Late Quaternary Depositional History, Holocene Sea-Level Changes, and Vertical Crustal Movement, Southern San Francisco Bay, California

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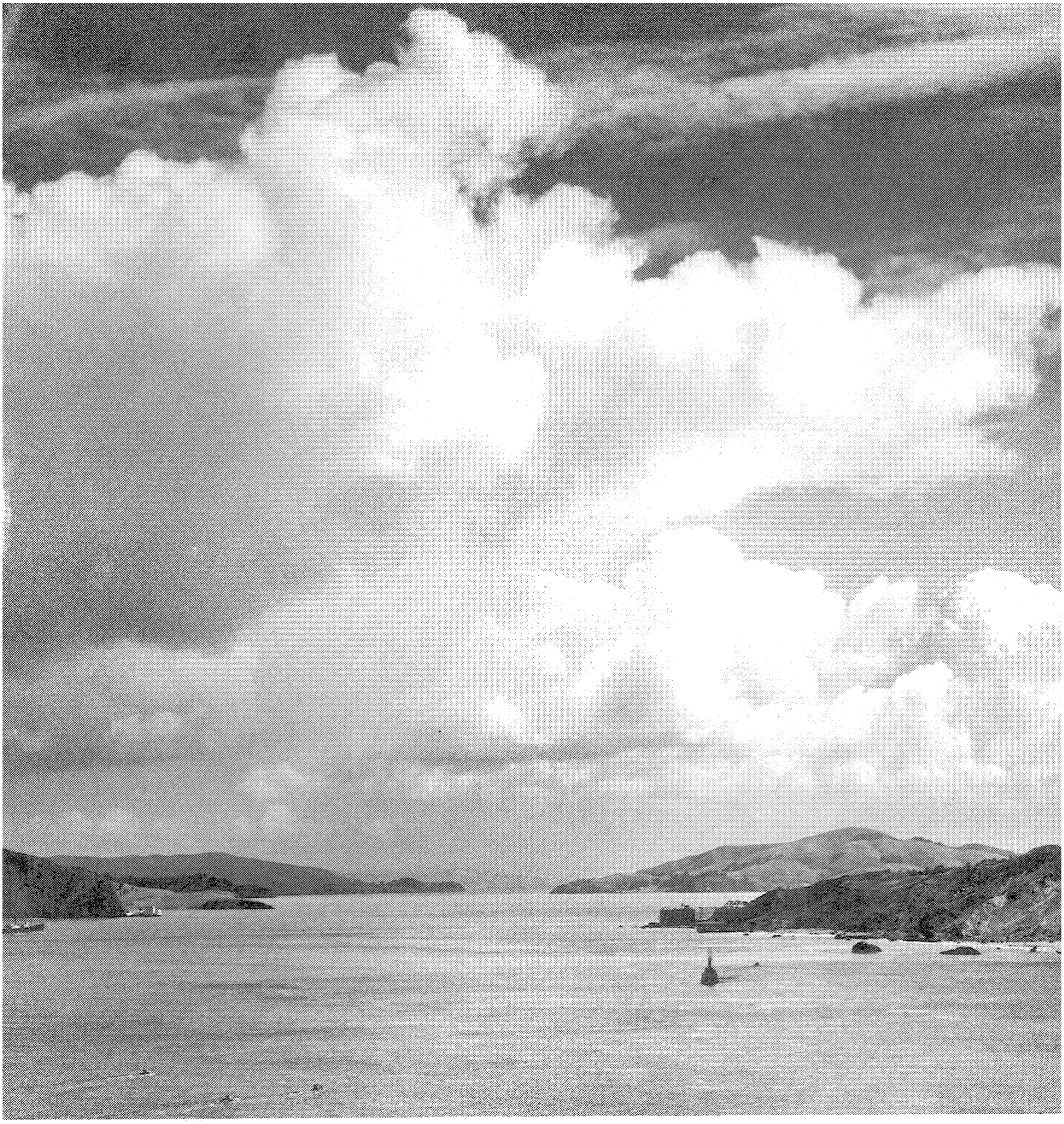

THE GOLDEN GATE

Entrance to San Francisco Bay, 1933. This is the way the entrance to the bay probably looked before settlement by man. View is northeast from above the Pacific Ocean. Today, the nearest points of land are spanned by the Golden Gate Bridge. The strait framed by the Golden Gate separates the Tiburon Peninsula (left) from Angel Island (right). The combined San Joaquin and Sacramento Rivers flowed through canyons now occupied by the distant strait and the Golden Gate 15,000 years ago. Photograph by Ansel Adams.

Late Quaternary Depositional History, Holocene Sea-Level Changes, and Vertical Crustal Movement, Southern San Francisco Bay, California

By BRIAN F. ATWATER, CHARLES W. HEDEL, *and* EDWARD J. HELLEY

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By Brian F. Atwater, Charles W. Hedel, and Edward J. Helley

ABSTRACT

Sediments collected for bridge foundation studies at southern San Francisco Bay, Calif., record estuaries that formed during Sangamon (100,000 years ago) and post-Wisconsin (less than 10,000 years ago) high stands of sea level. The estuarine deposits of Sangamon and post-Wisconsin ages are separated by alluvial and eolian deposits and by erosional unconformities and surfaces of nondeposition, features that indicate lowered base levels and oceanward migrations of the shoreline accompanying low stands of the sea. Estuarine deposits of mid-Wisconsin age appear to be absent, suggesting that sea level was not near its present height 30,000–40,000 years ago in central California.

Holocene sea-level changes are measured from the elevations and apparent ^{14}C ages of plant remains from 13 core samples. Uncertainties of ±2 to ±4 m in the elevations of the dated sea levels represent the sum of errors in determination of (1) sample elevation relative to present sea level, (2) sample elevation relative to sea level at the time of accumulation of the dated material, and (3) postdepositional subsidence of the sample due to compaction of underlying sediments.

Sea level in the vicinity of southern San Francisco Bay rose about 2 cm/yr from 9,500 to 8,000 years ago. The rate of relative sea-level rise then declined about tenfold from 8,000 to 6,000 years ago, and it has averaged 0.1–0.2 cm/yr from 6,000 years ago to the present. This submergence history indicates that the rising sea entered the Golden Gate 10,000–11,000 years ago and spread across land areas as rapidly as 30 m/yr until 8,000 years ago. Subsequent shoreline changes were more gradual because of the decrease in rate of sea-level rise.

Some of the sediments under southern San Francisco Bay appear to be below the level at which they initially accumulated. The vertical crustal movement suggested by these sediments may be summarized as follows: (1) Some Quaternary(?) sediments have sustained at least 100 m of tectonic subsidence in less than 1.5 million years (< 0.07 mm/yr) relative to the likely elevation of the lowest Pleistocene land surface; (2) the deepest Sangamon estuarine deposits subsided tectonically about 20–40 m in about 0.1 million years (0.2±0.1–0.4±0.1 mm/yr) relative to the assumed initial elevations of the thalwegs buried by these sediments; and (3) Holocene salt-marsh deposits have undergone about 5 m of tectonic and possibly isostatic subsidence in about 6,000 years (0.8±0.7 mm/yr) relative to elevations which might be expected from eustatic sea-level changes alone.

INTRODUCTION

Geologists long ago recognized geomorphic evidence of late Quaternary sea-level changes in the San Francisco Bay area. Lawson (1894, p. 266) interpreted the numerous islands, peninsulas, and small embayments near San Francisco (fig. 1) as former hills, ridges, and stream valleys recently submerged by the sea. He suggested that San Francisco Bay did not exist prior to this submergence and that the ancestral drainage of the San Joaquin-Sacramento Rivers flowed through the Golden Gate to a coastline some distance west of the present one. Gilbert (1917, p. 16–24) cited partial submergence of aboriginal shell mounds and historic retreat of the bayward edges of salt marshes as evidence of an ongoing relative sea-level rise.

Both Lawson and Gilbert initially attributed these sea-level changes to tectonic subsidence of the land. Subsequently, Louderback (1941; 1951, p. 84, 86) suggested that San Francisco Bay was created by a worldwide sea-level rise of about 100 m caused by melting of late Pleistocene (Wisconsin) glaciers.

The purpose of this study is to elucidate the late Quaternary history of the site of southern San Francisco Bay by dating post-Wisconsin sea levels, documenting earlier sea-level fluctuations, and measuring vertical crustal movement. This history contributes to the understanding of the recent sedimentary and tectonic history of the densely populated area around southern San Francisco Bay. In addition, it accounts for the foundation characteristics of late Quaternary sediments beneath and peripheral to the bay. Finally, it provides a time perspective on the principal geographic features of the San Francisco Bay area.

