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ANCIENT PROCESSES AT THE SITE OF SOUTHERN SAN FRANCISCO BAY: MOVEMENT OF THE CRUST AND CHANGES IN SEA LEVEL

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Several kilometers of sea water probably covered the site of San Francisco Bay 150 million years ago. Motion of lithospheric plates fostered sedimentary and structural accretion that subsequently transformed this oceanic abyss into a landmass. The current episode of right-handed movement along the San Andreas fault reflects sideways motion between lithospheric plates that began locally during the past 10-15 million years. Concurrent vertical movement in the vicinity of the Bay, though at least 20 times slower than displacement along the San Andreas fault, probably created the bedrock trough that now contains much of the Bay and closed a strait that once linked the site of the Bay with the Pacific Ocean. Sediment beneath the floor of the Bay suggests that at least four ephemeral estuaries have occupied the site of the Bay during the past 700,000 years. These estuaries presumably reflect global fluctuations in sea level caused by exchange of water between oceans and continental glaciers. The present estuary originated when the Pacific Ocean entered the Golden Gate about 10,000 years ago. Most of the growth of this estuary occurred during the next 5,000 years. Sites of human habitation contemporaneous with this episode of rapid submergence have not yet been discovered in central California, perhaps because they now lie beneath the mud and water of San Francisco Bay.

Though recently transfigured by bridges, levees, and fill, the site of San Francisco Bay[1] has undergone far greater changes during the geologic past. Events recorded by local rocks begin 100-200 million years ago when the oldest of these rocks accumulated beneath several kilometers of sea water. Since that time, the site of the Bay has hosted deep and shallow seas, stream valleys, and hills, as well as estuarine embayments such as we have today (Louderback 1951; Taliaferro 1951; Howard 1951).

Many processes contributed to ancient geographic changes at the site of the Bay. This chapter relates the evolution of southern San Francisco Bay to two major agents of change: (1) movement of the Earth's crust during the past 150 million years, which largely built the bedrock foundation that transformed the site of the Bay from ocean abyss to continental hills and valleys; and (2) worldwide sea-level fluctuations during the past few million years, which have caused episodic submergence and emergence of low-lying valleys and thereby created such ephemeral embayments as the present San Francisco Bay estuary.

CRUSTAL MOVEMENT

Many geologists now attribute movement of the Earth's crust near San Francisco Bay to the

[1] The "San Francisco Bay estuary" refers herein collectively to San Francisco, San Pablo, and Suisun bays; Carquinez Strait; tidal marshes surrounding these bodies of water; and the Sacramento-San Joaquin Delta (see Atwater et al. 1979; Fig. 2). San Francisco Bay, abbreviated "the Bay," borders San Pablo Bay about 7 km southwest of Pinole Point. The part of San Francisco Bay located south of the latitude of the Golden Gate is informally designated southern San Francisco Bay.

