25, p. 27-40.

Phleger, C. F., 1971, Effect of salinity of growth of a salt marsh grass: Ecology, v. 52, p. 908-911.

Poland, J. F., 1971, Land subsidence in the Santa Clara Valley, Alameda, San Mateo, and Santa Clara Counties, California: U.S. Geol. Survey Misc. Field Studies map MF-336. (Scale 1:125,000).

Purer, E. A., 1942, Plant ecology of the coastal salt marshlands: Ecol. Monogr., v. 12, p. 83-111.

Rantz, S. E., 1971, Mean annual precipitation and precipitation depth-duration-frequency data for the San Francisco Bay region, California: U.S. Geol. Survey open-file rept.

Redfield, A. C., 1972, Development of a New England salt marsh: Ecol. Monog., v. 42, p. 201-237.

Ringgold, Cadwalader, 1852, A series of charts, with sailing directions, embracing surveys of the Farallones, the entrance to the bay of San Francisco, bays of San Francisco and San Pablo, straits of Carquines and Suisun bay, confluence of the deltic branches of the Sacramento river (with the middle fork) to the American river, including the cities of Sacramento and Boston, state of California: J. T. Towers, Washington, D. C., 48 p.

Rollins, G. L., 1973, Relationships between soil salinity and the salinity of applied water in the Suisun marsh of California: Calif. Fish and Game, v. 59, p. 5-35.

Rowntree, R. A., 1973, Morphological change in a California estuary - sedimentation and marsh invasion at Bolinas lagoon: unpub. Ph.D. dissertation, Dept. of Geography, Univ. California Berkeley, 271 p.

San Francisco Bay Conservation and Development Commission, 1969, The San Francisco Bay Plan: 43 p.

Schlemon, R. J., and Begg, E. L., 1973, Late Quaternery evolution of the Sacramento-San Joaquin Delta, California: Ninth Congress of the International Union for Quaternery Research, Proceedings, p. 259-266.

Shalowitz, A. L., 1964, Shore and sea boundaries: U. S. Coast and Geodetic Survey, Publication 10-1, v. 2, 749 p.

Taylor, N., 1939, Salt tolerance of Long Island salt marsh plants: Circ. N. Y. State Mus., v. 23, p. 1-42

U.S. Army Corps of Engineers, 1963, Technical report on San Francisco Bay barriers, Appendix "E": U.S. Army Engineer District, San Francisco, 136 p.

U. S. National Climatic Center, 1969-1975: Climatological Data, California: (Annual Summary): v. 73-79, no. 13.

Vogl, R. J., 1966, Salt marsh vegetation of Upper Newport Bay, California: Ecology, v. 47, p. 80-87.

Wier, W. W., 1950, Subsidence of peat lands of the San Joaquin-Sacramento Delta, California: Hilgardia, v. 20, p. 37-56.

Plate 1.--Shorelines of the San Francisco Bay estuary during the past 10,000 years. The 125-year-old shoreline is based on maps of the historic margins of the estuary by Gilbert (1917, p. 76) and Nichols and Wright (1971). The locations of older shorelines are estimated by projecting sea-level changes during the past 10,000 years (i.e., water levels in a bathtub) onto maps of the land surface that was inundated by the growing estuary during this time (i.e., the sides of the bathtub). We assume the following sea levels, expressed relative to present mean sea level and based on data from the southern arm of the estuary (fig. 2; Atwater, Hedel, and Helley, unpub. data): 4,000 years ago, -6.4 m (-21 ft); 8,000 years ago, -16.0 m (-53 ft); and 10,000 years ago, -56.0 m (-183 ft). The topography of the land surface inundated by the San Francisco Bay estuary is modified from reconstructions by Goldman (1969, plate 3) and the U.S. Army Corps of Engineers (1963, plates 6-7). These topographic reconstructions are most accurate for the southern arm of the estuary and least accurate for the open-water areas of the northern part of the estuary because of variations in the abundance and quality of bore-hole data.

Plate 2.--Historic changes in the distribution of natural tidal marshes of the San Francisco Bay estuary. Marshes of the San Joaquin- Sacramento Delta ca. 1850 are traced from a photographic enlargement of a map by Gilbert (1917, p. 76; scale 1:887,000). Marshes fringing the remainder of the estuary are traced from a photographic reduction of a map by Nichols and Wright (1971; scale 1:125,000). The map by Nichols and Wright is a compilation of plane-table sheets, most of which were drawn by topographers of the U. S. Coast Survey between 1850 and 1860 (original scale generally 1:10,000). Modern marshes subject to natural tidal inundation are sketched from a land-use planning map by the San Francisco Bay Conservation and Development Commission (1969; scale approximately 1:250,000) and from topographic maps published by the U. S. Geological Survey (1968 and 1973 editions; scale 1:24,000). Some marshes smaller than 0.1 km^2 may be omitted from our compilation.

Plate 1.--Shorelines of the San Francisco Bay estuary during the past 10,000 years. The 125-year-old shoreline is based on maps of the historic margins of the estuary by Gilbert (1917, p. 76) and Nichols and Wright (1971). The locations of older shorelines are estimated by projecting sea-level changes during the past 10,000 years (i.e., water levels in a bathtub) onto maps of the land surface that was inundated by the growing estuary during this time (i.e., the sides of the bathtub). We assume the following sea levels, expressed relative to present mean sea level and based on data from the southern arm of the estuary (fig. 2; Atwater, Hedel, and Helley, unpub. data): 4,000 years ago, -6.4 m (-21 ft); 8,000 years ago, -16.0 m (-53 ft); and 10,000 years ago, -56.0 m (-183 ft). The topography of the land surface inundated by the San Francisco Bay estuary is modified from reconstructions by Goldman (1969, plate 3) and the U.S. Army Corps of Engineers (1963, plates 6-7). These topographic reconstructions are most accurate for the southern arm of the estuary and least accurate for the open-water areas of the northern part of the estuary because of variations in the abundance and quality of bore-hole data.

Plate 2.--Historic changes in the distribution of natural tidal marshes of the San Francisco Bay estuary. Marshes of the San Joaquin- Sacramento Delta ca. 1850 are traced from a photographic enlargement of a map by Gilbert (1917, p. 76; scale 1:887,000). Marshes fringing the remainder of the estuary are traced from a photographic reduction of a map by Nichols and Wright (1971; scale 1:125,000). The map by Nichols and Wright is a compilation of plane-table sheets, most of which were drawn by topographers of the U. S. Coast Survey between 1850 and 1860 (original scale generally 1:10,000). Modern marshes subject to natural tidal inundation are sketched from a land-use planning map by the San Francisco Bay Conservation and Development Commission (1969; scale approximately 1:250,000) and from topographic maps published by the U. S. Geological Survey (1968 and 1973 editions; scale 1:24,000). Some marshes smaller than 0.1 km^2 may be omitted from our compilation.