ACKNOWLEDGMENTS

Most of the core samples on which this study is based were collected and logged by the California Division of Bay Toll Crossings. State engineers and geologists who participated in bridge foundation

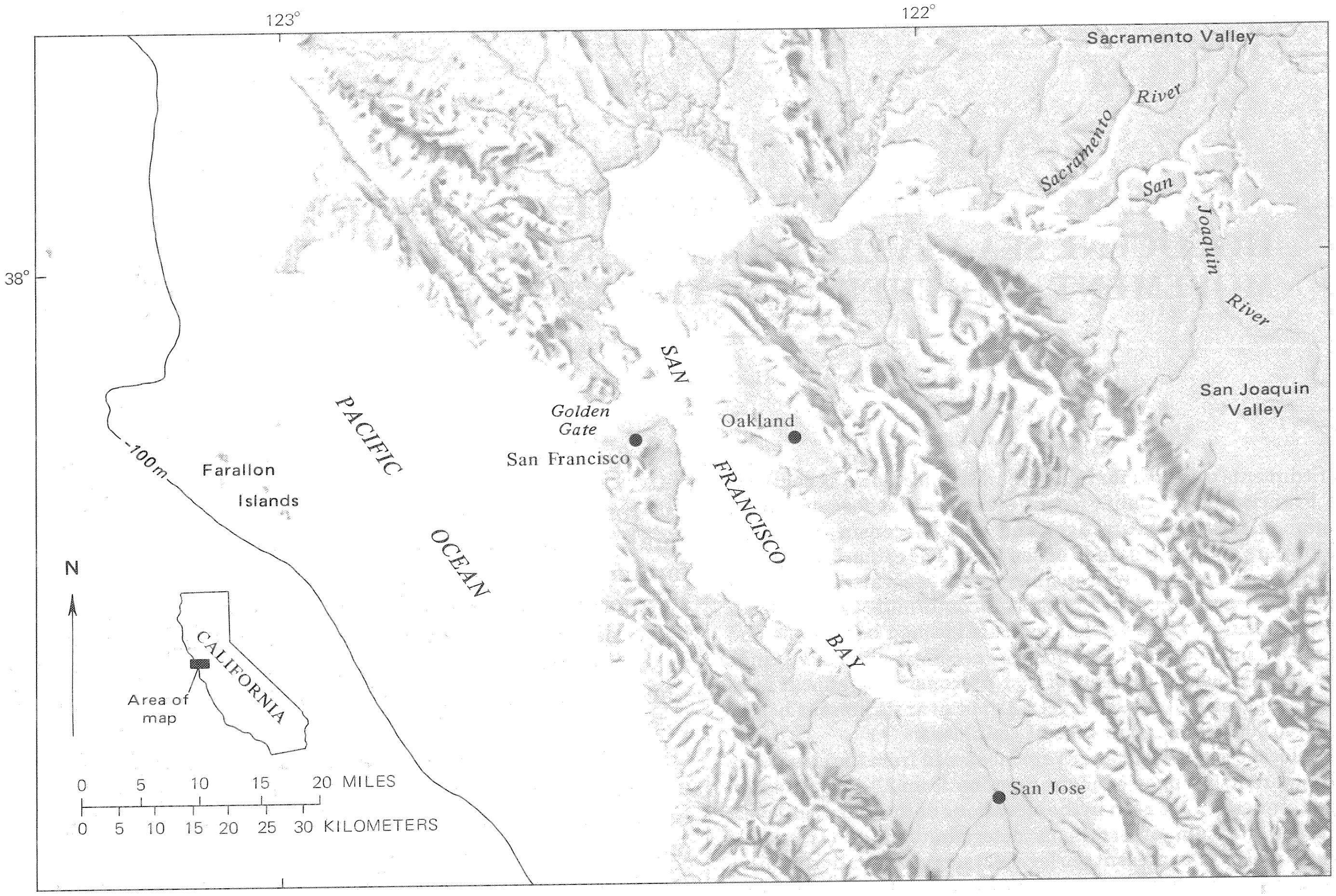

FIGURE 1.—Modern San Francisco Bay and adjacent continental-shelf area. As used in this report, southern San Francisco Bay refers to the part of the bay that lies south of the latitude of the Golden Gate. The 100-m isobath approximates the shoreline position 15,000 years ago.

studies include: S. K. Atkinson, T. Baker, R. H. Barnwell, C. C. Bohannon, F. R. Carraro, T. Daukas, J. W. Driskill, G. G. Emerson, T. Fox, S. Hernon, H. S. Hunt, S. Kelsey, M. C. Knickelbein, B. McCreary, J. Marzotto, M. Matsumoto, D. Morgan, J. M. Oxendine, J. W. Rolston, R. S. Samuelson, W. R. Schott, W. M. Schwartz, P. D. Trask, C. Venskus, and J. E. Wright. Fossil identifications for this report were made by W. O. Addicott (mollusks and barnacles), J. A. Barron and C. W. Hedel (diatoms), R. E. Arnal and B. F. Atwater (foraminifers), and P. C. Valentine (ostracodes). Photographs of pelecypods were taken by Kenji Sakamoto, and scanning electron micrographs of microfossils were taken by Robert L. Oscarson.

METHODS

The stratigraphy developed in this paper is based on samples collected for bridge foundation studies. Since 1946 the California Division of Bay Toll Crossings has contracted the drilling of approximately 600 boreholes into sediments under southern San Francisco Bay. All of the boreholes penetrated firm terrestrial sediments beneath Holocene estuarine deposits, and some extended more than 100 m below sea level.

Borehole information assembled by Bay Toll Crossings engineers consists of samples, hand specimen descriptions, stratigraphic cross sections, and the results of soil-mechanics tests. The samples, representing 20-50 percent of the drilled sediments, were collected in metal tubes 5-8 cm in diameter. Some samples were sealed in the tubes, whereas others were extruded and placed in glass jars. Many of the sealed tube samples were subsequently destroyed during laboratory tests. About 5,000 remaining tube and jar samples have been donated to the U.S. Geological Survey.

Most Bay Toll Crossings samples have changed during storage. Holocene estuarine deposits have undergone the most obvious alteration, including precipitation of gypsum and jarosite (Andrei Sarna-Wojcicki and Julius Schlocker, oral commun., 1974), replacement of framboidal pyrite by limonite, and color changes from gray to olive and brown. In addition, calcareous fossils may have dissolved in these sediments because of oxidation of pyrite or other reactions that increase the concentration of hydrogen ions. However, the common absence or decomposition of calcareous fossils in desiccated samples of Holocene estuarine deposits (such as in borehole 11, section *A-A'*, pl. 1) is probably due to dissolution prior to coring. This natural dissolution is evidenced by the absence of calcareous fossils in many of the fresh core samples we have collected from Holocene estuarine mud.

Sediments from 18 Bay Toll Crossings boreholes were examined for this study. Paleoecological interpretations are based in part on color, texture, authigenic mineralogy, bulk density or moisture content, and penetration resistance of sediments, and on megascopic plant and animal fossils. In addition, splits of about 175 samples from these boreholes were washed through sieves with a mesh opening of 0.063 mm for separation of foraminifers, ostracodes, diatoms, seeds, and microscopic authigenic minerals. Nearly all of these washed samples come from sediments less than 60 m below modern sea level, and most come from Holocene estuarine deposits. Finally, paleoecological interpretations were extrapolated to additional Bay Toll Crossings boreholes using the hand-specimen descriptions and physical properties recorded by the soils engineers.

Carbon-14 dates (pl. 1) were prepared with proportional gas counting techniques by Isotopes, Inc. Because of the small size of samples and the tendency of plant fragments to disintegrate when washed, carbon was obtained by burning entire sample splits rather than by concentrating plant fragments.

LATE QUATERNARY DEPOSITIONAL HISTORY

Numerous worldwide fluctuations of sea level during late Quaternary time are known from marine-terrace and paleoclimatic records, but to date we have discerned only a few corresponding changes in depositional environment at the site of southern San Francisco Bay (fig. 2). Evidence of some fluctuations that are not presently recognized in sediments under the bay may have been removed by erosion. Evidence of others is probably contained in sediments located more than 60 m below sea level and not examined during this study.

ESTUARINE DEPOSITS

Deposits of the earliest known estuary situated in the vicinity of the present southern San Francisco Bay contain a tuff approximately 1 m.y. (million years) old (table 1; Sarna-Wojcicki, 1976) and are consequently of early Pleistocene age. This earliest estuary probably connected with the Pacific Ocean via a shallow marine embayment at the site south of San Francisco in which sediments of the Merced Formation were deposited. These sediments were later deformed and uplifted. Freshwater drained to this estuary from the Great Valley, as evidenced by the presence of Great Valley detritus in a coeval part of the Merced Formation (Hall, 1966).

The youngest known estuarine deposits of Pleistocene age under southern San Francisco Bay were probably produced by Sangamon high stands of the sea. Although no unconformities have been recognized within the Sangamon estuarine deposits, the record of sea levels at New Guinea (fig. 2; Chappell, 1974, p. 568) suggests that the Sangamon estuary may have expanded and contracted several times in response to sea-level changes 70,000–130,000 years ago. The maximum areal extent of the Sangamon estuary was probably at least as great as that of the post-Wisconsin estuary because, despite postdepositional erosion, Sangamon estuarine deposits underlie most of the area of the post-Wisconsin estuarine deposits (pl. 1).

Data from the Atlantic continental shelf of the United States suggest that sea level approached its present height 30,000–40,000 years ago (middle Wisconsin) (Milliman and Emery, 1968). Estuarine sediments of this age appear to be absent under southern San Francisco Bay. Presumably, if the volume of estuarine deposits that would have accumulated at the site of southern San Francisco Bay during this high stand of sea level would be comparable to the volume that has accumulated during post-Wisconsin time, a considerable part of these middle Wisconsin estuarine sediments should have survived late Wisconsin erosion, as suggested by the preservation of large volumes of Sangamon estuarine deposits (pl. 1). Consequently, the apparent absence of middle Wisconsin estuarine deposits under southern San Francisco Bay indicates that local sea level did not approach its present height 30,000–40,000 years ago. The improbability of a middle Wisconsin high stand of the sea in California has also been argued by Birkeland (1972, p. 446), who cited the general absence of post-Sangamon marine terraces in central and southern California.

Estuarine sediments have accumulated at the site of southern San Francisco Bay during the past 10,000 years in response to the post-Wisconsin sea-level rise. Representative fossils from these sediments are illustrated in figures 3 and 4.