SAN FRANCISCO BAY

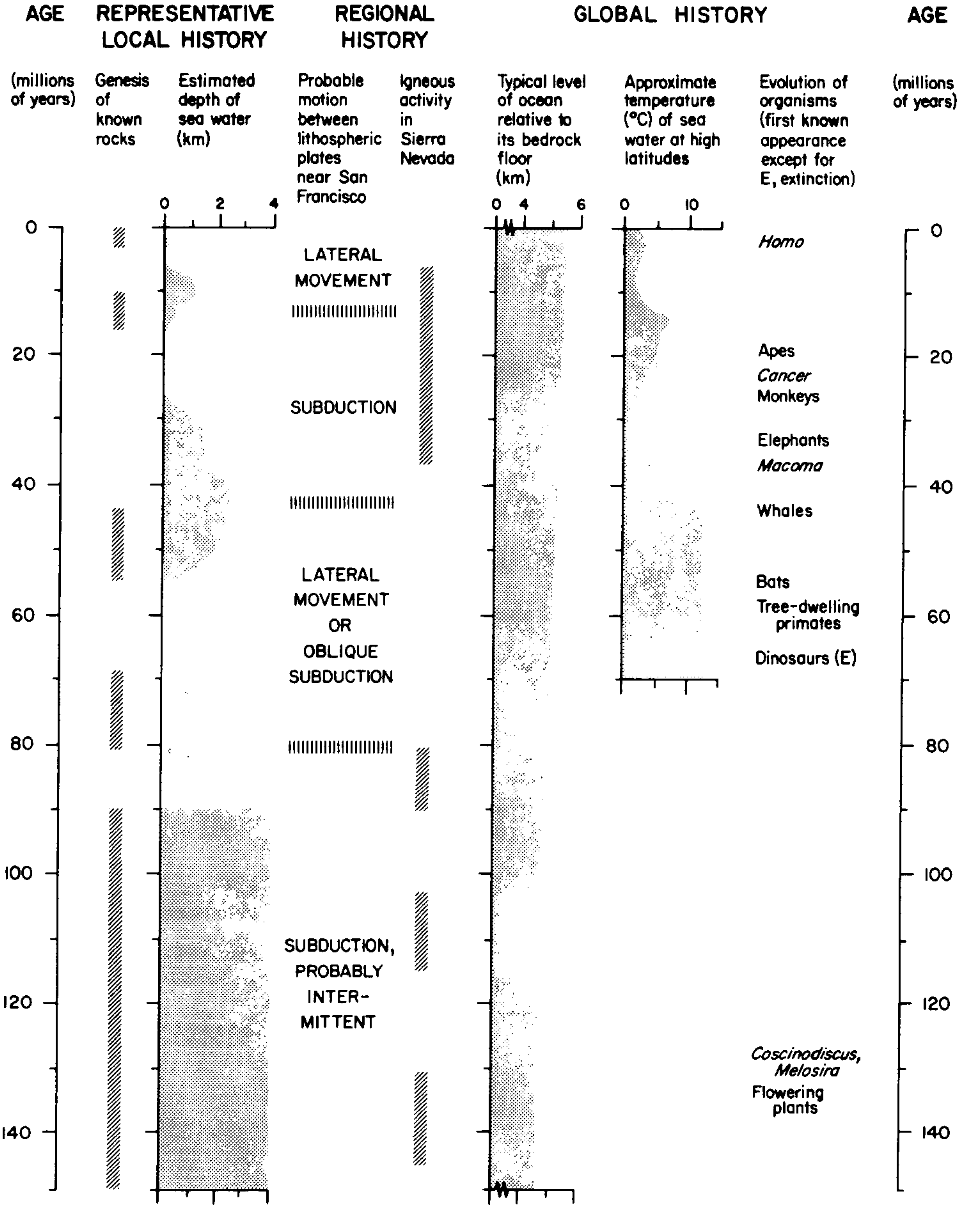

Fig. 1. Elements of local, regional, and global history for the past 150 million years. Local history refers to events and conditions recorded by rocks between southern San Francisco Bay and the San Andreasfault (Graham and Church 1963; Dibblee 1966; Page and Tabor 1967; Clark 1968; Beaulieu 1970: 41, 82, 97). Time periods indicated by bars give maximum probable ranges in age for these rocks. Most of the rocks originated on or beneath the ocean floor. Depths of overlaying water, inferred from such features as fossils and layering, imply multiple episodes of submergence and emergence. No attempt is made to estimate local depths from the 60- to 80-million-year-old rocks because, like some other rocks in western North America (Swe and Dickinson 1970; Blake and Jones 1974; Jones et al. 1977), they may have migrated from a distant place of deposition.

motion of slablike pieces of crust and upper mantle called lithospheric plates (T. Atwater 1970; Blake and Jones 1974). A boundary between plates has probably spanned or flanked the site of San Francisco Bay during most of the past 100-200 million years. For much of this time a western plate (or plates), composed partly of oceanic basalt and a veneer of oceanic sediment, may have slid beneath a continental plate along a roughly north-south-trending zone of convergence. This process, labeled "subduction" (Fig. 1), would have telescoped and imbricated large quantities of crust and upper mantle at or near the site of the Bay. Resulting accumulations of rock would have added substantially to the thickness of the local crust and helped to transform the site of the Bay from an abyssal ocean to shallower seas and dry land.

Today's right-handed displacement along the San Andreas fault and its branches reflects sideways motion between plates rather than subduction. In the vicinity of San Francisco, the current episode of sideways motion (lateral movement, Fig. 1) probably began within the past 15 million years.

Not all recent crustal movement, however, mimics sideways motion between plates. During the past few million years, for example, the crust has risen along the Pacific coast and subsided at the site of southern San Francisco Bay (Lawson 1914; Radbruch 1957; Christensen 1965; Schlocker 1974: 72-74; Bradley and Griggs 1976; Atwater et al. 1977; Helley et al. in press). It is not evident how much, if any, of this vertical motion occurred along known lateral faults. The reasons for uplift and subsidence in the vicinity of the Bay likewise remain mysterious, although one strong possibility is that lateral motion causes compression or extension of the crust where faults diverge from the trend of horizontal plate motion (Crowell 1974; T. Atwater 1970).

It is tempting to depreciate the effects of vertical movement near San Francisco Bay over the past 1 million years, because horizontal movement has been so much faster. While lateral offset along the San Andreas fault has averaged about 10-30 m per millennium (see caption to Fig. 2), subsidence at the site of southern San Francisco Bay and uplift along the Pacific coast to the west have averaged no more than 0.5 m per millennium (Table 1). Nevertheless, vertical movement has contributed to geographic changes. Crustal subsidence, for example, largely created the bedrock trough that contains much of the Bay (Lawson 1914; Louderback 1951; Atwater et al. 1977). A likely consequence of the uplift was the closure of former connection between the Pacific Ocean and the site of the Bay. This connection, located 15-20 km south of the Golden Gate, is evidenced by marine sediments younger than about 0.5 million years that are situated as much as 50 m above modern sea level (the Colma Formation of Bonilla 1971). If, as seems probable from oxygen-isotope records (Fig. 3), sea levels of the past 0.5 million years have not reached such high elevations, then the former strait marked by these sediments has been uplifted. These examples imply that

Depths for long periods lacking a local rock record are estimated from depositional environments of immediately older and younger rocks. Zero depth indicates emergence from the sea. Important processes of regional significance include motion of lithospheric plates (T. Atwater 1970; Travers 1972; Blake and Jones 1974) and igneous activity in the Sierra Nevada (Evernden and Kistler 1970: 17; Lipman et al. 1972). Global changes include a gradual rise in sea level (Vasil'kosskiy 1973), a sporadic decline in temperature of sea water at high latitudes (Savin et al. 1975), and appearance or extinction of organisms (McAlester 1968:87, 112, 123, 130). Italicized names denote some of the genera whose living representatives are mentioned elsewhere in this volume: *Coscinodiscus* and *Melosira*, common among estuarine diatoms; *Macoma*, the genus of clams now including the mudflat-dwelling *M. balthica; Cancer*, generic name of the dungeness crab; and *Homo*, an evolutionary late-comer now represented by approximately 5 million humans near the San Francisco Bay estuary. Times of first appearance for these genera follow Wornardt (1972), Cox et al. (1969), Brooks et al. (1969:509), and Leakey (1976).