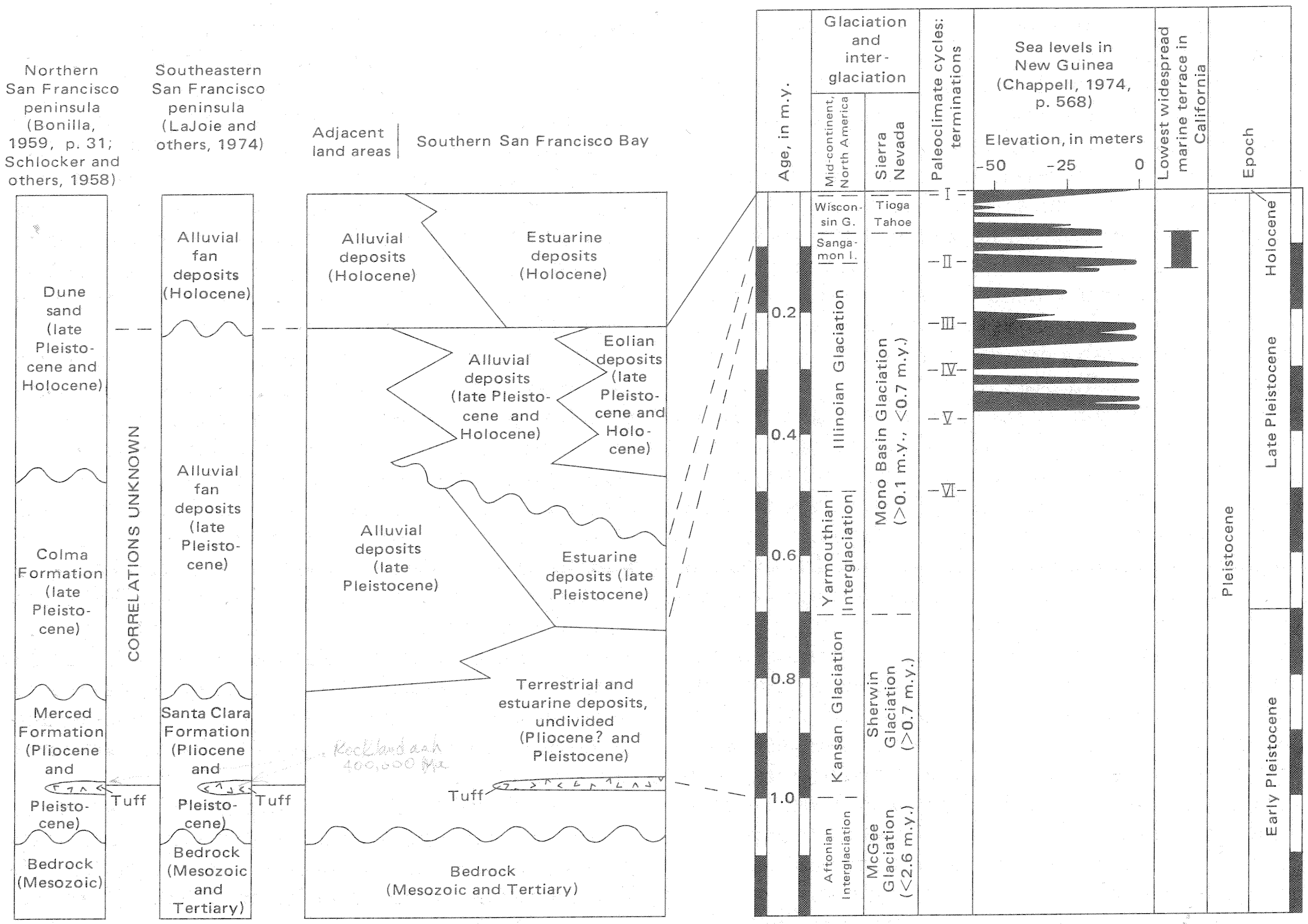

FIGURE 2.—Chronology for sediments under southern San Francisco Bay and their time-stratigraphic correlation with sediments of adjacent land areas, with late Quaternary glacial, climatic, and sea-level events, and with the lowest widespread marine terrace in California. Correlations are approximate where lines are dashed. Vertical scale of right side of main stratigraphic column is approximately proportional to thickness of units near borehole 2 (map, pl. 1). Wavy lines indicate unconformities, zig-zag lines indicate interfingering of time-equivalent units. Glacial chronology for mid-continental North America and epoch boundaries after Berggren and VanCouvering (1974, p. 144); glacial chronology for Sierra Nevada after Wahrhaftig and Birman (1965, p. 308, 331); paleoclimatic cycles from Broecker and VanDonk (1970, p. 181); age range of marine terrace from compilation by Birkeland (1972, p. 443). Correlation of tuff in type Merced Formation after Sarna-Wojcicki (1976). Radiometric ages of this tuff range from 0.4 to 2.6 m.y., but the most probable age is around 1.0 m.y. (A. Sarna-Wojcicki, written commun., 1975; see table 2).

TERRESTRIAL DEPOSITS

Estuarine deposits of different ages under southern San Francisco Bay are separated by alluvial and eolian sediments and by erosional unconformities and surfaces of nondeposition. These features indicate lowered base levels and oceanward migrations of the shoreline accompanying low stands of the sea.

Alluvial deposits of Wisconsin age under southern San Francisco Bay were not recognized by Louderback (1951, p. 87–88) and Treasher (1963, p. 24). These authors apparently mistook alluvial sediments for desiccated estuarine deposits. Presumably, the Sangamon estuarine deposits exposed at the Wisconsin land surface sustained oxidation, desiccation, leaching of calcareous fossils, and penetration by roots to a depth of several meters. Sediments between the Sangamon and post-Wisconsin estuarine deposits, however, average 15-25 m in thickness, contain much more sand and gravel than the adjacent estuarine deposits, and lack foraminifers, diatoms, and estuarine molluscs (pl. 1). Consequently, we interpret most of the Posey Formation of Trask and Rolston (1951) and much of the older bay mud of Treasher (1963) as alluvial deposits rather than desiccated estuarine sediments (fig. 5).

Eolian sands of Wisconsin age under southern San Francisco Bay were probably derived from flood plains and beaches on the broad continental shelf that was exposed during low sea-level stands. These sands were transported across low-lying parts of San

TABLE 1.—*Description and interpretation of sediments and bedrock under southern San Francisco Bay*

Color notations given according to the Munsell system

Unit	Lithology	Stratigraphy	Age	Environment of deposition	Correlations
Estuarine deposits (Holocene; post-Wisconsin).	Clay and silty clay with rare sand and gravel. Dark gray (5Y 3/0.5 to 5Y 4/1) fresh, dark grayish brown (2.5Y 4/2) and olive gray (5Y 4/2) in oxidized samples. Commonly contain framboidal pyrite. Slight to strong H_2S odor. Gypsum, limonite, and jarosite present in desiccated samples. Soft and normally consolidated; bulk density 1.45-1.75 g/cm^3, higher in sand and lower in peaty mud; moisture content 40-90 percent, lower in sand and higher in peaty mud. Typically contain diatoms, pelecypods, and foraminifers; rarely contain ostracodes. Locally include peaty muds containing roots and sparse seeds of estuarine marsh plants.	Cover stream valleys, alluvial fans, and sand dunes of latest Pleistocene (Wisconsin) and early Holocene age. Locally interfinger with late Holocene alluvium at margins of present estuary. Maximum thickness about 40 m over drowned valleys near San Francisco.	Presently forming. Oldest dated deposits approximately 9,300 years ago; oldest deposits near Golden Gate, if preserved, probably 10,000-11,000 years ago.	Ca. 9,500 years ago: small brackish estuary extending no further south than Hunters Point. Ca. 9,500-7,000 years ago: rapidly enlarging estuary, progressively less diluted by fresh water and locally fringed by tidal marshes Ca. 7,000 years ago to 1850 A.D.: slowly enlarging estuary with fringing salt marshes that have prograded during the past several thousand years.	Equivalent to bay mud of Trask and Rolston (1951) and to normally consolidated member of younger bay mud of Treasher (1963, p. 15).
Alluvial deposits (late Pleistocene and Holocene; Wisconsin in part).	Clay, silt, sand, gravel, and rare peat. Graded sequences common beneath contact with Holocene estuarine deposits. Inorganic sediments gray, brown, and yellowish brown; peat black; clay and silt commonly mottled. Fine-grained sediments firm to stiff, overconsolidated: bulk density 1.9-2.2 g/cm^3 (120-135 lb/ft^3), moisture content 15-25 percent; softer gray clay and silt locally present immediately beneath Holocene estuarine deposits. Bulk density of peat 1.3-1.5 g/cm^3 (80-95 lb/ft^3). Fine-grained deposits contain sparse roots and root molds; peats contain at least 50 percent plant remains, commonly including *Scirpus*(?) seeds.	Disconformably overlie Sangamon(?) estuarine deposits. Thickness typically increases southeastward from less than 15 m near San Francisco to more than 25 m between Menlo Park and Fremont (pl. 1, *C-C'*).	Oldest deposits over 40,000 years old but probably less than 100,000 years old. Include late Holocene deposits under margins of southern San Francisco Bay.	Alluvial fans and trunk stream of valley now occupied by southern San Francisco Bay estuary. Trunk stream was a tributary to ancestral San Joaquin-Sacramento Rivers. Peats immediately beneath Holocene estuarine deposits near San Francisco record freshwater-marsh conditions in valleys that were probably ponded as base levels rose rapidly in response to early Holocene sea-level changes.	Coeval with Holocene and late Pleistocene alluvial fan deposits of Helley, Lajoie, and Burke (1972). Include Posey Formation of Trask and Rolston (1951), some basal peat in bay mud of Trask and Rolston (1951), preconsolidated member of younger bay mud of Treasher (1963, p. 15), and part of sand deposits and bay mud of Treasher (1963, p. 15).
Eolian deposits (late Pleistocene and Holocene; Wisconsin in part).	Fine- and medium-grained sand with subordinate silt. Sand grains angular to rounded, mainly subrounded and rounded. Yellowish brown, dark grayish brown (2.5Y 4/2), and olive gray (5Y 4/2.5). Bulk density 1.9-2.2 g/cm^3, moisture content 15-25 percent. Remains of burrowing estuarine invertebrates locally present at contact with Holocene estuarine deposits.	Overlie and locally may interfinger with Wisconsin alluvial deposits. Probably extend southeastward from Golden Gate to the vicinity of San Mateo (pl. 1, map). Maximum thickness, near Oakland, at least 15 m (Trask and Rolston, 1951, p. 1104).	Overlie peaty sediments older than 40,000 years in borehole 7 (pl. 1, *A-A'*); therefore, oldest eolian deposits may be over 40,000 years old. Deposition may have persisted into Holocene time, but most eolian deposits probably accumulated during latest Pleistocene (Wisconsin) time.	Dunes locally separated by stream valleys and bedrock hills. Sand derived from flood plains and beaches on broad continental shelf exposed during lower sea-level stands and transported from the west across low-lying parts of San Francisco and through Golden Gate (Cooper, 1967, p. 48-52). Extensive primary beach sands of Holocene age in southern San Francisco Bay are unlikely because of the predominance of clay-size sediments in known Holocene shoreline deposits. A fluvial environment for eolian deposits is excluded by their height above presumably coeval fluvial deposits and by their uniform grain size.	Lithologically correlative and probably coeval with some of extensive dune sands in San Francisco (Cooper, 1967; Schlocker and others, 1958; Bonilla, 1965) and with the Merritt Sand in Oakland (Lawson, 1914, p. 15). Equivalent to most of the Merritt Sand of Trask and Rolston (1951) and to some of the sand deposits of Treasher (1963, p. 15).
Estuarine deposits (late Pleistocene; Sangamon).	Clay and silty clay with rare sand and gravel. Dark greenish gray (5GY 4/1) fresh, commonly altering to olive gray and dark grayish brown during storage; locally mottled immediately beneath unconformable contact with fluvial deposits. Gypsum commonly precipitated during storage. Typically firm and slightly overconsolidated: bulk density 1.7-1.85 g/cm^3, moisture content 30-50 percent; locally stiffer near unconformable contact with Wisconsin sediments.	Overlie pre-Sangamon terrestrial deposits. Maximum thickness approximately 30 m.	Disconformably overlain by terrestrial deposits over 40,000 years old in borehole 7 (pl. 1 *A-A'*); therefore older than 40,000 years. Separated from underlying tuff of Merced Formation (1.1±0.4 m.y. old) by at least 20 m of alluvial sediments and at least one major unconformity in borehole 2 (location of this borehole shown on map, pl. 1).	Estuary probably similar in size and shape to the Holocene San Francisco Bay. Water depths of at least 20-40 m near mouth of estuary indicated by molluscan assemblage east of Yerba Buena Island (W. O. Addicott, written comm., 1973; sample elevation 45 m below present sea level).	Probably coeval with the lowest widespread marine terrace of coastal California (fig. 2) and with some of the late Pleistocene alluvial fan deposits of Helley, Lajoie, and Burke (1972). Include most of the San Antonio Formation.

Table 1.—*Description and interpretation of sediments and bedrock under San Francisco Bay—Continued*

Unit	Lithology	Stratigraphy	Age	Environment of deposition	Correlations
Estuarine deposits (late Pleistocene; Sangamon)—Continued	Commonly contain estuarine diatoms, pelecypods, and foraminifers similar to those in Holocene deposits. Locally include peaty clays near contact with older terrestrial deposits.		Represent the youngest major Pleistocene high sea-level stand, as shown by their great extent and thickness and by the apparent absence of overlying pre-Holocene estuarine deposits. Therefore correlated with the Sangamon Interglaciation and regarded as 75,000–125,000 years old.		
Terrestrial and estuarine deposits, undivided (Pliocene? to late Pleistocene).	Clay, silt, sand, and gravel. Estuarine deposits contain sparse mollusks, foraminifers, ostracodes, and diatoms and include a tuff 87 m below present sea level in borehole 2 (location of this borehole shown on map, pl. 1). This tuff correlates with a tuff in the type Merced Formation (Sarna-Wojcicki, 1976).	Unconformably overlie Mesozoic and Tertiary(?) rocks. Extend at least 130 m below sea level east of Yerba Buena Island (Trask and Rolston, 1951, p. 1081) and at least 200 m below sea level in *B-B'* and *C-C'* (pl. 1) (Finlayson and others, 1967, pl. 5; Meade, 1967, p. 40–41).	Oldest deposits probably Pliocene, youngest deposits coeval with Sangamon estuary. Potassium-argon dates on tuff in type Merced Formation are 0.44±0.18 m.y., 0.7±0.5 m.y., 1.1±0.5 m.y., 2.1±0.3 m.y. (G. B. Dalrymple and M. Lanphere, written commun., 1975), and 1.5±0.8 m.y.(Hall, 1966). A fission-track date on this tuff is 1.1±0.4 m.y. (C. Naeser, written commun., 1974).	Basins subjected to oscillating sea levels and modified by tectonic processes. Basins of about 1 m.y. ago disrupted by later folding and faulting (Lajoie and others, 1974).	Pliocene(?) and early Pleistocene sediments coeval with Merced and Santa Clara Formations. Younger sediments possibly coeval with some of late Pleistocene alluvial fan deposits of Helley, Lajoie, and Burke (1972). Equivalent to parts of Alameda Formation (Trask and Rolston, 1951) and older bay mud of Treasher (1963, p. 15).
Bedrock (Mesozoic and Tertiary).	Predominantly clastic sedimentary rocks and igneous rocks, in part altered by low-temperature metamorphism.	Late Mesozoic Franciscan rocks and serpentinite form the known stratigraphic and structural basement. Although directly overlain by Quaternary deposits near San Francisco, Franciscan rocks may be mantled by other Mesozoic or Tertiary rocks under other parts of southern San Francisco Bay.		These rocks formed in various ancient marine, continental, and plutonic environments that were subsequently destroyed by crustal movement.	

Francisco by prevailing westerly winds (Cooper, 1967, p. 48–52).

The lowest base level at the Golden Gate during Wisconsin time was probably about 70 m below present sea level. This base level is suggested by bedrock sills located about 5 km east and northeast of the Golden Gate, the lowest of which is 65 m below present sea level (Carlson and McCulloch, 1970). Consequently, assuming that sea level during the late Wisconsin glacial maximum stood about 100 m below present sea level (Flint, 1971, p. 322), the late Wisconsin shoreline must have been located west of the Golden Gate on what is now the continental shelf (fig. 1).

Plant fossils dated at 23,600 years old and found 10 km southeast of Menlo Park (map, pl. 1) about 8 m below present sea level show a relative abundance of cedar and Douglas fir and a relative scarcity of oak and redwood, thus suggesting a cooler, wetter climate than today (David P. Adam, oral commun., 1973). Associated animal fossils indicate that Rancholabrean vertebrates, including camels, bison, horses, sloths, and mammoths, roamed the late Wisconsin valley now occupied by southern San Francisco Bay (Edward J. Helley and Kenneth R. Lajoie, unpub. data).

HOLOCENE SEA LEVELS

RELATION OF DATED SAMPLES TO FORMER SEA LEVELS

Holocene sea levels are typically dated by the radiocarbon ages of plant or animal remains that initially accumulated near sea level. The roots of salt-marsh plants are the principal materials dated for this study and represent upper intertidal conditions. Additional control on the age of former sea levels is given by dated plant remains from intertidal or uppermost subtidal environments and from predominantly freshwater marsh environments at or above the highest tides (table 2).

SALT-MARSH DEPOSITS

With the possible exception of eelgrass (*Zostera*), an aquatic plant which is very rare or absent in San Francisco Bay today, plants which inhabit salt marshes are the only ones that can produce peaty estuarine muds composed largely of roots in growth positions. Therefore the principal feature of salt-marsh deposits that differentiates them from other estuarine sediments is the abundance of roots in growth positions. Additional diagnostic characteristics of salt-marsh deposits include a typical abundance of arenaceous foraminifers, a scarcity or

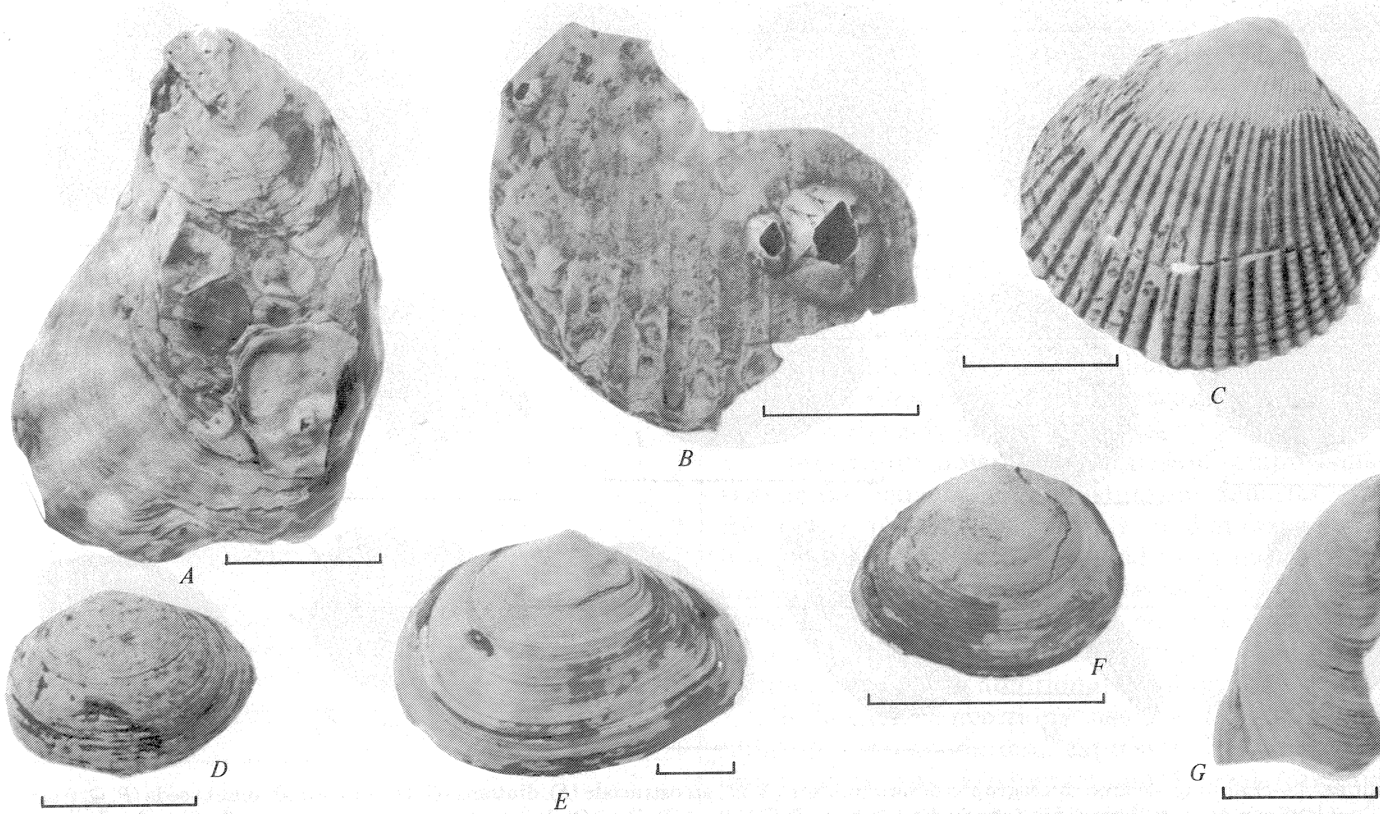

FIGURE 3.—Representative pelecypods from post-Wisconsin estuarine sediments under southern San Francisco Bay. Scale bar represents 1 cm. *A, Ostrea lurida* Carpenter; *B, Balanus* sp. (barnacle) attached to a fragment of *Clinocardium* cf. *C. nuttalli* (Conrad); *C, Clinocardium nuttalli* (Conrad); *D, Cryptomya californica* (Conrad); *E, Macoma nasuta* (Conrad); *F, Macoma balthica* (Linné); *G, Mytilus edulis* (Linné), fragment.

absence of calcareous fossils (Phleger, 1970, p. 532–533), and a local abundance of framboidal pyrite and insect remains (table 2).