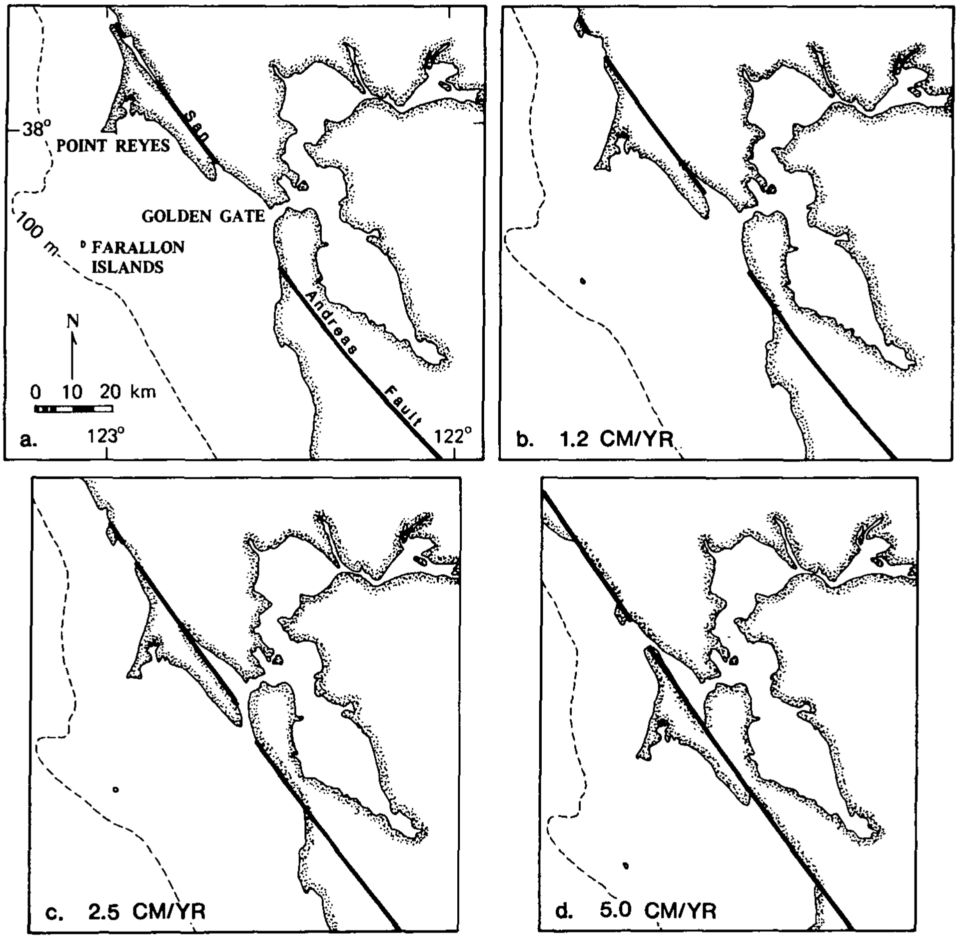

Fig. 2. Hypothetical geography of the San Francisco area 1 million years ago, assuming various rates of right-lateral movement along the San Andreas fault. Geographic reconstructions (B-D) were prepared by cutting a modern map (A) and undoing the lateral displacement that would result from 1 million years of movement at indicated rates. Except where modified for cartographic simplicity, diagrams B-D make no other changes in shorelines and do not compensate for deposition, erosion, sea-level changes, vertical crustal movement, or horizontal offset along other faults. Rates of displacement assumed in diagrams B and C span most of the range of plausible values for movement along the San Andreas fault over the past several million years. Offset during the past 30 million years, as determined by matching distinctive rocks on opposite sides of the fault, averages about 1-3 $cm \cdot yr^{-1}$ (compilations by Grantz and Dickinson 1968; and Dickinson et al. 1972). These rates overlap with estimates of historic offset, which average about 2.5-3.5 $cm \cdot yr^{-1}$ (Nason and Tocher 1970; Savage and Burford 1973). Appreciably faster movement (D) requires that the San Andreas fault accommodate most of the relative motion between bounding plates, which averages about 6 $cm \cdot yr^{-1}$ (Vine 1966; Graham and Dickinson 1978). Such a monopoly seems unlikely because the boundary between plates is considerably more diffuse than a single fault (T. Atwater 1970). Diagram D neglects relocation of fault movement on the San Francisco peninsula; about 10-25 km of indicated offset would probably have occurred along an ancestral trace of the San Andreas fault located as much as 7 km to the west, the present trace having displaced 100-million-year-old rocks by only 25-40 km (Bailey et al. 1964:160; Dibblee 1966).

the hypothetical maps (Fig. 2) may badly misrepresent the ancient landscape by ignoring the vertical component of crustal movement.

CHANGES IN SEA LEVEL

People have long surmised that relative motion between land and sea helped to create San Francisco Bay. Perhaps the oldest surviving statement of this hypothesis is the aboriginal tradition recorded in the diary of Mariano Payeras (1769-1823), a California missionary:

> "The day, May 28 [1818]. I left the presidio of N. P. [San Francisco] accompanied by P. Luis Gil, and Captain Don Luis Arguello in a launch at about 11 o'clock in the morning and from the wharf we came down as far as the middle of the port[.] [W]hat is now the port of San Francisco was formerly according to the tradition of the old ones an oak grove, and without water other than of a river that crossed at its foot, and in evidence of this tradition, they say you still find in the port and marsh, trunks and roots of oak trees" (Payeras 1818).[2]

Pioneer English-speaking geologists also surmised submergence of a bygone valley. Andrew C. Lawson (1894) interpreted the numerous islands, peninsulas, and small embayments near San Francisco as former hills, ridges, and stream valleys drowned by the sea. Inferring that San Francisco Bay did not exist before this submergence, Lawson proposed that the ancestral drainage of the San Joaquin and Sacramento Rivers must have flowed through the Golden Gate to a coastline situated some distance to the west. Grove Karl Gilbert (1917:16-24) deduced submergence not only from drowned topography but also from eroded shorelines and submerged aboriginal middens.

During the past 30 years, geologists have learned about additional motion between sea and land by searching beneath the floor of the Bay. Most of the evidence has come from core samples, plugs of sediment that were collected by engineers to assist in the design of footings for bridges and buildings (Trask and Rolston 1951; Treasher 1963; Goldman 1969). Constituents and properties of these samples, particularly their fossils, grain size, color, and density, commonly indicate whether the sediment accumulated in an estuary or in a stream valley (Atwater et al. 1977). Interpreted in this manner, core samples suggest that estuaries and stream valleys–at least four of each–have alternately occupied the site of the Bay during the past 1 million years (Figs. 3,4; Wagner 1978:137-138). Thus, no fewer than three cycles of submergence and emergence preceded the episode of inundation that created the present estuary.

Origins of Relative Motion between Sea and Land

Global fluctuations in sea level caused by the exchange of water between oceans and continental glaciers are principally responsible for episodic submergence and emergence of the site of the Bay over the past million years. During glacial ages, sheets of ice as thick as several kilometers covered large areas of land at northerly latitudes, particularly in northern Europe, Canada, and northernmost parts of the continental United States (Flint 1971:73-80). In addition, smaller glaciers occupied alpine areas further south, including parts of the Sierra Nevada such as Yosemite Valley (Wahrhaftig and Birman 1965). When this land ice formed, it withdrew large quantities of

[2] Bancroft (1884:247) equates aboriginal peoples with "the old ones", Spaniards with the antecedent of "they", and the whole of San Francisco Bay with the "port of San Francisco". Payeras implies that the trunks and roots came from both evergreen and deciduous oaks ("encinos" and "robles").

water from the oceans, and when it melted, the water returned. Resulting fluctuations in sea level measured as much as 100-150 m, spanned many thousands of years, proceeded as rapidly as 10-20 m per millennium, and probably overshadowed other kinds of motion between sea and land near San Francisco (Table 1).