The salt-marsh deposits used to date sea-level changes were collected at or slightly above the contact between Holocene estuarine deposits and underlying terrestrial sediments, thereby minimizing uncertainties due to postdepositional compaction and settlement. By analogy with the historic salt marshes of southern San Francisco Bay (Hinde, 1951, p. 219; Nichols and Wright, 1971; map, pl. 1), these basal salt-marsh deposits accumulated in the upper intertidal zone at the fringes of the estuary, but at lower sea levels than today. Most of these marshes were eventually submerged by the rising sea as evidenced by the common overlapping of basal salt-marsh deposits by lower intertidal and subtidal sediments.

Salt-marsh deposits were not sampled near the base of Holocene estuarine deposits in some Bay Toll Crossings boreholes, such as numbers 6, 7, 18, 24, 29, and 39 (pl. 1). The apparent absence of basal salt-marsh deposits in these boreholes may be explained in part by gaps between core samples. No basal marsh deposits were found, however, in boreholes 13 and 26–29 (pl. 1), in which basal estuarine sediments were carefully sampled. Collectively, this evidence suggests that salt-marsh plants may have been unable to colonize stretches of Holocene shorelines because the rate of relative sea-level rise exceeded local rates of sedimentation (Bloom, 1967a, p. 36), or that salt-marsh deposits submerged by rising Holocene sea levels may have been locally removed by wave erosion.

INTERTIDAL AND UPPERMOST SUBTIDAL DEPOSITS

Estuarine sediments lacking roots in growth positions, containing shallow-water calcareous fossils, and resting on alluvial or eolian deposits probably accumulated in intertidal or uppermost subtidal environments. The plant remains in these sediments are regarded as detrital.

FRESHWATER MARSH DEPOSITS

Sediments composed dominantly of plant remains, containing *Scirpus*? seeds, and lacking foraminifers and diatoms larger than 0.063 mm are found immediately beneath Holocene estuarine deposits in buried Wisconsin valleys near San Francisco at elevations between -25 and -45 m (*A–A′*, pl. 1; Calif. Div. Bay Toll Crossings, 1966, and unpub. cross sections, 1970). These sediments probably accumulated in marshes located at or above the highest tides. Freshwater marsh deposits do not appear to underlie Holocene estuarine sediments between San

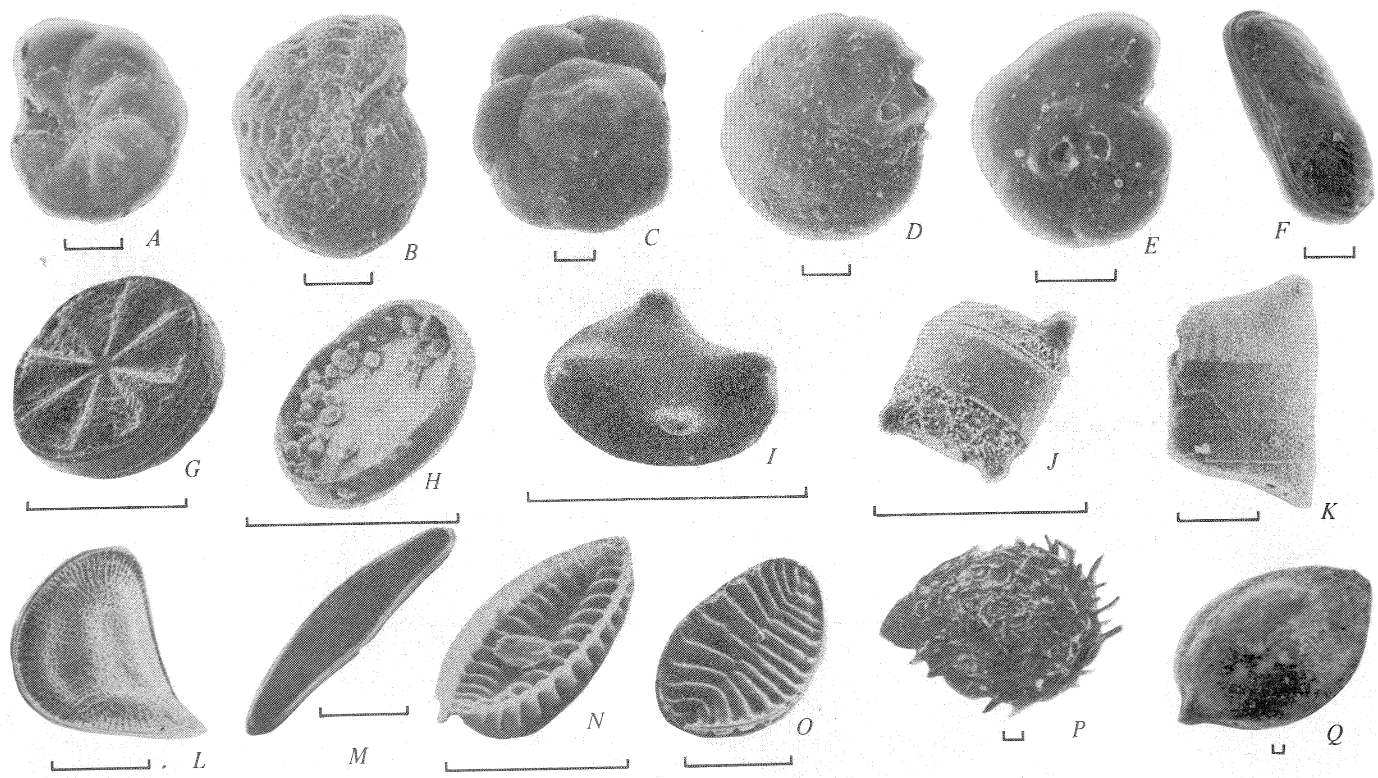

FIGURE 4.—Scanning electron micrographs of foraminifers (*A–E*), an ostracode (*F*), diatoms (*G–O*), and marsh-plant seeds (*P, Q*) from post-Wisconsin estuarine sediments under southern San Francisco Bay. Scale bar represents 0.1 mm. *A, Elphidium incertum obscurum* (Williamson) var. *obscurum* Voloshinova; *B, Elphidium gunteri* Cole; *C, Ammonia beccarii* (Linné); *D, Elphidiella hannai* (Cushman and Grant); *E, Trochammina inflata* (Montagu); *F, Cytheromorpha* sp.; *G, Actinoptychus splendens* (Shadbolt) Ralfs; *H, Coscinodiscus* sp. (note framboidal pyrite in frustule); *I, Aulacodiscus kittoni* Arnott; *J. Biddulphia* sp.; *K, Isthmia nervosa* Kützing; *L, Campylodiscus* sp.; *M, Cymbella* cf. *C. aspera* (Ehrenberg) Cleve; *N, Surirella* sp.; *O, Surirella*? sp.; *P, Salicornia* sp.; *Q, Scirpus*? sp.

Mateo and Hayward and between Menlo Park and Fremont (sections *B–B′* and *C–C′*, pl. 1).

NUMERICAL UNCERTAINTIES IN SEA-LEVEL DATA

The 100–320-year uncertainties in the ^{14}C ages of Holocene sea levels (table 2) incorporate laboratory errors only. Other possible errors are difficult to estimate. The possibility of contamination of salt-marsh deposits by roots of younger marsh plants (Kaye and Barghoorn, 1964, p. 72) is ignored because the resultant decrease in sample age is probably no greater than a few centuries under conditions of rising sea level. The error caused by the time gap between death of plant material and its final accumulation as detritus is also ignored except in borehole 17 (section *B–B′*, pl. 1), where detrital wood must be regarded as reworked fossil material because it is several thousand years older than the associated estuarine sediments.

The elevations of Holocene sea levels are determined by the equation

$$H=h-h_o+s,$$

where H is the elevation of a former sea level, h is the modern sample elevation, h_o is the sample elevation at the time of deposition, and s is the postdepositional subsidence of the sample. Measured and estimated errors contributed by these factors typically total ±2–±4 m in this study.

MODERN SAMPLE ELEVATION (h)

The uncertainty in modern sample elevation (table 2) is the approximate sum of errors in (1) the elevation of the top of the borehole, (2) the depth of the sample interval within the borehole, and (3) the position of the dated sample within the sample interval. This uncertainty averages about ±0.5 m and does not exceed ±1.0 m.

SAMPLE ELEVATION AT TIME OF DEPOSITION (h_o)

The elevation ranges of modern salt-marsh plants approximate the elevations at which Holocene salt-marsh deposits accumulated. The lowest natural surfaces of tidal marshes in the San Francisco Bay estuary are located about 0.5 m below mean sea level and are colonized by cordgrass

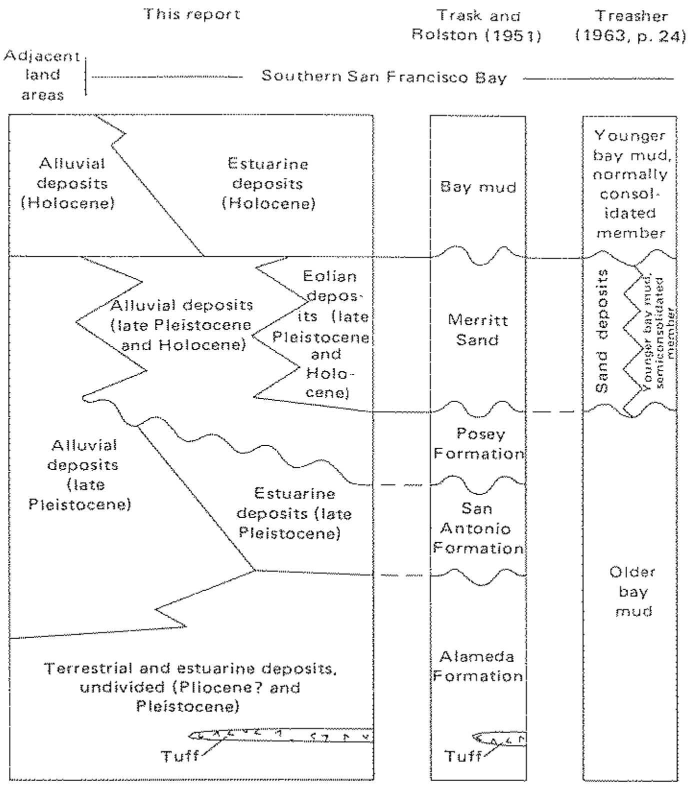

FIGURE 5.—Comparison of stratigraphic nomenclature for sediments under southern San Francisco Bay. Wavy lines indicate unconformities; zig-zag lines indicate interfingering of time-equivalent units. Lines between columns correlate rock-stratigraphic units and are dashed where correlations are approximate.

(*Spartina foliosa*) or tules (predominantly *Scirpus californicus*). These large plants are replaced by smaller plants, predominantly pickleweed (*Salicornia pacifica*) and salt grass (*Distichlis spicata*), at elevations greater than 0.5-1.0 m above mean sea level (Hinde, 1954; Atwater and Hedel, 1976). The highest elevation of abundant *Salicornia* and *Distichlis* approximately equals that of the highest tides, varies geographically with local tidal amplification, and ranges from about 1.5 m above mean sea level near San Francisco to about 2.0 m above mean sea level near Menlo Park.

Although plant remains have not been positively identified, most of the dated tidal-marsh deposits appear to contain the small roots and rhizomes of high-marsh plants (*Salicornia* and *Distichlis*) rather than the robust rhizomes of low-marsh plants (*Spartina* and *Scirpus*). These dated roots and rhizomes probably penetrated a few decimeters below the surfaces of the marshes. Consequently, most of the dated salt-marsh plant remains probably accumulated about 0-1.5 to 0-2.0 m above former mean sea levels, the upper limit varying with local tidal range (table 2).

The paleobathymetry of the dated intertidal or uppermost subtidal deposits has an uncertainty of ±1.5 m. Freshwater marsh deposits provide only upper limits on the elevation of sea level at the time of their accumulation (table 3).

POSTDEPOSITIONAL SUBSIDENCE (*s*)

Postdepositional subsidence (table 2) is likely where sediment overburden has placed a load on compressible sediments beneath the dated samples. Errors in thickness and consolidation of the compressible sediments lead to uncertainties as large as ±2.5 m in the subsidence estimates.

Uncertainty about the thickness of compressible sediments beneath dated estuarine deposits and freshwater peats results from 1- to 3-m discontinuities in sampling between dated horizons and the underlying noncompressible terrestrial deposits. Typically, the location of the contact within the discontinuity is unknown and cannot be determined without very costly additional drilling.

Settlement corrections assume the following ranges of consolidation, expressed in percent of initial thickness: freshwater-marsh peat (organic matter content probably greater than 50 percent), 15-40; salt-marsh mud (organic matter content probably less than 25 percent), 33-67; nonmarsh estuarine mud, 40-80; and soft alluvial clay within 5 m of the dated sample, 80-100. These estimates are based on the following data: (1) freshwater peat buried by 3-10 m of Holocene estuarine mud for 1,000-6,000 years in Connecticut has been compressed to 13-44 percent of its initial thickness (Bloom, 1964, p. 603) and (2) a column of mud with an initial porosity of 80 percent, an initial thickness of 3 m, and an overburden of 30 m will theoretically compress to 50 percent of its initial thickness (Weller, 1959, p. 290).

The settlement corrections generally neglect compaction of Pleistocene estuarine deposits and stiff or coarse-grained terrestrial sediments. Between Menlo Park and Fremont, however, they include about 0.5 m of compaction of Pleistocene clay due to ground water withdrawal (Poland, 1971). Repeated leveling around the margins of southern San Francisco Bay by the U.S. Geological Survey and the U.S. Coast and Geodetic Survey suggests that this historic land subsidence dwindles northwest of Menlo Park and Fremont.

THE HOLOCENE TRANSGRESSION

The small quantity and large uncertainties of sea-level data prevent resolution of low-

TABLE 2.—*Data on Holocene sea levels*

[All linear measurements in meters; see plate 1 for location of boreholes]

Bore-hole No.	Sample elevation relative to modern mean sea level (h)	Principal dated material	Environmental indicators[1]	Sample elevation at time of deposition relative to former mean sea level (h_o)[2]	Postdepositional subsidence (s) of dated sample caused by compaction of underlying sediments (T = thickness of compressible sediments; S = settlement): Holocene estuarine deposits		Late Pleistocene and Holocene terrestrial deposits		Pleistocene deposits, groundwater withdrawal (Poland, 1971)		Elevation of mean sea level at time of accumulation of dated material relative to modern mean sea level (H)	Age and analytical uncertainty in ^{14}C years before 1950 A.D. (half life =5,568 years) (see pl. 1)
					T	S	T	S	S	Total s		
35	-7.9±0.5	Roots of salt-marsh plants.	Abundant roots, probably in growth positions; *Trochammina inflata* (Fa); *Campylodiscus* (Dp).	1.0±1.0	2.0	0.5–3.0	0.0–1.5	0.0–0.4	0.3–0.7	2.4±1.6	-6.5±3.1	3,360±105
25	-6.6±0.3	Fragments of salt-marsh plants.	Abundant plant fragments, probably detrital, and *Salicornia* seeds (A, s); *Elphidium* spp. (Fc); *Ostrea lurida* (P,s); shells broken and probably detrital	-0.5±1.5	0.3–1.0	0.1–1.5	0	0	0	0.8±0.7	-5.3±2.5	3,930±105
36[3]	-9.0±0.3	Roots of salt-marsh plants.	Abundant roots, probably in growth positions; *Trochammina inflata* (Fa); framboidal pyrite.	1.0±1.0	0.0–2.0	0.0–3.0	2.0–3.0	0.0–0.8	0.3–0.7	2.4±2.1	-7.6±3.4	5,745±185
32	-11.4±0.5	do	Abundant roots, probably in growth positions; *Trochammina inflata* (Fa); *Campylodiscus* (Dp).	1.0±1.0	0.0–1.0	0.0–2.0	0.0–1.0	0.0–0.3	0.3–0.7	1.6±1.3	-10.8±2.8	5,845±100
33	-10.8±0.5	do	do	1.0±1.0	0.0–1.0	0.0–2.0	2.0–3.0	0.0–0.8	0.3–0.7	1.9±1.6	-9.9±3.1	6,200±320
12	-11.8±0.5	do	Abundant roots in growth positions; *Trochammina inflata* (Fa); *Cymbella* (Dp).	0.7±0.7	0	0	0	0	0	0	-12.5±1.2	6,485±110
21	-9.2±0.3	do	Abundant roots, probably in growth positions; *Campylodiscus* (Dp).	0.9±0.9	0.5–2.5	0.2–5.0	0	0	0	2.6±2.4	-7.5±3.6	6,855±115
11	-24.6±0.7	do	Abundant roots, probably in growth positions; *Campylodiscus* (Dp); framboidal pyrite.	0.7±0.7	1.5–2.5	0.6–5.0	2.0–3.0	0.0–0.8	0	3.2±2.6	-22.1±4.0	8,230±135
10[3]	-21.0±1.0	do	Abundant roots, probably in growth positions; *Trochammina* sp. (Fa); *Campylodiscus* (Dp), *Hyalodiscus* (Dc).	0.7±0.7	0.0–2.0	0.0–4.0	0.0–2.0	0.0–0.5	0	2.2±2.2	-19.5±3.9	8,295±135
16	-18.7±0.3	do	Abundant roots, probably in growth positions; *Campylodiscus* (Dp).	0.9±0.9	0.0–1.0	0.0–2.0	2.0–3.0	0.0–0.8	0	1.4±1.4	-18.2±2.6	8,365±135
3[3]	-32.5±1.0	Remains of fresh- or brackish-water marsh plants	Abundant roots in growth positions, and abundant *Scirpus?* seeds (A, f); rare limonitized framboidal pyrite.	Probably above highest tides.	0	0	0–2	0–2	0	1±1	Below -31.5±2.0	8,885±145
4	-39.5±0.5	Chunks of wood.	Abundant detrital wood; *Ammonia beccarii, Elphidium* sp. (Fc); *Cytheromorpha* sp. (O); *Cocconeis, Surirella, Cymbella* (Dp); *Valvata* (G, f), *Psidium* (G, f); *Thoecamoebina* (fresh- and brackish-water protozoans); mosquito larvae (R. E. Arnal, written commun., 1974).	0.0±1.5	0	0	0	0	0	0	-39.5±2.0	9,255±310