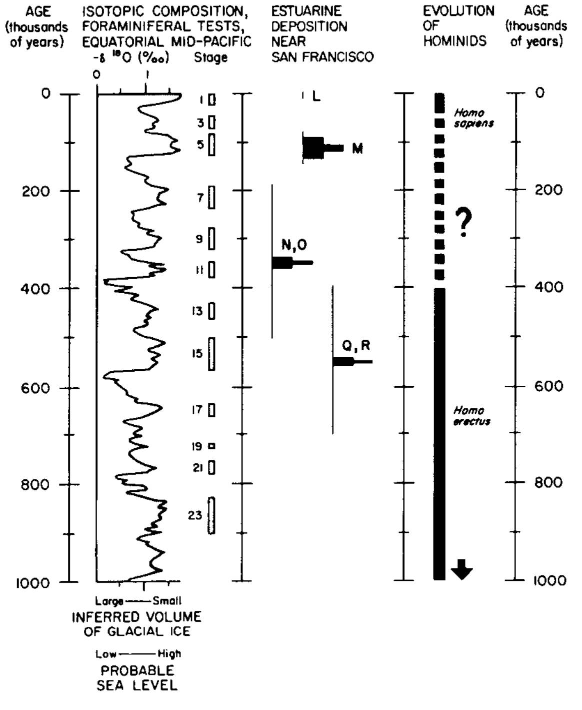

Fig. 3. Probable ages of known estuarine sediment between San Francisco and Oakland. Letters identify units of sediment labeled in Fig. 4. Thin vertical lines show range of likely ages as determined from radiocarbon dates (unit L; Atwater et al. 1977), as estimated from the amino-acid stereochemistry of fossil clams and oysters (unit N; Brian Atwater and John F. Wehmiller, unpublished data), as limited by the magnetic polarity and radiometric ages of volcanic ash (unit Q; C. Naser pers. comm.); G. Dalrymple and M. Lanphere pers. comm.; Sarna-Wojcicki 1976; J. Hillhouse pers. comm., and as required by superposition (unit M underlies sediment older than 40,000 years [Atwater et al. 1977], units N and O underlie unit M, as do units Q and R [Ross 1977]). Bars attached to vertical lines represent time required to build thickest remaining part of unit(s) at average sedimentation rates of 1 m (thick bars) and 3 m (thin bars) per millennium. Measured thicknesses have been multiplied by 1.4 to correct for post-depositional compaction. Assumed rates of deposition are typical average rates for unit L, computed from radiocarbon dates and sediment thicknesses reported by Atwater et al. (1977). The graph at left (Shackleton and Opdyke 1976) shows the relative proportion of heavy (^{18}O) and light (^{16}O) oxygen in the fossil shells (tests) of one-celled marine animals (foraminifera). Variable rates of accumulation have allowed biological mixing and burrowing of bottom sediment to squash some peaks and accentuate others (Schackleton and Opdyke 1976) so that changes in oxygen-isotope composition merely suggest the approximate frequency and relative magnitude of glaciation and sea-level change. Except where dated by reversals in direction of the Earth's magnetic field, isotopic changes are correlated with time by assuming a constant sedimentation rate of 1 cm per millenium (Shackleton and Opdyke 1976). Ranges in age for hominids follow summaries by Leakey (1976) and Tattersall and Eldredge (1977).

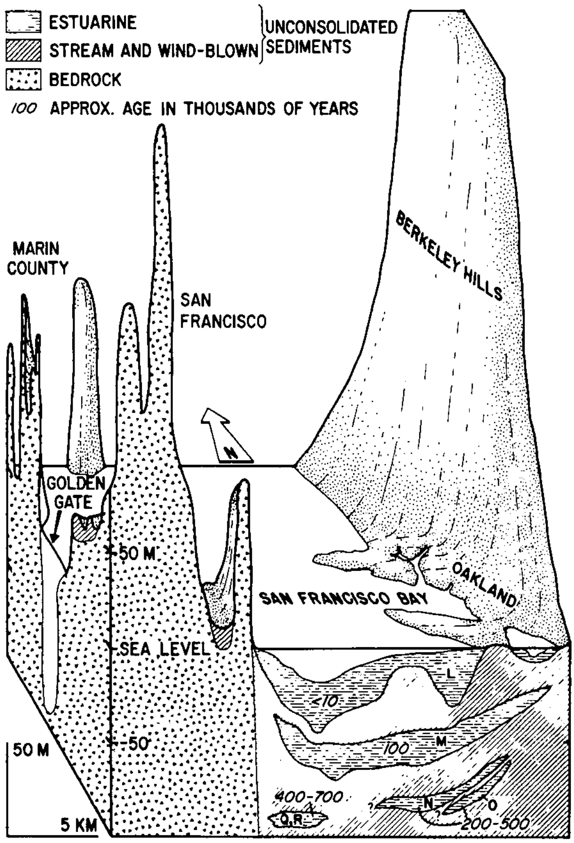

Fig. 4. Generalized cross section of some rocks and sediment near San Francisco. Front panel modifies and combines two slightly different cross sections: one by Ross (1977), and the other by Atwater et al. (1977, sections A-A'). Both sections rely on samples and descriptions from boreholes that explored the foundations of proposed bridges, moles, and tunnels. Estuarine sediment is keyed by letter to Fig. 3. Ranges in age for estuarine sediment below unit M reflect uncertainties in measurement rather than long episodes of deposition. Shorelines of the bay denote reach of highest tides circa 1850 (Nichols and Wright 1971).

If ice ages account for the fluctuating sea levels, then what accounts for the ice ages? Currently foremost among a multitude of theories are motion of lithospheric plates and changes in the Earth's rotation and orbit.

Motion of lithospheric plates promoted the ice ages by rafting continents to high latitudes (Ewing and Donn 1956; Donn and Shaw 1977). About 50 million years ago, oceans rather than continents covered the geodetic poles of the Earth. It seems unlikely that large ice sheets routinely covered these polar seas because the surface water was warm—perhaps 10-12°C (Savin et al. 1975; Fig. 1)—owing to communication with low-latitude oceans. Later, however, drifting continents gradually displaced these mild seas and disrupted interchange of polar and equatorial water. Resulting insolation and refrigeration of polar regions apparently prepared these areas for continental glaciation.

Cycles in the orientation of the Earth's axis and the shape of its orbit probably triggered the

TABLE 1. SOME KINDS OF RELATIVE CHANGE IN LEVEL BETWEEN LAND AND SEA. MAGNITUDES AND RATES GIVE ESTIMATES FOR THE VICINITY OF SAN FRANCISCO BAY DURING THE PAST ONE MILLION YEARS.