TABLE 2.—*Data on Holocene sea levels—Continued*

Bore-hole No.	Sample elevation relative to modern mean sea level (*h*)	Principal dated material	Environmental indicators[1]	Sample elevation at time of deposition relative to former mean sea level (h_o)[2]	Postdepositional subsidence (*s*) of dated sample caused by compaction of underlying sediments (T = thickness of compressible sediments; S = settlement): Holocene estuarine deposits T	Holocene estuarine deposits S	Late Pleistocene and Holocene terrestrial deposits T	Late Pleistocene and Holocene terrestrial deposits S	Pleistocene deposits, groundwater withdrawal (Poland, 1971) S	Total *s*	Elevation of mean sea level at time of accumulation of dated material relative to modern mean sea level (*H*)	Age and analytical uncertainty in ^{14}C years before 1950 A.D. (half life =5,568 years) (see pl. 1)
2	-37.5±0.5	Remains of fresh-water marsh plants	Predominance of plant remains over inorganic detritus; abundant *Scirpus*? seeds (A, f).	Above highest tides.	0	0	2-6	0-4	0	2±2	Below -35.5±2.5	9,280±120

[1] Explanation of symbols:
A=marsh angiosperm
Fa = foraminifer, arenaceous; typically lives in salt marshes
Fc = foraminifer, calcareous; typically lives in lower intertidal and subtidal environments
O = ostracode
Dp = diatom, pennate
Dc = diatom, centric
P = pelecypod
G = gastropod
s = salinity range predominantly saltwater and brackish water
f = salinity range predominantly brackish water and freshwater

See figures 3 and 4 for photographs of some of these organisms, and plate 1 for additional ecological information.
[2] Estimates based on analogy with vertical distribution of seed plants, diatoms, and foraminifers (Hinde, 1954; Arnal and others, 1977; Phleger, 1970, p. 532-533) in modern environments.
[3] Borehole not shown on cross sections (pl. 1).

amplitude sea-level oscillations, so a smoothed curve was visually fitted to the data points (fig. 6). This curve displays a more than tenfold decrease in slope between 8,000 and 6,000 years ago. On the average, sea level in the vicinity of southern San Francisco Bay rose about 2 cm/yr from 9,500 to 8,000 years ago, but it has risen only 0.1-0.2 cm/yr from 6,000 years ago to the present. A similar change in rate appears in sea-level records from other parts of the world (for example, Milliman and Emery, 1968) and probably coincides with the disappearance of the large Wisconsin ice sheets (Bloom, 1971, p. 368).

Extrapolation of the sea-level curve to the presumed late Wisconsin base level, located about 65-70 m below modern sea level at the Golden Gate (*A*, fig. 7), indicates that the rising sea entered the Golden Gate 10,000-11,000 years ago. Driven by the sea-level rise of several centimeters per year, an estuary then spread rapidly, advancing about 30 m/yr along the course of the trunk stream draining the site of southern San Francisco Bay and reaching the vicinity of Menlo Park by 8,000 (*G*, fig. 7) years ago (fig. 7). Subsequent shoreline changes have been more gradual because of the decrease in rate of sea-level rise.

A change from predominantly fresh- and brackish-water diatoms in estuarine sediments about 8,500-9,300 years old to predominantly marine diatom assemblages in younger sediments (boreholes 4, 5, 6, section *A-A'*, pl. 1) indicates increasing salinity. This increase was probably caused by the rapid early growth of the estuary. Assuming a nearly constant long term inflow of freshwater, the large increases in water volume accompanying this growth should have resulted in substantially greater

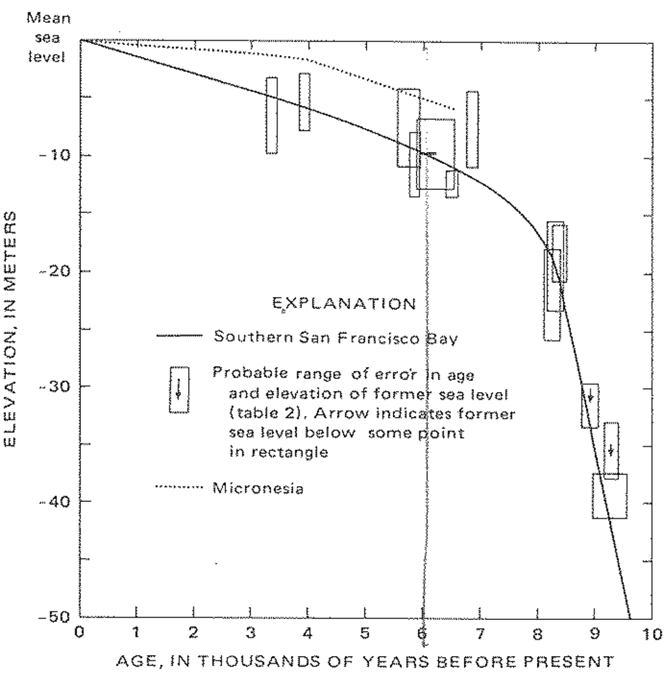

FIGURE 6.—Holocene sea-level changes in the vicinity of southern San Francisco Bay. The curve for Micronesia, shown for comparison, approximates Holocene eustatic sea-level changes according to Bloom (1970, p. 1901).

average water salinities by permitting larger proportions of saltwater to enter the estuary.

Changing rates of sea-level rise largely control the stratigraphic distribution of salt-marsh deposits. The sea-level rise of several centimeters per year probably exceeded most local sedimentation rates, so tidal marshes before 8,000 years ago were scarce and small and, moreover, were ultimately submerged by

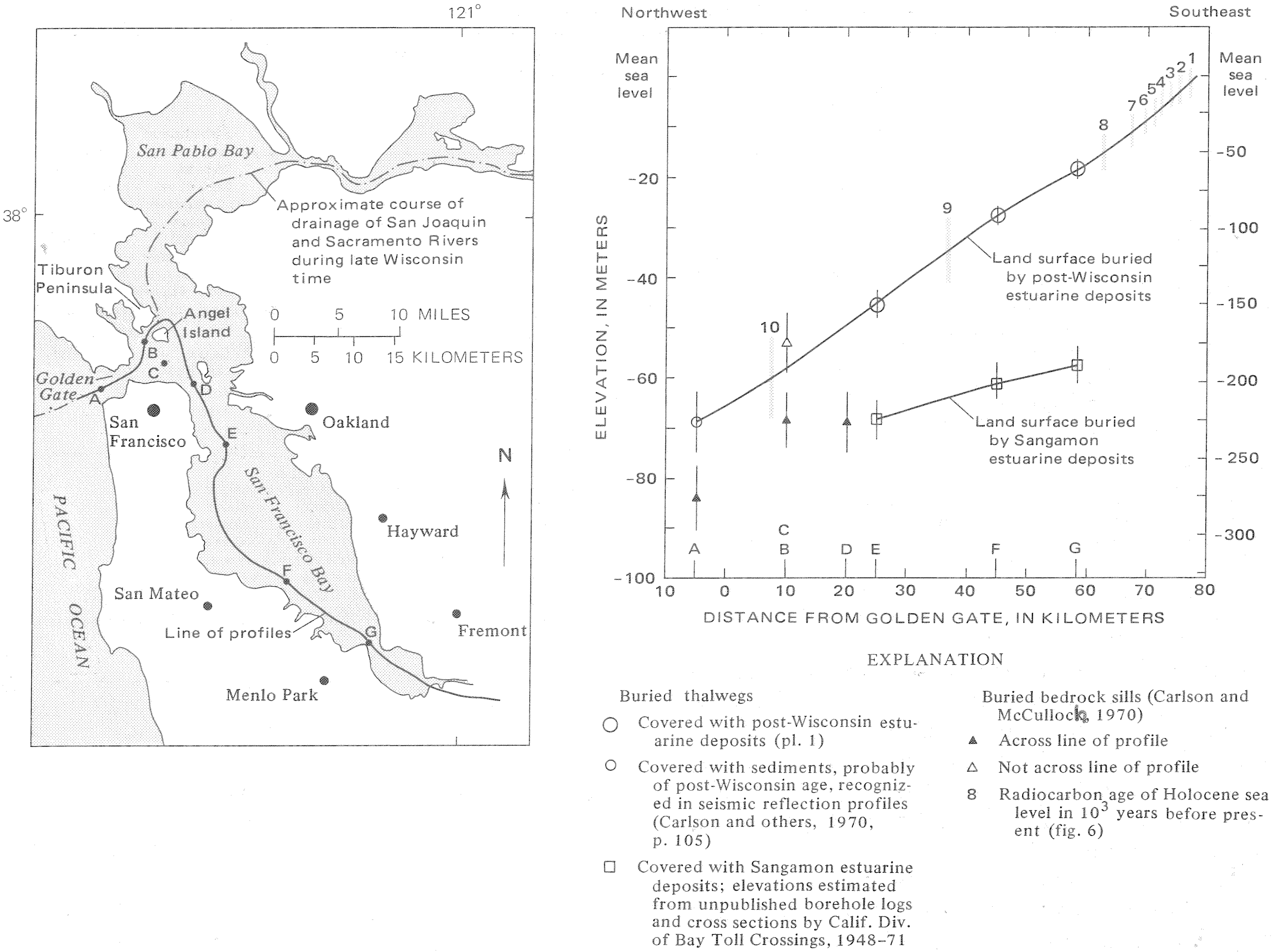

FIGURE 7.—Longitudinal profiles of buried land surfaces under southern San Francisco Bay. Profiles are based primarily on the elevations of buried thalwegs (lines of maximum valley depth) at points A, E, F, and G. Point E is located between boreholes 4 and 5 (*A-A'*, pl. 1), point F, approximately at borehole 17 (*B-B'*, pl. 1), and point G, between boreholes 32 and 34 (*C-C'*, pl. 1). The upper profile is also based on the elevations of bedrock sills (points A, B, and D), which indicate the deepest possible base levels during late Wisconsin time. All vertical bars show approximate uncertainties in elevations of thalwegs and sills. We speculate that the late Wisconsin trunk stream draining the site of southern San Francisco Bay met the drainage of the San Joaquin–Sacramento Rivers north and east of Angel Island because the bedrock sill between Angel Island and Tiburon Peninsula (B) is about 15 m lower than the sill between San Francisco and Angel Island (C); therefore the profile of the land surface buried by post-Wisconsin estuarine deposits loops north of Angel Island. The intersection of Holocene sea levels with this profile shows the rapid longitudinal growth of the post-Wisconsin estuary from 10,000 to 8,000 years ago and the subsequent decline in the rate of longitudinal growth.

the rising sea. Later, the declining rate of sea-level rise was approached and finally surpassed by the rate of sediment accumulation in much of the estuary, permitting progradation of mudflats and salt marshes. Most of the bayward growth of marshes has occurred during the past several thousand years, as evidenced by the lower intertidal and subtidal deposits which typically lie no more than a few meters below mean sea level beneath the historic salt marshes (boreholes 13, 26, 27, 29, 30, 32, 38, 39, sections *B-B'* and *C-C'*, pl. 1).