Principal Causes	Maximum Probable Magnitude (m)	Typical Duration	Typical Average Rate $(m \cdot 1000\ yr^{-1})$	Oscillatory (O) or Uni-directional (D)	References
Rise or fall of the sea[1]					
Waves, swells	5	seconds			
Astronomical tides	3	hours			
Meteorological tides atmospheric pressure, wind, river discharge	5	hours, days, years	NA[2]	O	Lisitzin (1974)
Astronomical cycles of tides	1	weeks, years			
Exchange of H_2O between oceans and glaciers	150	thousands of years	1-20	O	Flint (1971: 315-342)
Reduction in area of oceans because of continental accretion; increase in volume of ocean water because of liberation of water from the earth's interior	1	billions of years	0.001	D	Vasil'kovskiy (1974); partial record shown in Fig. 1, this chapter
Subsidence or uplift of coastal land[1]					
Adjustment of the earth's crust to addition or removal of sea water and glacial ice	10	thousands of years	0.1-1.0	O	Bloom (1971); Clark et al. (1978)
Vertical crustal movement probably related to motion of lithospheric plates	300	thousands and millions of years	0.5-0.5	D,O	Bradley and Griggs (1976); Atwater et al. (1977)

[1] Motion referenced to a stable plane or point such as the center of the earth

[2] NA - Not applicable

principal episodes of glaciation and deglaciation that have occurred since polar lands approached their present positions. According to a theory named after one of its advocates, Mulutin Milankovich, these astronomical cycles have periodically prevented the summer sun from melting all of a winter's snow at high northerly latitudes. Considerable support for the Milankovich theory comes from changes in the ratio of heavy (^{18}O) to light (^{16}O) oxygen in fossil cells of one-celled marine animals (Hays et al. 1976). It seems likely that, during the past one million years, these changes have mainly reflected the oxygen-isotope composition of sea water (Shackleton and Opdyke 1976: 459). The ratio of ^{18}O to ^{16}O in sea water depends on evaporation and fresh-water input because water containing ^{18}O evaporates less readily than water containing ^{16}O. Thus, a high concentration of ^{18}O in fossil shells ($-\delta^{18}O$ between 0 and 1, Fig. 3) implies the large glaciers and low sea levels of the ice ages, and lower concentrations of ^{18}O ($-\delta^{18}O$ greater than 1) imply small glaciers and high sea levels, such as we have today.

Legacies of Ancient Sea Levels

Ephemeral estuaries probably occupied low-lying areas at or near the site of the Bay each time the sea approached its present level during the past 0.5-1.0 million years (that is, during most odd-numbered stages in Fig. 3). Sediment from at least four of these estuaries has been found beneath the site of the Bay (Ross 1977; Fig. 4), and evidence of other estuaries probably remains to be discovered or confirmed. The youngest known estuarine sediment corresponds to the current high stand of the sea (Figs. 3, 4: unit L, stage 1) and its immediate predecessor (unit M, stage 5). Older sediment (units N, O, Q, P) cannot yet be assigned to a single isotopic stage because of uncertainty about its age (Fig. 3, thin vertical lines).[3]

Crustal subsidence appears to have moved some estuarine deposits below the reach of glacial-age streams, thereby limiting the erosion of units M, N, O, Q, and R during low stands of the sea. The continuity, thickness, and depth of unit M, for instance, seem best explained by a downward crustal movement of 20 m (Atwater et al. 1977). Older estuarine sediment also appears to have subsided, though not fast enough to escape considerable erosion. Largely as the result of such erosion, known sediment beneath the floor of the Bay records neither the full number nor the full duration of Pleistocene high stands of the sea (Fig. 3).

Growth of the Most Recent Estuary

The episode of submergence that created San Francisco Bay began about 15,000-18,000 years ago, when glaciers of the last ice age started their retreat (Prest 1969). At the onset of glacial retreat, the Pacific Ocean lapped against a shoreline located near the Farallon Islands (Fig. 6). In order to meet this shoreline, the combined Sacramento and San Joaquin Rivers must have flowed through the Golden Gate and traversed an exposed continental shelf. Some of the riverborne sand that reached flood plains and beaches on the shelf was probably swept by westerly winds into the ancient dunes that covered much of the site of San Francisco and extended across the site of the Bay to Oakland (Atwater et al. 1977). Southeast of these dunes was a broad stream valley in which roamed now-extinct species of camel, horse, bison, and ground sloth (Helley et al. in press).

Most of the submergence that transformed this landscape occurred earlier than 5,000 years ago (Fig. 6). Initial migration of shorelines brought the rising sea into the Golden Gate about 10,000 years ago. During the next few thousand years, the newborn estuary spread as rapidly as 30 $m \cdot yr^{-1}$ across low-lying areas in response to a rise in relative sea level that averaged nearly 2

[3] J. F. Wehmiller, J. W. Hillhouse, Andrei Sarna-Wojcicki, and I are refining the chronology of sediments below unit M. Ages shown in Figs. 3 and 4 will probably be revised by us and by others.

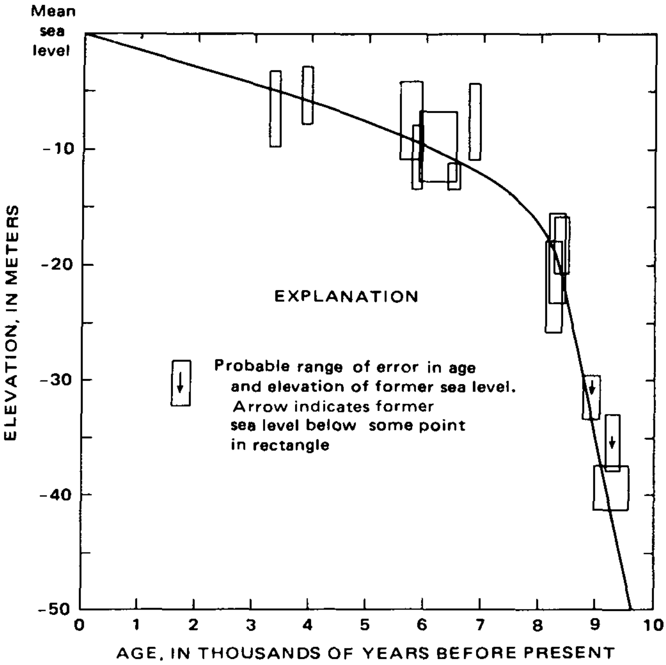

Fig. 5. Changes in sea level relative to land during the past 10,000 years at the site of southern San Francisco Bay (after Atwater et al. 1977). Boxes represent uncertainty in reckoning former sea levels from radiocarbon ages and elevations of plant fossils from unit L (Fig. 4). Most of the dated fossils originated as vascular plants in ancient tidal marshes. By analogy with their modern counterparts (Atwater et al. 1979, Figs. 7, 10), these plants probably grew very close to contemporaneous sea levels. See Kvenvolden (1962) and Storey et al. (1966) for additional radiocarbon dates pertaining to changes in sea level at the site of San Francisco Bay.

$cm{\cdot}yr^{-1}$ (Fig. 5; Atwater et al. 1977). Thereafter, relative sea level changed more slowly because, by 5,000 years ago, glaciers had reached approximately their present size (Bloom 1971). Submergence since that date has averaged only 0.1-0.2 $cm{\cdot}yr^{-1}$ and probably includes a large component of crustal subsidence (Atwater et al. 1977).

The difference in rates of submergence before and after 5,000 years ago may influence the apparent antiquity of human habitation in the vicinity of San Francisco Bay. Settlement of the Americas began at least 20,000 years ago, and by 10,000 years ago people inhabited much of the continental United States (Haynes 1969). However, no known archeological site in central California appears much older than 5,000 years (Gerow and Force 1968:174). One way to approach this problem is to assume that traces of the earliest central Californians have been covered by the rising sea. Given the rapidity of changes in sea levels and shorelines 5,000-10,000 years ago, sites of habitation located at that time along the shores of estuaries must now lie beneath mud and tidal water. Sites younger than 5,000 years, alternatively, postdate rapid submergence and would therefore more likely escape total inundation (K. Lajoie pers. comm.).

How old, then, is the aboriginal tradition recorded by Mariano Payeras? If originated by people who actually saw the site of the Bay before widespread submergence, this tradition must be nearly 10,000 years old. Such antiquity, though improbable, cannot be ruled out in light of Lajoie's hypothesis. Alternatively, the tradition originated as entertainment or science among people of the past 5,000 years. Too late to observe a stream at the site of the Bay, some of these people may nevertheless have deduced its former presence; perhaps, like Gilbert and Lawson, they read ancient history from soggy middens and drowned topography.

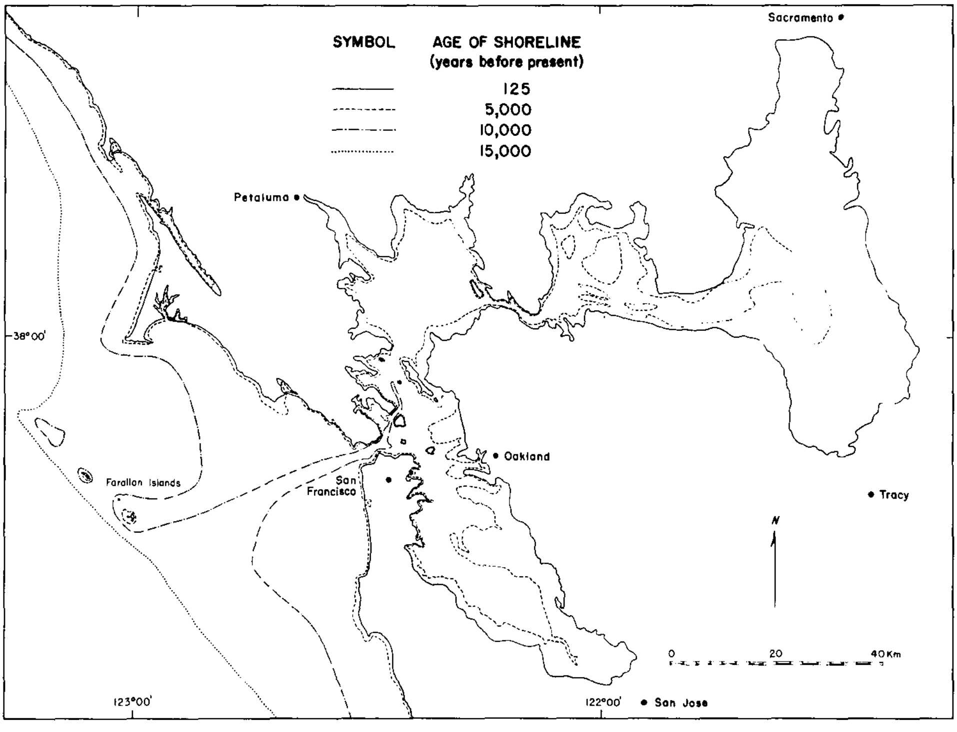

Fig. 6. Approximate high-tide shorelines near San Francisco during the past 15,000 years. The 125-year-old shoreline, based on compilations by Gilbert (1917:76) and Nichols and Wright (1971), denotes the landward edge of tidal marshes before human encroachment or, where no marsh was present, the high-water line circa 1850. Locations of older shorelines are estimated by projecting sea levels of the past 15,000 years onto the land surface inundated by the growing estuary during this time. We assume the following sea levels, expressed relative to present mean sea level (Fig. 5; Flint 1971:321): 5,000 years ago, -8 m; 10,000 years ago, -55 m; and 15,000 years ago, -100 m. Topography of the ancient land surface east of the Golden Gate follows reconstructions by Goldman (1969, pl. 3), the U. S. Army Corps of Engineers (1963, pls. 6-7), Carlson et al. (1970), and B. Atwater, S. D. McDonald, and D. R. Nichols (unpublished data). Because of variations in abundance and quality of boreholes and acoustic profiles, these topographic reconstructions are most accurate for the southern arm of the estuary and least accurate for open-water areas of the northern part of the estuary. Topography of the ancient land surface west of the Golden Gate is inferred mostly from modern water depths as shown on NOS Nautical Charts 5402 and 5502. Local adjustments uncontrolled by boreholes or subbottom profiles attempt to correct for differences between modern bathymetry and ancient topography. Location of the 10,000-year-old shoreline between San Francisco and the Farallon Islands depends greatly on such adjustments and is therefore extremely speculative.

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LITERATURE CITED

Atwater, B. F., C. W. Hedel, and E. J. Helley. 1977. Late Quaternary depositional history, Holocene sea-level changes, and vertical crustal movement, southern San Francisco Bay, California. U. S. Geol. Surv. Prof. Paper 1014. 15 pp.