VERTICAL MOVEMENT OF THE EARTH'S CRUST

EVIDENCE AND RATES OF SUBSIDENCE

Evidence of vertical crustal movement at the site of southern San Francisco Bay was first reported by Lawson (1914, p. 3), who observed that late Cenozoic structural features bound the valley that is partly flooded by the bay. Subsequently, Louderback (1951, p. 83) proposed that the bedrock surface under this valley had been downwarped during Quaternary time. Both men asserted that the valley containing southern San Francisco Bay had been shaped not only by running water but also by vertical tectonic movement of the Earth's crust.

Several additional lines of evidence suggest that subsidence of the valley floor has taken place and permit rough estimates of the rates of subsidence (table 3): (1) Quaternary(?) sediments are situated at least 200 m below present sea level, (2) Wisconsin

TABLE 3.—*Evidence and inferred rates of crustal downwarping in the vicinity of southern San Francisco Bay*

Evidence	Rate (mm/yr)	How measured	Time period	Origin
Quaternary(?) sediments situated at least 200 m below present sea level.	[1]>0.07	Elevation difference between deepest Quaternary sediments and level at which they were probably deposited.	1.5 m.y. (Quaternary)	Tectonic
Wisconsin thalweg situated higher than the deepest Sangamon estuarine deposits.	[2]0.2±0.1 [3]0.4±0.1 [4]0.4±0.1	Differences in elevation between the thalwegs covered with Sangamon and post-Wisconsin estuarine deposits (fig. 6).	0.1 m.y. (late Pleistocene; Sangamon and Wisconsin).	Do.
Relative sea-level rise is greater than that expected from eustatic sea-level changes alone.	[1]0.8±0.7	Comparison of post-Wisconsin sea levels at southern San Francisco Bay with those at Micronesia, an area of presumed crustal stability (fig. 5).	6,000 years (Holocene).	Tectonic and possibly isostatic.

[1]Applies to most of site of southern San Francisco Bay below latitude of Hayward.
[2]Applies to site between boreholes 4 and 5 (*A-A'*, pl. 1).
[3]Applies to site near borehole 17 (*B-B'*, pl. 1).
[4]Applies to site between boreholes 32 and 34 (*C-C'*, pl. 1).

trunk streams were unable to cut through the deepest Sangamon estuarine deposits, and (3) the late Holocene rise in sea level exceeds what might be expected from eustatic sea-level changes alone.

QUATERNARY SEDIMENTS AT LEAST 200 M BELOW PRESENT SEA LEVEL

Sediments of Quaternary age may extend at least 200 m below present sea level under much of southern San Francisco Bay, particularly between San Mateo and Hayward and between Menlo Park and Fremont (Finlayson and others, 1967, pl. 5; Meade, 1967, p. 40-41). Assuming that they were deposited during the past 1.5 million years and within 100 m of present sea level, these sediments probably have been lowered by tectonic subsidence of at least 0.07 mm/yr.

Conceivably, an extremely low stand of sea level could have allowed streams draining the bay basin to grade to a base level 200 m below present sea level, thereby allowing Quaternary sediments to accumulate at lower elevations than we assume. However, such a stand of the sea during Pleistocene time is unlikely because it is lower than what might be expected from ice volumes during Pleistocene glacial maxima (Flint, 1971, p. 84) or from the overall rise of sea level independent of glacioeustatic fluctuations (Vasil'kovskiy, 1973, p. 857).

WISCONSIN THALWEGS HIGHER THAN THE DEEPEST SANGAMON ESTUARINE DEPOSITS

The volume of Sangamon estuarine deposits remaining after Wisconsin erosion appears to be close to the volume of post-Wisconsin estuarine sediments under most of southern San Francisco Bay (pl. 1). The Sangamon deposits persisted in such quantity because Wisconsin trunk streams were unable to cut through them: the thalwegs (lines of maximum valley depth) of Wisconsin trunk stream are located at least 15 m above the deepest Sangamon estuarine deposits. Assuming that the trunk stream draining the bay basin during the low stand of sea level before the first major marine transgression of Sangamon age was similar in location, base level, and gradient to the trunk streams during the major low stands of sea level of Wisconsin age, the early Sangamon estuarine deposits must be tectonically depressed below the Wisconsin thalwegs.

The differences in elevation between the ancient land surfaces covered with Sangamon and post-Wisconsin estuarine deposits should approximate the magnitude of this tectonic subsidence during Sangamon and Wisconsin time, a period of about 100,000 years. Assuming that the initial longitudinal profiles of these land surfaces were similar in gradient and elevation, the present differences in elevation between the profiles (fig. 7) indicate the following average rates of tectonic subsidence : 0.2±0.1 mm/yr, between San Francisco and Oakland; 0.4+0.1 mm/yr, between San Mateo and Hayward and between Menlo Park and Fremont.

RELATIVE SEA-LEVEL RISE GREATER THAN THAT EXPECTED FROM EUSTATIC SEA-LEVEL CHANGES ALONE

The record of post-Wisconsin sea levels at southern San Francisco Bay can be used as a datum to determine vertical crustal movement by comparison with sea-level data from areas of presumed crustal stability. Sea level has risen more rapidly in the vicinity of southern San Francisco Bay than in Micronesia by 0.8±0.7 mm/yr during the past 6,000 years (fig. 6). Assuming that the relative sea-level rise in Micronesia approximates purely eustatic changes (Bloom, 1970, p. 1901), the more rapid submergence at the site of southern San Francisco Bay represents downward crustal movement.

Tectonic subsidence is probably the principal component of this crustal movement. Given the range of our uncertainties, the rates of tectonic subsidence during the last 100,000 years of Pleistocene time may be considered equivalent to the rate of late Holocene crustal downwarping (table 3). If the actual rate of Holocene downwarping is as high as 1 mm/yr, however, then tectonic subsidence has accelerated or has been augmented by isostatic downwarping of the continental margin. The likelihood of isostatic adjustment to post-Wisconsin seawater loads has been established for the Atlantic coast of the United States by Bloom (1967b), but at present we cannot differentiate its effects from those of tectonic subsidence in the vicinity of southern San Francisco Bay.

AGE OF THE BEDROCK DEPRESSION CONTAINING SOUTHERN SAN FRANCISCO BAY

Rates of tectonic subsidence can be extrapolated to estimate the age of the structural trough that contains southern San Francisco Bay. For example, the top of Mesozoic bedrock under southern San Francisco Bay is located as much as 200 m below present sea level near Menlo Park (R. M. Hazelwood, oral commun., 1975). Assuming that streams flowing in this area cut no deeper than 100 m below present sea level during a Pleistocene glaciation, this bedrock surface has undergone at least 100 m of tectonic subsidence. Extrapolation of local tectonic subsidence rates, which averaged 0.3–0.5 mm/yr during Sangamon and Wisconsin time, indicates that this subsidence began as recently as 0.2–0.3 m.y. ago.

The structural trough appears to be older in some other areas. The depth to bedrock along the east shore of southern San Francisco Bay near Hayward, for instance, probably exceeds 300 m (R. M. Hazelwood, oral commun., 1975). At subsidence rates of 0.3–0.5 mm/yr, this depth suggests an age of at least 0.4–0.7 m.y. Furthermore, a tuff about 1 m.y. old is found in estuarine sediments 87 m below present sea level in borehole 2 (table 1). This tuff indicates that a structural trough may have been located just east of the site of San Francisco during early Pleistocene.

SUMMARY AND CONCLUSIONS

1. Two units of estuarine deposits are recognized in sediments less than 60 m below present sea level at the site of southern San Francisco Bay (table 1; pl. 1). These deposits were produced by Sangamon and post-Wisconsin high stands of sea level (fig. 2). Estuarine sediments of middle Wisconsin age appear to be absent, suggesting that local sea level was not near its present height 30,000–40,000 years ago.

2. The estuarine deposits of Sangamon and post-Wisconsin age are separated by alluvial and eolian deposits and by erosional unconformities and surfaces of nondeposition (pl. 1). These features indicate lowered base levels and oceanward migrations of the shoreline accompanying low stands of the sea.

3. The late Wisconsin shoreline was situated some distance west of the site of San Francisco (fig. 1). The rising post-Wisconsin sea entered the Golden Gate 10,000–11,000 years ago. As sea level rose about 2 cm/yr, an estuary spread across adjacent land areas as rapidly as 30 m/yr until about 8,000 years ago. Subsequent inundation has been more gradual because the rate of sea-level rise has declined at least tenfold since 8,000 years ago, averaging only 0.1–0.2 mm/yr from 6,000 years ago to the present (figs. 6, 7).

4. Some of the sediments under southern San Francisco Bay appear to be situated below the level at which they initially accumulated. The vertical crustal movement suggested by these sediments (table 3) may be summarized as follows: (a) Some Quaternary(?) sediments have tectonically subsided at least 0.07 mm/yr relative to the lowest likely Pleistocene land surface; (b) the deepest Sangamon estuarine deposits have subsided tectonically 0.2–0.4±0.1 mm/yr relative to the assumed initial elevations of the thalwegs buried by these sediments; and (c) Holocene salt-marsh deposits have undergone about 0.8±0.7 mm/yr of tectonic and possibly isostatic subsidence relative to elevations that might be expected from eustatic sea-level changes alone.

5. Rates of tectonic subsidence and the depth to Mesozoic bedrock indicate that the structural depression containing southern San Francisco Bay may be as young as 0.2–0.3 m.y. in some areas.

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