Atwater, B. F. et al. 1979. History, landforms and vegetation of the estuary's tidal marshes. Pages 347-386 *in* T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, Amer. Assoc. Advance. Sci., San Francisco, Calif.

Atwater, T. 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. Geol. Soc. Amer. Bull. 81:3513-3536.

Bailey, E. H., W. P. Irwin, and D. L. Jones. 1964. Franciscan and related rocks and their significance in the geology of western California. Calif. Div. Mines and Geol. Bull. 183. 173 pp.

Bancroft, H. H. 1884. History of California, 1542-1800, vol. 1; volume 18 of The Works of Hubert Howe Bancroft. A. L. Bancroft & Co., San Francisco, Calif. 744 pp.

Beaulieu, J. D. 1970. Cenozoic stratigraphy of the Santa Cruz Mountains and inferred displacement along the San Andreas fault. Ph.D. Thesis. Stanford University, Stanford, Calif. 101 pp.

Blake, M. C., and D. L. Jones. 1974. Origin of Franciscan melanges in northern California. Pages 345-357 *in* R. H. Dott, Jr. and R. H. Shaver, eds. Modern and Ancient Geosynclinal Sedimentation. Soc. Econ. Paleont. and Mineral., Special Publication 19.

Bloom, A. L. 1971. Glacial-eustatic and isostatic controls of sea level since the last glaciation. Pages 355-379 *in* K. K. Turekian, ed. The Late Cenozoic Glacial Ages. Yale University Press, New Haven, Conn.

Bonilla, M. G. 1971. Preliminary geologic map of the San Francisco South Quadrangle and part of the Hunters Point Quadrangle, California. U. S. Geol. Surv. Misc. Field Invest. Map MF-311, scale 1:24,000.

Bradley, W. C., and G. B. Griggs. 1976. Form, genesis, and deformation of central California wave-cut platforms. Geol. Soc. Amer. Bull. 87(3):443-449.

Brooks, H. K. et al. 1969. Arthropoda 4. Pages 400-641 *in* R. C. Moore, ed. Treatise on Invertebrate Paleontology, part R. Geol. Soc. Amer. and University of Kansas, Lawrence, Kan.

Carlson, P. R., T. R. Alpha, and D. S. McCulloch. 1970. The floor of San Francisco Bay. Calif. Geol. 23:97-107.

Christensen, M. N. 1965. Late Cenozoic deformation in the Central Coast Ranges of California. Geol. Soc. Amer. Bull. 76:1105-1124.

Clark, J. A., W. E. Farrell, and W. R. Peltier. 1978. Global changes in postglacial sea level: a numerical calculation. Quat. Res. 9(3):265-287.

Clark, J. C. 1968. Correlation of the Santa Cruz Mountains Tertiary—implications for San Andreas history. Pages 166-180 *in* W. R. Dickinson and Arthur Grantz, eds. Proceedings of Conference on Geologic Problems of San Andreas Fault System. Stanford University Pubs. Geol. Sci., vol. 11.

Cox, L. R. et al. 1969. Mollusca 6, Bivalvia. Pages 1-951 *in* R. C. Moore, ed. Treatise on Invertebrate Paleontology, part N. Geol. Soc. Amer. and University of Kansas, Lawrence, Kan.

Crowell, J. C. 1974. Origin of late Cenozoic basins in southern California. Pages 190-204 *in* W. R. Dickinson, ed. Tectonics and Sedimentation. Soc. Econ. Paleont. Mineral. Special Publication 22.

Dibblee, T. W., Jr. 1966. Geologic map of the Palo Alto 15-minute quadrangle, California. Calif. Div. Mines and Geol. Map Sheet 8, scale 1:62,500.

Dickinson, W. R., D. S. Cowan, and R. A. Schwickert. 1972. Test of the new global tectonics–discussion. Amer. Assoc. Petrol. Geol. Bull. 56:375-384.

Donn, W. L., and D. M. Shaw. 1977. Model of climate evolution based on continental drift and polar wandering. Geol. Soc. Amer. Bull. 88:390-396.

Evernden, J. F., and R. W. Kistler. 1970. Chronology of emplacement of Mesozoic batholith complexes in California and Western Nevada. U. S. Geol. Surv. Prof. Paper 623. 42 pp.

Ewing, M., and W. L. Donn. 1956. A theory of ice ages. Science 123:1061-1066.

Flint, R. F. 1971. Glacial and Quaternary geology. John Wiley, New York. 892 pp.

Gerow, B. A., and R. W. Force. 1968. An analysis of the University Village complex; with a reappraisal of central California archeology. Stanford University Press, Stanford, Calif. 109 pp.

Gilbert, G. K. 1917. Hydraulic-mining debris in the Sierra Nevada. U. S. Geol. Surv. Prof. Paper 105. 154 pp.

Goldman, H. B. 1969. Geology of San Francisco Bay. Pages 9-29 *in* H. B. Goldman, ed. Geologic and Engineering Aspects of San Francisco Bay Fill. Calif. Div. Mines and Geol. Special Rep. 97.

Graham, J. J., and C. C. Church. 1963. Campagnian foraminifera from the Stanford University campus, California. Stanford University Pubs. Geol. Sci. 8: 107 pp.

Graham, S. A., and W. R. Dickinson. 1978. Evidence for 115 kilometers of right slip on the San Gregorio-Hosqri fault trend. Science 199(13):179-181.

Grantz, A., and W. R. Dickinson. 1968. Indicated cumulative offsets along the San Andreas fault in the California Coast Ranges. Pages 117-119 *in* W. R. Dickinson and Arthur Grantz, eds. Proceedings of Conference on Geologic Problems of San Andreas Fault System. Stanford University Pubs. Geol. Sci., vol. 11.

Haynes, C. V. 1969. The earliest Americans. Science 166:709-715.

Hays, J. D., J. Imbrie, and N. J. Shackleton. 1976. Variations in the earth's orbit–pacemaker of the ice ages. Science 194:1121-1132.

Helley, E. J., K. R. Lajoie, W. E. Spangle, and M. L. Blair. In press. Flatland deposits of the San Francisco Bay region, California–their geology and engineering properties, and their importance to comprehensive planning. U. S. Geol. Surv. Prof. Paper 943. 290 pp.

Howard, A. D. 1951. Development of the landscape of the San Francisco Bay counties. Pages 95-106 *in* O. P. Jenkins, ed. Geologic Guidebook of the San Francisco Bay Counties. Calif. Div. Mines Bull. 154.

Jones, D. L., N. J. Silberling, and J. Hillhouse. 1977. Wrangellia–a displaced terrane in northwestern North America. Canadian J. Earth Sci. 14(11):2565-2577.

Kvenvolden, K. A. 1962. Normal paraffin hydrocarbons in sediments from San Francisco Bay, California. Amer. Assoc. Petrol. Geol. Bull. 46(9):1643-1652.

Lawson, A. C. 1894. The geomorphogeny of the coast of Northern California. University of California Dep. Geol. Bull. 1:241-271.

Lawson, A. C. 1914. Description of the San Francisco district (Tamalpais, San Francisco, Concord, San Mateo, and Hayward quadrangles). U. S. Geol. Surv. Geol. Atlas, Folio 193. 25 pp.

Leakey, R. B. 1976. Hominids in Africa. Amer. Sci. 64(2):174-178.

Lipman, P. W., H. J. Prosktka, and R. L. Christiansen. 1972. Cenozoic volcanism and plate tectonic evolution of the western United States, Part I, early and middle Cenozoic. Phil. Trans. R. Soc. London, Series A. 271:217-248.

Lisitzin, E. 1974. Sea-level changes. Elsevier Oceanography Series, 8. 286 pp.

Louderback, G. D. 1951. Geologic history of San Francisco Bay. Pages 75-94 *in* O. P. Jenkins, ed. Geologic Guidebook to the San Francisco Bay Counties. Calif. Div. Mines Bull. 154.

McAlester, A. L. 1968. The history of life. Foundation in earth science series. Prentice-Hall,

Englewood Cliffs, N. J. 151 pp.
Nason, R. D., and D. Tocher. 1970. Measurement of movement on the San Andreas fault. Pages 246-254 *in* L. Mansinha et al., eds. Earthquake Displacement Fields and the Rotation of the Earth. D. Reidel Publishing Co., Dordrcht, Holland.
Nichols, D. R., and N. A. Wright. 1971. Preliminary map of historic margins of marshland, San Francisco Bay, California. U. S. Geol. Surv. Open-File Map, scale 1:125,000.
Page, B. M., and L. L. Tabor. 1967. Chaotic structure and decollment in Cenozoic rocks near Stanford University, California. Geol. Soc. Amer. Bull. 78:1-12.
Payeras, M. 1818. Noticia de un viage a San Rafael (MS). Page 153 *in* Espediciones y Caminatas, 1806-1821, *in* Archivo de la Santa Barbara, tom. IV.
Prest, V. K. 1969. Retreat of Wisconsin and recent ice in North America. Geol. Surv. Canada Map 1257A, Scale 1:5,000,000.
Radbruch, D. H. 1957. Areal and engineering geology of the Oakland West Quadrangle, California. U. S. Geol. Surv. Misc. Geol. Invest. Map. I-239, scale 1:24,000.
Ross, B. E. 1977. The Pleistocene history of San Francisco Bay along the Southern Crossing. M.S. Thesis. San Jose State University, San Jose, Calif. 121 pp.
Sarna-Wojcicki, A. M. Correlation of the late Cenozoic tuffs in central California by means of trace and minor element chemistry. U. S. Geol. Surv. Prof. Paper 972. 30 pp.
Savage, J. C., and R. O. Burford. 1973. Geodetic determination of relative plate motion in central California. J. Geophys. Res. 78:832-845.
Savin, S. M., R. G. Douglas, and F. G. Stehli. 1975. Tertiary marine paleotemperatures. Geol. Soc. Amer. Bull. 86:1499-1510.
Schlocker, J. 1974. Geology of the San Francisco North Quadrangle, California. U. S. Geol. Surv. Prof. Paper 782. 109 pp.
Shackleton, N. J., and N. D. Opdyke. 1976. Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239 late Pliocene to latest Pleistocene. Pages 449-464 *in* R. M. Cline and J. D. Hays, eds. Investigation of Late Quaternary Paleooceanography and Paleoclimatology. Geol. Soc. Amer. Mem. 145.
Storey, J. A., V. E. Wessels, and J. A. Wolfe. 1966. Radiocarbon dating of recent sediments in San Francisco Bay. Calif. Div. Mines and Geol. Min. Inf. Service 19(3):47-50.
Swe, W., and W. R. Dickinson. 1970. Sedimentation and thrusting of late Mesozoic rocks in the Coast ranges near Clear Lake, California. Geol. Soc. Amer. Bull. 81:164-188.
Taliaferro, N. L. 1951. Geology of the San Francisco Bay counties. Pages 117-150 *in* O. P. Jenkins, ed. Geologic Guidebook of the San Francisco Bay Counties. Calif. Div. Mines Bull. 154.
Tattersall, I., and N. Eldredge. 1977. Fact, theory, and fantasy in human paleontology. Amer. Sci. 65:204-211.
Trask, P. D., and J. W. Rolston. 1951. Engineering geology of San Francisco Bay, California. Geol. Soc. Amer. Bull. 62:1079-1110.
Travers, W. B. 1972. A trench off central California in Late Eocene-Early Oligocene time. Pages 173-182 *in* R. Shagam et al., eds. Studies in Earth and Space Sciences, Harry Hess volume. Geol. Soc. Amer. Mem. 132.
Treasher, R. C. 1963. Geology of the sedimentary deposits in San Francisco Bay, California. Calif. Div. Mines and Geol. Special Rep 82, pp. 11-24.
U. S. Army Corps of Engineers. 1963. Technical report on San Francisco Bay barriers, Appendix E. U. S. Army Engineer District, San Francisco. 136 pp.
Vasil'kovskiy, N. P. 1973. Sea level changes in the geological past. P. P. Shirsov Inst. Oceanology, U.S.S.R. Acad. Sci. pp. 847-859.
Vine, F. J. 1966. Spreading in the ocean floor—new evidence. Science 154:1405-1415.
Wagner, D. B. 1978. Environmental history of central San Francisco Bay with emphasis on foraminiferal paleontology and clay mineralogy. Ph.D. Thesis. University of California, Berkeley, Calif. 274 pp.
Wahrhaftig, C., and J. H. Birman. 1965. The Quaternary of the Pacific Mountain system in Cali-

fornia. Pages 299-340 *in* H. E. Wright, Jr. and D. G. Frey, eds. The Quaternary of the United States. Princeton University Press, Princeton, N. J.

Wornardt, W. W., Jr. 1972. Stratigraphic distribution of diatom genera in marine sediments of the western United States. Palaeogeog., Palaeoclim., Palaeoecol. 12:49-74.